The Fertigation Bible

Technologies to optimise fertigation in intensive horticulture.

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About the Fertigation Bible

The Fertigation Bible has been prepared to provide useful practical information to the horticultural sector of the diverse technologies available for all aspects of fertigation within the EU. The technologies have been organised into the following chapters:

Each of chapters 2-12 consists of a series of technical descriptions (TDs) of individual technologies. Each technology is described in terms of:

- Purpose/aim of the technology
- Regions, crops and cropping systems where it is used
- Working principle of operation
- Operational conditions
- Cost data
- Benefits for the grower – advantages and disadvantages
- Technological, socio-economic and regulatory bottlenecks and limitations
- Techniques resulting from this technology
- Supporting systems required
- Development, i.e. if it is in a research or development stage, or has been commercialised
- Who provides the technology

A list of abbreviations used through the Fertigation Bible can be found at the end of the document. A total of 125 such technology descriptions are provided.

Considerable effort was made to ensure that the Fertigation Bible is as comprehensive as possible. Various members of the FERTINNOWA project, from 23 organisations from 9 countries, have worked on this document to describe the most commonly-used and promising technologies that are commercially available or are expected to be so in the near future.

If you wish to cite the Fertigation Bible and its contents, please consider the following suggestions:

1) For the FB as a whole, treat the FB as a book: Thompson, R.B, Delcour, I., Berkmoes, E., Stavridou (Editors) (2018). The Fertigation Bible. http://www.fertinnowa.com/the-fertigation-bible/
2) For individual technical descriptions: Berkmoes, E., Lechavallier, E. (2018). Lined (rain) water storage. In: R.B. Thompson, I. Delcour, E. Berkmoes, E. Stavridou (Eds). The Fertigation Bible. pp. 2-12–2-21. http://www.fertinnowa.com/the-fertigation-bible/
3) The details of the citation would follow the procedures of the formatting style of the document being prepared

Our special thanks goes to Joachim Audenaert (PCS) for his very effective work to organise, initiate and encourage the writing of the technical descriptions that form the basis of Fertigation Bible.

While much effort was made to include all relevant technologies, it is possible that some relevant technologies have not been included. Also, given the size of the European Union, the information on prices is to inform of the likely price range. Similarly, with suppliers, the information is usually limited to one to several different regions of the contributing author/s. We have tried to make the description of each technology as complete as possible, but in the context of the EU, we accept that there will be some gaps.

We hope that you find this document useful.

The Fertigation Bible Team

EXECUTIVE SUMMARY

Fertigation is the practice of applying fertiliser to a crop via the irrigation system. In the context of horticulture (fruit, vegetable and ornamental production), fertigation is most commonly used with drip irrigation. The large, rapid and ongoing increase in the adoption of drip irrigation in horticulture has facilitated a similar on-going increase in the use of fertigation.

This document, “The Fertigation Bible”, has been prepared by the FERTINNOWA project (www.fertinnowa.com) whose main objective is to provide useful information to the horticultural sector of the diverse technologies available for all aspects of fertigation. In addition to this document, the FERTINNOWA project is developing information in various user-friendly formats (factsheets, practice abstracts, all available at www.fertinnowa.com) related to all aspects of fertigation.

The combined use of fertigation with pressurised irrigation systems, such as drip or advanced sprinklers, provides numerous potential practical advantages to the grower. Amongst the most important advantages, of combined fertigation and pressurised irrigation, are the reduction and often elimination of mechanical fertiliser application with the associated labour savings, reduced total irrigation volumes, automation of both irrigation and nutrient application, and the potential for a much more precise control over irrigation and nutrient application throughout a crop.

Currently, and increasingly in the future, horticulture in the European Union (EU) will be conducted in the context of reduced water supply and the implementation of regulations to reduce environmental impacts. In addition to the practical and economic advantages of fertigation, increasing environmental, political and consumer pressure to reduce water use and the loss of nutrients to natural water bodies will make fertigation increasingly attractive to growers.

An optimally effective fertigation system in the context of modern farming is more than the addition of nutrients to the water, it involves optimising various steps in an on-farm water cycle in which water enters the farm from natural sources, passes through the crop production process and is returned to the natural environment. In this context, fertigation can be considered to involve a sequence of processes that form the “fertigation sequence”.

For this document, the fertigation sequence has been considered to consist of the following broad sections and sub-sections:

- Providing water
- Optimising water quality (sub-sections: chemical composition, particle removal, control of algae, disinfection)
- Fertigation equipment (sub-sections: irrigation, nutrient addition, soilless systems)
- Fertigation management (sub-sections: irrigation, nutrients and salinity)
- Reducing environmental impact - nutrient removal and recovery

In addition, describing many of the techniques and technologies available to optimise the various parts of the fertigation sequence, this document identifies the practical technical and management issues associated with optimising the use of these technologies. Each of the 125 techniques and technologies presented in this document is described in the following terms:

- Purpose/aim of the technology
- Working Principle of operation
- Operational conditions
- Costs
- Technological bottlenecks
- Benefit for the grower
- Supporting systems needed
- Development phase (Is it commercialised, in development etc.?)
- Who provides the technology
- Regulatory bottlenecks
- Socio-economic bottlenecks

The following paragraphs provide an overview of many of the techniques and technologies presented in each of the broad sections of the fertigation sequence referred to previously.

For the provision of water for fertigation, the available technologies for enhancing the supply of water include those that minimise losses by drainage from storage basins (lining storage basins) or by evaporation (covers, underground storage) and tools for calculating the dimensions of water storage facilities. The collection of rainwater and of condensed water from greenhouses increases the volume of available water. In water storage facilities, floating pumps have advantages.

Ensuring adequate water quality is fundamental for ensuring optimal crop irrigation and water management, and for the effective and on-going operation of the main fertigation unit. Four classes of technologies can be considered: 1) altering chemical composition, 2) particle removal, 3) control of algae, and 4) disinfection; the latter is mostly for fertigation systems with recirculation of drainage water. The tools and techniques for modifying chemical composition include various physical methods for removal of unwanted chemical components such as reverse and forward osmosis, ion exchange, electrodialysis, and nanofiltration amongst others, and also chemical methods such as pH adjustment. The tools and techniques for particle removal include a variety of filtration methods. For the control of algae in storage basins, a range of various diverse techniques is available. Amongst others, these include control with different chemicals, the use of aquatic plants or fish, the use of blue dye, the use of introduced water fleas, and the use of ultrasound technologies. A similarly wide range of diverse techniques is available for the disinfection of incoming water or of recirculating nutrient solutions where recirculation is practised. These include chemical addition (e.g. peroxide, chlorination), filtration systems (sand, biofiltration), physical processes (thermal disinfection and ultraviolet disinfection) and physio-chemical processes (photocatalytic oxidation, ozonisation, ionisation procedures).

Fertigation equipment can be considered as being equipment used for irrigation, and for nutrient addition. In this document, soilless cropping systems are also considered as being fertigation equipment. Irrigation equipment includes pipes for drip systems, drip emitters, subsurface drip irrigation (SDI), and innovative pipes and drippers with anti-microbial and anti-roots functionalities. There are numerous systems for nutrient addition such as simple fertiliser tanks, injection pumps, equipment with magnetic-drive pumps, mixing tanks, and manual and automatic venturi systems. Numerous substrates are available for use as the growing medium, the principal ones being rock wool, perlite and coconut fibre (coir). Closed and semi-closed substrate systems with complete and partial recirculation, respectively, are management options that have appreciable technical component. In addition to conventional substrate growing systems, a variety of hydroponic systems, with recirculation, are available, including Ebb and Flow, Nutrient Film Technique and Deep Flow Technique.

Fertigation management, at crop level, involves both irrigation and fertiliser management. A wide variety of diverse techniques and technologies are available to optimise irrigation management. For irrigation management, these methods can be broadly considered as being irrigation strategies, calculations of crop water requirements based on estimated crop water use, sensors to assess soil water status, sensors to assess crop/plant water status, and the use of decision support systems (DSS) to assist with calculation of crop water requirements. Additionally, there are some techniques that are specific to substrate-grown crops.

For nutrient management, techniques and technologies presented include fertiliser recommendation schemes, analysis of soil-water extracts or of the soil solution, analysis of leaf tissue or plant sap, various optical sensors to assess crop nitrogen status, and models and decision support systems (DSSs) that assist with the calculation of crop nutrient requirements. Additionally, nutrient management involves the choice of fertilisers such as slow release and organic fertilisers. Nutrient and irrigation management of fertigated crops also involves salinity management - available tools include established agronomic approaches, and also newer sensor approaches. For nutrient management of substrate-grown crops, there are procedures to measure the nutrient content and salinity of the drainage and root zone solutions.

Various “end-of-pipe” solutions are available for nutrient removal and recovery from water draining from crops. The nutrient removal and recovery techniques include physio-chemical procedures such as adsorption media for phosphorus, electrochemical phosphorous precipitation, and modified ion exchange, and biological approaches such as nutrient removal in constructed wetlands, moving bed biofilm reactors and the use of duckweed.

The preceding section “About the Fertigation Bible” explains the organisation and use of this document.

Chapter 1. Introduction

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1.1. Brief explanation of fertigation

Fertigation is the practice of applying fertiliser to a crop via the irrigation system. Consequently, both irrigation water and fertiliser are applied using the same irrigation distribution system. While fertigation is mostly used with drip irrigation systems, it is also used with mobile sprinkler irrigation systems e.g. centre pivot, linear move and fixed sprinkler systems. In the context of horticulture (fruit, vegetable and ornamental production), fertigation is most commonly used with drip irrigation. The large, rapid and ongoing increase in the adoption of drip irrigation in horticulture has facilitated a similar on-going increase in the use of fertigation. This is occurring in many horticultural regions in the European Union (EU), and throughout the world.

Applying fertiliser by fertigation reduces and often eliminates the use of mechanical fertiliser application. The combined use of fertigation with drip or advanced sprinkler irrigation systems provides numerous potential advantages.

The advantages include:

- Increased capacity to optimise crop water and nutrient use efficiencies
- Fertiliser applied directly to the crop root zone where required (with drip irrigation)
- Precise amounts of water and nutrients can be applied as required by the crop
- An enhanced capacity to adapt irrigation and nutrient management to the particular requirements (crop, site, climate) of individual crops
- Reduced water and nutrient use, and negative environmental impacts
- Appreciable savings on costs and time associated with mechanical fertiliser application
- The capacity to rapidly respond to previous applications of fertiliser and/or irrigation that were deficient or excessive
- Capacity for increasing yield and product quality by optimising nutrient and water supply
- Reduced soil compaction because of less traffic of heavy equipment

For effective on-going operation, fertigation systems have certain requirements. These requirements include:

- Adequate design and selection of components of the fertigation/irrigation system
- Adequate water quality for fertigation/irrigation
- Careful selection and management of fertilisers to avoid incompatibilities between specific fertilisers (e.g. phosphorus and calcium) to avoid emitter and pipe clogging
- Use of fertilisers with adequate solubility
- Adequate maintenance and operation of all components to ensure optimal operation of system e.g. filters
- Simultaneous crop management of irrigation, nutrition, salinity
- The irrigation system must have a high application uniformity to ensure uniform application of nutrients

1.2. Broad categories of fertigation systems used in the EU

When considering types of fertigation systems, there is a wide range of different types of systems with which fertilisers are applied to crops with irrigation water. These systems, for combined fertiliser application and irrigation, range from simple fertiliser tanks, in which fertiliser is placed in the tank and the irrigation water is then manually diverted through the tank, enabling individual applications of one or more compatible fertilisers, to fully-automated, computer-controlled systems in which concentrated fertiliser solution from two or more large tanks (each with one, two or several dissolved fertilisers) are added to irrigation water in a controlled manner providing nutrient solutions containing all nutrients required by crops in specific concentrations, in all irrigations. In its most sophisticated form, these advanced automatic systems are used with the recirculation of drainage from substrate-grown crops, and adjustment of the composition of the recycled solution. Between these two extreme forms of fertigation systems, there are many degrees of complexity and automation. Nearly, all systems use some form of filtration to reduce the risk of particles blocking irrigation drippers and pipes. There are numerous options for the types of equipment that can be used in fertigation systems, and in the variations of these types of equipment.

With the simpler manual systems, fertigation may be used for individual fertiliser applications such as for one, two or several side-dressing applications or for supplementary fertiliser applications when required. When used in this manner, fertiliser addition by fertigation is supplementary to conventional fertiliser addition by a tractor-driven fertiliser spreader. With the computer-controlled system with two or more tanks of concentration fertiliser solutions, generally, all fertiliser addition is made through the fertigation system. Simple fertiliser tanks can be used for frequent fertiliser application, but there is a high labour requirement and incompatible fertilisers must be applied in separate irrigations.

All fertigation systems require choices of equipment and technologies at the various stages of the management chain associate with fertigation. Broadly, the fertigation management chain consists of the following stages:

1) Abstraction of water from a water source
2) Storage of water - irrigation water, and drainage water where collected
3) Selection of the growing system/medium
4) Preparation of water for fertigation/irrigation
5) Nutrient addition
6) Application to crop through the irrigation system
7) Crop irrigation management
8) Crop nutrient management
9) Pathogen, salinity and nutrient management of recycled drainage water (where recirculation conducted)
10) “End-of-pipe” solutions for removal of nutrients and pest production products from discharged drainage water (where practised, or where is or will be required by legislation)

The main objectives of the FERTINNOWA project (www.fertinnowa.com) are to provide information on all aspects of fertigation to growers, advisors and other stakeholders of best technologies and practices, and to inform them of state-of-the-art and innovative solutions to on-going problems and unresolved issues.

1.3. The economic importance of the fruit and vegetable sector in the Europe Union

Apart from its established role in providing produce for a nutritious human diet, the fruit and vegetable production sector plays a fundamental role in the rural economy of the EU. The fruit and vegetable production sector accounts for approximately 37% of the value of EU agricultural output, which is achieved on approximately 3% of the area of cultivated land in the EU (ARELFH et al, 2016). The ornamental sector which occupies an appreciably smaller surface area within the EU is a high-value industry that is expanding.

The total value of production of fruit and vegetables in the EU is estimated to be more than 50 billion € and takes place on 1.4 M farm holdings (ARELFH et al, 2016). The estimated annual economic turnover of the whole fruit and vegetable supply chain, including post-harvest, wholesaling and distribution channels is estimated to be 150 billion € and to involve approximately 750000 employees.

The total EU fruit and vegetable production is approximately 120 M tons, of which approximately 70 M tons are consumed fresh, the rest is processed (such as grapes used for wine, tomatoes used for paste, oranges and apples for juice, etc.) (ARELFH et al, 2016). Included in the 120 M tons are approximately 21 M tons of grapes grown for wine on approximately 3 M ha. Of the 70 M tons of fresh produce, fresh fruit production accounts for 36 M tons and fresh vegetable production for 34 M tons.

1.4. Irrigation and fertigation of horticultural crops in the EU

Irrigation is commonly used with horticultural crops in the EU. In southern regions of the EU, irrigation is often essential for economically-viable production. In north-west and central-east regions, supplemental irrigation is often required to ensure high and stable production and product quality. In greenhouses, irrigation is the only source of water for crops.

During recent decades there has been a strong tendency for increased use of drip irrigation and pressurised sprinkler irrigation systems, and less use of surface irrigation methods, such as furrow and flood irrigation, in horticultural production. There has been a particularly strong adoption of drip irrigation in fruit and vegetable production. Using Spain as a representative country from southern Europe, the total irrigated land surface was 3.6 M ha in 2016 (21% of the total agricultural surface area), of which 1.9 M ha used drip irrigation (MAPAMA, 2017). The area with drip irrigation, in Spain, is increasing appreciably each year; in the period 2004 to 2016, it increased by 54%. In 2016 in Spain, 80% of irrigated fruit trees used drip irrigation and 55% of irrigated vegetable crops used drip irrigation (MAPAMA, 2017). In Spain in 2016, 93% of citrus fruit trees, 29% of citrus fruit trees other than citrus, and 89% of vegetable and flower crops were irrigated (MAPAMA, 2017).

The use of fertigation with horticultural crops is consistently and rapidly increasing in the EU. Commonly, fertigation is used with drip irrigation. In general, it appears that with more extensively-grown horticultural crops, such as less intensive fruit tree and vegetable production that simple fertigation tanks are used, and that with more intensive production such as greenhouse crops and the more intensive vegetable production systems and some intensive fruit production systems that computer-controlled, multiple tanks, fertigation systems are more commonly used. In general, it appears that the majority of fertigation systems are simple fertigation tanks, and the proportion of computer-controlled multiple tank systems is increasing, particularly in intensive vegetable production.

1.5. The various stages of the "fertigation process"

To be optimally effective and sustainable, fertigation requires good management through the entire process from the abstraction of water through to the management of irrigation water and nutrients applied to the crop. Pressure on the EU horticultural industry to reduce environmental impacts is increasing and will continue to increase. Currently, in Flanders, Belgium, greenhouse growers with soilless crops cannot discharge nutrient-rich wastewater into surface water. In The Netherlands, greenhouse growers with soilless cropping will have to comply with the legislation of zero discharge, to natural water bodies, of plant protection products by 1 January 2018, and of nitrogen and phosphorus, by 2027.

It is likely in the future, that EU growers will be increasingly required to optimise all aspects of water and nutrient management. In addition, to enhancing management throughout the entire crop production process, there will definitely be situations where there will be a requirement for "end-of-pipe" technologies to reduce contaminants in drainage water entering water bodies.

Fertigation can be considered to involve a sequence of processes. The FERTINNOWA project is developing a comprehensive database, presented in various formats (factsheets, practice abstracts, this document; all available at www.fertinnowa.com), of information related to all aspects of the fertigation chain, which has been broadly organised into the following sections:

- Providing water
- Optimising water quality
    - Chemical composition
    - Particle removal
    - Control of algae
    - Disinfection
- Fertigation equipment
    - Irrigation
    - Nutrient addition
    - Soilless systems
- Fertigation management
    - Irrigation
    - Nutrients and salinity
- Reducing environmental impact

- Nutrient removal and recovery
- Removing plant protection products

This structure will be maintained for the current report, except for “Removing plant protection products” which is covered elsewhere in products from the FERTINNOWA project. The schematic representation in Figure 1-1 shows these aspects in sequence.

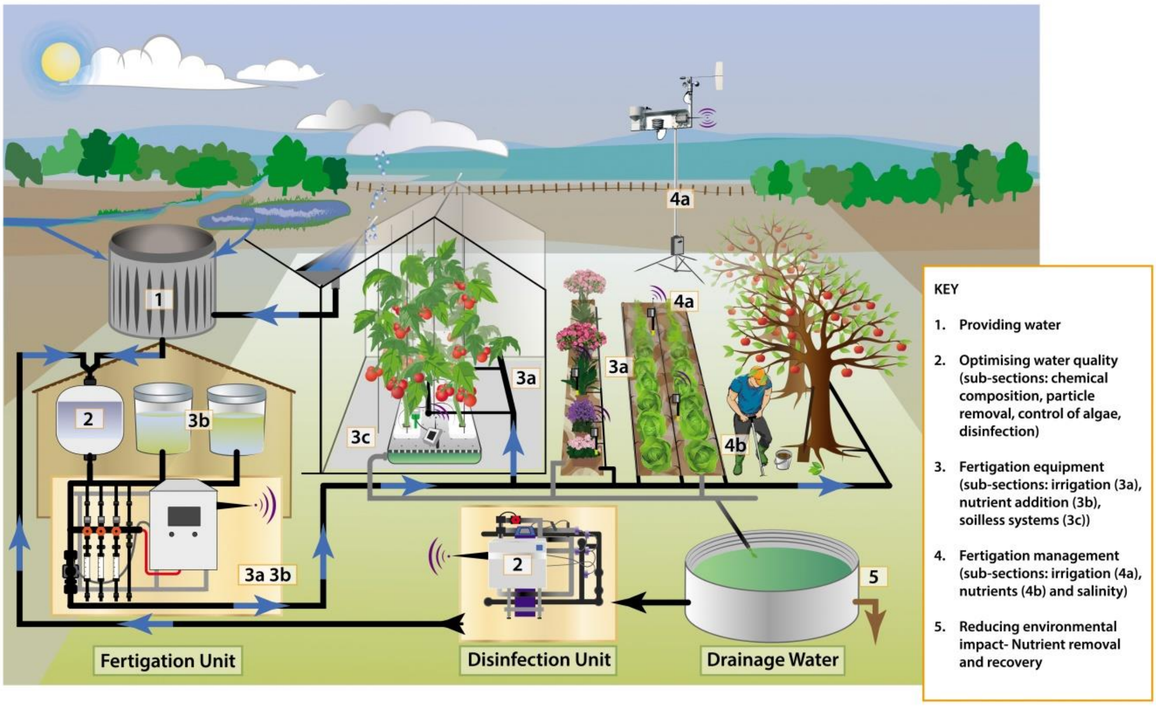

Figure 1-1. Schematic diagram to illustrate the various stage of the “fertigation process”

1.6. Brief, generalised description of major options for each stage of irrigation/fertigation process

Following is a list of many of the technologies described in this document. The list includes many but not all of these technologies. Additionally, this document while describing most of the currently used and the most promising technologies is not a complete list of every available technology.

1.6.1. Provision of water

The technologies available for enhancing the supply of water include those that minimise losses by drainage (lining storage basins) or by evaporation (covers, underground storage) and tools for calculating the dimensions of water storage facilities. With greenhouses, the collection of rainwater, and the collection of condensed water increase the volume of available water. In water storage facilities, floating pumps have advantages over housed or submerged pumps for supplying the stored water to the irrigation/fertigation system. The context of the provision of water, in this document, is general; it deals with the management of water on the farm. The next section that deals with optimising water quality presents technologies that will be used selectively with water from different sources.

1.6.2. Optimising water quality

Numerous technologies are available to optimise the quality of water being introduced into the fertigation system for irrigation/fertigation. Water from different types of water sources can have different treatment requirements. These technologies can be considered as being in four general groups of techniques of: 1) altering chemical composition, 2) particle removal, 3) algal removal, and 4) disinfection. Some of these technologies are also applicable to recirculating nutrient solutions.

The tools and techniques for modifying chemical composition include (a) various physical methods, for removal of unwanted chemical components, such reverse and forward osmosis, ion exchange, electrodialysis, and nanofiltration amongst others, and (b) chemical methods such as pH adjustment. The tools and techniques for particle removal include a wide variety of filtration methods. For the control of algae in storage basins, a wide range of diverse techniques are available; amongst others, these include control with different chemicals, the use of aquatic plants or fish, the use of introduced bacteria and enzymes, the use of blue dye, the use of introduced water fleas, and the use of ultrasound technologies. A similarly wide range of diverse techniques is available for the disinfection of incoming water or recirculating nutrient solutions where recirculation is practised. These include chemical addition (e.g. peroxide, chlorination, and acid), filtration systems (sand, biofiltration), physical processes (thermal disinfection and ultraviolet disinfection) and physio-chemical processes (photocatalytic oxidation, ozonisation, ionisation procedures).

1.6.3. Fertigation equipment

Fertigation equipment can be considered as consisting of irrigation and nutrient addition equipment. Additionally, soilless cropping systems (including substrates) can be considered as being fertigation equipment. Basic irrigation equipment includes pipes and drippers for drip systems. Innovative irrigation equipment includes subsurface drip irrigation (SDI), and innovative pipes and drippers with anti-microbial and anti-root functionalities. There are a variety of systems for nutrient addition, including simple fertiliser tanks, injection pumps, equipment with magnetic-drive pumps, mixing tanks, and manual and automatic venturi systems. Numerous substrates are available for use as the growing medium, the principal ones being rockwool, perlite and coconut fibre (coir). Apart from substrate choice, a variety of hydroponic systems are available, including Ebb and Flow, Nutrient Film Technique and Deep Flow Technique; in these systems, the nutrient solution is recirculated. Substrate growing systems were originally open systems in which drainage was not collected and entered the soil. The use of closed systems, with drainage collection and recirculation, is now commonly-used, particularly in northern EU countries, to optimise water and nutrient use, and to minimise pollution. Depending on water quality, soilless growing systems have to be managed as semi-closed systems in some environments in order to avoid yield reductions due to the accumulation of salinity or potentially harmful elements such as sodium or chloride.

1.6.4. Fertigation management

Fertigation management, at crop level, involves both irrigation and fertiliser management. Fertigation with localised irrigation systems, particularly drip irrigation, commonly provides a technical potential for precise management of both irrigation and nutrition. With fertigation systems associated with localised irrigation, small amounts of both water and nutrients can be applied frequently throughout a crop. However, effective management tools must be used to optimise both irrigation and nutrient management so that growers can take advantage of this advanced technical capacity for precise management.

A wide variety of diverse techniques and technologies are available that can be used to optimise irrigation management of fertigated crops; these, of course, can be used just for irrigation. In broad terms, these methods can be considered as being irrigation strategies, calculations of crop water requirements based on estimated retrospective crop water use, calculations of anticipated crop water requirements, sensors to assess soil water status, sensors to assess crop/pant water status, and the use of decision support systems (DSS) to assist with calculation of crop water requirements. Additionally, there are some techniques that are specific to substrate-grown crops.

Examples of irrigation strategies are deficit irrigation and partial root drying. Examples of calculations of crop water requirements based on estimated retrospective crop water use are water balance methods, such as that developed by the United Nations Food and Agriculture Organisation, and also the use of weather sensors. Examples of the anticipation of crop water requirements are the use of weather forecast related tools. Numerous sensors and technologies can be used to assess soil water status providing information on when and how much irrigation to apply, such as tensiometers, granular matrix sensors, time domain reflectometry sensors, capacitance probes, digital penetrating radar, and the neutron probe. Similarly, various sensors can be used to assess crop water status providing information of when irrigation is required; examples include thermal infrared sensors, leaf turgor sensors, dendrometers, and the pressure chamber system. Decision support systems (DSSs) can be used to simplify the calculation of crop water requirements estimated retrospectively or with forecast weather data. In substrate production, different systems are available for automating irrigation, like slab balances, drain sensors, and the demand tray system.

As with irrigation, a wide variety of diverse techniques and technologies are available that can be used to optimise the nutrient management of fertigated crops. These include the various traditional fertiliser recommendation schemes involving soil analysis, the analysis of soil-water extracts or of the soil solution to adjust fertiliser programs, the analysis of leaf tissue or plant sap to adjust fertiliser programs, various optical sensors that can be used to evaluate crop nitrogen status, and models and DSSs that assist with the calculation of crop nutrient requirements. Additionally, nutrient management involves the choice of fertilisers, of for example slow release and organic fertilisers. Nutrient management of fertigated crops also involves salinity management - available tools include established agronomic approaches, and also newer sensor approaches. For nutrient management of substrate-grown crops, there are procedures to measure the nutrient content and salinity of the drainage and root zone solutions.

1.6.5. Reducing environmental impact

Various "end-of-pipe" solutions are available for nutrient removal and recovery from water draining from crops. The nutrient removal and recovery techniques include physio-chemical procedures such as adsorption media for phosphorus, electrochemical phosphorous precipitation, and modified ion exchange, and biological approaches such as nutrient removal in constructed wetlands, moving bed biofilm reactors, and the use of duckweed.

1.7. Brief description of problems associated with irrigation/fertigation in horticulture

Being the combination of irrigation and fertilisation, the environmental problems associated with fertigation are those related to both irrigation and fertilisation. Also, given that many horticultural systems using fertigation are intensively managed systems with frequent irrigation, high fertiliser applications, and that many use plant protection products (PPP); the intensive management practices increase the possibility of environmental problems.

1.7.1. Competition for water resources

In the southern regions of EU close to the Mediterranean Sea, in such countries as Italy, Spain, Greece, France, irrigation is often required to meet much or all of crop water requirements for open field horticultural production. In central and northern Europe, generally supplementary irrigation is used during dry summers and on sandy soils for open field production. In greenhouse cultivation, irrigation provides all water used by the crop.

In the warmer and drier southern regions, irrigation can account for much of the use freshwater resources by human activities. For example, in Spain and Italy, agriculture (including horticulture) accounts for 70-80% of the use of fresh water. Given the increasing demand for fresh water associated with population growth, rising living standards, industrialisation and by tourism, there is on-going pressure to use less water for irrigation of agricultural crops. This is particularly so in the southern countries, where fresh water reserves are limited, irrigation is the major use, and there are substantial tourism infrastructures. In contrast, in Flanders, where precipitation volumes are significantly higher, agriculture and horticulture account for only 6-8% of the use of fresh water. Industry and households are the biggest users of fresh water volumes there (Messely et al., 2008).

Additionally, there is increasing societal interest in the amenity value and the environmental services provided by freshwater resources. In some regions, these issues are adding to the pressure on agriculture and horticulture to reduce the use of water for irrigation. For example, in The Netherlands and in Flanders, Belgium (Anonymous, 2017), plans are being developed to restrict the use of freshwater resources, by agriculture and horticulture, during drought periods to prevent shortages of fresh water for consumers.

1.7.2. Declining volume and quality of local water resources

Associated with increasing competition for limited freshwater resources, are the declining availability and quality of some freshwater resources. This particularly applies to groundwater resources in southern European regions but it is also occurring in North- West

European countries like Belgium. It is not uncommon for the extraction of groundwater for irrigation, and other uses, to exceed natural replenishment, a situation known as "over-pumping" which results in declining piezometric levels of aquifers. Declining piezometric levels signify that the depth at which groundwater is encountered is dropping, indicating a reduction in the volume of aquifer water, which is known as "aquifer depletion". Consequently, the wells to extract water must be made progressively deeper, thereby increasing pumping costs. In coastal aquifers, declining piezometric levels remove or substantially reduce the positive pressure of aquifer water at the interface with sea water. This can result in "saltwater intrusion" when highly saline sea water enters the aquifer at the land-sea interface, making the aquifer in those regions unusable for irrigation.

Drainage from crops receiving irrigation has a higher salt concentration than the irrigation water applied because of fertiliser addition, the leaching of salts in the soil, and crop evapotranspiration. When this more saline drainage water enters underlying aquifers it contributes to salinisation of the aquifers. As this groundwater is later used for irrigation, a cycle of increasing salinisation takes place. This is an issue in the drier southern regions of the EU where groundwater is commonly used for irrigation and the soils generally have higher contents of salts.

1.7.3. Nitrate contamination of aquifers and surface water

High yielding horticultural crops require the addition of nitrogen. Generally, the applications of nitrogen (N) are in excess of 100 kg N/ha, and in very high yielding crops can be several hundred kg N/ha. In soil, all applied mineral N (in ammonium (NH_4) based fertilisers) and simple organic N forms (e.g. urea) are rapidly converted to nitrate (NO_3). When the supply of N exceeds crop demand, NO_3 accumulates in soil. Nitrate is highly soluble and does not interact with soil particles. When drainage occurs, the accumulated NO_3 is leached from the crop root zone eventually entering aquifers.

In aquifers in their natural state, the concentration of NO_3 is very low, being normally less than 5 mg NO_3/L (Burkartaus et al., 2008). Nitrate leached from agricultural land can result in appreciable contamination. Nitrate contamination of aquifers is a public health concern because of metahaemoglobina, also known as "blue baby syndrome", which is a medical condition affecting infant children and unborn foetuses. This condition develops when nitrite (NO_2) in blood blocks the capacity of foetal haemoglobin to transport oxygen. It is a serious condition that can be fatal. When infant children have several months of age, the oxygen-carrying capacity of their haemoglobin is no longer blocked by nitrite (NO_2). Infants can consume NO_2 in infant formula milk prepared with NO_2 contaminated water or through breastfeeding. Nitrite can be passed to foetuses through the placenta. Nitrate can be converted to NO_2 by certain bacteria in wells and in the human body. To avoid the risk of metahaemoglobina, limits are imposed on the concentration of NO_3 and NO_2 in both groundwater and surface water. In the EU, the limit is 50 mg NO_3/L (11.3 mg NO_3-N/L); the limit recommended by the World Health Organisation (WHO) and that applied in the USA is 44 mg NO_3/L (10 mg NO_3-N/L). The limit for NO_2 is 0.5 mg NO_2/L (0.1 mg NO_2-N/L); in the EU; the recommendation of FAO and that applied in the USA is 4.4 mg NO_3/L (1 mg NO_2-N/L). These limits were developed for drinking water and are applied to water bodies, both subterranean and superficial.

There are other health concerns associated with the presence of NO_3 in drinking water related to various cancers in adults (Follet & Follet, 2008), but these appear to be mostly suggestions rather than being clearly supported by scientific evidence (Follet & Follet, 2008).

1.7.4. Eutrophication of surface waters

Eutrophication is the process of nutrient enrichment enhancing the growth of particular species in an ecosystem. Aquatic ecosystems have evolved in conditions of very low nutrient concentrations. The addition of N and/or phosphorus (P) originating from intensive agriculture changes the ecological balance, promoting the rapid growth of certain species. In freshwater systems, N is usually the nutrient that most limits growth, and in saline aquatic systems, P is usually the most limiting nutrient. Additions of N in freshwater systems and P in salt water systems provoke the rapid growth of algae on the water surface, known as "algal blooms". Algal growth can have direct effects on the ecosystem through reduced light penetration and changed species composition. Additionally, toxins produced by the algae can be toxic to aquatic and mammalian species. Following the death of the algae, the subsequent decomposition of the algal biomass can consume much of the dissolved oxygen in the water resulting in conditions of low dissolved oxygen, known as "hypoxia" or negligible dissolved oxygen, known as "anoxia". Hypoxic and anoxic conditions are deadly to various aquatic species. In addition to effects on aquatic ecosystems, eutrophication can negatively affect the amenity value of water bodies that have a tourist or recreational value.

Eutrophication is a common problem in water bodies adjoining areas with intensive agricultural production. There are numerous examples throughout the world where intensive agricultural systems have caused eutrophication of surface waters, and through combinations of algal growth and of hypoxic or anoxic conditions, have substantially negatively affected aquatic ecosystems. Some examples from recent years, some of which are on-going are: the coast of Brittany in France, the Baltic Sea, the Mar Menor lagoon near Murcia in Spain, Lake Erie, Chesapeake Bay, and coastal regions of Gulf of Mexico in the USA, and the Murray-Darling river system in Australia.

1.8. Growers' concerns regarding fertigation identified by the FERTINNOWA benchmark study

Between May and October 2016, FERTINNOWA carried out a benchmark survey on 371 horticultural farms in different parts of the EU to investigate their irrigation and fertilisation practices, and the challenges and problems they face at the technical, socio-economic, and legislative level. Three major areas were studied: 1) the management of supply water and storage, 2) water and nutrient management, and 3) the methods used to limit the environmental impact. The questionnaire that was used is available at http://www.fertinnowa.com/wp-content/uploads/2016/10/D3.1-Questionnaires.pdf.

Considering the source of irrigation water, 60% of the surveyed growers used groundwater as their main water source. In North-West Europe, it was common to also use rainwater. In the Mediterranean region, the most common source of water was groundwater. In Central-East Europe, the use of surface water was more common than in the other regions. A number of important unresolved problems related to water supply were identified.

Approximately one-third of the interviewed growers were concerned about having access to sufficient volumes of water, that is they wished to avoid water shortages. In some regions, growers diversified water sources to reduce the risk of not having sufficient water. However, in areas such as the Mediterranean regions, this was not always an option. The mineral composition of irrigation water was a large and common concern. Growers would like to have technologies that improve water quality related to the salinity of their supplied water, both with respect to the overall electrical conductivity (EC) and the concentrations of potentially harmful elements such as sodium (Na) and chloride (Cl). The management of high concentrations of iron was mentioned by some growers to be a particular problem. Generally, for the issues related to the concentration of specific ions, growers were often unaware of the available solutions or have not implemented them for economic reasons.

Approximately two-thirds of interviewed growers stored water on the farm. There were some major problems related to water storage, in particular, the growth of (micro) algae in the stored water. This problem was mentioned by 30% of the interviewed growers. Usually, short-term solutions are applied by growers to control algae growth (e.g. cleaning the storage facility or the filters), but no technological solution was mentioned by growers that they considered to be effective over the long term. Moreover, the growers had little knowledge of factors influencing algal growth.

Crop sanitary problems (fungal, bacterial) were mostly related to the use of recirculated drain water on soilless crops. There is increasing interest in systems to disinfect or treat drain water before recirculation such as ultraviolet (UV), slow sand filtration, chlorination, reverse osmosis, use of ozone etc., but the cost is a barrier that is restricting implementation. Additionally, some growers have doubts about the effectiveness of some of these technologies/systems, or they cannot implement them because of technical limitations such as treatment capacity (volume or flow), space, use of strictly regulated chemicals, high maintenance requirements or because of legislative limitations such as national regulations regarding worker safety and discharges to the environment.

Growers reported that water quality issues affected the maintenance of irrigation systems because of the development of biofilms or chemical precipitation; both issues can result in clogging of emitters and/or in the uneven distribution of water and nutrients to crops. These issues were mentioned by numerous growers as problems preventing optimal irrigation management. It appeared that some growers preferred to over-irrigate, to deal with these issues, in order to avoid under-irrigation in some areas of their crops.

Almost two-thirds of interviewed growers considered the visual appearance of the crop or soil when managing irrigation. For 20% of the growers, it is the only way to monitor irrigation. For other growers, visual appearance is used together with tools such as soil sensors, climate data collection or decision support systems. In cropping systems that are highly sensitive to irrigation, such as soilless systems, there is more use of such tools and they are generally used to automatically initiate irrigation. In general, soil (and substrate) sensors are more used than crop sensors. There is potential to increase the adoption of the various tools for assisting with irrigation management. Growers are receptive to such tools but expressed their preference for simple and reliable tools, that are “ready-to-use”, and with proven cost-effectiveness. Automation of irrigation and fertigation is of interest for the majority of growers who currently use manual systems. For irrigation, growers mostly rely on technical advisors. However, it would be helpful for growers interested in particular technologies/systems to see them demonstrated, and to receive feedback from growers who are using those technologies/systems.

For nutrient management, growers reported a lack of suitable on-farms tools or local services (affordable and reliable local analytical services, ion-specific sensors to monitor nutrient solution concentrations etc.). Such tools and services would assist them to monitor the nutrient status of their crops and to make subsequent adjustments to nutrient addition regimes to maintain optimal crop nutrient status and to reduce excessive nutrient application. As with irrigation, growers were interested in automation for nutrient addition, even for relatively simple devices such as automatic measurement and control of EC and pH.

In general, very few growers used nutrient recommendation schemes. The reasons expressed by the growers were:

- they are not developed for all the horticultural species
- they are out-dated (because of new varieties and/or production methods)
- they are unknown to growers
- too complicated for practical on-farm use
- growers lacked confidence in them

Clearly, tools are required that assist grower to manage fertilisation to avoid over-fertilisation and the associated losses of nutrients to the environment. However, such tools have to address growers' requirements regarding species, varieties and cropping methods, and they must be user-friendly. Effective technology transfer programs should be conducted to inform and to demonstrate these tools to growers.

The practices that growers use to minimise negative environmental impacts were different depending on whether the growers produced in soilless or soil based cropping systems. Of the growers in the survey who used soilless cropping, approximately 75% partially or totally recirculated drain water, 22% did not collect drainage, and 3% collected drain water but did not recirculate. Amongst the growers who did not recirculate or only partially recirculated drain water, techniques to recirculate drain water that avoided accumulation of harmful ions and avoided the spreading of diseases were of interest to and were known to growers. While, an appreciable percentage of growers with soilless systems either discharged drain water continuously or periodically, only a very small number controlled the composition of or treated the drain water prior to discharge. Given the increasingly strict legislation on effluent discharge to the environment in North-West Europe, it is very likely that growers will be increasingly interested in relevant technological solutions.

With soil-grown crops, flushing the soil to avoid the accumulation of salts (i.e. increased EC) was done by 13% of growers with soil-grown crops. However, this practice also leaches nutrients such as nitrogen, causing pollution of water resources. More sustainable solutions to control and mitigate soil salinity were highly requested by growers.

In general, there is a lack of solutions to treat "cleaning water/wastewater", that is the water used to rinse components of the irrigation system such as filters, storage facilities etc. Often this water is directly discharged to water bodies or to the soil, although it may contain potentially harmful chemicals from cleaning products. Because of the relatively small volumes of water associated with cleaning/rinsing, no technologies have been developed for that purpose. It gives food for thought because frequent and effective maintenance would result in fewer problems (clogging, disease spreading), but it would result in a larger volume of wastewater to be dealt with.

As a general observation considering all of the issues addressed in the survey, we found that growers are generally not aware of all the available technologies that could assist them to resolve some of the issues and problems that they are facing. To consider, a new tool or technology, growers have to firstly be convinced of the effectiveness of the solution. The next major bottlenecks for implementation are the investment costs and the availability of data on cost-effectiveness. Other bottlenecks can be linked to the operational conditions (bottlenecks linked to technical aspects, maintenance needed, etc.) and to national legislation. The objective of the current document is to provide growers and technicians with an overview of many of the available tools and technologies that are available to resolve issues related to various aspects of fertigation management.

1.9. Brief description of climate change consequences and the role of fertigation in adaptation of horticulture

The horticulture sector is highly dependent on the prevailing climate, and the expected changes to climate are likely to have a major impact on this sector (Ramos et al. 2011; van Lipzig & Willems, 2015). Climate Change, also referred to as Global Climate Change or (enhanced) Global Warming, is the observed and the further expected increase in the average temperature of the Earth's climate system. Expected future impacts of climate change will differ between regions. Anticipated effects include increasing air temperatures, rising sea levels, and changing patterns and annual amounts of precipitation. Likely changes include more frequent extreme weather events such as heat waves, droughts, and heavy rainfall with floods. Major threats related to water supply and crop growth, that are particularly relevant for the horticultural sector, are:

- Changes in annual amounts, distribution and intensity of rainfall
- Other factors that will reduce water availability for irrigated horticulture such as reduced run-off, reduced groundwater recharge, and increased demand from other sectors
- Changes in water requirements of crops. Increased temperature will lead to increased evapotranspiration rates and increasing crop water demand
- Change in water availability because of drought or flooding (extreme weather events induced by climate change)
- Increasing salinisation of fresh (ground) water systems in coastal areas (saltwater intrusion)
- Increasing temperatures will affect the suitability of regions for particular crop species. It is anticipated that there will be a northern migration of the production of many fruit and vegetable crops

- Increased frequency of extremely high temperatures will adversely affect the processes of pollen production and fertilisation of fruit and vegetable species; these processes are very sensitive to high temperatures

Insufficient available water commonly affects crop production in one-third of the EU. Water scarcity and drought are no longer issues confined to southern Europe. Water over-abstraction, particularly for irrigation purposes but also for industrial use and urban development, is one of the main threats to the EU water environment. This is not only an issue for arid regions with low rainfall. Temperate areas, such as Belgium, with intense agricultural, tourism and industrial activities also suffer from frequent water shortages and/or expensive supply solutions, during droughts and drier summer periods.

In some countries in southern Europe, approximately 80% of the total freshwater abstraction is used for agricultural purposes, nearly all of which is for irrigation. Crop water demand (water consumed during the growing season) depends on the crop species, the timing of the crop growing season, and the atmospheric evaporative demand which is influenced by various climatic factors such as air temperature, atmospheric humidity and wind speed. Climate change will have both negative and positive effects on crop water use, by, respectively, increasing the atmospheric evaporative demand during crop growth, and by shortening the crop growing period because of more rapid growth and development on account of higher temperatures.

Adaptation measures and the integrated management of water are needed to address future competing demands for water between agriculture, domestic use, industry, tourism, energy, and ecosystem services. New, or at least enhanced, irrigation infrastructures will be required in some regions. Possible responses to global climate change include mitigation by emissions reduction and adaptation measures to increase the resilience of existing agricultural and other systems.

Climate change is likely to affect the production and finances of horticultural growers, and there are also likely to be economic, ecological and social impacts at the local regional scale. For example, changes in growing conditions (water availability, temperature, pests) will affect the sales of produce, land use and the economic infrastructure, which will all have social and political repercussions.

Apart from extreme weather events, the time scale in which climate change is occurring is of decades which allows time for an adaptation of the European horticultural sector to make itself more resilient and to make adjustments to zones of production. Adaptation measures can occur at different levels and by using diverse technologies such as using drip irrigation to reduce water use, the use of closed systems of recirculation with soilless cropping, the use of netting, etc. The following chapters provide information on technologies that will assist with this process of adaptation.

1.10. Relevant legislation related to problems associated with irrigation/fertigation in horticulture

Water use and pollution caused by agricultural activities are amongst the most important environmental issues in Europe. Agriculture accounts for the largest share of land use in

Europe (ca. 50% of overall land area). Agriculture in Europe accounts for approximately 33% of total water use and is the largest source of nutrient pollution in the water (European Environment Agency, 2012). Given the common requirement of the horticultural sector for irrigation, it is clear that this sector makes an important contribution to environmental pressure on European water resources.

A number of Directives and policy requirements have been developed by the European Union (EU) as well as the sector itself (e.g. certification schemes) that affect fertiliser use and irrigation in horticulture in the EU. The most important of these are listed in Table 1-1.

Table 1-1. Overview of most important directives and policy that affect fertiliser use and irrigation in horticulture

General legislation and policy	Aim and comments
Common Agricultural Policy (CAP)	The CAP supports investments to conserve water, improve irrigation infrastructures and enables farmers to improve irrigation techniques
Water Framework Directive (WFD), including the Nitrate Directive	To achieve good qualitative and quantitative status of all water bodies Nitrate Directive: to protect water quality across Europe by preventing nitrate from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices
Nitrate Directive	Reduction of pollution from agricultural nitrogen
Sustainable Use of Pesticides Directive	Reduced the risks and impacts of pesticides on human health; on the environment, and for promoting Integrated Pest Management
Drinking Water Directive	Mandates minimum health standards in water intended for human consumption, making linkages with other water-related policies
EU climate policies	Climate policies address GHG emissions from land use manure management and the use of fertilisers
“Environmentally friendly” certification schemes	Labels such as ‘EKO, Bio, SKAL or organic farming’ create added value to the product

A Directive is a legal act of the European Union which requires member states to achieve a particular result without dictating the means of how to achieve that result. Directives can be distinguished from regulations which state the practices that must be followed. Directives normally leave member states with a certain amount of liberty as to the exact rules to be adopted. In general, with the exception of Directives related to the Common Agricultural Policy, Directives are addressed to all member states that are responsible for their implementation.

The implementation of EU Directives such as the Nitrate Directive (EU, 1991), the Water Framework Directive (Anonymous, 2000) (which incorporates the earlier Nitrate Directive), the Drinking Water Directive (Anonymous, 1998) has direct effects on agricultural practices. This can be clearly seen in the countries of north-west Europe where the Nitrate Directive has been most rigorously implemented until now. The implementation of the Nitrate Directive requires firstly that regions with nitrate contamination of aquifers and/or eutrophication associated with nitrogen use in agriculture are declared Nitrate Vulnerable Zones (NVZs). The regions declared to be NVZs are required to implement Action Plans to reduce contamination with nitrate of agricultural origin. The Action Plans consist of a variety of practices such as an annual limit on nitrogen applied in the form of manure, the use of fertiliser recommendation schemes, limits on total amounts of N applied to crops, restriction on when and where N fertiliser can be applied, the requirement for the use of scientific irrigation scheduling practices etc. Some of these practices are mandatory, and others are recommended. Within NVZs, horticultural growers and farmers are obliged to adopt the mandatory practices, as specified by the regional legislation. Growers receiving payments from the Common Agricultural Policy (CAP), who are in NVZ, are obliged to implement the Action Plans in order to receive CAP payments as part of the cross-compliance mechanism.

1.11. Other sources of pressure related to problems associated with irrigation/fertigation in horticulture (e.g. consumers, buyers, certification schemes)

Consumers, particularly those in North-West (NW) and Central European countries are increasingly demanding of the way in which the fruit and vegetable, they purchase, are produced. This applies to minimal presence of pesticide residues in produce, and increasingly to the use of production methods that have a minimal negative environmental impact. The increasing demand for minimal environmental impact is reflected in the requirements of certification schemes which are becoming more and more important for access to major markets in NW and Central Europe.

One of the most common certification schemes for fruit and vegetables is GLOBAL GAP (https://www.globalgap.org/uk_en/) which is regarded as the minimum standard for most EU supermarkets. Over time, GLOBAL GAP is increasing its requirements/recommendations for fertiliser and irrigation management to reduce excessive applications of both N fertiliser and irrigation. GLOBAL GAP has three categories of compliance for desirable farm management practices, these are “major must”, “minor must” and “recommended”. An appreciable number of practices related to fertiliser and irrigation management are currently rated as minor musts, including the use of tools to calculate and optimise irrigation requirements, that fertiliser recommendations be provided by competent and qualified persons, and that records be kept of fertiliser applications noting the field, date, fertiliser type and amount applied. It is also recommended that, where feasible, measures be implemented to collect water, and where appropriate to recycle that water.

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Chapter 2. Providing water

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2.1.1. These techniques concern the issue

Preparation of irrigation water.

2.1.2. Regions

All EU regions.

2.1.3. Crops in which the issue is relevant

This is not crop specific since it considers overall irrigation water storage.

2.1.4. Cropping type

All cropping types.

2.1.5. General description of the issue

In horticultural production, considerable volumes of water are commonly required for irrigation to ensure optimal growing conditions for the crops. The very large amounts of water required and the high price of tap water force growers to use other sources of water. Where the climatic conditions are suitable, a good option is to use rainwater. In more humid regions, sufficient rainwater can be collected to meet the entire irrigation requirement of crops. In drier regions, rainwater collection can partially meet irrigation requirements, thereby reducing the demand on other water sources (e.g. groundwater). To enable the use of rainwater, there are practical issues that must be considered such as the collection of water, storage systems and the variability of rainwater in terms of quantity, timing and quality. Additionally, current legislation must be considered.

2.1.5.1. Sub-issue A: Tools for dimensioning water storages have to be expanded to new crops and regions

Some tools for dimensioning water storages for rainwater already exist. However, they are generally based on fixed tables, referring to a specific crop in a specific region (e.g. tomato crop with recirculation in the North-West region of Europe). Therefore, the existing models should be improved with data to adapt these models to other crops and regions (Central East, North of Spain, France, etc.). However, the availability of relevant data is an issue here.

2.1.5.2. Sub-issue B: Financial evaluation of water storage

Rainwater is seen as “free” or “very cheap water” of very good quality. However, rainwater storage is expensive when considering the installation costs of specially lined water storage facilities and the associated loss of production area. Therefore, a combined model that calculates the required dimensions of the storage area and simultaneously conducts a financial analysis is required to guide growers in designing a water storage facility.

To meet the last percentages of the water requirements with rainwater, a very large water storage volume is required. Therefore, dimensioning the water storage should be linked to a financial model that considers strategies such as meeting specified percentages of total crop water requirements and expected rainfall.

For any calculation of water storage, the collection area for rainwater (e.g. greenhouse roofs) must be considered first to calculate the water collection potential. So, this technique is used specifically for covered cropping systems. Dimensioning tools provide information on the relationship between the storages water volume and the % of the crops freshwater demand that can be fulfilled by the water stored in this volume. The tools are mainly based on long-term precipitation data and the weekly or daily freshwater demand of the crop. In for example the WADITO model, the additional water for rinsing filters and facilities or moistening the substrate is not included in the model. But this could quite easily be done by changing the programming.

2.1.5.3. Sub-issue C: Risk assessment of large-scale lined reservoirs

Recently, the size of greenhouses in North-West Europe has increased significantly. The construction of large greenhouses requires storage of very large volumes of rainwater and buffering at times of intensive rainfall, in order to prevent flooding of the surrounding area or creeks. Specific mathematical models are required for these calculations.

2.1.5.4. Sub-issue D: Clarification of national and regional legislation regarding new water storage approaches

Innovative practices for storing water include underground storage, which is being developed in the SubSol project. It is not clear if new innovative ways of storing water, like SubSol, are meeting the regional/national legislation of the European Member States.

2.1.5.5. Sub-issue E: Poor water quality of the first rainwater flush

The first flush of rainwater from a roof can contain pollutants (plant protection products (PPP) that have drifted, chalk, sediments from the roofs, chemicals used for cleaning the roofs, etc.) that can harm both the crop and the irrigation systems. In addition, nutrient-rich water enhances algal growth. An important issue is to prevent these pollutants from entering the storage system.

2.1.6. Brief description of the socio-economic impact of the issue

2.1.6.1. Financial evaluation of water storages

It is a misconception to consider rainwater as “free” or “very cheap” water. In many regions, the use of rainwater requires large-scale water storages, for example, a net volume of 5000 m^3/ha of soilless greenhouse tomato crops is required in North-West Europe to fulfil the yearly freshwater demand of the crop. The construction of this storage capacity is costly (4-45 €/m^3 storage capacity, land costs excluded) depending on the type of water storage considered. If you want to cover the crops freshwater demand throughout very wet and very dry years, a large volume of water has to be buffered. In the wet years or months, extra water can then be stored for use in the dry years or months. So to fulfil the last percentages of the crops water demand by use of rainwater, a serious enlargement of the water storage, leading to higher installation costs, is required.

2.1.6.2. Risk assessment of large-scale lined reservoirs

In densely populated regions, growers experience resistance from local residents who are afraid of potential flooding due to the loss of infiltration capacity caused by the construction of large-scale greenhouses and water storage.

2.1.7. Brief description of the regulations concerning the problem

In France, growers are forced by local laws to manage the rainwater diverted from infiltration into the soil because of the construction of greenhouses. In the UK, water that is captured on roofs and stored legally belongs to the grower who owns the structure. In case the water touches the ground before being stored, the laws that apply are different.

It is unclear if new ways of storing water, meet the legislation of the EU Member States.

2.1.8. Existing technologies to solve the issue/sub-issues

2.1.8.1. Sub-issue A (see 2.1.5): Expansion of tools for dimensioning water storages to new crops and regions

- WADITO
- Waterstromen (Wageningen University)

2.1.8.2. Sub-issue D (see 2.1.5): Clarification of national and regional legislation regarding new water storage principles like SubSol

Under groundwater storage is permitted in most Member States as this concerns water storage at a smaller scale (3000 m^3). It is not clear if principles like SubSol (10000 m^3) water storage are permitted in all Member States. Current legislation mentions the small scale, lined, underground reservoirs. SubSol inflicts possible risks since huge amounts of water are stored in underground water layers, which are unlined and in contact with the deeper groundwater. Legislation applying to this type of storage should be clarified.

2.1.8.3. Sub-issue E (see 2.1.5): Poor water quality of the first rainwater flush

Filters might remove sediments and chalk from the first flush, while residues of PPP that adhere to the roof after being transported there by drift, might be reduced by treating the greenhouse roof with a coating of titanium oxide (photocatalytic oxidation occurs). It is unclear if the coatings on greenhouse windows are allowed in food production areas. In addition, if this technique is somewhat expensive, growers will refuse to use it.

2.1.9. Issues that cannot be solved currently

Sub-issue B (see 2.1.5): Financial evaluation of water storage: It is not known if these evaluations are available for the moment; surveys are required.

Sub-issue C (see 2.1.5): Risk assessment of large-scale lined reservoirs: In France, this is conducted by engineering consultants, but every study is site-specific. In Flanders as well, site-specific studies are carried out. For other countries and regions, surveys are needed.

2.1.10. References for more information

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2.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions (TDs)

Type A: < 750 m^3 or < 100 m^2 Type B: 750 – 5000 m^3 or 100 – 250 m^2 Type C: > 5000 m^3 or > 250 m^2 *excluding parcel costs

	Technology	Water storage type	Cost		Required	Weaknesses	Strengths	Limitations
			Installation	Maintenance				
Water storage systems	Lined water basin	*aboveground*: basin	*Type A*: too small *Type B*: 5-9 €/m^3 capacity* *Type C*: 4 €/m^3 capacity*	*Annually:* algae control + 5% of the installation cost	Algae and evaporation (in warmer climates) prevention	Commercial space loss due to storage Algae issues and evapotranspiration	Long lifespan	For water storages > 1000 m^3 Depth depends on underground Top 0,5 m buffer area Lower 0,5 m unavailable: sediments and too hot (low water levels)
	Lined water silo	*aboveground*: silo	*Type A*: 23 €/m^3 capacity* *Type B*: 26 €/m^3 capacity* *Type C*: too big	*Annually*: algae control + 5% of the installation cost Strength check/2 years	Algae prevention	Limited loss of commercial space Max. lifespan: 15 years Algae issues and evapotranspiration	Not avail.	> 500 m^3 is not common in practice Depth is limited Top 0,5 m buffer area Lower 0,5 m unavailable: sediments and too hot (low water levels)
	Ferro concrete reservoir (preformed)	*underground*	1,5 - 2 m^3: 500 €/pc.: incl. delivery, digging and installation Pipes: 5 €/m^2	Not avail.	None	Not avail.	Nearly constant water temperature Long lifespan Prevents algae and evaporation	Available for water storages smaller than 20 m^3
	Ferro concrete reservoir (formed on site)	*underground*	No data	Not avail.	None	Not avail.	Not avail.	Size limit not defined
	Klimrek buffer	*underground*	30-45 €/m^3 storage capacity (excl. installation cost)	Not avail.	None	Not avail.	Not avail.	Must fit between the support poles of the greenhouse Depth limit not defined
	Infiltration crates	*underground*	45 €/m^3 storage capacity (excl. installation cost)	Not avail.	None	Not avail.	Not avail.	Must fit between the support poles of the greenhouse Depth limit not defined
	SubSol water storage	*underground*	*Type A* and *B*: N.A. *Type C*: 25000 - 50000 € per installation	Not avail.	None	Not avail.	Not avail.	Water availability depending on water layers in the underground

	Technology	Water storage type	Cost Installation	Cost Maintenance	Required	Weaknesses	Strengths	Limitations
Dimensioning water storages	Standard tables for dimensioning water storage	*aboveground*: basin or silo	Published in books and articles	None	None	Not applicable	Not applicable	For water storage of 500-6000 m³ Only for recirculated soilless tomato crops in NW Europe Depth is not defined
	WADITO	*aboveground*: basin	Commercial advice depends on the requested calculations	None	Computer skills	Not applicable	Not applicable	Combination of max. 5 storages The weekly freshwater demand should be covered Long-term climate data set (at least 10 years)
	Waterstromen	*aboveground*: basin or silo	Freely available on the web	None	Computer skills	Not applicable	Not applicable	1 water storage
Water storage covers	Foil	*aboveground*: basin or silo	*Type A*: 20 €/m² *Type B* and *C*: 9 €/m²	Not avail.	None	Not avail.	- Prevents algae and evaporation - Prevents sediment suction	Not avail.
	Steel cover	*aboveground*: basin or silo	*Type A*: 100 €/m² *Type B* and *C*: N.A.	Not avail.	None	Not avail.	Not avail.	Maximum size 100 m²
	Balls	*aboveground*: basin or silo	*Type A*: 14 €/m² *Type B* and *C*: 13,75 €/m²	Not avail.	None	Not avail.	Not avail.	Not avail.
Water collection	Collecting condensed water	*aboveground*	Costs of the land 6000 €/ha: accessories and installation of gutters in multi-span arched-roof greenhouses	Not avail.	None	*Parral greenhouse*: contact with steel network forms drops *Multispan*: low slope near ridges makes drop sliding difficult	Avoids dripping of condensed water on the crop Reduces the crop disease risk Good quality and sustainable water source	Low quantities of water captured: theoretically 750 L/m² year (tomato & eggplant in Almería, Spain) Availability of adequate plastic cladding materials Required angle 14-40° High T, condensations rate: max. 2 months anti-drip effect
Equipment	Floating pumps	*aboveground*: basin or silo	Company-specific	Not avail.	None	Clogging by algae Development of biofilm on surface	Prevents sediment suction	Not avail.

2.3. Lined (rain) water storage

(Authors: Els Berckmoes[21], Esther Lechevallier[4])

2.3.1. Used for

Preparation of irrigation water.

2.3.2. Region

All EU regions.

2.3.3. Crops in which it is used

All crops. Rainwater is a preferred water source in case of crops that are sensitive to sodium like strawberries, sweet peppers, lettuce, dandelion lettuce, leek, endive and roses.

2.3.4. Cropping type

All cropping types.

2.3.5. Description of the technology

2.3.5.1. Purpose/aim of the technology

In many European regions with intensive horticultural activity, rainwater quality is perfect for irrigation purposes. In most regions, the water contains no or very low concentrations of sodium and other elements. The aim of rainwater harvesting and storage is to assure:

- Rainwater availability during the cropping season. In many cases the precipitation pattern differs from the crop water demand, requiring water storage to cover the crop water demand. Figure 2-1 gives an example of the monthly water requirement of a specific eggplant crop with recirculation and the average monthly rainfall in Flanders
- Availability of water with very low sodium content in order to prevent sodium accumulation. This is essential in order to maintain recirculation of the nutrient solution of soilless grown crops

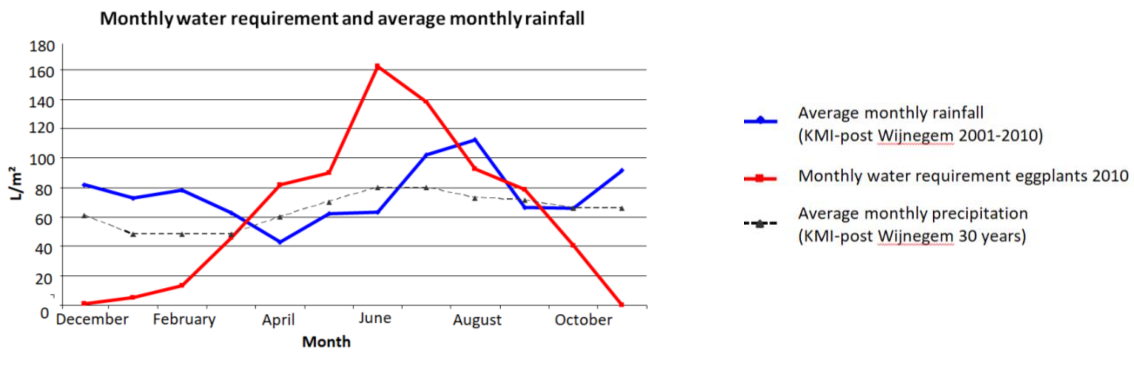

Figure 2-1. Evolution of the water demand in soilless eggplants undercover and the annual average precipitation (L/m²) in Flanders

2.3.5.2. Working Principle of operation

Lined water storage systems

"Lined" refers to the presence of a boundary between the underground and the stored water. In case of unlined water storage, there is no artificial boundary between the stored rainwater and the shallow groundwater that is present.
In order to construct a water storage, several steps have to be carried out.

A soil survey is required before dimensioning and drawing the rainwater storage. Knowledge of, for example, deeper ground layers, the groundwater table and groundwater table fluctuations are essential in order to choose the water storage depth.

Correct dimensioning of the water storage: water needs depend on several parameters like the annual precipitation pattern, the crop specific water demand pattern, parameters related to the constructions (greenhouses, tunnels, container fields, etc.). More details can be found in 2.6 Tools for dimensioning water storages.

Excavation work: Large water reservoirs mainly consist of soil walls or dikes. In general, these dikes are partially embedded to withstand the water pressure of the stored water. The quality and strength of the dikes must be looked at before and during construction.

Construction of the dikes: The excavated soil is useful for the dike construction. However, humus-rich soils should be avoided since decomposing humus influences the strength of the dikes. Loamy soil is preferred. Although the dimension of water storages varies significantly, the dimensions of the dikes are more fixed. Dikes are constructed at an angle of 45° and the upper width ranges between 0,8 and 1,2 m. In case of bigger water basins, thicker dikes are provided at the opposite side of the main wind direction to deal with waves.

Drainage system: in case the bottom of the water storage lies beneath or close to the groundwater table, a drainage system is required (Figure 2-2). This system will keep the groundwater level underneath the water storage level. In addition, the drainage system will discharge a possible excess of air (due to decomposition of organic matter). Both groundwater and air accumulation underneath the foil (Figure 2-3) can cause serious damage to the dikes and the foil itself.

Figure 2-2. Left: Installation of the drainage system underneath the bottom of the water reservoir. Right: Drain tubes of coco fibre are placed in the gutters. The gutters are filled with sand to assure a good drainage of the groundwater (Source: PSKW)

Figure 2-3. Bubbles indicate the presence of water or air underneath the foil. In case bigger bubbles are formed, this can lead to the rupture of the foil. Water underneath the foil also can harm the dikes (Source: PSKW)

Installation of the foil: Putting the foil in place requires much manpower (Figure 2-5). The foil is placed in the middle of the reservoir and then unfolded. At the upper part of the dikes, small ditches are provided (Figure 2-4). The foil is then placed in these ditches. Finally, these ditches are filled again and the foil is fixed. In case (small) rocks are present in the soil, it is desirable to install a protective cloth at first.

Figure 2-4. Fixating the foil to the dikes (Source: PSKW)

Figure 2-5. Pulling the foil into the water reservoir (Source: PSKW)

<u>Finishing the dikes</u>: In case foils with higher UV-sensitivity are applied, the dikes should be covered to protect the foils. This can be done by installing protection sheets. The opposite part of the dike can be covered with foil or grass can be sown.

Installing the supply and drain pipes: The installation of both the supply and drain pipes can occur in 2 ways: waterproof pipelines through (Figure 2-6) or over the dikes.

Installation of safety ropes is essential to climb the dikes in case someone is drowning.

Figure 2-6. Installation of a waterproof pipeline through one of the dikes (Source: PSKW)

Water silos

Water silos are made of a steel wall with a plastic foil in it (Figure 2-7).

In case the silo is installed at ground level, the subsurface should be levelled. In a later phase, the water silo will be anchored in the soil.

In case the silo is placed in an excavation, the soil is removed until 80 cm underneath the ground level. Again the subsurface should be levelled. The bottom level of the silo should be at least 20 cm above the highest groundwater level. In case of higher groundwater levels, a drainage system should be installed. A sand layer of 10 cm is applied in order to prevent sharp rocks and roots to penetrate the silo. Concrete tiles are placed in a circle at the base of the walls. In case the water silo is placed in an excavation pit, the lower row of silo plates should be covered with a special coating until 30 cm above ground level.

Figure 2-7. Water silo (www.waterportaal.be)

During the installation of the silo plates, it is important that:

- Thicker plates are positioned in the lower circles, thinner plates in the upper circles
- Plates should move up half a plate compared to the lower circle of plates
- Plates should be installed roof-like, preventing rainwater to seep between the plates and the foil

Finally, a protection cloth is installed, after which the foil is installed. In case of water silos, PolyVinyl Chloride (PVC) or Astryn foils are used. The higher elasticity of EPDM-foils makes this type of foils less suited for silos.

2.3.5.3. Operational conditions

Lined reservoirs

The dimension of the dikes: In most cases, lined reservoirs are partially built above the ground level. This implies that certain guidelines have to be maintained when constructing the rainwater basin. The dikes have to be designed in relation to the water pressure of the stored water.

In case of large water reservoirs, it may be appropriate to split the water storage (Figure 2-8) into several basins in order to avoid billow.

Figure 2-8. Intermediate dike separating 2 water reservoirs to avoid billow

Water silos

- Dimension: Water silos are made of iron panes that are nailed together. This limits the storage capacity as higher volumes of stored water lead to increased water pressure which may cause ruptures. The maximum content of a water silo is around 2000 m³, although volumes of 500 m³ are more common
- Lifetime: Corrosion of the plates causes weaker spots, which can cause cracking of the silo (Figure 2-9). Therefore, silos have to be checked frequently

Figure 2-9. A silo has cracked due to corrosion of the lower plates (http://www.hyente.com/nieuws.html)

Percentage of available water

At the top of the water storage a "maximum storage level" should be respected. This means that you cannot use the water storage for 100% (Figure 2-10). Generally, the upper 50-75 cm of water storage is not exploited. This area is a buffer for rainwater when excessive precipitation occurs and/or to prevent waves to run over the dikes. In case the water runs over the dikes, this can cause serious damage to the strength of the dike and even cause breaching of the dikes. The lower 50 cm of the water storage is also unused as this water may contain higher concentrations of sediments and the water temperature is too high.

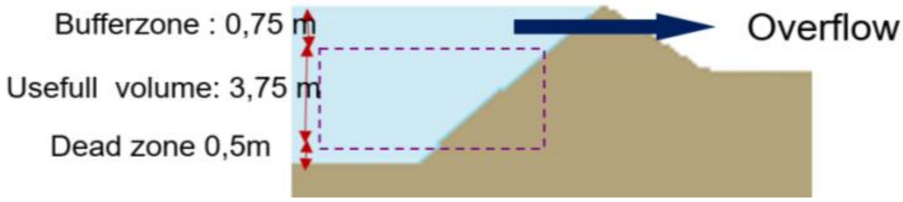

Figure 2-10. Schematic overview of the different zones in the water storage. Only the middle water volume, referred to as "useful water" is available to fulfil the crop water demand

Climate

Precipitation amounts may limit the possibilities to construct a cost-effective water storage. In areas with small amounts of rainfall (Southern part of Europe) or very high precipitation amounts spread over very few precipitation days, it may not be cost-effective to construct big rainwater storages.

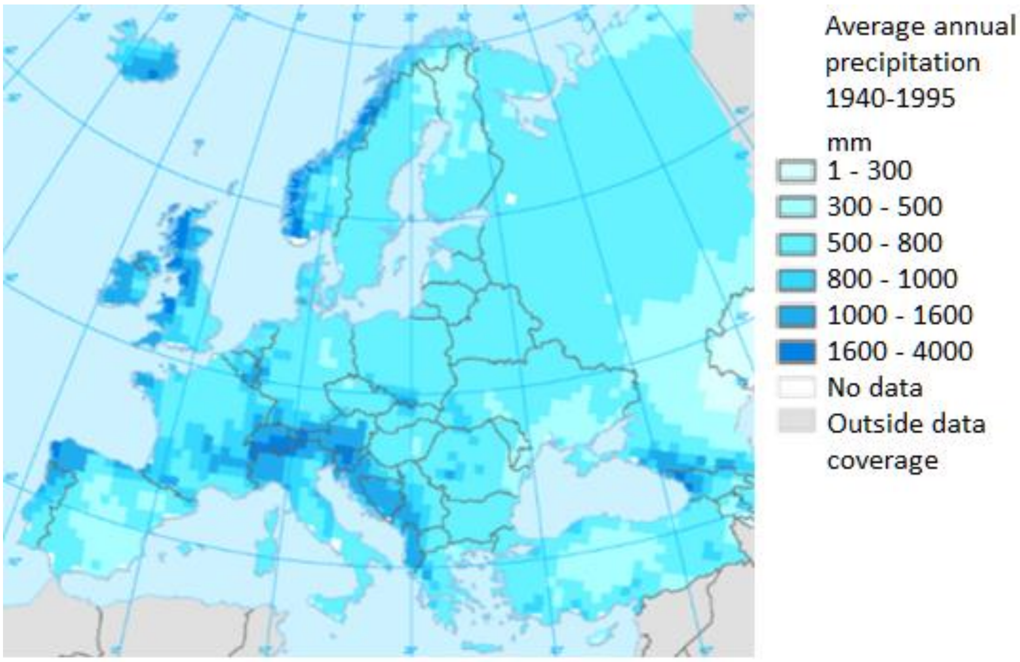

Figure 2-11. Annual average precipitation in Europe (www.eea.europe.eu)

2.3.5.4. Cost data

Installation cost

The costs for the water storages depend on several factors:

- Construction costs (excavation works, installation of drainage pipes, etc.)
- Material (PVC, Astryn, EPDM) and thickness of the foil (generally 0,5 or 1 mm)
- Protective covers (obliged for water silos, recommended for lined water basins in case roots or small rocks are present in the underground)

- Metal plates in case of a water silo

The cost of a water storage is highly related to the company-specific circumstances. In Table 2-1 some examples are given for lined water reservoirs and in Table 2-2 for water silos.

Table 2-1. Some examples of investment costs for lined water reservoirs/water basins

Investments	1000 m³	2000 m³	3000 m³	50000 m³
Excavation, Foil*, Pipes	7941 €	Not avail.	13613 €	Not avail.
Diverse (installation, etc.)	1134 €	Not avail.	2269 €	Not avail.
Total cost (without parcel costs)	9075 €	16650 €	15882 €	200000 €
Costs for parcel of water basin (18,15 €/m²)	15428 €	24502 €	36300 €	Not avail.
Total cost (parcel costs included)	24503 €	41152 €	52182 €	Not avail.

*foil types are not specified.

Table 2-2. Some examples of investment costs for water silos

	250 m³ - 1190 cm x 231 cm		1000 m³ - 1830 cm x 385 cm	
Investments	Astryn	EPDM	Astryn	EPDM
Water silo	2106 €	2106 €	8096 €	8096 €
Water silo foil Astryn 0,5 mm	2567 €	Not applicable	5754 €	Not applicable
Water silo foil EPDM 1,0 mm	Not applicable	4715 €	Not applicable	10226 €
Water silo cover (floating)	1138 €	1138 €	2334 €	2334 €
Total cost (without parcel costs, installation by grower)	5811 €	7959 €	16184 €	20656 €
Costs for parcel of water basin (18,15 €/m²)	2178 €	2178 €	4991 €	4991 €
Total cost (incl. parcel costs)	7989 €	10137 €	21175 €	25647 €

Maintenance

The costs for maintenance of the lined water storages (Table 2-3) include reparations for the foil, maintenance of pumps etc.

Table 2-3. Estimation of the maintenance costs for water silos and water reservoirs

Maintenance	1000 m³	3000 m³
Lined reservoirs (5% of investment cost, cost for parcel excluded)	454 €	794 €
Water silos (1,5% of investment cost, cost for parcel excluded)	431 €	794 €

Remark: Water silos should be checked by professional companies. A check costs around 200-300 € and should be carried out every 2 years once the silo has reached the age of 7 years.

2.3.5.5. Technological bottlenecks

The first flush of harvested rainwater can contain pollutants like residues of plant protection products (drift on greenhouse roofs), chalk, sediments, etc.

Zinc (Zn) recovering can be a bottleneck in old greenhouses. A sealant can be required to protect the gutter of the greenhouses to prevent Zn leaching in the rainwater storage.

Varying precipitation patterns or insufficient rainfall in some regions (South-Europe).

Algae development (see Chapter 5. Optimising water quality – control of algae) and sedimentation problems (see 2.9 Floating pumps) can occur.

Evapotranspiration can lead to serious water losses in for example Southern-Europe.

Rainwater is not buffered and can be acidic. Therefore, the pH should be controlled and countered if necessary (see Chapter 3. Optimising water quality – Chemical composition).

2.3.5.6. Benefit for the grower

Advantages

- Good quality water
- Allows recirculation for most of the crops (even some for which it is indispensable)
- Independence to regulations related to groundwater

Disadvantages

- Use of “commercial space”
- Low buffering capacity of the rainwater
- Risk of contamination of the water storage with pesticides/Zn/chalk

2.3.5.7. Supporting systems needed

- Drainage system
- Foils: different types of foils are possible (Astryn, PVC, EPDM)
- Geotextile, placed underneath the foil when small rocks, roots, etc. are present
- A (floating) pumping system (see 2.9 Floating pumps)
- Water level sensors to alert the grower in case a maximum/minimum level is reached
- Treatment for pH adjustment if needed (see Chapter 3. Optimising water quality – Chemical composition)
- (Emergency) valves to prevent flooding of the water reservoir during excessive rainfall or to deviate the rainwater in case of a problem with the rooftop (cleaning the rooftop, bleaching)
- Equipment to prevent algae (see Chapter 5. Optimising water quality – Control of algae)
- Emergency ropes

2.3.5.8. Development phase

This technology is commercialised.

2.3.5.9. Who provides the technology

- Several types of water storages are built by engineering consultancy companies
- Foils: Albers Alligator, etc.
- Silos: Benfried, Brinkman, etc.

2.3.5.10. Patented or not

This technology is not patented.

2.3.6. Which technologies are in competition with this one

- SubSol water storage: Systems to store water in the deeper groundwater layers and to retrieve it again afterwards (The Netherlands, Portugal, etc.) (see 2.5)
- Under groundwater storage systems like infiltrations crates, concrete cisterns, etc. (see 2.4)

2.3.7. Is the technology transferable to other crops/climates/cropping systems?

The availability of rainwater in some regions (e.g. Mediterranean region) is a bottleneck to use rainwater.

2.3.8. Description of the regulatory bottlenecks

If a grower wants to build a big rainwater storage, a study of impact is required by the national/regional authorities in order to evaluate the risk for flooding, contribution to drought stress, etc. (Flanders, France).

In some countries/regions, growers have to complete long procedures before finally receiving the building permit for a water reservoir (Slovenia, Flanders, the UK, etc.).

2.3.9. Brief description of the socio-economic bottlenecks

Fulfilling the last percentages of a crop's water demand requires very big water storages. To make it possible to increase the percentage of water demand fulfilled by rainwater from 86-95% you should increase the water storage capacity from 3000-4000 m^3, which is an increase of 33% in water storage dimension in order to fulfil an extra 9% of the crops water demand by rainwater. The installation of a water storage for rainwater is space consuming. In case this area could have been used to build a greenhouse or to grow a crop, this cost should be implemented in the calculations to determine the cost of a cubic meter of rainwater.

On the other hand, water and nutrient savings due to efficient recirculation should also be taken into account. Currently, financial models are not linked to dimensioning models.

2.3.10. Techniques resulting from this technology

There are no techniques that result from this technology.

2.3.11. References for more information

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2.4. Underground water storage

(Authors: Ronald Hand[24], Els Berckmoes[21], Georgina Key[1])

2.4.1. Used for

- Preparation of irrigation water
- More efficient use of water

2.4.2. Region

All EU regions.

2.4.3. Crop(s) in which it is used

All crops.

2.4.4. Cropping type

- Protected
- Soil-bound
- Soilless

2.4.5. Description of the technology

2.4.5.1. Purpose/aim of the technology

Store bigger volumes of water in an outlined reservoir without the loss of productive area, which occurs when water is stored in water silos or water basins.

2.4.5.2. Working Principle of operation

Different methods are applied for outlined underground water storage.

Concrete water reservoirs

For the outlined underground water storage, mainly ferro concrete cisterns are used. These cisterns are installed at the time of the construction of new greenhouses or the nearby buildings. Plastic cisterns can be used when smaller water volumes have to be stored.

Dynamic water buffers: Klimrek Water Buffer

The irrigation water reservoir features a double liner that creates two compartments (Figure 2-12). Rainwater is stored in the upper compartment, referred to as the "floating compartment". Other water, for example, from a nearby creek, is stored in the lower compartment. The design implements that the reservoir is 100% full at all times, which is necessary since the greenhouse floor is floating on this water storage. When rainwater is excessively available, the system is able to store 100% rainwater. In periods of rainwater scarcity, the lower compartment is filled from other sources to maintain the water level.

At the front of the reservoir, there is an overflow ridge where the side is slightly lower so that any excess water can drain from the lower compartment. When rainwater flows into the upper compartment, the excessive water in the lower part drains automatically.

If water is taken out of the rainwater compartment, the floor will lower slightly. A simple switch will be triggered and activates the pumps that fill the lower compartment with water.

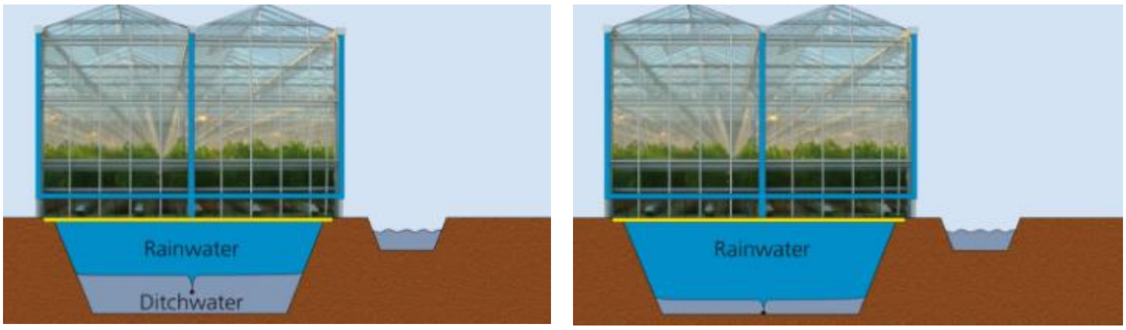

Figure 2-12. Schematic view of the Klimrek Water Buffer. The scheme at the left shows the situation when both the upper and lower compartments are filled with water. The right picture shows the increased volume of the upper water layer when rainfall occurs (http://www.klimrek.com/klimrek-reservoir-irrigation-water)

Infiltration crates

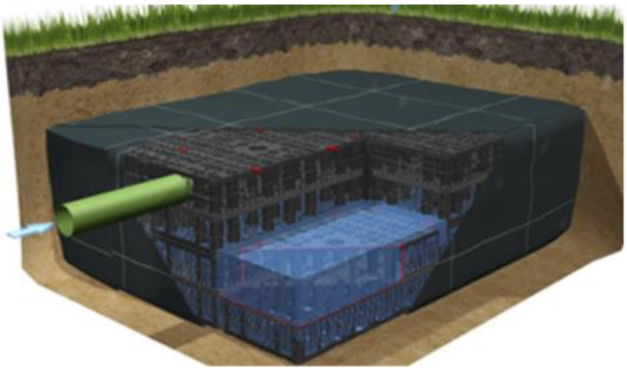

Figure 2-13. Example of an infiltration crate (http://www.bpo.nl/en/portfolio/infiltration-crate/)

2.4.5.3. Operational conditions

Only for greenhouses under construction because the inner grounds of the building are dug up and replaced by the water storage. Other operational conditions are shown in Table 2-4.

Table 2-4. Overview of operational conditions of the different systems

System	Limitations
Plastic tanks	Limited scale to 5 m³
Ferro concrete tank: - Preformed - Constructed on site	Limited scale: 1,5-20 m³ Starting from 20 m³
Klimrek Water Buffer	Limited to each greenhouse compartment*
Infiltration crates	Limited to each greenhouse compartment* Groundwater levels may be an issue

* No storage under a load-bearing pole (placed at regular intervals in the greenhouse).

2.4.5.4. Cost data

Only for greenhouses under construction because the inner grounds of the building are dug up and replaced by the water storage. Table 2-5 gives an overview of the related costs.

Table 2-5. Overview of the costs

Item	Costs
Plastic tanks	0,33-1,56 €/m³ storage capacity*
Ferro concrete tank: - Preformed - Constructed on site	200-350 €/m³ storage capacity** 200-240 €/m³ storage capacity*
Klimrek Water Buffer	30-45 €/m³ storage capacity*
Infiltration crates	45 €/m³ storage capacity *

*installation cost excluded.
**installation cost included.

2.4.5.5. Technological bottlenecks

For the Klimrek Water Buffer and the infiltration crates, the storages are mainly placed under the greenhouse floor. Poles, bearing the greenhouse roof, may not be placed upon both systems, so the dimension of the systems is limited to the span width of the greenhouse. The adjustments of the Klimrek Buffer Water system are based on pumps.

Oxygen levels should be maintained in the subsurface water storages in order to avoid anaerobic degradation processes and a biofilm in the underground storages should be prevented.

2.4.5.6. Benefit for the grower

Advantages

- No loss of productive area
- Minimal problems regarding algae
- Minimal problems regarding evapotranspiration losses
- Cooler water
- Less biological contaminations (bird droppings, etc.)
- Storage capacity to catch all precipitation

Disadvantages

- Higher costs
- Leakages are hard to fix

2.4.5.7. Supporting systems needed

- Pumps
- Switches and steering program (Klimrek Buffer)

2.4.5.8. Development phase

This technology is commercialised.

2.4.5.9. Who provides the technology

Klimrek Buffer: Klimrek productions (http://www.klimrek.com).

Infiltration crates: Gaasbox: JES product Development, HTW Infiltratie Uden, BPO, etc.

2.4.5.10. Patented or not

No patents for this technology have been found.

2.4.6. Which technologies are in competition with this one

- Water storage in lined reservoirs (see 2.3)
- Water storage in water silos (see 2.3)

2.4.7. Is the technology transferable to other crops/climates/cropping systems?

Lined subsurface water storage cisterns can be used both in covered crops and crops in the open air, as long as the surface area for water collection is sufficient.

In case of infiltration crates and Klimrek Buffer, the system is probably limited to the soilless covered crops, as soil cannot be used as a growing medium in this system and the surface for water capture must be sufficient.

2.4.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks known for this technology.

2.4.9. Brief description of the socio-economic bottlenecks

The cost per m³ storage capacity for subsurface water storage is significantly higher when compared to lined water reservoirs and water silo’s, especially when costs for the required surface area are excluded. In case the costs for the lost producing area are included, this financial gap becomes much smaller.

2.4.10. Techniques resulting from this technology

Klimrek Water Buffer (Klimrek producten): a closed plate and plastic that fills with caught rainwater. The bottom is pushed upwards by groundwater. If the box is filled with rainwater, there is no groundwater present, if there is no rainwater, the groundwater pushes the box towards to surface.

Gaasboxx (Figure 2-14): Underground honeycomb mesh that supports structures and growing systems in which water can be stored.

Figure 2-14. Installation of Gaasboxx (https://jesproducts.nl/gaasboxx-systeem.htm)

2.4.11. References for more information

[1] Klimrek producten (2017). Retrieved from http://www.klimrek.com/klimrek-buffer-voor-gietwater on 21/03/2017

[2] JES product development (2017). Retrieved from http://jesproducts.nl/gaasboxx-systeem.htm on 21/03/2017

2.5. Subsurface Water Solutions

(Authors: Ronald Hand[24], Els Berckmoes[21], Georgina Key[1])

2.5.1. Used for

- Preparation of irrigation water
- More efficient use of water

2.5.2. Region

All EU regions.

2.5.3. Crop(s) in which it is used

All crops.

2.5.4. Cropping type

All cropping types.

2.5.5. Description of the technology

2.5.5.1. Purpose/aim of the technology

The aim of subsurface water solutions is to protect, enlarge and utilise fresh groundwater resources through advanced groundwater management and freshwater supply.

2.5.5.2. Working Principle of operation

Sophisticated new well design, configuration and management allow for maximum control over the water resources, which goes far beyond the levels of control provided by standard water management techniques. This makes these solutions applicable in coastal areas (Figure 2-15, Figure 2-16), where groundwater management is a severe challenge because of the presence of saline and brackish groundwater.

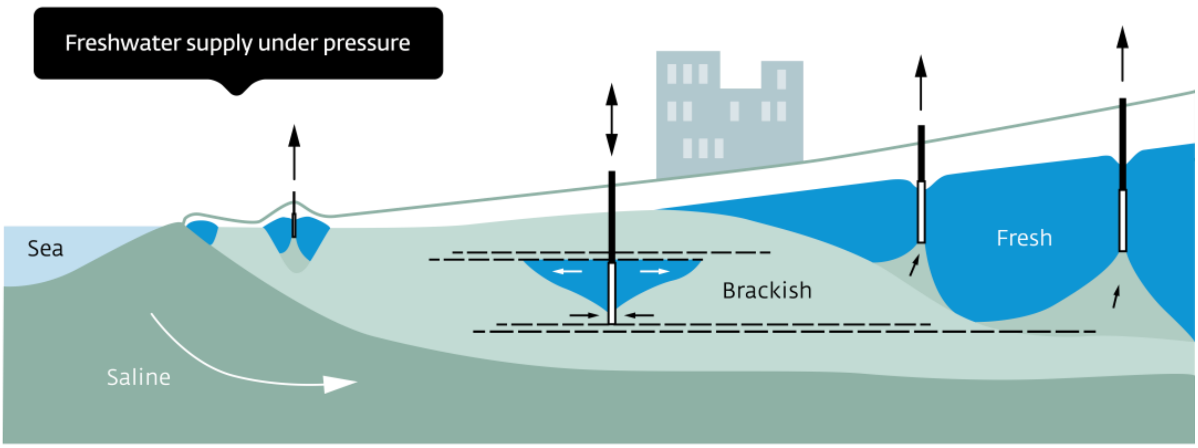

Figure 2-15. Current freshwater supply in coastal areas under pressure due to salinisation of groundwater abstraction wells and unsuccessful aquifer storage and recovery (ASR) of freshwater surpluses in brackish aquifers (http://www.subsol.org/about-subsol/reference-sites)

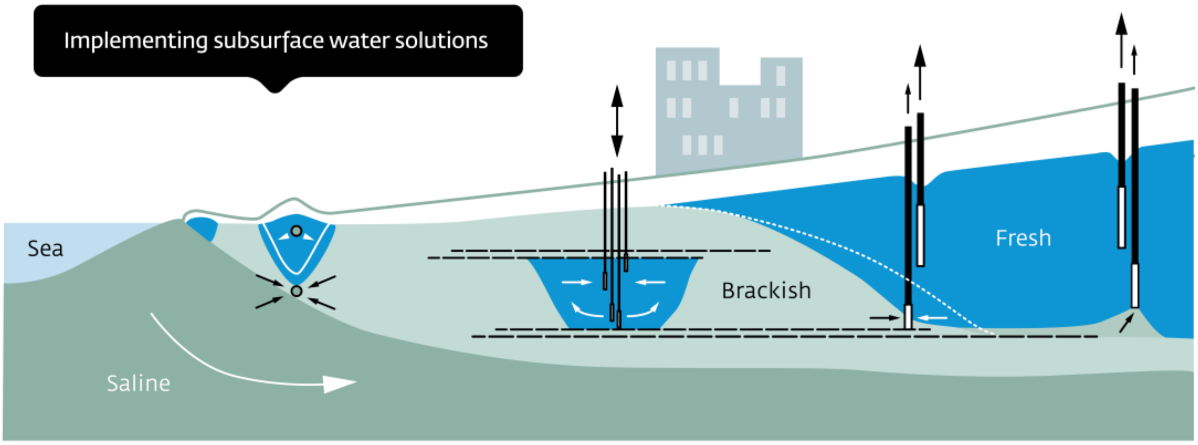

Figure 2-16. Subsurface water solutions to counteract salinisation by dedicated well systems to inject and recover freshwater while intercepting brackish-saline groundwater (http://www.subsol.org/about-subsol/reference-sites)

2.5.5.3. Operational conditions

- Typically a supply of 5000-1000000 m³/year
- For individual agriculturists or agricultural clusters
- Requires suitable aquifers (permeable sand layers or carbonates) in order to use wells for infiltration and recovery
- Coastal areas. Infiltration can be beneficial in areas with fresh groundwater to counter declining water levels and lower the iron levels in abstracted groundwater.

2.5.5.4. Cost data

- For installation: 25000-500000 € (scale-dependent)
- Yearly maintenance or inputs needed: 2000 €/year
- Approximately 0,05 €/m³

2.5.5.5. Technological bottlenecks

Automation of the installation: Solid operation of Aquifer Storage and Recovery systems (ASR, Figure 2-17) and interception wells requires automation to guarantee optimal pre-treatment, infiltration and recovery of the freshwater and minimal maintenance/downtime. This can be achieved by making sensor-based decisions and regular backflushing of pre-treatment filters and infiltration wells.

Maximal recovery of the freshwater stored in brackish-saline aquifers: Freshwater can easily become “irrecoverable” due to lateral drift and buoyancy effects, where the infiltrated high-quality water is mixed with brackish groundwater, making the recovered water mostly unsuitable for irrigation (Figure 2-18).

A priori prediction of the effectiveness: A very heterogeneous natural (subsurface) system is used, so information on the subsurface and crucial parameters on groundwater flow are essential. Secondly, these parameters need to be transferred into calculation tools to predict the effectiveness of subsurface water solutions.

Figure 2-17. Use of aquifer storage and recovery (ASR) in the Dutch greenhouse sector. Rainwater is pre-treated by slow sand filtration and infiltrated in a deep aquifer (sand layer, approximately 10 – 50 m deep)

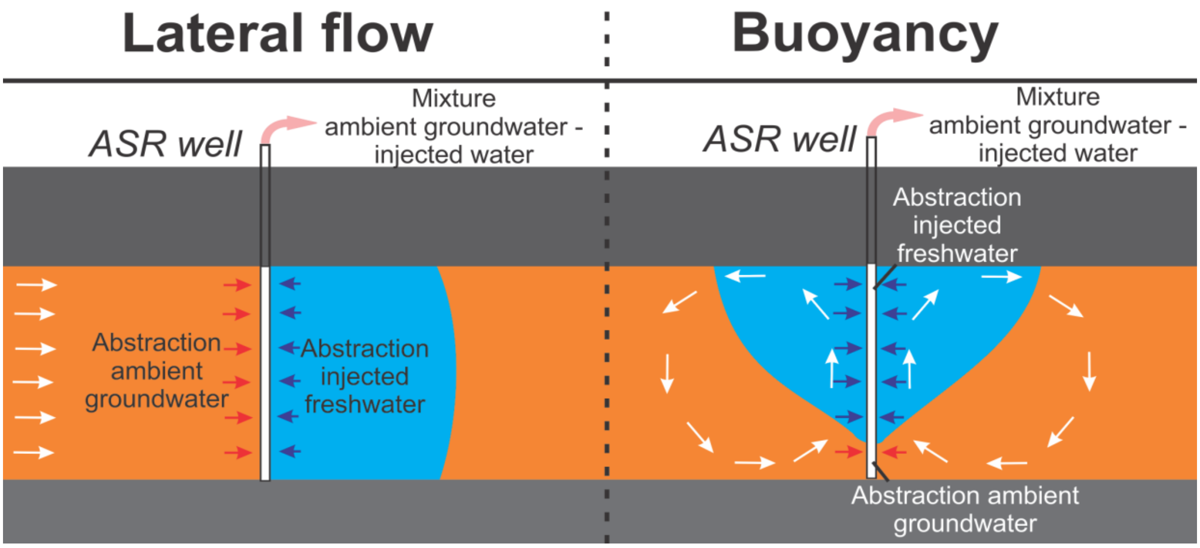

Figure 2-18. Admixing of more saline, ambient groundwater during recovery of injected freshwater by lateral flow and buoyancy effects

2.5.5.6. Benefit for the grower

Advantages

- Limited claim on aboveground land
- Increased freshwater available
- Better water quality (preservation)

Disadvantages

Success is uncertain due to the lack of data of the subsurface.

In general, growers at reference sites were positive (The Netherlands). At the replication site Dinteloord (200 ha of greenhouses), it was even decided to expand the system in the future.

2.5.5.7. Supporting systems needed

- Groundwater injection/abstraction wells
- Pre-treatment
- Pumps
- Programmable logic controller
- Monitoring

2.5.5.8. Development phase

Field tests are being conducted in Nootdorp (2 ha orchids), 's Gravenzande (Westland, 27 ha tomatoes) and Freshmaker Ovezande (fruit orchard): www.kwrwater.nl/en/projecten.

The technique has also been commercialised: AFC Nieuw-Prinsenland, Dinteloord and abound 100 systems in the Bleiswijk area, Aalsmeer, Agriport A7.

2.5.5.9. Who provides the technology

Several engineering companies in the agricultural sector provide this technology:

- Codema B-E de Lier: http://codema.nl (SubSol Member)
- Meeuwse Handelsonderneming: www.meeuwse-goes.com
- Allied Waters: http://www.alliedwaters.com/collabs/salutions

2.5.5.10. Patented or not

This technology is not patented.

2.5.6. Which technologies are in competition with this one

- Brackish water reverse osmosis (see Chapter 3. Optimising water quality - Chemical composition)
- Above ground rainwater storage (see 2.3)
- External water supply (surface water, piped water)

2.5.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, even to high-end horticulture, industries and the drinking water sector.

2.5.8. Description of the regulatory bottlenecks

Water Framework Directive regarding groundwater quality: It should be guaranteed that infiltration does not negatively impact the groundwater quality. National regulations to verify the infiltration water quality can be strict (high-frequency of sampling and analyses), negatively impacting the business cases.

In the Netherlands, the Water Act and Soil Protection Act apply on a national scale and a Regulation by the Dutch Water Authorities (small-scale systems) and the Province (large-scale systems) applies regionally.

2.5.9. Brief description of the socio-economic bottlenecks

Acceptance by the public: willingness to store water with a different quality and potential contaminants in a (normally) "clean" subsurface. Especially if this is in the vicinity of drinking water well fields.

2.5.10. Techniques resulting from this technology

Technique A: Freshkeeper (KWR, Vitens Water Supply)

Dual-zone abstraction against water well salinisation. Fresh and brackish groundwater are pumped simultaneously from different depths, providing control over the position of the fresh-brackish interface. The pumped brackish water may serve as an additional water source for high added value freshwater applications after desalination (see Figure 2-19).

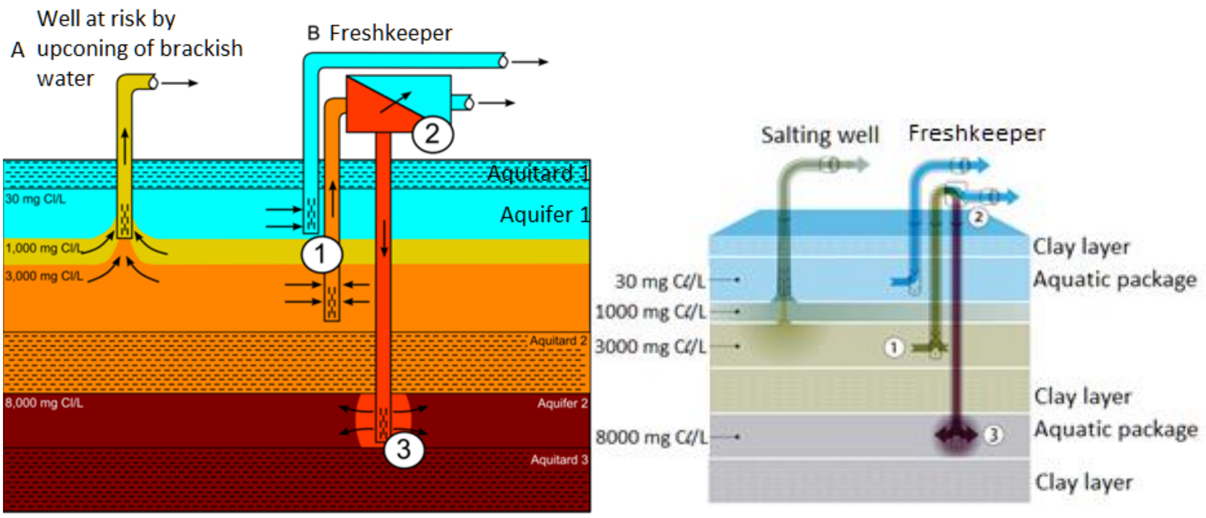

Figure 2-19. Freshkeeper Vitens Water Supply (Zuurbier et al. 2017, www.SubSol.org)

Technique B: Freshmaker (KWR, Meeuwse Goes BV)

Enlarging, protecting and utilising freshwater lenses (convex layers of fresh groundwater that float on top of denser saltwater) with horizontal wells. This technique was initiated by the recent development of horizontal directional drilled wells (HDDWs). HDDWs enable abstraction of deeper saltwater below the freshwater lens over a long transect, while a second, shallow HDDW allows for infiltration and abstraction of large freshwater volumes (Figure 2-20, Figure 2-21).

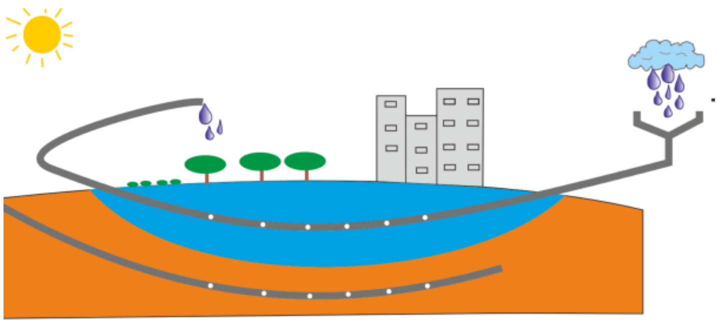

Figure 2-20. Illustration Freshmaker Meeuwse Goes (www.kwrwater.nl/projecten/zoet-zout-ovezande)

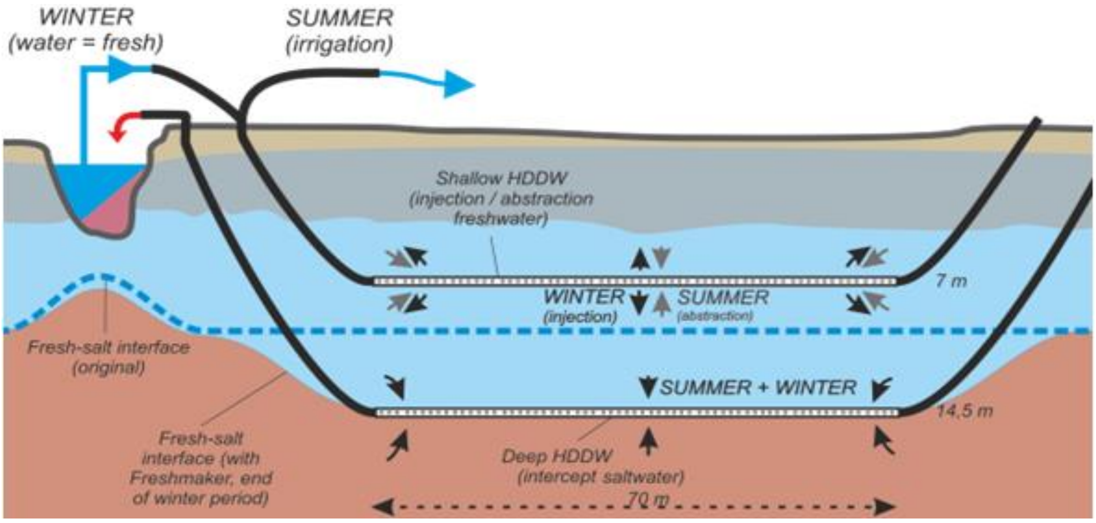

Figure 2-21. Freshmaker Meeuwse Goes (HDDW: horizontal directional drilled well) (Zuurbier et al. 2017)

Technique C: ASR-coastal (KWR, Codema B-E de Lier)

Temporal storage of freshwater in brackish groundwater. Standard aquifer storage and recovery (ASR) approaches are unsuitable in brackish groundwater environments. ASR-coastal uses multiple partially penetrating wells to enable deep injection and shallow recovery of freshwater, which demonstrated a boost in freshwater recovery from less than 20% to more than 60% of the injected freshwater. See Figure 2-22 till Figure 2-24.

These first subsurface water solutions applications have all been developed within public-private partnerships of innovators in the water market and they are starting to gain the interest from the market's early adopters.

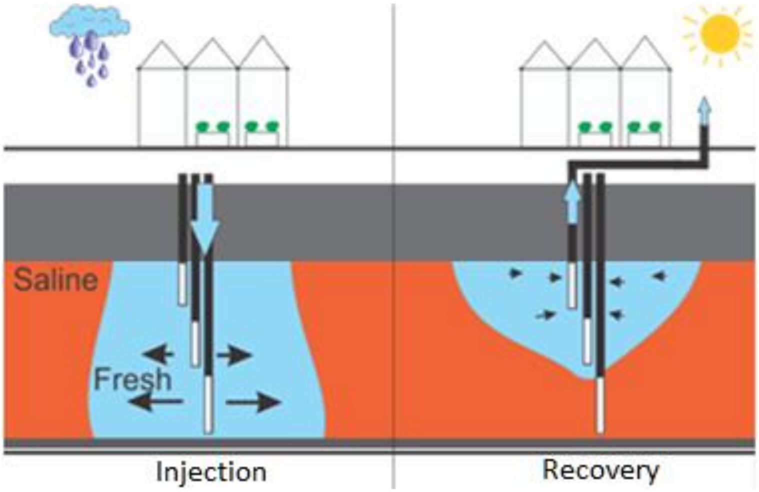

Figure 2-22. Aquifer Storage and Recovery for horticulture (www.SubSol.org)

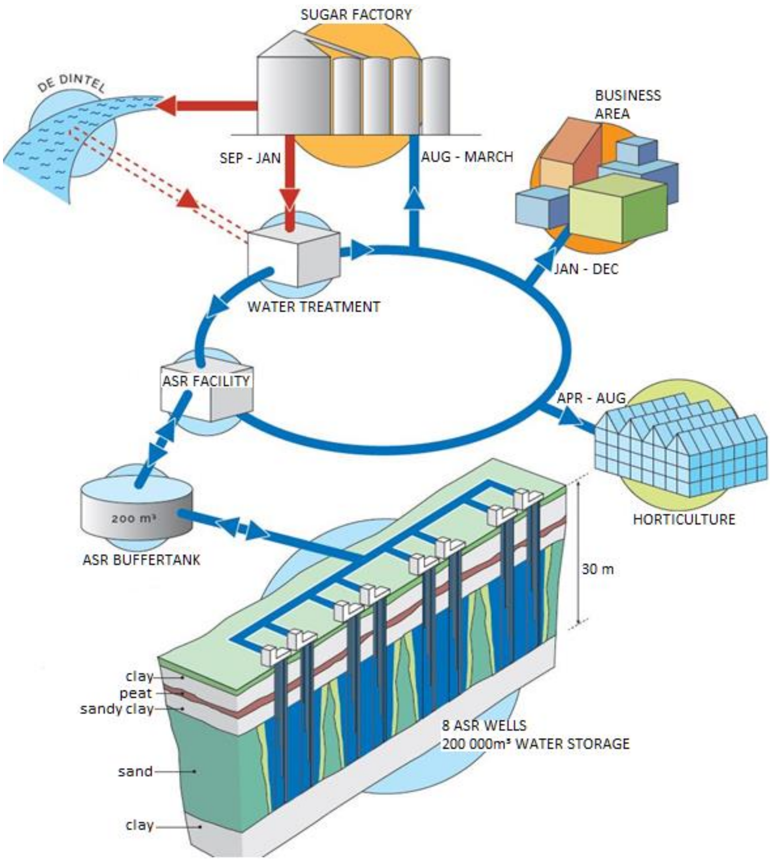

Figure 2-23. Aquifer Storage and Recovery for horticulture (www.SubSol.org)

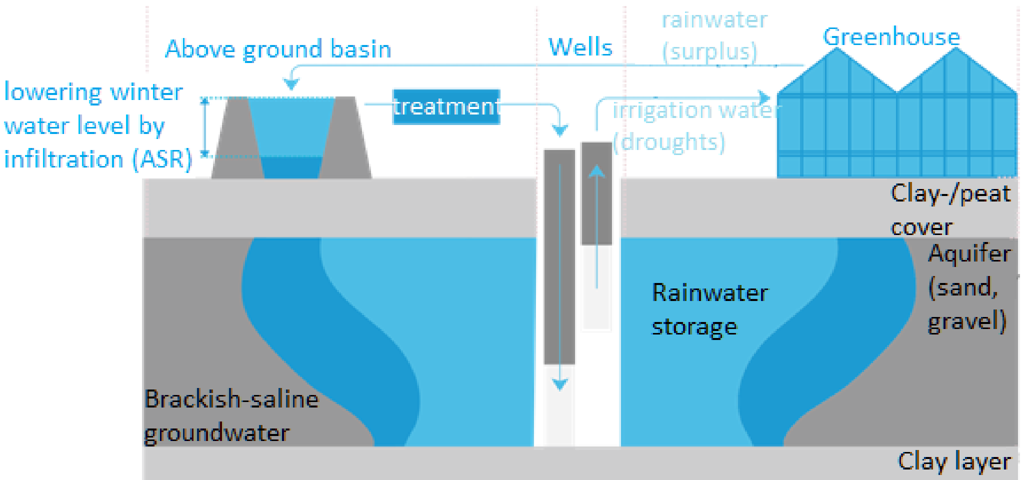

Figure 2-24. Aquifer Storage and Recovery for horticulture (Westland horticulture)

2.5.11. References for more information

[1] SubSol (2017). Retrieved from www.SubSol.org on 10/03/2017

[2] Zuurbier, K. G., Raat, K. J., Paalman, M., Oosterhof, A. T., & Stuyfzand, P. J. (2017). How subsurface water technologies (SWT) can provide robust, effective, and cost-efficient solutions for freshwater Management in Coastal Zones. *Water Resources Management*, *31*(2), 671-687

2.6. *Tools for dimensioning water storages for greenhouse crops*

(Authors: Els Berckmoes[21], Esther Lechevallier[4])

2.6.1. Used for

Preparation of irrigation water.

2.6.2. Region

All EU regions.

2.6.3. Crop(s) in which it is used

All crops.

2.6.4. Cropping type

All cropping types.

2.6.5. Description of the technology

2.6.5.1. Purpose/aim of the technology

The aim of these tools is to provide specific advice regarding the dimensions of water storages for rainwater harvesting for greenhouse crops.

Rainwater harvesting is being promoted to solve water problems for agricultural and horticultural uses in many European regions as rainwater contains very low concentrations of sodium and chlorine. This makes rainwater a high-quality water source, especially in soilless cropping systems where recirculation is applied.

Although rainwater is considered as a low-cost water source, rainwater storage can be quite expensive. The described tools aim to dimension the water storage in relation to water consumption of the greenhouse crops.

2.6.5.2. Working Principle of operation

Standard tables

For many years the advice for dimensioning rainwater storage for greenhouse crops was based on standard tables like the ones of Van Woerden (2001) and CTIFL (2002). These tables (Table 2-6 and Table 2-7) give an overview of the necessary volume of rainwater storage in function of the desired implementation of the water needs for 1 ha greenhouse.

Table 2-6. Necessary water storage capacity and required ground surface in function of the desired percentage of rainwater in the total water demand of 1 hectare of greenhouse crops

Water storage (m³)	% of rainwater in total water demand of the crop	Ground surface (m²)	
		Water silo	Water basin
500	60	225	500
1000	70	450	850
1500	75	675	1100
2000	80	900	1350
2500	83	Not avail.	1850
3000	86	Not avail.	2000
4000	95	Not avail.	2500

Table 2-7. Necessary water storage capacity and required volume of alternative water sources for 1 hectare of greenhouse tomato crops (CTIFL, 2002)

Water storage (m³/ha)	% of rainwater in total water demand of the crop	Rainwater used (m³/ha)	Water volume required of additional sources (m³/ha)
500	65	4800	2700
1000	70	5200	2300
2000	80	6000	1500
3000	86	6400	1100
4000	92	6900	600
5000	96	7200	300
6000	100	7500	0

Models based on crop water consumption and precipitation characteristics

These models are mainly based on long-term data sets of climatological parameters (precipitation, solar radiation, evapotranspiration, etc. - Figure 2-25) and datasets or models for the crops' specific water uptake. Both the Flemish model of Verdonck & Berckmoes (WADITO) and the Dutch model of Glastuinbouw Waterproof are based on this principle.

For example, WADITO is based on a daily simulation of the water level in the water storage. The daily rainwater supply is based on the climatic data (1965-2013). Transmission losses, losses due to evapotranspiration and overflow are integrated into the model. Water consumption through the greenhouse crop is based on daily average water consumption (based on long-term water consumption data). In the case of the model of Glastuinbouw Waterproof, the daily water consumption of the crop is based on the solar radiation.

The model provides the possibility to upload company-specific parameters in order to improve the accuracy of the model. As a result, the model will give the current percentage of the crop water demand that can be fulfilled with the stored rainwater. In addition, the model shows the frequency and average and maximum volume of water shortage for the dataset of 1965-2013.

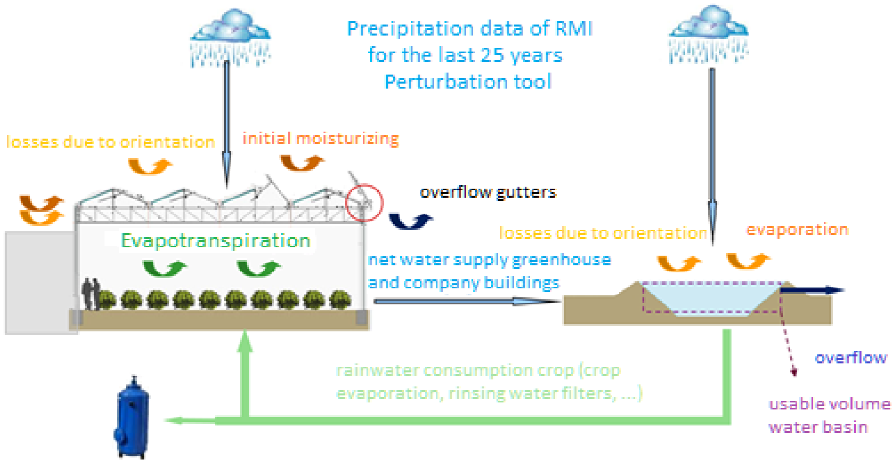

Figure 2-25. Overview of the water streams on which the general principle of the dimensioning is based in WADITO (Source: Berckmoes et al.)

2.6.5.3. Operational conditions

Requirements for applying the different tools are presented in Table 2-8.

Table 2-8. Overview of the limitations of the different dimensioning tools

Tool/Table	Dimension (m^3)	Crop	Type of water storage	Cropping system	Region
Table Van Woerden	500-4000	Tomato	Water basin Water Storage	Greenhouse Soilless	The Netherlands
Table CTIFL	500-6000	Tomato	Not defined	Greenhouse Soilless	Bretagne
WADITO	≥ 500	Standard crops (tomato, sweet pepper, strawberry, lettuce, azalea, roses) All crops: in case weekly freshwater demand is known	Water basin	Greenhouse Soilless Soilbound	Belgium (Mechelen)
Waterstromen	≥ 500	Tomato, sweet pepper, cucumber, roses, ficus, gerbera	Water basin	Greenhouse Soilless	The Netherlands

2.6.5.4. Cost data

Table 2-9. Cost data

Calculation system	Costs
Table Van Woerden	Not avail.
Table CTIFL	Not avail.
WADITO	This model is specialised in the company-specific simulation and is therefore not freely available. The costs for the advice depend on the company-specific conditions and complexity
Waterstromen	The model is publicly available on the website of Waterproof

2.6.5.5. Technological bottlenecks

Rainfall characteristics differ from region to region: e.g. coastal region versus mountains.

In order to provide company-specific advice, the models require long-term rainfall data.

2.6.5.6. Benefit for the grower

Advantages

Company-specific advice regarding dimension water storage.

Disadvantages

General tables: lack of specificity. Sweet pepper crops require significantly less water storage capacity when compared to tomato crops.

2.6.5.7. Supporting systems needed

- Long-term climatological data (rainfall, irradiation, evapotranspiration water, etc.)
- Data on crop water demands (on a daily basis)

2.6.5.8. Development phase

- Research: Spin-offs have developed to dimension the required buffer capacity for greenhouse crops, to dimension rainwater storage for other applications besides irrigation (like the washing of vegetables, etc.) and to dimension water storage facilities for container fields. Provided by: Proefstation voor de Groenteteelt (PSKW)
- Field tests: WADITO and WADITO for container fields are being validated continuously on several test locations
- Commercialised: Advice based on WADITO has been carried out for the construction of 3 new greenhouses (25 ha) and an extension of 2 greenhouses (15 ha) in Belgium

2.6.5.9. Who provides the technology

- Table of van Woerden, provided by Wageningen University Department Praktijkonderzoek Plant en Omgeving
- Table of CTIFL, provided by CTIFL
- Online calculation program, provided by Glastuinbouw Waterproof
- Calculating the company-specific optimal dimension for rainwater storage for (so far only Dutch growers') greenhouse crops: Waterstromen by Wageningen University

2.6.5.10. Patented or not

This technique is not patented.

2.6.6. Which technologies are in competition with this one

There are no technologies that are in competition with the water dimensioning tools.

2.6.7. Is the technology transferable to other crops/climates/cropping systems?

The dimensioning tools can easily be transferred to other crops, climates and cropping systems if the water consumption of the crop/application and daily weather data are available.

The WADITO model is currently being transferred to different other applications:

- Dimensioning of the storage of rainwater and nutrient-rich runoff for container fields (experimental stage)
- Dimensioning of the rainwater storage for rainwater used to, for example, wash leek on small farms (commercial stage)
- Dimensioning of buffer capacities of rainwater storages and risk assessment for flooding due to heavy rainfall for medium- to large-scale greenhouses (field test)

2.6.8. Description of the regulatory bottlenecks

In many European regions, rainwater is considered the most sustainable and qualitative water source for irrigation purposes. However, in several countries growers have to follow procedures in order to receive a permit to build a water storage facility.

In regions like Flanders, stringent security regulations oblige growers to provide a buffer capacity in case of heavy rainfall.

2.6.9. Brief description of the socio-economic bottlenecks

Most of the models take into account the desired percentage of water consumption of the crop to be fulfilled with rainwater. Models do not sufficiently take into account the cost-benefit of the rainwater storage. Although rainwater is mostly referred to as a low-cost water source, the costs for water storage can be high (construction of a water storage, control of algae, loss of productive area, etc.). These costs and costs of alternative water sources should be taken into account to calculate the optimal water storage dimension.

2.6.10. Techniques resulting from this technology

- Online tool Glastuinbouw Waterproof , provided by Glastuinbouw Waterproof
- WADITO (Proefstation voor de Groentettteelt)

2.6.11. References for more information

[1] van Woerden, S. C. (2001). Kwantitatieve informatie voor de Glastuinbouw 2001-2002, Praktijkonderzoek Plant en Omgeving, p. 134

[2] Berckmoes, E., Decombel, A., Dierickx, M., Mechant, E., Lambert, N., Vandewoestijne, E., Van Mechelen, M., & Verdonck, S. (2013). Telen zonder spui, chapter 8, pp. 30-38

[3] Glastuinbouw Waterproof (2017). Retrieved from https://www.glastuinbouwwaterproof.nl/kaswaterweter on 10/03/2017

[4] Le Quillec, S., Brajeul, E., Sedilot, C., Raynal, C., Letard, M., & Grasselly, D. (2002). Gestion des effluents des cultures légumières sur substrat. CTIFL, ISBN 2-87911-187-0

2.7. Water storage covers

(Authors: Ronald Hand[24], Els Berckmoes[21])

2.7.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

2.7.2. Region

All EU regions.

2.7.3. Crop(s) in which it is used

All crops.

2.7.4. Cropping type

All cropping types.

2.7.5. Description of the technology

2.7.5.1. Purpose/aim of the technology

Water storage covers are used to overcome the following storage-related problems:

- Algal bloom: water covers prevent sunlight from entering the stored water volume
- Evapotranspiration losses: by covering the water storage, water temperature is lowered some degrees and evaporated water is (partially) kept in the water storage
- Contamination: in case the covers are tied down to the walls, contaminations are not mixed with the stored water

2.7.5.2. Working Principle of operation

Water storage covers can be installed as a fixed or a floating construction.

Fixed covers

The cover is mainly made of a plastic foil that is stretched over the water storage. The covers are tied down to the walls (Figure 2-26). In this way both precipitation, but also contaminants, like bird droppings, dust, leaves, etc. are prevented from entering the water.

In some cases, steel covers are made. The price of these covers is much higher compared to the plastic covers.

Floating covers

Floating covers are being applied to both water silos and water basins. The stored water is covered with floating materials (foils, balls, etc.) in order to shield the water volume from sunlight. As algae need sunlight to survive, algal development is prohibited this way.

Figure 2-26. Fixed cover stretched over a water silo

2.7.5.3. Operational conditions

Fixed covers

- Impermeable foils are limited to a diameter of 5,5 m. In case a support is installed, the diameter can be increased to 15,5 m
- Steel covers are limited to a diameter of 12 m
- Permeable foils have no limitations, but the water storage tank is limited

Floating covers

Have a diameter of 8,3 m and more and can be fabricated in all shapes.

2.7.5.4. Cost data

Costs for water silo and water basin covers are respectively shown in Table 2-10 and Table 2-11.

Table 2-10. Overview of installation costs for fixed and floating covers for water silos

Type of cover	Small: 25 m²	Medium: 250 m²	Large: 500 m²
Fixed steel cover	100 €/m²	Not avail.	Not avail.
Fixed permeable plastic cover	10 €/m²	6 €/m²	5,5 €/m²
Floating permeable cover	20 €/m²	9 €/m²	9 €/m²
Floating balls	16 €/m²	15 €/m²	14 €/m²

Table 2-11. Overview of installation costs for covers for water basins

Type of cover	Small: 1000 m²	Medium: 5000 m²	Large: 10000 m²
Kristaldek®	40 €/m²	40 €/m²	40 €/m²
Floating balls	14 €/m²	13,75 €/m²	13,75 €/m²

2.7.5.5. Technological bottlenecks

- Larger floating foils have to be correctly installed by specialised personnel
- Covers must be resistant to heavy weather conditions (hail, winds, frost, etc.)
- Floating covers are attractive biotopes for water birds, which can lead to contamination of the upper water layer

2.7.5.6. Benefit for the grower

Advantages

- Very effective to prevent algal bloom
- Quickly achieving results (after 2 weeks)
- Evaporation reduction up to 90-95%
- Fixed covers prevent precipitation and contaminants from entering the water
- Floating balls are easy
- Floating balls prevent waterfowl from entering the reservoir and nesting in the water

Disadvantages

- Higher installation costs
- Floating covers are attractive biotopes for water birds, leading to dirty covers
- Leaves and other particles can still enter the water storage
- Qualified staff is required to install the floating covers
- Sediments are accumulated on the foil and can facilitate plant growth
- Floating balls prevent ducks from entering the reservoir and nesting in the water
- Some cover types are less resistant to wind

An overview of the advantages and disadvantages of the different cover types is given in Table 2-12.

Table 2-12. Overview of advantages and disadvantages of the different types of floating covers

Parameter	Floating cover	Floating balls	Fixed cover
Prevention of inflow of contaminants	good	sufficient	good
Prevention of algal bloom	very good	very good	very good
Evaporation reduction	very good	very good	very good
Ease of installation	mediocre	very easy	easy
Maintenance requirements	low	very low	low
Sediment deposition on the cover	low	very low	mediocre
Wind resistance	very high	mediocre	mediocre

Figure 2-27. Floating covers seem to be an ideal biotope for water birds which soil the cover (Source: Els Berckmoes)

2.7.5.7. Supporting systems needed

- Some floating foils require a floating structure
- In case of the LP-dek, a flexible hose is required to discharge precipitation falling on the cover
- Atlas cords (Figure 2-28) can be a tool to prevent birds landing on the floating covers of big water storages
- In case of floating balls, a sieve or a net has to be installed to avoid balls entering pipelines

Figure 2-28. Atlas cords can be a tool to prevent water birds from landing on the floating covers (Source: Els Berckmoes)

2.7.5.8. Development phase

This technology is commercialised.

2.7.5.9. Who provides the technology

Covers: Royal Brinkman, Albers Alligator (Netherlands).

Floating balls: Beekenkamp verpakkingen (Netherlands).

2.7.5.10. Patented or not

Some of the covers are patented, such as for example:

- LP-dek® from Albers Alligator
- Kristaldek® from Albers Alligator
- Shadow Balls™

2.7.6. Which technologies are in competition with this one?

- Regarding algae control: all technologies to control/prevent algal bloom
- Regarding reduction of evaporation: under groundwater storage

2.7.7. Is the technology transferable to other crops/climates/cropping systems?

The technology can be applied to crops where water is stored and algal bloom and/or evapotranspiration losses must be prevented.

2.7.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks known for this technology.

2.7.9. Brief description of the socio-economic bottlenecks

Costs related to water storage coverage are experienced as high by growers. This price should be compared to the benefit resulting from the technology, being the absence of algae, prevention of evaporation losses, cleaner water, reduction of organic material in the water, etc. An economical estimation of these benefits is currently missing.

2.7.10. Techniques resulting from this technology

Fixed water silo cover (LP-Dek®, Albers Alligator)

This patented, fixed water cover is applied to water silos. The cover is unique as the cover itself moves along with the water level. The cover is constructed in a way this foil covers the water storage surface and the inner sides of the storage as the water volume decreases or increases. In the centre of the foil, a vent is installed to exchange gasses. Water falling on the fixed cover is discharged through a hose (see Figure 2-29).

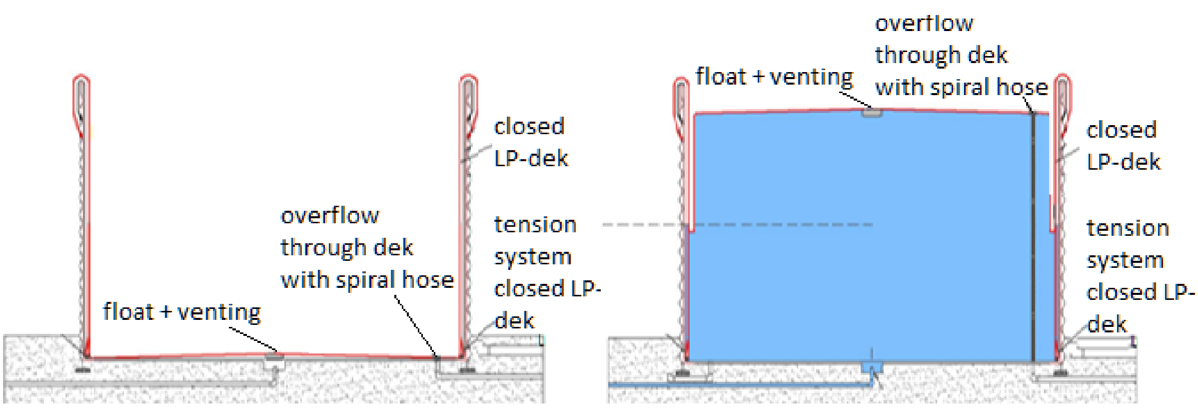

Figure 2-29. Scheme of the closed LP-Dek® (http://www.albersalligator.com)

Floating water cover (Kristaldek®, Albers Alligator; MultiF®, Albers Alligator; Air Float, Brinkman; PAS Drijfdek)

Kristaldek® (Figure 2-30) is a floating cover, made of a coated fabric impervious to light. The cover itself exists of a central foil with dimensions similar to the bottom surface. Floating bodies are attached to this fabric foil. At the sides of the floating foil vertical slabs are attached, preventing light to enter the water body underneath the cover. The cover itself is attached to the shores by use of flexible cables.

Air float and PAS Drijfdek are floating covers designed for water silos.

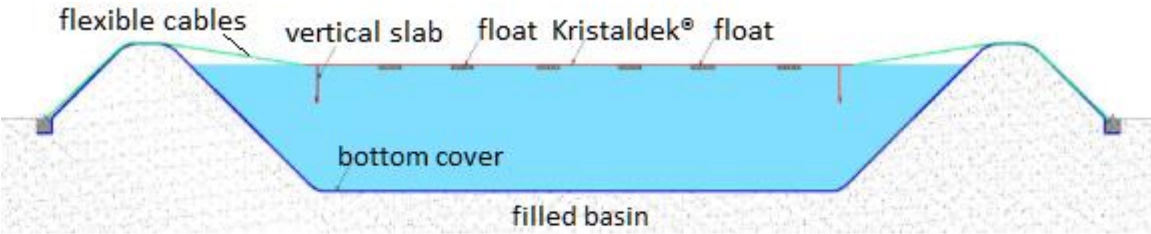

Figure 2-30. Schematic view of the Kristeldek®. The central foil covers the area of storage floor. Vertical slabs at the sides of this foil, preventing light to enter the water body. Elastic cords, keep everything in place

In Figure 2-31 to Figure 2-33 the installation of this type of cover is illustrated.

Figure 2-31. Installing the floats (Source: PSKW)

Figure 2-32. Ballast is attached to the vertical slabs,attached all around the floating horizontal foil (Source: PSKW)

Figure 2-33. Manpower is needed to put the foil in its final position, so installation takes some hours (Source: PSKW)

Floating balls (Armor BallTM, HexprotectTM, Shade Ball TM solutions, Beekenkamp)

Hollow balls with a spherical or hexagonal form are placed in the water storage. Depending on the shape of the balls, a coverage of 91-99% can be reached in case sufficient balls are inserted into the storage.

Figure 2-34. Depending on the shape of the floating balls, a coverage up to 91-99% can be reached (Beekenkamp)

2.7.11. References for more information

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2.8. Collecting condensed water

(Authors: Juan José Magán[9], Elisa Suárez –Rey[11])

2.8.1. Used for

More efficient use of water.

2.8.2. Region

All EU regions.

2.8.3. Crop(s) in which it is used

Crops in greenhouses.

2.8.4. Cropping type

- Protected
- Soil-bound
- Soilless

2.8.5. Description of the technology

2.8.5.1. Purpose/aim of the technology

This technology aims to collect the water condensing on the cover surfaces of the greenhouse in order to avoid its dripping on the crop (reducing the risk of crop diseases) and to use it in crop irrigation as a good quality and sustainable water source.

2.8.5.2. Working Principle of operation

Air in the atmosphere is a combination of dry air and water vapour. The capacity of the air to contain water vapour decreases with temperature. If the temperature of a surface immersed in the air is equal or lower than the dew temperature (temperature for full air saturation), then dew is formed on that surface (Figure 2-35). The cover and metal structure are frequently the coldest spots in greenhouses due to contact with the outside air and the emission of longwave radiation. These are the first surfaces of the greenhouse where dew appears.

Figure 2-35. Condensation on a greenhouse glass wall

Condensation in greenhouses tends to occur more frequently early in the morning, when solar radiation reaches the crop, thereby increasing transpiration and air humidity in the greenhouse, but plant (fruits) and cover temperature increases more slowly than air temperature. However, it is also possible during the night and the afternoon, when the temperature drops sharply and the greenhouse is humid due to crop transpiration.

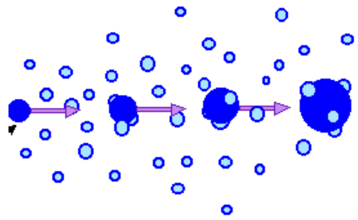

Figure 2-36. Droplet growth by coalescence
(https://www.shodor.org/os411/courses/411c/module07/unit02/page04.html)

Condensation on a surface may take place following two structural types:

- Condensation wets the entire surface and forms a continuous film, then constituting a new condensation surface of size equal to the initial surface
- Condensation occurs on a triple contact surface: solid, gas and the surface of the drops previously condensed. Here, drops are organised individually, initially having a microscopic size and increasing in size by merging with steam molecules. This phenomenon is known as coalescence (Figure 2-36). When the drop is big enough to reach a gravity force higher than capillarity (cohesion forces), its breaking point is reached and the drop slides over the condensing surface, allowing being collected

In a complete condensation cycle, four different phases can be distinguished: 1) a dry phase; 2) a condensation phase without run-off; 3) a condensation phase with run-off and 4) an evaporation phase.

Climatic variables involved in the phenomenon of condensation on a surface are basically air humidity and temperature, condensing surface temperature and wind speed. Condensation is also affected by the properties of the condensing surface.

2.8.5.3. Operational conditions

As a consequence of the different surface tension of cladding materials, condensation on glass surfaces usually appears as a film of water (Figure 2-38) which facilitates its run-off, while on many plastic films, condensation appears as drops which makes run-off more difficult. This also has a consequence on light transmission because of the higher reflection in the second case (Figure 2-37).

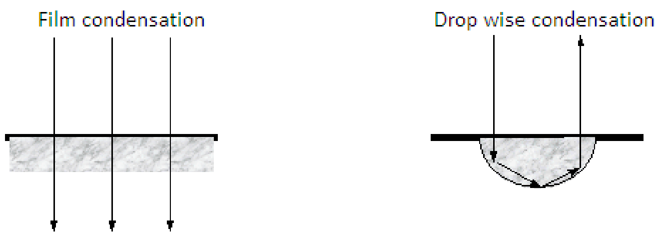

Figure 2-37. Effect of condensation on light transmission

There are a number of methods to produce a continuous layer of condensed water, such as treatment of the film surface or oxidation of the polymer surface, but the most efficient method for agricultural films is the incorporation of additives during the manufacturing process (anti-drip plastic). In Figure 2-38 it is possible to see the different behaviour with respect to condensation of a conventional plastic compared to an anti-drip plastic. In a study carried out in Almería (Spain), the average condensation recovery in the conventional and the anti-drip plastics in a closed greenhouse without crop, but with gutters filled with water covering almost 10% of soil surface was 0,08 and 0,228 L/m²/day, respectively. The small quantity of water collected in case of the normal plastic indicates that most of the water evaporated in the greenhouse, falls down to the floor after condensation or is retained in the plastic until evaporating during the day. In case of the anti-drip plastic, water collection is very efficient. These values of water collection cannot be extrapolated to commercial greenhouses but even then, they show the effectiveness of anti-drip plastics, which are able to collect almost 300% more than normal plastics.

Figure 2-38. Behaviour respect to condensation of different plastic types: left, anti-drip plastic with film condensation; right, conventional plastic with dropwise condensation

The same closed greenhouse was tested as a passive solar desalination system (Figure 2-39), now using the whole surface as a reservoir (of saline water). The experimental data indicate that it is possible to collect around 750 L/m² of condensed water per year (in addition to rainwater). A limiting factor for the commercial use of this system is the price of the land, apart from the availability of adequate plastic cladding materials with high duration of the anti-drip effect under high temperature and condensation rate conditions. The duration of the anti-drip effect under such extreme conditions is presently only a few months. However, it may extend to more than one year in conventional growing conditions.

Figure 2-39. Picture of closed greenhouse used as passive solar desalination system

Measurements were carried out in commercial Venlo-type greenhouses growing tomato, cucumber and eggplant in Almería. The glasshouse where the cucumber was grown was located in an area with warmer nights in winter, which affected the results (Table 2-13).

A study in southern France gave average daily rates of 0,23 L/m²/day. The observed differences observed can be related to the thermal jump between the indoor and outdoor environment that was maintained in each case.

Table 2-13. Overview of condensation water recovered in different studies

<table>
<tr><th>Crop</th><th>Period</th><th>Roof material</th><th>Accumulated condensation volume</th><th>Max. daily rate</th><th>Average daily rate</th></tr>
<tr><td>Tomato</td><td>Oct-June</td><td>Glass</td><td>27,7 L/m²</td><td rowspan="2">0,4 L/m²/day</td><td rowspan="2">0,11 L/m²/day</td></tr>
<tr><td>Tomato</td><td>Oct-June</td><td>Plastic</td><td>27,0 L/m²</td></tr>
<tr><td>Cucumber</td><td>Feb-March</td><td>Glass</td><td>Not avail.</td><td>0,15 L/m²/day</td><td>0,04 L/m²/day</td></tr>
<tr><td>Eggplant</td><td>Oct-May</td><td>Glass</td><td>11,6 L/m²</td><td>Not avail.</td><td>0,05 L/m²/day</td></tr>
</table>

2.8.5.4. Cost data

Installation of gutters for collecting condensed water in multi-span arched-roof greenhouses costs about 6000 €/ha, including the gutters, accessories and labour.

2.8.5.5. Technological bottlenecks

In parral-type greenhouses, the plastic film covering the roof is held between two galvanised steel networks and attached to an array of tension wires that connect the vertical posts supporting the roof. Condensed water from the internal roof cover frequently comes into contact with the steel network, forming drops that fall onto the crop. Condensed water collection is inefficient in these greenhouses (common in southeast Spanish Mediterranean).

In multi-span arched-roof greenhouses covered with plastic film, the roof slope near the ridges is very low, which makes drop sliding difficult on this part of the cover. Zabeltitz (2011) published some requirements, depending on the material of the roof:

- Conventional plastics without anti-drip additives: slope > 14° = formation of runoff lines. Most of the water moving in these runoff lines falls before reaching the collecting gutter
- Normal plastic: slope > 15% = occurrence of a lot of dripping: both in the centre of the greenhouse (because of the low slope) and the rest of the greenhouse (because the angle is high and produces a quick drop sliding with dripping from the runoff lines)
- Plastic with anti-drip additives: angle between 14° and 40° = less dripping: dripping will come almost exclusively from the central area of the greenhouse (where the angle is usually low), while in the case of normal plastic

Anti-drip additives added to the plastic tend to migrate towards the surface and are washed away by condensation. Anti-drip properties are usually lost before the end of the lifespan of the plastic. Multi-layer plastics use one of their central layers as a reservoir of anti-drip additives so that they continuously supply replacement to the additives lost by washing. However, this reservoir can be lost quite quickly in extreme conditions.

Another cause of dripping in multi-span arched-roof greenhouses is the contact of drops with the anti-insect net usually placed in the vents, which also hinders drop sliding. Finally, in this greenhouse type, the cladding material is tied to the structure by a special long piece joined to the rainwater gutter, where the plastic is usually bent towards the inside of the greenhouse for a higher resistance. The plastic surplus also makes drop sliding difficult and promotes dripping, if not cut properly.

Venlo type greenhouses (extensively used in cold areas) are equipped for collecting condensation. Multispan arched-roof greenhouses covered with plastic film (which are more typical of mild winter areas) are not always equipped for an efficient recovery.

2.8.5.6. Benefit for the grower

Advantages

- High-quality water for irrigation
- Reduced disease risk

Disadvantages

- Low quantities of water captured
- Low efficiency

2.8.5.7. Supporting systems needed

The gutters collecting the condensation have to be connected to pipes transporting the water to the reservoir.

2.8.5.8. Development phase

This technology is commercialised.

2.8.5.9. Who provides the technology

Companies building industrial greenhouses also install systems for condensation recovery.

2.8.5.10. Patented or not

This technique is not patented.

2.8.6. Which technologies are in competition with this one

- Active dehumidification systems
- Heat exchangers in closed greenhouses

2.8.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this technology is applicable to most greenhouses.

2.8.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

2.8.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks.

2.8.10. Techniques resulting from this technology

In some Venlo-type greenhouses, there are two gutters for condensed water collection (Figure 2-40). The upper gutter collects the condensation coming from the roof, as well as the rainwater in the outside part and the lower gutter collects the condensation produced on the upper gutter.

Figure 2-40. Picture of Venlo-type greenhouse with a double gutter for condensed water collection (Source: Santiago Bonachela)

In multi-span arched-roof greenhouses and some Venlo-type greenhouses, a gutter under the gutter for rainwater collection can be installed for condensation recovery (Figure 2-40), condensation slides from the cladding material to the lower gutter through the upper gutter.

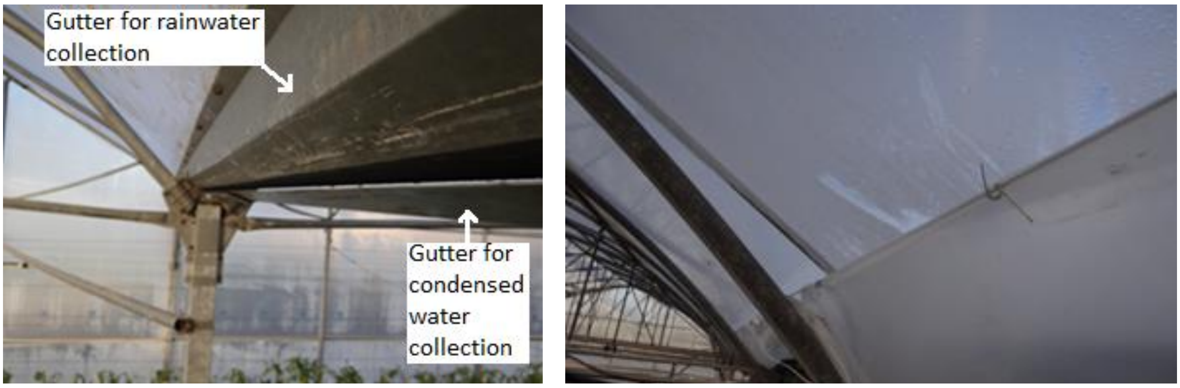

Figure 2-41. A multi-span arched-roof greenhouse with a gutter for condensed water collection. Left: separate gutter. Right: gutter made from the plastic surplus

Some growers in Almería using multi-span arched-roof greenhouses covered with plastic film make a gutter from the plastic surplus in order to ensure condensation recovery (Figure 2-41, Right).

2.8.11. References for more information

[1] Feuilloley, P., & Guillaume, S. (1990). The Heat Pomp: a Tool for Humidity Excess Control in Greenhouses. CEMAGREF, BTMEA, *54*, 9-18

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[3] Bonachela, S., Hernández, J., López, J. C., Perez-Parra, J. J., Magán, J. J., Granados, M. R., & Ortega, B. (2009, June). Measurement of the condensation flux in a venlo-type glasshouse with a cucumber crop in a Mediterranean area. In *International Symposium on High Technology for Greenhouse Systems: GreenSys2009 893*, pp. 531-538

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2.9. Floating pumps

(Authors: Esther Lechevallier[4], Els Berckmoes[21], Justyna Fila[6])

2.9.1. Used for

Preparation of irrigation water.

2.9.2. Region

All EU regions.

2.9.3. Crop(s) in which it is used

All crop types.

2.9.4. Cropping type

All cropping types.

2.9.5. Description of the technology

2.9.5.1. Purpose/aim of the technology

Floating pumps enable to pump water from a certain level above the bottom of the water storage in order to:

- avoid the uptake of floating particles (sediment, aquatic plants, algae, etc.)
- pump cooler water (from the lower water levels)
- pump water at the centre of the water storage where the depth is maximal

2.9.5.2. Working Principle of operation

Like the term “floating” pumps indicates, the pumps are floating in the water body. The pump is not lying on the bottom of the reservoir like in a normal storage (Figure 2-42), but it is raised by a float (e.g. a floating raft made of empty water cans) or attached to a support (e.g. a pole).

Pumps attached to a float

When the pump is attached to a float, the pump will follow the water level variations. A flexible pipe can be attached to the float and anchored so that pump moves in a range of approximately 0,5 m below the water surface and the bottom of the water storage (Figure 2-43).

Floating pump attached to a fixed structure

In case the pump is attached to a fixed structure, the pump will be positioned just above the bottom of the water basin to avoid sediment uptake (Figure 2-44). The pump depths can then be adjusted manually.

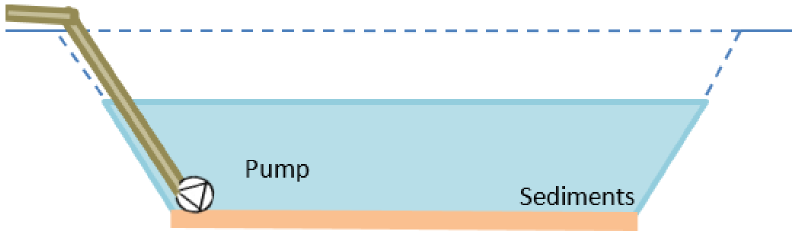

Figure 2-42. System with a fixed position of the pump at the bottom of the water storage (Source: Esther Lechevallier)

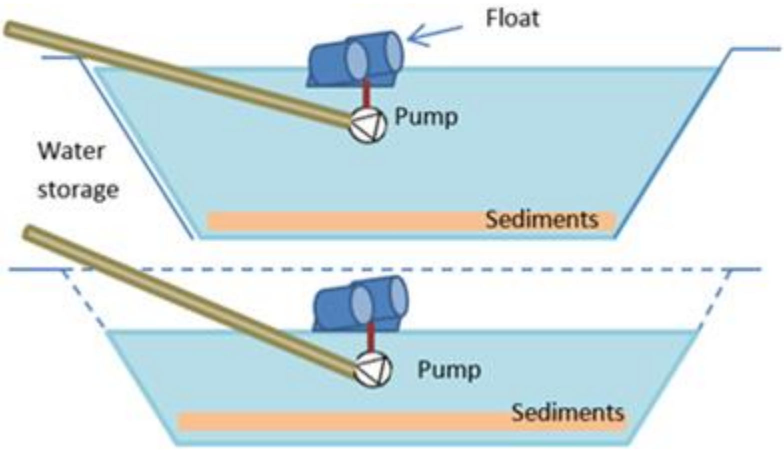

Figure 2-43. Floating pump attached to a raft. Changes of the water level will change the depth of the pump (Source: Esther Lechevallier)

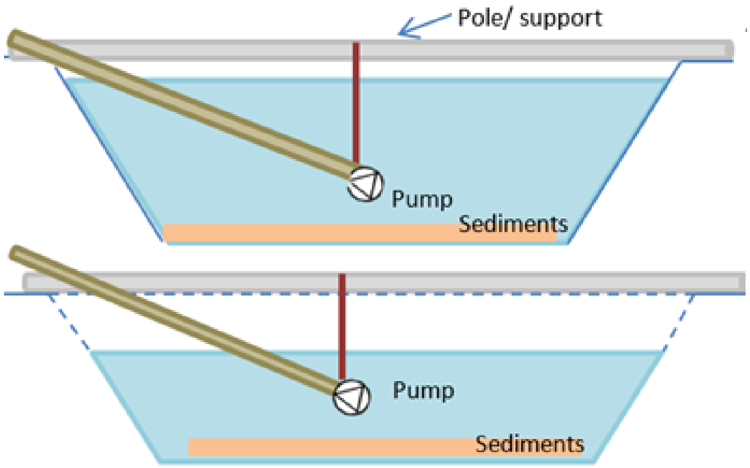

Figure 2-44. Floating pump attached to a support system. The position of the pump in relation to the bottom of the water body, will not change due to the changes in the water level (Source: Esther Lechevallier)

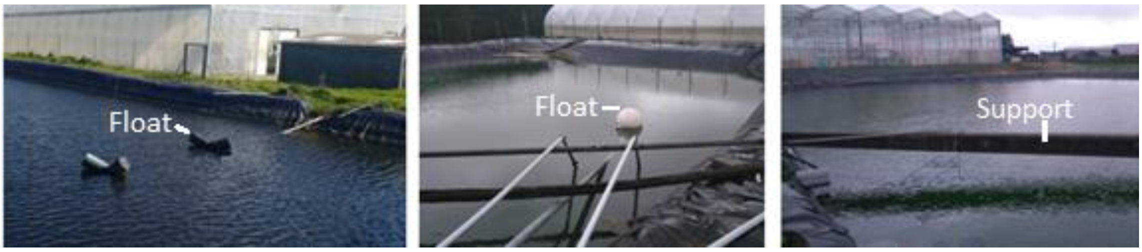

Figure 2-45. Examples of different constructions of floating pumps. Left and middle: pumps attached to floats; Right: floating pump attached to a fixed structure, in this case, a pole (Source: CATE)

2.9.5.3. Operational conditions

Pumps attached to a float

There are no limitations regarding scale, capacity, etc. but there are for the depth of water extraction. As the water level decreases, the floats will also move towards the bottom of the water storage. In case of very low water levels, the pumps must be switched off in order to avoid suctions of both sediments and water with too high water temperature.

Floating pump attached to a fixed structure

The width of the water storage can limit fixing the support and in case of very low water levels, the pump must be lowered manually. The uptake of sediments and water with too high water temperature should also be avoided here.

2.9.5.4. Cost data

Generally, floating systems are manufactured by the growers themselves. Costs depend on the type of pump and material used for the implementation (wooden pole with suspension, floating raft, etc.). Maintenance costs are limited to an installations check from time to time.

2.9.5.5. Technological bottlenecks

In case of very low water levels in the water storage, the floating pump must be switched off automatically or manually because of a risk for uptake of sediments or warmer water. In general, a minimum level of 0,5 m above the bottom of the reservoir is maintained.

2.9.5.6. Benefit for the grower

Advantages

- Avoids suction of sediments at the bottom of the water storage
- Avoids suction of algae at the water surface
- Easy implementation
- Water can be pumped from the middle of the storage where the depth is maximal
- Extraction of slightly warmer water from 20-30 cm below the water surface in winter

Disadvantages

- Pumps must be switched off in case of low water levels
- Pumps attached to a fixed structure have to be lowered manually to have the maximal benefit (higher water temperatures in winter, cooler in summer)

2.9.5.7. Supporting systems needed

- A simple screen filter at the insert opening of the pump to avoid suction of floating particles
- A flexible pipe so the floating pumps can follow the water level
- A fixed structure, including a system to lift or lower the pump
- A system to switch off the pump automatically in case of low water levels (sensors)

2.9.5.8. Development phase

This technology is commercialised: many growers install the floating pumps themselves.

2.9.5.9. Who provides the technology

Most of the local equipment companies provide these pumps.

2.9.5.10. Patented or not

This technology is not patented.

2.9.6. Which technologies are in competition with this one

- Fixed pumps
- Technologies avoiding sediments to enter water storages, e.g. water storage covers
- Technologies to prevent sediment build up, e.g. a vacuum cleaner for water storages

2.9.7. Is the technology transferable to other crops/climates/cropping systems?

This technology is not linked to regions, crops or cropping systems. It is directly linked to the methods of water storage (water basins or water silos).

2.9.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks known for this technology.

2.9.9. Brief description of the socio-economic bottlenecks

There are no economic bottlenecks because of the low cost of this technology.

2.9.10. Techniques resulting from this technology

There are no techniques resulting from this technology.

2.9.11. References for more information

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Chapter 3. Optimising water quality - Chemical composition

Coordinators: Wilfred Appelman[22], Ilse Delcour[19]

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3.1. Introduction Optimising water quality - Chemical composition

3.1.1. These techniques concern the issue

Preparation of irrigation water.

3.1.2. Regions

All EU regions.

3.1.3. Crops in which the problem is relevant

The technologies described in this chapter are general technologies that apply to all crops, since they consider general issues and technologies for optimising the chemical quality of irrigation water. However, when using these technologies, it must be kept in mind that there are appreciable differences in the tolerance or sensitivity of different crops to salinity (salt content) and to harmful individual elements such as sodium (Na) or chloride (Cl). For example, Phalaenopsis (moth orchid) is very sensitive to salinity, while tomato is appreciably more salt tolerant. Crop sensitivity or tolerance to salinity and the composition of the water supply influence the requirements, for a given site, regarding the technologies described in this chapter.

3.1.4. Cropping type

For all crops and cropping systems, it is essential to maintain an acceptable quality of irrigation water with regards to salinity and to the composition of chemical elements and compounds. In addition to crop species, the type of cropping system influences the required water quality. For soilless growing systems with recirculation of drainage, the requirements for the quality of irrigation water, regarding salinity, Na and Cl, are high in order to ensure that the accumulation of these components during recirculation commences from relatively low base values.

Where groundwater is used, commonly, the salinity and chemical composition are issues that have to be taken into consideration for decisions related to crop selection. Additionally, the water may require treatment prior to being suitable for irrigation. These issues are particularly important in drier Mediterranean regions where groundwater, with a higher salt content, is commonly used. In some Mediterranean regions, an on-going increase in the salinity of groundwater is occurring which may progressively increase the requirement for the treatment of irrigation water. Water treatment is likely to increasingly become an issue for soil-grown crops in these regions, and will be of particular interest for free-draining soilless cropping that, in the future, may be required to implement recirculation.

Given the common tendency of increasing salinity of groundwater, and the possible obligation to recirculate drainage in soilless systems, the issue of the chemical composition of irrigation water is likely to be of increasing importance for the foreseeable future within the European Union.

3.1.5. General description of the issue

The supply of irrigation water of adequate quality is a fundamental factor for horticultural crop production. In addition to describing the relevant technologies for modifying the chemical composition of irrigation water, this chapter describes the problems and issues associated with the improvement of the chemical quality of irrigation water, focussing on the overall salinity, nutrients, Na, Cl, iron (Fe), and manganese (Mn).

As mentioned previously, crops differ appreciably regarding their sensitivity to salinity. Consequently, quantitative criteria have been established for individual crop species, related to the chemical quality of the irrigation water for optimal growth and production. The chemical quality of irrigation water can differ considerably depending on the region, water type, the nature of the aquifer etc.

In general, optimal water quality management requires maintaining the concentration of nutrients and salinity at the desired level, and the removal of unwanted components, such as particular elements and compounds. When nutrient solutions are recirculated, accumulation of ballast salts occurs. These ballast salts are salts that are consumed only in minor amounts by the crops. When the concentration of these salts increase appreciably, phytotoxic effects can occur. Sodium commonly causes problems in European coastal areas where horticultural production takes place. By maintaining low levels of Na in the irrigation water, water can be recycled for longer, and the frequency of purging recirculating water is reduced. In soil grown crops, Na accumulation can also negatively affect crop growth and production.

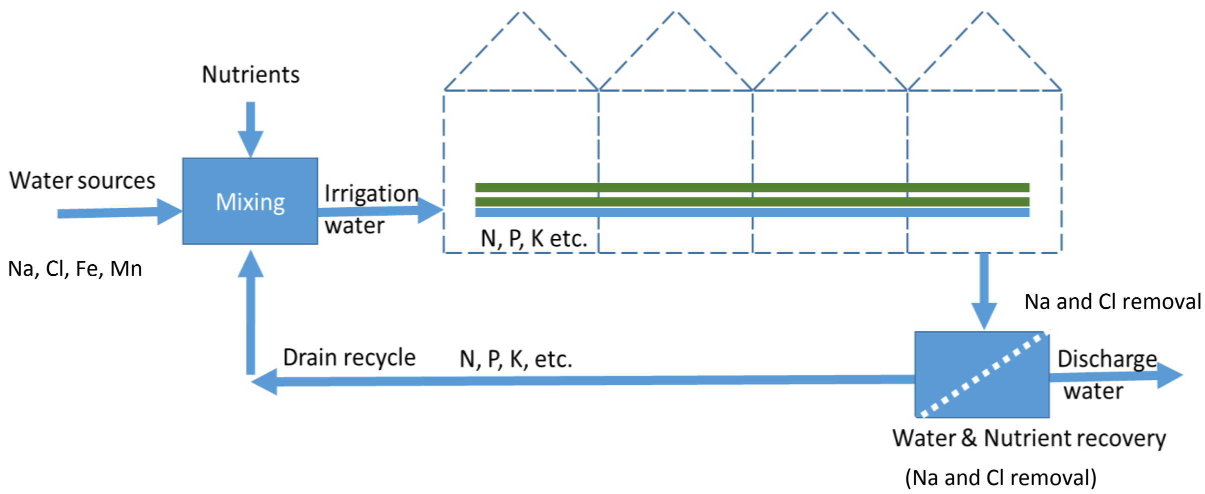

Figure 3-1. Schematic approach of a closed water system in (greenhouse) horticulture

The problems associated with nutrients and salts concern (Figure 3-1) are:

- Desalination
- Preparation of irrigation water by removal of Fe and Mn
- Accumulation of potentially plant-toxic concentrations of salts as Na and Cl in closed water cycles
- Costs of nutrient removal

- Water quality requirements
- Water quality monitoring

The problems described in this chapter are also closely related to the issues described in 1) chapter 4 which deals with removal of particles in the irrigation water, 2) chapter 11 which deals with optimal nutrient management, and 3) chapter 12 which deals with nutrient removal and recovery from discarded drainage water to limit environmental impact.

3.1.5.1. Sub-issue A: preparation of irrigation water by removal of Fe and Mg

When groundwater containing Fe (in ionic forms, dissolved inorganic complexes, organic complexes colloidal or suspended forms) is pumped from aquifers for irrigation, partial oxidation occurs. The resulting oxidised forms of Fe can precipitate causing fouling and clogging of the irrigation systems. Water sources containing Fe concentrations exceeding 0,5 ppm cannot be used in drip irrigation systems without pre-treatment.

Iron removal is an established technology; however, for the effective operation of this technology, good management of the system is required, particularly of pH, alkalinity and the occurrence of oxidation. The cost and footprint (area occupied) of these systems can also be issues.

3.1.5.2. Sub-issue B: Desalination

The main problems in desalination are:

- Fouling of the membrane systems used for desalination

Membrane systems, like reverse osmosis, nanofiltration, electro-dialysis, and membrane distillation are sensitive to fouling. Often a pre-treatment, that removes particles, is required. Additionally, salts with low solubility may precipitate and can cause fouling. Lowering the pH can reduce the problem.

- Discharge of concentrates of desalination

Most of the desalination technologies are based on the concentrating principle. In addition to clean water (permeate), a concentrated (salt) stream (concentrate) is produced that must be disposed of. The discharge of this concentrate can cause environmental problems and/or is limited by regulation.

Modified Ion Exchange technology produces a concentrated stream which could be suitable for reuse. Field tests still have to confirm this.

- Low selectivity

Most of the desalination technologies appreciably and non-selectively reduce the concentrations of all salts including useful nutrients. In the case of recirculation of nutrient solutions, the removal of crop nutrients is undesirable. Also, the concentrate (see above) cannot be applied to crops, because it may contain high concentrations of Na, Cl and other harmful ions.

3.1.5.3. Sub-issue C: Need for a more holistic approach

In general, the technologies for nutrient removal focus on the removal of salts. The capacity for removal of plant protection products (PPP), micro-organism or other harmful agents is not always clear. A more holistic approach to the removal of various undesirable agents could be useful for both technical and economic reasons.

3.1.5.4. Sub-issue D: Need for validation of the removed nutrients to make water treatment economically feasible

In comparison to the relatively low cost of water, the costs for water treatments can be high. This is particularly so for treatments for use with recirculation. Feasibility could be improved by the use of more selective technologies that would selectively enable the recycling of crop nutrients. In general, the generated nutrient streams are dissolved, liquid fertilisers. As storage or transport over long distances is expensive, it is preferable that these regenerated nutrients are used on-site, or if this is not possible, that they are further concentrated prior to transport or storage.

3.1.5.5. Sub-issue E: Need for better understanding of the crops chemical water quality requirements and threshold values

For different crop species, requirements and threshold values for chemical water quality vary appreciably. Growers are not always aware of these threshold values. In case of horticultural crops, there is a need for a good understanding of a specie's tolerance to salinity and to Na and Cl. As an example, in The Netherlands, on-going research studies are investigating the response of different species to Na concentrations.

3.1.5.6. Sub-issue F: Water quality monitoring of recirculated nutrient solutions

One of the problems associated with maintaining good water quality is determining the Na content. This is normally done by manual sampling of the nutrient solution followed by laboratory analyses, which is combined with online monitoring of the total electrical conductivity (EC).

3.1.6. Brief description of the socio-economic impact of the issue

Having optimal chemical composition of irrigation water provides a series of benefits which apply to irrigation, fertigation and recirculation; these include:

- Reduction of the frequency of purging water from soilless growing systems with recirculation which will result in reduced emissions (decreasing the costs of purifying/discharging this water)
- Reduction of the amount of fresh nutrients required which reduces the fertiliser cost of the grower
- Less groundwater withdrawal

This can be seen in The Netherlands with the example of closing the water and nutrient cycles in soilless cultivation systems. These systems are already common in Dutch greenhouse horticulture (more than 80% of the greenhouse surface area). In greenhouse areas, with intensive soilless cultivations, the quality of the surface waters often does not meet the standards for good chemical and ecological water status of natural water bodies, as required by the Water Framework Directive 2000/60/EC. The recirculating nutrient solution may be discarded when there is doubt about the quality of its chemical composition. On average, 10% of the nutrient solution is discharged yearly. Soilless cultivation in the Netherlands uses 6,5 M m^3/year of fresh water, and annually emits 1300 tons of N, 200 tons of P, and 1134 kg of PPPs. Calculations suggest that eliminating these discharges of recirculating nutrient solutions will reduce the use of fresh water by 2,6 M m^3/year and reduce the water pollution by nutrients and PPPs by 60%, in The Netherlands.

3.1.7. Brief description of the regulations concerning the problem

In some countries or regions, there are restrictions regarding the discharge of concentrates from water purification processes. These concentrates often contain high levels of undesired salts as Na; and depending on the type of technology used, can also contain plant nutrients and other problematic substances as PPPs. For the discharge of these concentrates from desalination, which also known as brines, the appropriate regulations for the region should be identified. Depending on the composition of these concentrates, it may not be permitted to discharge them to surface waters or to sewers, or to transport them. In general, there are:

- Limits for the discharge of concentrates
- Regulations regarding transport of secondary materials

3.1.8. Existing technologies to solve the issue

The following technologies, to improve the chemical quality of irrigation water, are described in this chapter:

- pH change
- Iron and Mn removal: Flocculation / coagulation: removal of Fe = Fe filter (= combination of flocculation + filtration (sand filter))
- Desalination
    - forward osmosis
    - reverse osmosis
    - membrane distillation
    - modified ion exchange
    - electrophysical precipitation
    - electrolysis/ electrodialysis
    - capacitive deionisation

3.1.9. Issues that cannot be solved currently

At this moment, issues which need to be solved, but for which adequate solutions do not yet exist, are:

- High costs of desalination
- Destination of concentrates / brines from desalination
- The need for a selective removal of Na

- The need for a holistic approach

For some technologies, there is a need for demonstration at a location to show the practical value.

3.1.10. References for more information

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3.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions (TDs)

Technology	Cost			Requirements	Strengths	Weaknesses	Technology development stage
	Investment	Maintenance	Total cost				
Concentration of ions							
Capacitive deionisation	35-100 k€	Energy: 0,5- 2,5 kWh/m³	1-5 €/m³	Basic agronomic knowledge Basic computer skills	No chemicals or anti-scaling products required water recovery rate 80-90%	Optimisation of electrodes is required More efficient for low salinity feed waters	Pilot to commercial
Electrophysical precipitation (EpF)	Not avail.	Not avail.	Not avail.	Minimal maintenance Pre-treatment	Low energy consumption	Risk of fouling Handling of reject water and rinsing water required Hydrogren formation	Pilot to commercial
Electrodialysis	9-64 k€ /year (1-10 m³/ h)	Energy: 0, 05 kWh/m³ Operational cost: 2-15 k€ /year (1-10 m³/ h)	1,3-2,6 €/m³		High energy efficiency	Not selective Electrodialysis becomes less economical when extremely low salt concentrations in the product are required	Pilot to commercial
Modified Ion Exchange	50-100 k€ (120 m³/day unit)	Cost of chemicals is recovered by the values of the fertilisers produced Resin (replaced once in 5-10 years) cost 1000-5000 €		Chemical background	Production of fertilisers Low fouling potential Semi-selective removal of sodium	Complex system	Pilot to commercial

Technology	Cost			Requirements	Strengths	Weaknesses	Technology development stage
	Investment	Maintenance	Total cost				
Nanofiltration	200-1000 €/m³/day Membranes add 20-45 €/m²	Energy: 0,15 kWh/m³	0,2-1 €/m³, depending on the scale of the installation.	Only very little attention by staff is needed Pre-treatment	Reliable water quality Disinfection Easily automated Continuous water supply Selectivity	Sensitive to fouling Handling of reject water and rinsing water required More expensive membranes	Commercial
Concentration of water							
Reverse osmosis	30 k€ (200m³/day)	Energy: 2-3 kWh/m³	0,5-3 €/m³	Pre-treatment	Continuous water supply Reliable technology Easily scalable	Membrane fouling might occur Discharge of concentrated streams (10-50%) No selectivity Limited boron removal to 1 mg/l	Commercial
Forward osmosis	Not avail.	Energy: 1,3-1,5 kWh/m³	Not avail.	Concentrated drawing solution (e.g., liquid fertiliser)	Operates at mild process conditions Lower risk of membrane fouling	Multiple steps required to obtain high-quality water	Pilots, no practical experience in horticulture
Membrane distillation	900 €/m³ /day	Energy: 2,8 kWh/m³	0,94-1,61 €/m³	Few manual actions required Pre-treatment	Continuous water supply Multivalent ions are separated, monovalent ions are partially removed Disinfection of bacteria	Fouling and plugging risks Discharge of concentrated streams	Pilots

Technology	Cost			Requirements	Strengths	Weaknesses	Technology development stage
	Investment	Maintenance	Total cost				
Other							
pH change/adjustments	3000 €	Storage tanks of neutralisation chemicals must be kept full		Calibration of pH probe			Commercial
Iron removal	for 2 ppm flow & 10 m^3/h (aeration pump, rapid sand filter 2 tanks x 850 mm, a mixing tank and a disc filter): 4300 €			Simple operation	Low cost Continuous water supply No chemicals required	Footprint (m²) Handling of reject water and rinsing water required Limited ability to remove Fe	Commercial

3.3. Reverse Osmosis

(Authors: Wilfred Appelman[22], Willy van Tongeren[22], Ockie van Niekerk[16])

3.3.1. Used for

Preparation of irrigation water.

3.3.2. Region

All EU regions.

3.3.3. Crop(s) in which it is used

All crops.

3.3.4. Cropping type

All cropping types.

3.3.5. Description of the technology

3.3.5.1. Purpose/aim of the technology

Reverse osmosis (RO) is a technology for desalination of brackish or salt (sea) water producing demineralised water and a concentrated saline water stream. It is used for large scale water treatment for preparing water suitable for drinking and for production processes, and for wastewater treatment.

Treating brackish groundwater for use as irrigation water

For sustainable greenhouse farming, irrigation water with low sodium content is essential. To make brackish groundwater suitable for irrigation, desalination by RO can be used. Additionally, RO can be used for the treatment of wastewater streams for subsequent recycling or for discharge.

In horticulture applications, RO is commercially and widely used for treating brackish groundwater.

Treating sea water for use as irrigation water

Reverse osmosis (RO) is widely used for the desalination of seawater (SWRO) in large scale installations which can be used for irrigation purposes especially in the southern part of Europe.

Treating drain-water so can be recycled

Pilot research has been conducted on treating drain water for recycling and it has provided good results. RO for drain water recycling is not yet developed to a commercial solution.

3.3.5.2. Working Principle of operation

Reverse osmosis is a technology that uses a semipermeable membrane to remove ions, molecules and larger particles from water. In reverse osmosis, an applied pressure is the driving force, which is needed to overcome the osmotic pressure caused by the amount of salt dissolved in the water. Reverse osmosis can remove many types of dissolved and suspended particles from water, including bacteria. It is used in industrial processes and for the production of potable (i.e. drinking) water.

Reverse osmosis systems remove total dissolved ions at a typical rejection rate of 95-99%.

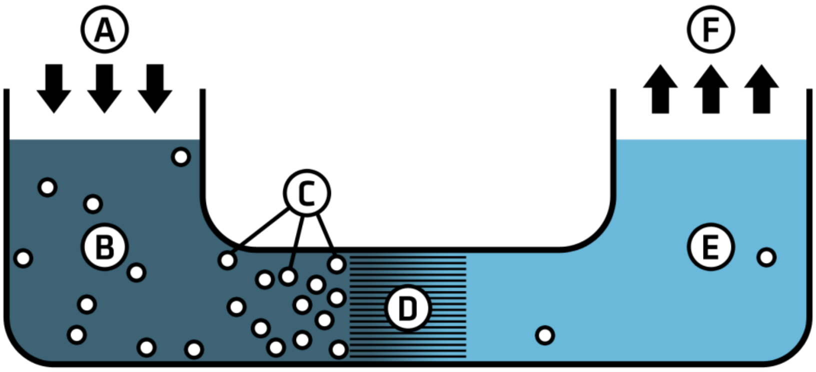

Figure 3-2. Principle of reverse osmosis: A – Applied pressure B – Salt containing water in C – Contaminants D – Semi-permeable membrane E – Demineralised water out F – Distribution (Wikipedia, 2016)

For horticultural purposes, low-pressure RO systems have been designed (operating to a maximum of 8 bar) to be used on brackish groundwater. These systems can be manufactured using plastic materials instead of high-pressure metal equipment.

When using groundwater, a well for groundwater extraction and re-injection of brine concentrate is needed. When using sea water, additional treatment of boron may be needed. For treating drain water in substrate cultivation, and to upgrade it to irrigation water, the water can be tested to see if pre-treatment is necessary.

For higher salt contents, like sea water, larger systems with a pressure of up to 60 bars are used.

3.3.5.3. Operational conditions

No specific operational conditions.

3.3.5.4. Cost data

Total costs (operating expenses (OPEX) and capital expenditures (CAPEX)) for water: 0,5-3 €/m³, depending on the scale of the installation. Energy costs (electricity) 2-3 kWh/m³.

For a typical RO installation to deliver 200 m^3/day, an investment of approximately 30000 € is required.

3.3.5.5. Technological bottlenecks

Membrane fouling is one of the important bottlenecks. With good pre-treatment and monitoring, this can be overcome.

3.3.5.6. Benefit for the grower

Advantages

- Continuous water supply
- Reliable and mature technology
- Easily scalable, that is it can be adapted to larger capacities, depending on the requirement

Disadvantages

- Discharge of concentrated streams
- No selective removal of specific element of compounds when recycling drainage water
- The RO technology produces a concentrate stream (in practice of about 10-50% when using brackish groundwater) which must be re-injected
- Conventional RO membranes are not able to reduce the boron concentration in the permeate to below 1 mg/L, which can be harmful to specific crops

3.3.5.7. Supporting systems needed

In general, none; however, when RO systems are to be used in to recover drain water, a combination with Ultrafiltration, as a pre-treatment, can be considered.

3.3.5.8. Development phase

- Experimental phase: for treatment and recycling drain water and wastewater treatment plant effluent
- Field tests: several field tests with new design concepts
- Commercialised: for seawater and groundwater desalination

3.3.5.9. Who provides the technology

There many suppliers all over the world, some are very large companies, like Suez and Veolia, but also many small and medium enterprises such as Priva, Bruine de Bruin, Lenntech, Logisticon, and Hatenboer.

3.3.5.10. Patented or not

Reversed Osmosis technology is a generic technology. System suppliers build their own systems using RO membrane modules from several membrane manufacturers. Special aspects or process concepts have been or are being patented, for example the Airo and Puro process concepts.

3.3.6. Which technologies are in competition with this one

Several other technologies can be used to produce desalinated water. Examples are ion-exchange, electrodialysis, capacitive di-ionisation, membrane distillation, forward osmosis and nanofiltration. See the corresponding technology descriptions, in this chapter, for more information.

3.3.7. Is the technology transferable to other crops/climates/cropping systems?

The system is applicable for all types of water streams and since it is built in modular systems, it is easy to upscale.

3.3.8. Description of the regulatory bottlenecks

3.3.8.1. Implementation at the regional level

In general, the discharge of the concentrate is restricted in a number of countries. When using reverse osmosis on brackish groundwater that is extracted from the one aquifer, the concentrate (brine) can be discharged back into a second aquifer. These brine concentrates, 10-50% of the total volume, can contain anti-scaling agents. This is causing environmental concerns and is not in line with the Water Framework Directive (WFD).

3.3.9. Brief description of the socio-economic bottlenecks

There are no specific socio-economic bottlenecks for the use of RO itself. The technology has a high level of retention (>99%) of salts and produces demineralised water which is considered safe to use. For both groundwater and seawater (SWRO) treatment, there are concerns on the environmental effect of the concentrate on aquatic and marine life.

3.3.10. Techniques resulting from this technology

There is a big difference in the type of membrane modules (tubular, spiral wound, hollow fibres) and in the design of RO systems depending on scale, type of membrane module and operating conditions. However, the basic principle is always the same. There are many suppliers with their own systems and concepts, but there are no essential differences in the technology used. Some special forms are:

AiRO, where the RO elements are placed vertically and pressurised air is periodically used to prevent fouling of the system.

The PURO concept is an integrated concept where the RO unit is located deep within the well itself. The groundwater is treated in the subsurface and pumped to the surface while the brine concentrates remain behind. Benefits are that the installation can save energy using the pressure of the deep groundwater for the process with a very small footprint (area occupied by the system) of the installation.

3.3.11. References for more information

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[7] Delft Blue Water project, http://www.delftbluewater.nl/

3.4. Membrane distillation

(Authors: Wilfred Appelman[22], Willy van Tongeren[22])

3.4.1. Used for

- Preparation of irrigation water
- More efficient use of water/ reuse
- Minimising the impact to the environment by nutrient discharge
- Concentration of aqueous streams e.g. for nutrient recovery

3.4.2. Region

All EU regions.

3.4.3. Crop(s) in which it is used

All crop types.

3.4.4. Cropping type

All cropping types.

3.4.5. Description of the technology

3.4.5.1. Purpose/aim of the technology

Membrane distillation (MD) combines membrane filtration with distillation to produce clean (demineralised) water from different aqueous sources (surface water, drain water).

3.4.5.2. Working principle of operation

The working principle is shown in Figure 3-3. Membrane distillation was originally developed for desalination of seawater. The Dutch research institute, TNO has developed the Memstill® (membrane distillation) technology, where water from an aqueous feedstock (e.g. seawater) is selectively removed by evaporation and subsequent condensation thus producing high-quality demineralized-water and brine. Low-grade heat (waste heat) of temperatures below 100 °C can be used in this highly efficient process, which is characterised by counter-current flow of feedstock and brine in a compact membrane module. Major advantages of an MD membrane are the short travel distance for gas water vapour (the membrane thickness), allowing very compact installations in comparison with the other distillation technologies. A full segregation of the feed stream and the product stream is also achieved, which makes possible a very high salt retention. MD technology is an important alternative to state-of-the-art techniques for seawater desalination (like RO, multi-effect distillation). MD generally uses low-temperature heat, making it suitable for using waste heat and/or solar heat. Essentially no additives or antiscalants are needed to prevent (bio)fouling of the membrane in the MD module, in contrast to RO.

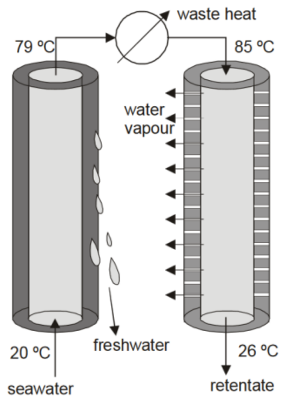

Figure 3-3. Scheme of a membrane distillation process as applied to seawater desalination

MD has developed into different configurations:

1) Direct contact MD. Both fluids are in contact with the membrane. The product stream circulates over a heat exchanger to remove the condensing heat of produced water and to maintain a driving force
2) Air gap MD. The air gap is used to reduce the "leakage" of heat by conduction through the membrane; the conductive leakage has a negative effect on the energy efficiency of the process. The disadvantage of this configuration is the additional resistance of both the air gap and the layer of condensing water to the transport of water vapour, leading to low fluxes (i.e. the production rate per m^2 of the membrane)
3) Sweep gas MD. The produced water vapour is transported to an external heat exchanger, where the water is condensed, the sweep gas is usually recycled to the MD unit
4) Vacuum MD. The resistance of the air gap is strongly reduced by applying a vacuum. The produced water vapour is led to a condensing surface, usually downstream of the vacuum pump

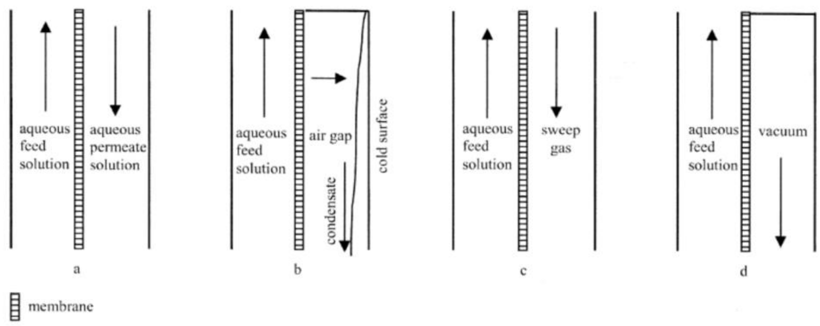

Figure 3-4. Various MD configurations: a) direct contact MD, b) air gap MD, c) sweep gas MD and d) vacuum MD (Meindersma et al., 2006)

3.4.5.3. Operational conditions

MD can be operated at near ambient pressure and at a temperature range of 40-95 °C. Other operational conditions are shown in Table 3-1. The systems consist of series of membrane modules, so can be built for broad range of capacities.

3.4.5.4. Cost data (both in time and €, for installation, maintenance or inputs needed)

Most often MD has been used for seawater desalination. The table below gives an overview of the typical technical performance and the specific costs of seawater desalination with MD and RO.

Table 3-1. Summary of operational and performance parameters of seawater desalination with Reverse Osmosis (RO) and membrane distillation (MD) (Shahzad et al, 2017).

Parameters	Reverse Osmosis (RO)	Membrane Distillation (MD)
Typical plant size (* 1000 m^3/day)	Up to 128	24
Unit capital cost ($/$m^3$/day)	1313	1131
Operating temperature (°C)	ambient	60-90
Electrical energy consumption (kWh/m^3 distillate)	1,5-3,65	2,8
Thermal energy consumption (MJ/m^3 distillate)	NA	360
Thermal energy consumption (kWh/m^3 distillate)	NA	100
Gain Output Ratio($kg_{distillate}$/kg_{steam})	NA	
Performance Ratio $kg_{distillate}$/MJ)	NA	Up to 5
Cost of water ($/$m^3$ distillate)	0,26-0,54	1,17-2,0
Technology growth trend	High	-
Environmental impact: temperature	Brine discharge at ambient temperature	Discharge is 10-15 °C hotter than ambient
Environmental impact: total dissolved solids (TDS)	TDS increase of 50-80%	TDS increase of 15-20%
CO2 emission (kg/m^3)	1,7-2,8	7,0-17,6
CO2 abatement ($/$m^3$)	-	0,18-0,35
Recovery rate (%)	30-50%	60-80%
Product water (ppm)	< 500	< 10
Ton of seawater required per ton of water production	2-4	5-8
Footprint (m^2/(m^3/h))	3,5-5,5	
Shut-down for maintenance	> 4/year	
Availability	92-96%	
Plant life (years)	10-15	

3.4.5.5. Technological bottlenecks

Membrane distillation technology is sensitive to the presence of surfactants which may cause wetting of the hydrophobic membrane. Therefore, a pre-treatment may be necessary. The technology uses heat as the driving force instead of mechanical pressure. Also, very concentrated water streams can be processed in comparison with reverse osmosis which is pressure driven and is limited by the osmotic pressure of the fluid to be treated.

Another bottleneck is that, in MD, there is a need for the development of membranes with higher fluxes to compete with other desalination technologies like reverse osmosis.

3.4.5.6. Benefit for the grower

Advantages

- Reliable water quality
- Easily automated
- Continuous water supply
- May replace RO membranes (no full removal of ions)
- Multivalent ions are separated (sulphates, phosphates, calcium, metals, etc.), monovalent ions are partially removed; partial separation of P versus N and K ions
- Reduction of colour and turbidity
- Water softening possible
- Little or no chemicals required
- Smaller volume of retentate (material retained by the membrane) than RO, with lower concentrations of ions also possible to reuse
- Disinfection of bacteria. It completely removes viruses, bacteriophages and macromolecules
- No chemicals required (except cleaning activities)
- Few manual actions required (only module replacements)

Disadvantages

- Fouling and plugging risks
- Pre-treatment may be required (pre-filtration 0,1-20 µm)
- Cleaning may be necessary due to membrane fouling
- Handling of reject water and rinsing water required

3.4.5.7. Supporting systems needed

Needed for supporting the MD process is:

- Pre-treatment of the water to be treated
- Availability of heat

3.4.5.8. Development phase

Field tests:

As part of the Dutch national project Greenhouse Horticulture Waterproof Substrate Culture, the feasibility of Memstill® membrane distillation was studied at a greenhouse horticulture operation using a pilot installation in 2012. The project's goal was to prevent emissions of nitrates, phosphates, and pesticides from substrate-grown crops in greenhouses.

The Memstill® pilot installation was able to reduce the concentration in the substrate drain water by a factor of 7 to 8, which means that more than 80% of the water can be recovered. The pilot shows a high retention of salts and nutrients. The Memstill® technology offers possibilities. It is expected that, following market development and upscaling, it will be possible to reduce the current initial costs, while the variable costs are now already lower than for reverse osmosis.

On the scale for describing the technology readiness level (TRL), MD can be considered as having a readiness of 4-6. That is from validation in laboratory environment System/subsystem model towards prototype demonstration in a relevant environment.

3.4.5.9. Who provides the technology

Membrane distillation processes are supplied by various manufacturers. Examples are:

- Aquastill, NL: http://aquastill.nl/ (modules, system)
- Hellebrekers Technieken, NL: http://www.hellebrekers.nl/memstill (system)
- I3 Innovative Technologies, NL: http://www.i3innovativetechnologies.com/ (modules)
- SolarSpring GMBH, D: http://www.solarspring.de/ (modules, system)
- Memsys, D: http://www.memsys.eu/ (modules, system)

3.4.5.10. Patented or not

Patents have been granted for specific applications and specific membrane and module types. However, MD is a generic technology available for application in horticulture. System suppliers build specialised systems using MD membrane modules from one or more membrane manufacturers, but also membrane suppliers have their own systems.

3.4.6. Which technologies are in competition with this one

Reversed osmosis can be considered as a competitive technology.

3.4.7. Is the technology transferable to other crops/climates/cropping systems?

The system is applicable for all types of water streams and is easy to upscale because it is a modular system. Pre-treatment is an important issue in most applications. Periodical chemical cleaning (in situ) of the membrane module may be needed due to membrane fouling.

3.4.8. Description of the regulatory bottlenecks

There are no known regulatory bottlenecks.

3.4.9. Brief description of the socio-economic bottlenecks

There are no specific socio-economic bottlenecks known yet for the use of MD itself. The technology has a high level of retention of salts and other molecules, except for volatile molecules. The produced water is usually considered safe to use. The technology has been demonstrated for seawater desalination.

3.4.10. Techniques resulting from this technology

1) MemPower: high-quality water and power from wastewater and waste heat (see animation of TNO MemPower). It is characterised by the production of a high-pressure distillate from which electricity can be harvested using a hydro turbine

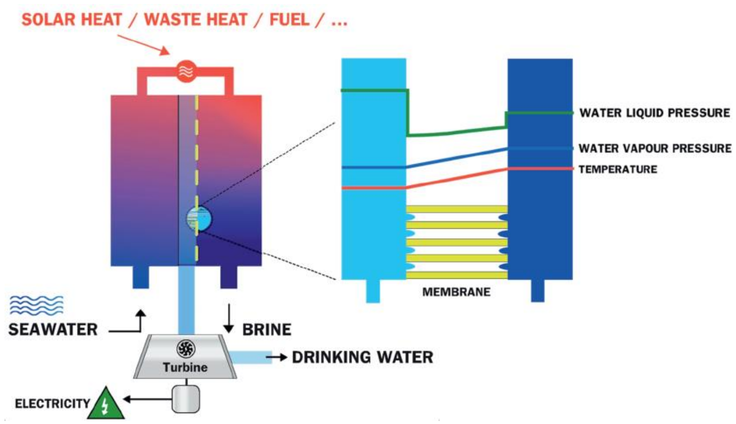

Figure 3-5. The principle of MemPower. Power is produced in membrane distillation by throttling of the distillate product causing the hydraulic pressure to increase towards the Liquid Entry Pressure (LEP) of the membrane. Power (= flow * pressure) can be harvested by a turbine

2) Osmotic distillation. This technology can be considered as isothermal membrane distillation. Instead of using a temperature difference over the membrane as driving force, a so-called draw liquid with a high osmotic pressure is used for dewatering of the feedstock. The same principle is also used in forward osmosis, with the difference that in osmotic distillation water vapour is permeated and no liquid water

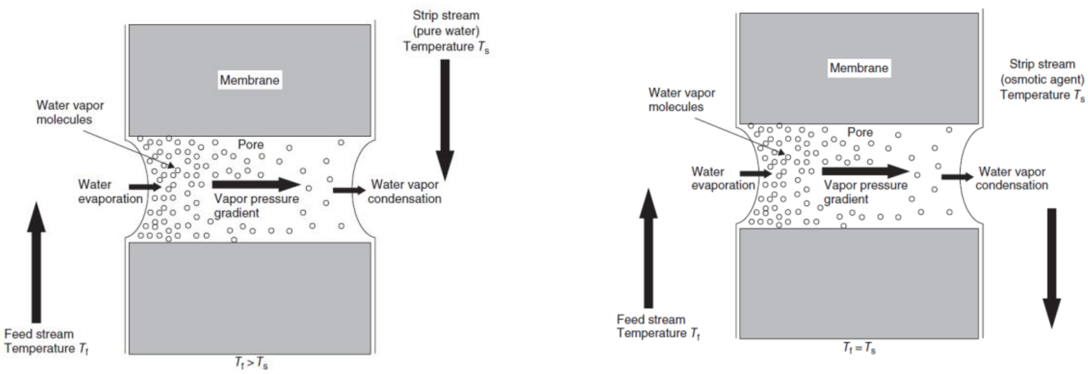

Figure 3-6. The principle of Membrane Distillation (left) and Osmotic Distillation (right). (Johnson and Nguyen, 2017)

3.4.11. References for more information

[1] Dutch Policy Document: Beleidskader: Goed gietwater glastuinbouw, November 2012 (https://www.glastuinbouwwaterproof.nl/grond/gietwater/nieuws/goed-gietwater-beleidskader-voor-duurzaam-geschikt-gietwater-voor-de-glastuinbouw/pagina/7/)

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[9] https://emis.vito.be/en/techniekfiche/membrane-distillation

3.5. Forward Osmosis

(Authors: Wilfred Appelman[22], Willy van Tongeren[22])

3.5.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

3.5.2. Region

All EU regions.

3.5.3. Crop(s) in which it is used

All crops.

3.5.4. Cropping type

All cropping types.

3.5.5. Description of the technology

3.5.5.1. Purpose/aim of the technology

The purpose of forward osmosis (FO) is to concentrate diluted aqueous streams. The technology can deal with a wide range of the brackish water which it concentrates to form highly concentrated solutions (brines). Forward osmosis also has the potential to treat wastewater by selective water removal using an osmotically active draw solution. For recovery of the permeated water, a draw solution recovery system needs to be added to the FO system. This can be reverse osmosis (RO) or membrane distillation (MD).

3.5.5.2. Working principle of operation

Forward osmosis is an osmotic process that, like RO, uses a semi-permeable membrane to separate water from dissolved solutes. The driving force for this separation is an osmotic pressure gradient, such that a “draw” solution of high concentration (relative to that of the feed solution), is used to induce a net flow of water through the membrane into the draw solution, thus effectively separating the feed water from its solutes. In contrast, the RO process uses a hydraulic pressure as the driving force for separation, which serves to counteract the osmotic pressure gradient that would otherwise favour water flux from the permeate to the feed. Hence, significantly more energy is required for RO compared to FO. However, FO requires a draw solution concentration system for recovery of water, and to allow reuse of the draw solution.

An additional distinction between the RO and FO processes is that the permeate water resulting from an RO process is in most cases fresh water ready for use. In the FO process, this is not the case, because the permeate water dilutes the draw solution. The membrane separation of the FO process, in effect, results in a “trade” between the solutes of the feed solution and the draw solution. Depending on the concentration of solutes in the feed (which determines its osmotic pressure and which dictates the necessary concentration of solutes in the draw to overcome this osmotic pressure) and the intended use of the product of the FO process, this step may be all that is required.

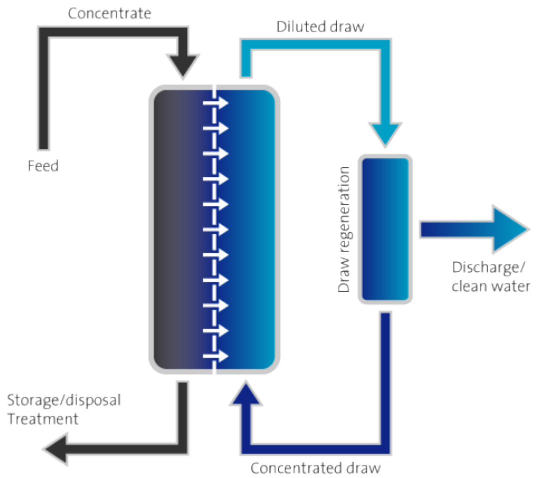

Figure 3-7. Principle of the Forward Osmosis system process with FO module (left) and draw regeneration unit (right) (Bluetec, 2017)

3.5.5.3. Operational conditions

FO operates at ambient conditions, i.e. atmospheric pressure and room temperature. A draw solution with high osmotic pressure is needed to drive the process.

Various types of draw solutions may be used: a) salt solutions from sodium cloride, magnesium chloride, lithium cloride, sulphates, ammonium bicarbonate (i.e. a dissolved mixture of ammonia and carbon dioxide), etc., b) solutions using dissolved organic compounds such as ethanol, sugars, etc., c) magnetic nanoparticles, concentrated wastewater, seawater, etc.

In some cases, FO can operate without a draw solution recovery system, this is called osmotic dilution. An example is the dilution of seawater before desalination by treated wastewater over an FO membrane.

3.5.5.4. Cost data (both in time and €, for installation, maintenance or inputs needed)

Limited studies have considered the economic and energetic feasibility of FO systems. For seawater desalination, combined FO–RO can potentially reduce the overall cost and energy use compared to standalone RO by driving the seawater salinity down in the FO dilution step.

It was estimated that approximately 1,3–1,5 kWh/m^3 is needed for an FO–RO system that dilutes seawater by drawing water from secondary wastewater effluent. This is lower than standalone single-pass RO which has an average energy consumption of around 2,5 kWh/m^3.

The potential energy savings were estimated by replacing a two-pass RO process and its associated pre-treatment step with an integrated FO–RO process. The integrated system resulted in lower specific energy (3 kWh/m^3), compared to that of a two-pass RO operating at 50% (4 kWh/m^3)(Figure 3-8a). A recent study obtained the energy required for standalone RO and FO–RO assuming certain efficiency rates for both configurations (Figure 3-8b).

The energy balance of the FO–RO system still exceeds that of the standalone RO process because of the energy penalty associated with the regeneration process. It has been established that FO–RO integration may prove to be favourable in a market where per unit cost of RO permeate is high (exceeds 0,1 \$/m^3). The integration of FO with RO can be justified as long as the flux in the dilution step is also sufficiently high (exceeds 30 lm^{2}h) (Figure 3-8c). This demonstrates a major gap in FO implementation and the need for research that can overcome two main obstacles: 1) low permeate flux and 2) high membrane cost.

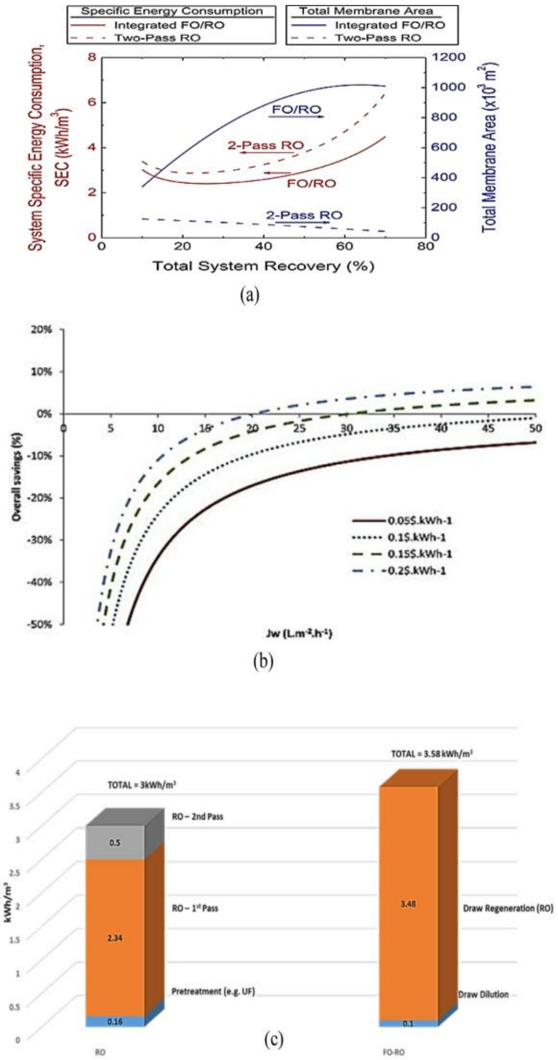

Figure 3-8. Findings comparing FO–RO to standalone RO demonstrate the current divide with regards to the economics and energetics of the system. (a) FO/RO outcompetes a standalone two pass RO. (b) FO–RO is energetically higher than RO when considering the low efficiency of FO process. (c) Overall energy savings using FO–RO would only be observed at flux greater than 30 L/h/m^2 and in markets where the actual cost of standalone RO is already high (Akther et al., 2015)

3.5.5.5. Technological bottlenecks

The fundamental performance characteristics of FO membranes are:

1) High water permeability
2) Low salt permeability
3) Structure of support layer with low Internal Concentration Polarisation. Internal Concentration Polarisation results in a lower driving force over the membrane, and therefore a lower water permeates flux, as would be expected based on the concentration of dissolved species in the bulk phases at both sides of the membrane

For the draw solution, it is necessary to have a high osmotic pressure and simultaneously that it can be dewatered at low energy consumption after it has been diluted with permeate water.

3.5.5.6. Benefit for the grower

Advantages

- FO operates at mild process conditions (low or no hydraulic pressures, ambient temperature)
- FO has high rejection of a wide range of contaminants
- FO utilises a high driving force obtained from the draw solution (an aqueous solution of 5 M magnesium chloride already generates a driving force of 1000 bar)
- FO may have a lower membrane fouling propensity than pressure-driven membrane processes
- FO equipment is very simple and easily scalable, and membrane support is less of a problem relative to RO
- FO concentrates the feed stream at mild conditions i.e. without mechanical or thermal degradation
- Energy can be harvested from the mixing of water and draw solution by Pressure Retarded Osmosis

Disadvantages

Disadvantages of FO systems (compared to RO systems) are that the process does not provide high-quality water in a single step. After the FO step, the high-quality water is mixed with the drawing solution and a second stage (RO, MD) is necessary to recover the water and regenerate the draw solution. Since the technology is new to the horticulture, as yet there is no practical experience.

3.5.5.7. Supporting systems needed

To operate an FO process, a draw solution is needed. The concentrated solution on the permeate side of the membrane is the source of the driving force in the FO process. Different terms used to describe the source of the driving force, such as osmotic agent, osmotic media, driving solution, osmotic engine, sample solution, or just brine. When selecting a draw solution, the main criterion is that it has a higher osmotic pressure than the feed solution.

3.5.5.8. Development phase

Experimental phase: The technology is TRL level 4 to 7. Through feasibility studies and duration tests with a pilot plant for sewage treatment, this technology will be further developed in the Eurostars route to a TRL level 7. Then a further scaling up to a demo plant will follow to reach TRL 9.

3.5.5.9. Who provides the technology

Forward Osmosis processes are supplied by various manufacturers. One example is: Bluetec, NL: http://www.blue-technologies.nl/technologies-forwardosmosis

3.5.5.10. Patented or not

The principle of FO has been known for some time. New patents can be generated concerning high-performance membranes and modules.

3.5.6. Which technologies are in competition with this one

Reverse osmosis and MD can be considered as a competitive technology, but these technologies could also be complementary to FO (or opposite) because they can be applied for water recovery and the regeneration of the draw liquid.

3.5.7. Is the technology transferable to other crops/climates/cropping systems?

The system is applicable for all types of aqueous streams (seawater, wastewater, liquid foods, etc.) and is easy to upscale because it is a modular system. Pre-treatment may be an important issue in many applications.

3.5.8. Description of the regulatory bottlenecks

There are no known regulatory bottlenecks.

3.5.9. Brief description of the socio-economic bottlenecks

Being an innovative technology, it requires specific knowledge to implement the system. As yet, there have been no applications in horticulture.

3.5.10. Techniques resulting from this technology

Energy can be harvested from mixing the permeate water and the draw solution in a process called Pressure Retarded Osmosis. An additional technology is needed for recovery of the draw liquid of FO.

3.5.11. References for more information

[1] Dutch Policy Document: Beleidskader: Goed gietwater glastuinbouw, November 2012 (https://www.glastuinbouwwaterproof.nl/grond/gietwater/nieuws/goed-gietwater-beleidskader-voor-duurzaam-geschikt-gietwater-voor-de-glastuinbouw/pagina/7/)

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3.6. Electrophysical precipitation

(Authors: Wilfred Appelman[22], Willy van Tongeren[22])

3.6.1. Used for

- Preparation of irrigation water
- Minimising the impact to the environment by nutrient discharge

3.6.2. Region

All EU regions.

3.6.3. Crop(s) in which it is used

All crops.

3.6.4. Cropping type

All cropping types.

3.6.5. Description of the technology

3.6.5.1. Purpose/aim of the technology

Electrophysical precipitation (EpF) replaces conventional chemical flocculation techniques with the advantage that the flocculants are made available electrolytically from solid-state electrodes.

3.6.5.2. Working Principle of operation

In EpF the water that has to be treated is passed through a reactor, in which an electric current flows past sacrificial electrodes. This results in electrochemical reactions; the sacrificial electrodes dissolve, releasing their metal ions. Metal hydroxide flocs are produced in the process. These electrolytically-generated metal hydroxide flocs have a high adsorption capacity and can bind to dispersed particles. In addition, there are co-precipitation and occlusion precipitation reactions, in which dissolved organic and inorganic substances are precipitated. The precipitated or adsorbed substances can then be separated mechanically.

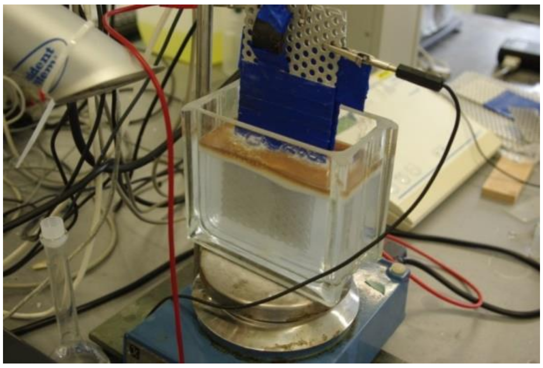

Figure 3-9. Illustration of lab scale principle of electro-coagulation

Figure 3-10. An example of a pilot installation for electrophysical precipitation in a horticultural greenhouse

Figure 3-11. An example of a pilot installation for electrophysical precipitation in a horticultural greenhouse

3.6.5.3. Operational conditions

There is no limit on scale and capacity. It depends on the application.

3.6.5.4. Cost data

This has to be determined by the specific application and at this moment there are no cost data available.

3.6.5.5. Technological bottlenecks

For the current application of this technology, no technological bottlenecks are known.

3.6.5.6. Benefit for the grower

Advantages

- Economically attractive and sustainable solution for the purification of industrial, process waters, and wastewaters
- No increase in salinity – recirculation is possible
- Robust process – discharge criteria can be met safely, reliably and lastingly
- Available quickly – standby operation possible
- Suitable for varying quantities of wastewater and pollutant load
- Minimal maintenance – staff savings and increased reliability
- Low energy consumption
- Iron or aluminium electrodes are inexpensive, readily available and easy to handle

- Using this process there are no costs for the purchase, handling, or the dispersal of flocculants

Disadvantages

- Pre-treatment may be required (pre-filtration 0,1-20 µm). Spiral wound modules always require pre-treatment
- Maybe sensitive to fouling
- Handling of reject water and rinsing water required
- Electrolysis gases (hydrogen formation)

3.6.5.7. Supporting systems needed

Since it is only aimed at lowering the concentration of scalable salts as phosphates and total organic carbon, pre-treatment of the water is needed. In the installation below, aimed at complete water cycle closure, the Epf is only part of the total installation (Figure 3-12).

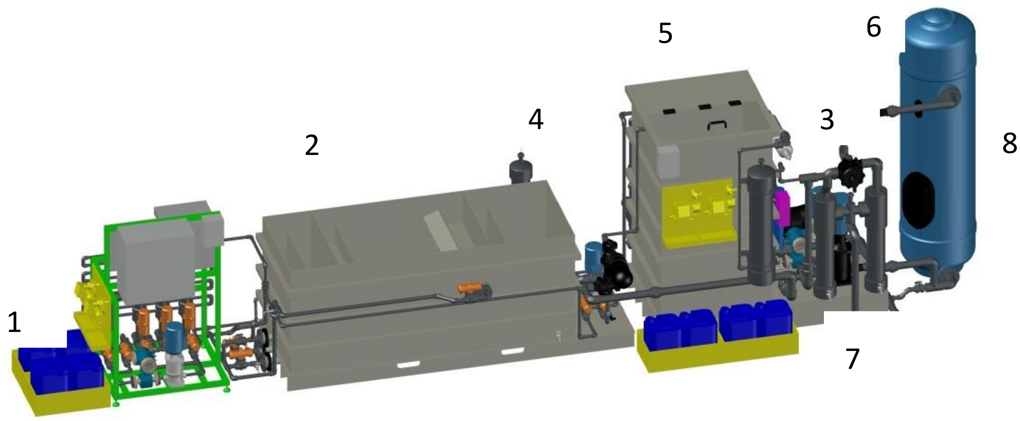

Figure 3-12. Scheme of the research plant for industrial research "Good pouring water". 1) pH control and a static mixer, 2) electro-coagulation, 3) candle filter, 4) disc filter, 5) intermediate storage 6) advanced oxidation, 7) reversed osmosis and 8) activated carbon filter

3.6.5.8. Development phase

Experimental phase: A pilot plant has been running [2015] with 0,1-1 m^3/h flow. The technology has been proven to remove organics as well as phosphates. The technology has yet to be tested for application in fertigation on a commercial scale.

3.6.5.9. Who provides the technology

- Fraunhofer IGB
- Hellebrekers Technieken (NL)

3.6.5.10. Patented or not

Installation for electrophysical precipitation is general unit operation. The precise dimensioning and characteristics, for example, to be used in a horticultural greenhouse could be protected by intellectual property rights.

3.6.6. Which technologies are in competition with this one

- Conventional chemical flocculation techniques
- Dosing commercial chemicals

3.6.7. Is the technology transferable to other crops/climates/cropping systems?

This technology can be applied to all crops.

3.6.8. Description of the regulatory bottlenecks

3.6.8.1. Implementation at the regional level

There may be requirements for the materials used for electrodes. Copper/aluminium electrodes can result in increased concentrations of these elements in the water.

3.6.9. Brief description of the socio-economic bottlenecks

There are no specific socio-economic bottlenecks for the use of MD itself. The technology has a high level of retention, except for volatile molecules; and the produced water is usually safe to use.

3.6.10. Techniques resulting from this technology

Not known.

3.6.11. References for more information

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3.7. Electrodialysis

(Authors: Wilfred Appelman[22], Willy van Tongeren[22])

3.7.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

3.7.2. Region

All EU regions.

3.7.3. Crop(s) in which it is used

All crops.

3.7.4. Cropping type

All cropping types.

3.7.5. Description of the technology

3.7.5.1. Purpose/aim of the technology

Electrodialysis (ED) is a membrane process that is used to remove ions from solutions.

3.7.5.2. Working Principle of operation

Electrodialysis is used to transport salt ions from one solute, through ion-exchange membranes, to another solute under the influence of an applied electric potential difference. This is done in a configuration called an ED cell. The cell consists of a feed (dilute) compartment and a concentrate (brine) compartment formed by an anion exchange membrane and a cation exchange membrane placed between two electrodes. In almost all practical ED processes, multiple ED cells are arranged in a configuration called an ED stack, with alternating anion and cation exchange membranes forming the multiple ED cells. Electrodialysis processes are different from distillation techniques and other membrane-based processes (such as reverse osmosis (RO)) in that dissolved particles are moved away from the feed stream rather than the reverse. Because the quantity of dissolved particles in the feed stream is far less than that of the fluid, ED offers the practical advantage of much higher feed recovery in many applications. A schematic representation of an experimental set-up is shown in Figure 3-13.

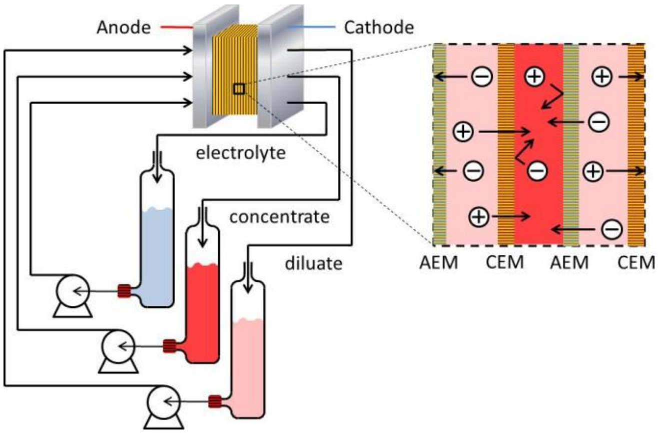

Figure 3-13. Schematic representation of the used set-up for Electrodialysis experiments (RESFOOD, 2015)

An electric current migrates dissolved salt ions, including nitrates and sodium, through an ED stack consisting of alternating layers of cationic and anionic ion exchange membranes. In the pilot set-up, monovalent selective membranes were used. This will separate the monovalent ions such as sodium and potassium from the valuable multivalent ions such as phosphate. Periodically, the direction of ion flow is reversed by reversing the polarity of the applied electric current. This will decrease the fouling of the membranes.

The overall flowchart of the pilot setup is shown in Figure 3-14.

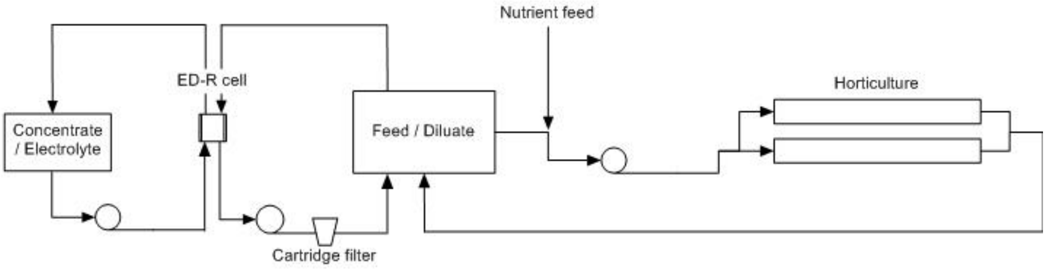

Figure 3-14. Flowchart ED pilot setup in horticulture (RESFOOD, 2015)

Figure 3-15. ED pilots (IEC, 2017)

3.7.5.3. Operational conditions

Although ED is a known process in the industry, there is little knowledge of full-scale implementations, with most current installations being smaller in scale. Due to the specificity of each application, extensive testing will be needed for a full-scale implementation.

Membrane pollution can occur in ED operation. It is recommended to remove dispersed particles, colloids or humus acids in advance. Sand filtration, cartridge filtration, microfiltration, ultra-filtration, flocculation methods or active carbon can be used for specific removal of these materials. Oils and fats must also be removed (by coagulation or active carbon). Regular membrane cleaning with specific cleaning products (acids, bases, etc.) may be necessary in a number of cases. The average life-span of ED membranes is between 5 and 7 years.

As a general rule of thumb, in practice, a limit of 3000 ppm of dissolved substances is regarded as the limit between cost-effective treatment via reverse osmosis and ED. If the concentration of dissolved substances is less than 3000 ppm, ED can be used, and if above 3000 ppm then reverse osmosis is more suitable. Another argument in favour of ED could be the need for high feed recovery.

3.7.5.4. Cost data

The major costs in ED are the membrane and electricity costs. The limiting current density determines the price of the ED process. Cost prices may vary greatly depending on the type of wastewater. In the RESFOOD project, an estimate was given based on a system which has a pre-treatment (Fleck filter, multimedia combined sand filter) together with an interest rate of 5%. The depreciation on the installation can be taken for 10 years while the membrane modules have a typical depreciation time of 5 years. The expected energy use of ED systems is about 0,05 kWh/m^3, with energy costs of approximately 0,08 €/kWh.

For an ED installation of the scale of 1-10 m^3/h (3500-50000 m^3/year), the CAPEX varies from 9-64 k€/year with an OPEX from 2-15 k€/year increasing with the size of the installation. Typical treatment costs (€/m^3) decrease with the size from 2,6 to 1,3 (€/m^3).

3.7.5.5. Technological bottlenecks

For a classic ED system, one only needs three simple (separate) liquid circuits: the dilutant flow, the concentrate flow, and the electrolyte for which volumes must be configured. Standard stacks are available with membranes appropriate for the required application. A standard electrical power supply is also available. For parameter optimisation, one can first run an ED pilot which contains specific instruments for following-up the process during the ED tests. Such instruments measure pressure, volume, temperature, pH and conductivity. Once conditions have been optimised for a particular application, an industrial installation can, in principle, operate independently without extensive instrumentation, once the optimised parameters have been set for the process limits. In this regard, an ED installation offers a fairly high operational certainty if (incidental) membrane pollution is prevented.

The current density limit is a limiting factor in ED. The last stack, with the lowest dilutant out concentration, is where the risk of limiting current density can occur. It is therefore recommended to determine the limiting current density via experiments and to use it in ED design software to determine the optimum (series) stack configuration (total length and total membrane surface). ED design is, as a result of concentration specifications, fully determined by the specific application.

Electrodialysis has inherent limitations, working best at removing low molecular weight ionic components from a feed stream. Uncharged, higher molecular weight, and less mobile ionic species will generally not be appreciably removed. Also, in contrast to RO, ED becomes less economical when extremely low salt concentrations are required in the product. Consequently, comparatively large membrane areas are required to satisfy capacity requirements for low concentration (and with low conductivity) feed solutions.

3.7.5.6. Benefit for the grower

Advantages

- Continuous operation of an ED system with a horticulture water supply can decrease the concentration of sodium in the circulation water
- Generally, in practice, a limit of 3000 ppm of dissolved substances is regarded as the limit between cost-effective treatment via reverse osmosis and ED: Thus, ED if lower than 3000 ppm and reverse osmosis if above 3000 ppm. Another argument in favour of ED could be the need for high feed recovery

Disadvantages

A disadvantage of continuously running an ED system is the removal of nutrients like nitrate and potassium.

3.7.5.7. Supporting systems needed

As with RO, ED systems require feed pre-treatment to remove species that coat, precipitate onto, or otherwise “foul” the surface of the ion exchange membranes. This fouling decreases the efficiency of the ED system. Particles of concern include calcium and magnesium compounds, suspended solids, silica, and organic compounds. Water softening can be used to remove hardness, and micrometre or multimedia filtration can be used to remove suspended solids. Water hardness, in particular, is a concern since scaling can build upon the membranes. Various chemicals are also available to help prevent scaling. Also, ED systems, with the capacity or reverse flow, ED-R, seek to minimise scaling by periodically reversing the flows of dilute and concentrate and polarity of the electrodes.

Suspended solids with diameters that exceeds 10 µm need to be removed, or else they will plug the membrane pores. There are also substances that are able to neutralise a membrane, such as large organic anions, colloids, iron oxides and manganese oxide. These disturb the selective effect of the membrane. Pre-treatment methods, which aid the prevention of these effects are active carbon filtration (for organic matter), flocculation (for colloids) and filtration techniques.

3.7.5.8. Development phase

Electrodialysis is an established process in different industries. In horticulture, the technology is not currently being used. However, relevant research has been conducted and is on-going. For example, in the RESFOOD (www.resfood.eu) project, which aimed to develop and test/demonstrate innovative “green” solutions for resource efficient and safe food production and processing.

- Research: In the EU RESFOOD (project the selective removal of monovalent ions from water has been demonstrated in both lab and practical setup. In RESFOOD, ED showed good potential. An average of 70% of monovalent ion removal selectivity was achieved in the pilot setup under demanding conditions
- Field tests: Operation of an ED system in a horticultural environment is capable of good performance if sufficient pre-treatment is available. Pre-treatment is required to prevent biological fouling and to prevent any organic material from clogging the ED cell. Taking into account that the pilot setup was a converted lab setup, it can be expected that a large-scale set-up will be a more resilient system. Continuous operation of an ED in a horticulture water supply can decrease the concentration of sodium in the circulation water. A disadvantage of continuously running the ED is the removal of nutrients like nitrate and potassium. The research to the effect of the ED technology on crop production performance and quality was not conclusive. There were effects of elevated sodium levels in the irrigation water on the crop production but this could not be determined as a quantitative significant effect
- Commercialised: ED systems are not yet commercialised for horticulture. The current state of the art in greenhouse horticulture production is the use of soilless growing systems using substrate materials and with recirculation of drain water; these systems are very efficient in terms of the water footprint. However, the recirculation of water results in the accumulation to harmful concentrations of sodium and other monovalent ions, as ballast components which not used by the crops. Consequently, the recirculating water must be periodically drained. Because this also implies emission of crop protecting agents, it is expected that measures such as completely closing the water cycle or the compulsory use of water treatment units will become compulsory.

3.7.5.9. Who provides the technology

Several suppliers, for example:

- IEC, www.iec.be
- Logisticon Water Treatment, www.logisticon.com/en
- GE's Water & Process Technologies, www.gewater.com/products/Electrodialysis-reversal-water-treatment
- Lenntech, www.lenntech.com/Electrodialysis.htm
- Novasep, www.novasep.com/technologies/industrial-Electrodialysis-technology.html
- MEGA a.s., http://ralex.eu/Horni-navigace/Kontakty.aspx

3.7.5.10. Patented or not

Although ED is a general technology, different suppliers and manufacturers use optimised systems protected by patents and other intellectual property rights.

3.7.6. Which technologies are in competition with this one

Other desalination technologies are in competition with is capacitive deionisation (CDI, etc.) as well as ion exchange, reversed osmosis and nanofiltration.

3.7.7. Is the technology transferable to other crops/climates/cropping systems?

The technology is transferable to any crop, climate and cropping system, as long as the water is of such quality that there is less than 3000 ppm of dissolved substances in general. Pre-treatment is needed otherwise.

3.7.8. Description of the regulatory bottlenecks

3.7.8.1. Implementation at the regional level

In general, the discharge of the concentrate resulting from ED processes is restricted in a number of countries.

It is expected that this situation will be comparable to the regulations for concentrates resulting from reversed osmosis. When using reverse osmosis on brackish groundwater, a concentrate remains (the brine) which is often discharged back into subsurface water. These brine concentrates, 10-50% of the total volume, can contain anti-scaling agents. This is causing environmental concerns and are practices that are not consistent with the requirements of the WFD.

3.7.9. Brief description of the socio-economic bottlenecks

The use of ED in (semi) closed horticultural growing systems can eliminate the need to purge the water when sodium concentrations build up. In countries like The Netherlands where companies that purge are required to have treatment technologies to remove crop protecting agents, the use of ED may avoid the need to invest in those treatment technologies. However, then growers lose the possibility to purge water for other reasons. This is an approach towards sustainable water management in horticulture that is only slowly becoming common practice.

3.7.10. Techniques resulting from this technology

Several technologies based on the ED exist, such as ED-R. This modified form of ED may help to largely avoid membrane pollution. In ED-R, the voltage at the electrodes is reversed every 30 to 60 minutes, simultaneously with the dilutant and concentration flow. This reverses the direction of ion transport (thus also the transport of pollutant substances), whereby the membrane is cleaned each time. Surface-active substances with polar groups may cause serious, perhaps irreparable, pollution to membranes.

3.7.11. References for more information

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3.8. Iron removal

(Authors: Jadwiga Treder[12], Ockie Van Niekerk[16])

3.8.1. Used for

Preparation of irrigation water.

3.8.2. Region

All EU regions.

3.8.3. Crop(s) in which it is used

All crops.

3.8.4. Cropping type

All cropping systems.

3.8.5. Description of the technology

3.8.5.1. Purpose/aim of the technology

Iron can be removed from groundwater by a process which combines oxidation, precipitation and filtration.

Iron is one of the most abundant metals of the Earth, commonly found in soil and water. Iron may be present in water in the following five forms: dissolved ionic, dissolved inorganic complexes, dissolved organic complexes, colloidal or suspended. The state of the iron in water depends, above all, on the pH and the redox potential. In groundwater, iron occurs usually in reduced form (bivalent iron in the dissolved form ferrous iron (Fe^{2+}) or $Fe(OH)^{+}$), but as soon as the water is pumped up for irrigation, partial oxidation occurs. In aerated water, the redox potential of the water is such as it allows oxidation of the Fe^{2+} to ferric iron (Fe^{3+}), which precipitates as ferric hydroxide ($Fe(OH)_3$). This precipated material is a potential clogging hazard in micro-irrigation systems. The concentration of iron in natural waters is frequently limited by the solubility of its carbonate form. Therefore, waters with high alkalinity often have lower iron contents than waters with low alkalinity. Water containing iron can be a very good environment for the growth of chemotropic bacteria. Bacteria, that grow well in iron rich aquatic environments (iron bacteria) such as filamentous genuses like *Gallionella Sp. Leptothris* and *Sphaerotilus* and also rod type genera such *Pseudomonas* and *Enterobacter*, react with the Fe^{2+} through an oxidation process. This changes the iron form to Fe^{3+} which is insoluble. The insoluble Ferric iron is surrounded by the filamentous bacteria colonies which creates a sticky iron slime gel that is responsible for clogging of drippers. Concentrations of Fe^{2+}as low as 0,15-0,22 ppm are considered as a potential hazard to drip systems. Practically any water that contains concentrations higher than 0,5 ppm of iron cannot be used with drip irrigation systems.

3.8.5.2. Working Principle of operation

The removal of iron from water is performed in two stages, chemical and physical:

Chemical stage – Oxidation → Precipitation

Iron oxidation and its removal is based on the transformation of the soluble form of Fe^{2+} to an insoluble form (Fe^{3+}). In simplified notation,

$4\ Fe^{2+} + O_2 + 2\ H_2O \rightarrow 4\ Fe^{3+} + 4\ OH$

$4Fe^{3+} + 4\ 0H^- + 8\ H_2O \rightarrow 4\ Fe(OH)_3 + 8\ H^+$

This equation shows that about 0,14 mg of oxygen is required for the oxidation of 1 mg of iron. Therefore, the oxygen concentration in aerated water is theoretically sufficient for the complete oxidation of iron normally present in natural groundwater. Oxidation also prevents the growth of iron bacteria, which together with residues, represent a clogging risk for micro-irrigation emitters. Iron can be oxidised using air or oxidising materials, such as chlorine, hydrogen peroxide, potassium permanganate, chlorine dioxide, ozone or a combination of aerobic oxidation. Iron oxidation by air is relatively cheap and most popular. After oxidation, insoluble iron hydroxide particles sediment to the bottom of the reservoir. In a closed system, air is injected into the irrigation system (before the filters) by air compressor or by injectors. When iron is oxidised by means of pressurised air, the oxygen concentration in the water rises in direct proportion to the air pressure in the system. The rise in oxygen concentration increases the iron oxidation rate considerably.

Physical stage - Filtration

After precipitation, iron hydroxide flocs are removed in rapid sand filters. The oxide particles are very small (1,5-50 µm); therefore, only sand filters can be used effectively. Rapid sand filtration is the preferred method since it is more economical, less complicated and generally avoids the use of chemicals.

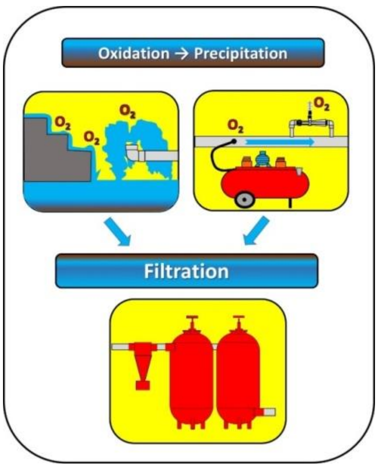

Figure 3-16. Scheme of the iron removal process

Iron oxidation by air can be executed in an open water reservoir or directly in a closed system. In open system systems several aeration systems are used for water aeration and efficient iron oxidation: cascades, spray aeration, tower aeration (co-current and counter current), venturi aeration, and plate aeration. This generates maximum surface-area exposure and contact time. In open systems under pH neutral or basic conditions (pH > = 7), over 70% of the iron is oxidised when exposed to air for about 30 minutes.

3.8.5.3. Operational conditions

The speed of the process depends on the pH of the water. When the pH is high, the oxidation of iron by air is fast. When the pH is low, the process is slower. Other water quality parameters like alkalinity (bicarbonate concentration), temperature, organic matter and some elements/ions have also been reported as having a significant effect on the rate of oxidation of iron.

The volume of the oxidation unit must be planned according to the capacity of the water pumping system. The time of contact should be long enough to allow a total oxidation of the iron according to the water pH. With larger volume reservoirs, it is useful to allowing an additional day or more, for sedimentation

Oxidation by aeration can be effective when the pH is higher than 7, the concentration of Fe^{2+} is <5 ppm, and little or no organic matter or other reducing agents are present. In acidic water with a pH level lower than 5,8, iron is found in a dissolved state and is very difficult to remove; however, in small concentrations, it does not lead to clogging. In systems that use compressed air for oxidation, vigorous mixing is required to ensure that the air dissolves and remains in the water for a long time, in order to oxidise the iron prior to water filtration. The addition of a hydro cyclone filter before the gravel (or sand) filters ensures that the air or oxidising agent is mixed well into the water and that some of the iron deposits are already separated. The addition of a long piece of wide-diameter (low velocity) pipe or a pressure tank can offer a simple and cheap solution for extending the total oxidation time. Iron removal requires low-velocity filtration, not exceeding 12,5 m^3/h. The size of the gravel affects the filter's absorption and the planned flow rate. For the accepted flow rate described above, quartz sand with grains of 0,65-0,85 mm in diameter and a depth of at last 60 cm can be used.

3.8.5.4. Cost data

For an example of a system used with a Fe^{2+} concentration of about 2 ppm and a flow rate of 10 m^3/h:

The components are: an aeration pump, rapid sand filter 2 tanks x 850 mm, a mixing tank and a disc filter. This system costs about 4300 €.

3.8.5.5. Technological bottlenecks

Iron hydroxide formed after oxidation is a complex of different iron hydroxide species and the referral to $Fe(OH)_3$ is a simplification. Therefore, the effectiveness of this technology depends upon many physical and chemical factors which must be taken into account when designing the complete system.

3.8.5.6. Benefit for the grower

Advantages

- Reliable water quality
- Automated easily
- Continuous water supply
- Low cost
- Simple operation
- Long-term use
- No chemicals required

Disadvantages

- The space required
- Handling of reject water and rinsing water required
- Limited ability to remove iron

3.8.5.7. Supporting systems needed

The removal of rinsing water could require temporary storage.

3.8.5.8. Development phase

Commercialised: many examples, e.g. whey treatment, wastewater, drinking water production.

3.8.5.9. Who provides the technology

Several suppliers:

- Wigo-Gąsiorowski, Poland
- Agrofim, Poland
- PPHU Soldrip Sp. z o.o., Poland
- TANAKE ul., Poland
- Mais automatisering, Belgium
- Hortiplan, Belgium

3.8.5.10. Patented or not

This technique has not been patented.

3.8.6. Which technologies are in competition with this one

Air or chemical oxidation and microfiltration.

3.8.7. Is the technology transferable to other crops/climates/cropping systems?

The system is widely applicable for all types of water streams and is easy to upscale because it is a modular system. Pre-treatment is an important issue in most applications.

3.8.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks known.

3.8.9. Brief description of the socio-economic bottlenecks

There are no specific socio-economic bottlenecks for the use iron removal systems.

3.8.10. Techniques resulting from this technology

Not known.

3.8.11. References for more information

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[2] Nakayama, F. S., & Bucks, D. A. (1991). Water quality in drip/trickle irrigation: a review. *Irrigation Science*, *12*(4), 187-192

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[4] Saroj Kumar Sharma (2001). Adsorptive Iron Removal from Groundwater. DISSERTATION

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3.9. Capacitive Deionisation

(Authors: Wilfred Appelman[22], Willy van Tongeren[22])

3.9.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

3.9.2. Region

All EU regions.

3.9.3. Crop(s) in which it is used

All crops.

3.9.4. Cropping type

All cropping types.

3.9.5. Description of the technology

3.9.5.1. Purpose/aim of the technology

Capacitive deionisation (CDI), also called capacitive desalination, electrochemical desalination or flow-through capacitor, is a desalination method. CDI technology was developed as a non-polluting, energy-efficient and cost-effective alternative to desalination technologies such as reverse osmosis and electrodialysis.

3.9.5.2. Working Principle of operation

In Capacitive Deionisation, water flows through a cell where an electrical field is created by a pair of electrodes. Ions are attracted toward the electrodes and accumulated. Different concepts have been developed:

- Membrane-based systems: the electrodes are separated from the water by membranes that selectively allow only positive or negative ions to pass
- Flow-through systems: in flow-through electrode CDI systems, the feed water flows through the electrodes, instead of flowing between them
- Hybrid systems: an electric field is used to draw sodium and chloride ions across ion-exchange membranes
- Entropy battery systems: instead of storing charge in the electrical double layer at the surface of the electrode, it is held in the chemical bonds, which is the bulk of the electrode

The operation of a conventional CDI system cycles through two phases: an adsorption phase where water is desalinated and a desorption phase where the electrodes are regenerated. During the adsorption phase, a potential difference over two electrodes is applied, and ions are then adsorbed from the water. The ions are transported through the interparticle pores of the porous carbon electrode to the intraparticle pores, where the ions are electrosorbed in the so-called electrical double layers. After the electrodes are saturated with ions, the adsorbed ions are released for regeneration of the electrodes. The potential difference between electrodes is reversed or reduced to zero. In this way, ions leave the electrode pores and can be flushed out of the CDI cell resulting in an effluent stream with a high salt concentration, the so-called brine stream or concentrate. Part of the energy input required during the adsorption phase can be recovered during this desorption step.

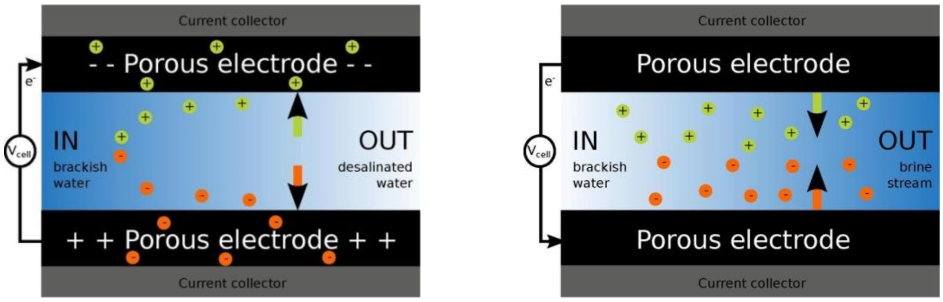

Figure 3-17. Operation of a conventional CDI system, step 1 adsorption (left) and step 2 desorption to regenerate the electrodes (right)

The working principle of a membrane-based CDI process is explained, based on the commercial CDI process CapDI, in the figure below.

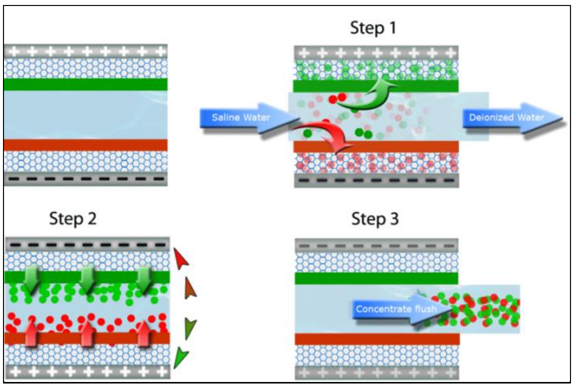

Figure 3-18. 3-step Membrane-based CDI process of water purification (CapDI) (Voltea, 2017)

Step 1. Purification: As saline water flows into the CapDI module, the oppositely charged electrodes attract the ions and pulls them through the selective membranes where the ions collect on the electrodes. Clean, desalinated water flows out of the system.

Step 2. Regeneration: Once the surfaces of the electrodes become saturated with ions, they are regenerated by reversing the electrical charge of the electrodes. Since identical charges repel, the ions are pushed out of the electrodes and become trapped between the membranes.

Step 3. Flushing: The concentrated brine between the two membranes is flushed from the system. The charge of the electrodes is returned to normal and the system is again ready to desalinate.

3.9.5.3. Operational conditions

The feed water quality requirements are that the total dissolved solids (TDS) should be < 2500 mg/L.

The footprint (surface area required) is relatively low as only a few square meters are needed for the installation. Possible outside buffer zones may also be required.

Limitations that a commercial CDI system would have to consider are:

- The CDI process is heavily dependent on the ion-adsorption capability of the capacitive electrode. At present, it is more suitable for brackish water desalination, and not suitable for high TDS water such as seawater
- The salt removal efficiency decreases as the solution temperature and flow rate increase
- TDS removal efficiency decreases at higher concentrations of TDS in the initial feed
- The system is also vulnerable to particles so pre-treatment e.g. by sand-filtration is needed

3.9.5.4. Cost data

- Energy consumption: 0,5-2,5 kWh/m^3
- Costs will depend on the scale, the feed water TDS and associated energy consumption. Costs are generally comparable to RO. For relative small scale, horticultural installations, costs of between 35000 € and 100000 € can be expected

In a field tests, costs of around 5 €/m^3 are mentioned, but it is expected that they will reduce to around 1 €/m^3.

3.9.5.5. Technological bottlenecks

Electrode scaling is one of the biggest issues encountered in CDI. Virtually all water sources contain calcium and magnesium ions, which are harmless in concentrations normally I feed water sources, but they can form precipitates at higher concentrations.

During operation, the negative electrode electrosorbs positive ions indiscriminately, including calcium and magnesium ions. When the unit is discharged, a build-up of magnesium and calcium compounds can occur when high concentrations of magnesium and calcium are released. To date, mild acids (such as citric acid) have been the preferred descaling method; however, process monitoring to determine when to descale the unit adds to the complexity.

3.9.5.6. Benefit for the grower

Advantages

- CDI does not require any chemicals such as biocides or anti-scalants
- CapDI typically recovers between 80% and 90% of the water it treats, compared to 50-70% for reverse osmosis
- Recovery range: up to 99% removal of salt
- The absence of applied pressure

- Polarity reversal results in self-cleaning of electrodes

Disadvantages

- The efficiency of electrodes for salt separation requires optimisation
- Limited data available for seawater desalination
- More efficient for low salinity feed water sources (TDS < 15000 mg/L)

3.9.5.7. Supporting systems needed

None.

3.9.5.8. Development phase

Commercialised: The application of the CDI technology is rather new. Commercial applications are known in the production of boiler feed water, desalination of groundwater and surface water with low TDS and in some industrial applications. Several companies supply installations for CDI and there are companies who supply information of user cases in greenhouse horticulture.

3.9.5.9. Who provides the technology

Suppliers of CDI equipment are:

- Voltea, www.voltea.com (the Netherlands)
- AquaEWP (USA)
- Atlantis (USA)
- Idropran Inc (Italy)
- LT Green Energy (Australia)
- Enpar (Canada), http://www.enpar-tech.com/ (Electro-Static Deionisation)

3.9.5.10. Patented or not

Although CDI is based on a relatively old principle, current suppliers all have own developments of which the intellectual property is protected with patents. In the EOB database, the term CDI results in 243 patents. Relevant IPC classification is C02F1/00 Treatment of water, wastewater, or sewage (C02F3/00 - C02F9/00 take precedence), C02F1/46 by electrochemical methods C02F1/4604 for desalination of seawater or brackish water.

3.9.6. Which technologies are in competition with this one

Alternative techniques comparable to CDI are:

- Nanofiltration
- Reversed Osmosis
- Ion Exchange
- Electrodialysis

3.9.7. Is the technology transferable to other crops/climates/cropping systems?

CDI is a very general technique that can be applied to most crops, both soil-less and soil-bound.

3.9.8. Description of the regulatory bottlenecks

3.9.8.1. Brief description of the European directive and implications for growers at European level

Regulatory bottlenecks are related to the discharge of the concentrate, see section 3.9.8.2.

3.9.8.2. Implementation at the country level

In general, the discharge of the concentrate is restricted in a number of countries.

The Netherlands: When using CDI on brackish groundwater that is extracted from the first aquifer, a concentrate is remaining (the brine) and often discharged back into the subsurface, the second aquifer. This is causing environmental concerns and not in line with the WFD. In the Netherlands, there is a policy on allowing this situation for a certain time.

3.9.8.3. Implementation at the regional level

There are no known regulatory bottlenecks.

3.9.9. Brief description of the socio-economic bottlenecks

There are no specific socio-economic bottlenecks for the use of CDI technology itself. The technology has a high level of retention (> 90%) and the produced water is considered safe to use.

3.9.10. Techniques resulting from this technology

Capacitive deionisation is also called:

- capacitive desalination
- electrochemical desalination
- flow-through capacitor
- Electro-Static Deionisation

3.9.11. References for more information

[1] Weinstein, L., & Dash, R. (2013). Capacitive Deionization: Challenges and Opportunities. *Desalination Water Reuse*, *23*, 34-37

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3.10. Nanofiltration

(Authors: Wilfred Appelman[22], Willy van Tongeren[22])

3.10.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

3.10.2. Region

All EU regions.

3.10.3. Crop(s) in which it is used

All crops.

3.10.4. Cropping type

All cropping types.

3.10.5. Description of the technology

3.10.5.1. Purpose/aim of the technology

Nanofiltration (NF) is a membrane separation technology that aims to retain (remove) colloidal particles and large molecules from the main water stream, as well as multivalent ions. Also, disinfection is obtained in NF; although pathogen populations may re-establish regrowth downstream, if no additional measures are taken.

NF is a relatively new technology, but is already proven, and it is being used for water sources with low total dissolved solid contents, such as surface water and fresh groundwater. The purpose may be water softening (polyvalent cation removal) and/or removal of organic compounds such as disinfection by-products. Practical applications are found in the chemical and pharmaceutical industry, the recovery of sodium hydroxide solutions, and in whey treatment in the cheese industry. Seawater desalination could be done with a simple combination of NF and RO. In most other situations, pre-treatment prior to NF is required and would be similar to pre-treatment for RO techniques.

3.10.5.2. Working Principle of operation

NF is a pressure driven membrane filtration process. Pressures are usually between 3 and 10 bar, but higher pressures are possible (up to 45 bars).

Small molecules (< 200 daltons) and monovalent salts will predominantly pass the membrane with the water, large molecules and multivalent ions are mostly retained. The pore size of NF membranes is smaller than ultrafiltration, ranging from 1-5 nanometres.

Membrane selectivity is sensitive to the composition of the water and the type of membrane. Membrane modules may be either a hollow fibre type (diameter ranging from

0,2-3 mm) or spiral wound, the latter is more sensitive to fouling/plugging, but allows higher operating pressures. Ceramic membranes, flat plate membranes and other types of membranes are also used. Polyamide is often used as the membrane material.

Operational schemes may include dead-end or cross-flow modes, as well as various, recycle modes to improve the separation quality of ions in the NF process (see below). Laboratory work is often required to determine the optimal configuration.

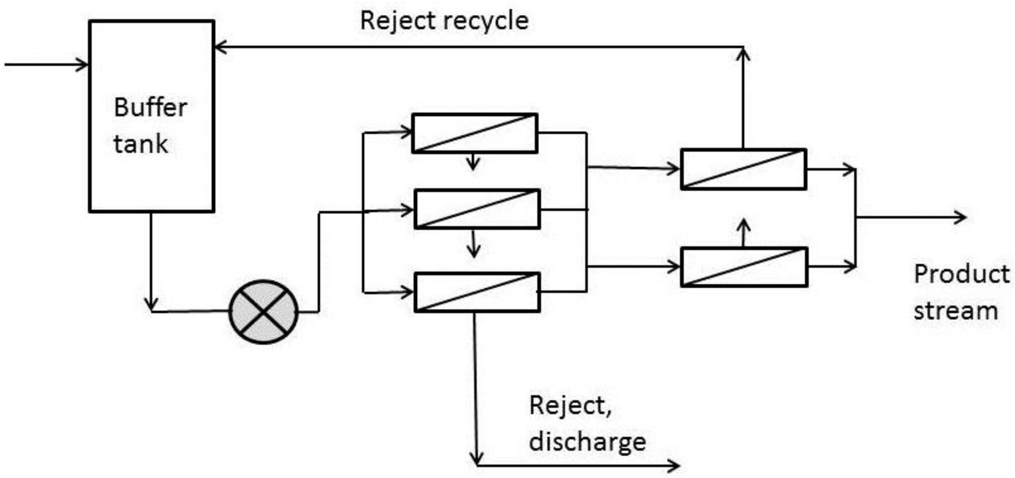

Figure 3-19. Two-stage nanofiltration process (3-2 configuration). The second stage will improve the overall separation of monovalent and multivalent ions

3.10.5.3. Operational conditions

NF units are easily scaled up to larger systems by applying more modules in parallel (or in series).

Membrane cleaning may be required when the water flow drops due to membrane fouling. Rinsing or backwashing (reversing the flow through the module) is relatively quick and is often an adequate solution. More severe fouling can be removed by occasional cleaning with solutions of detergents, acids and/or alkali.

Operational limitations vary depending on the quality of the membrane and the supplier (see the respective technical data sheets for more information). Examples of the characteristics of polyamide membranes are:

- max. 0,5 mg/l Fe, Al, Zn, Mn
- SDI level < 5; turbidity < 1
- no free chlorine or other oxidants (< 0,1 mg/l)
- maximum temperature: 40-50 °C
- maximum pressure: 45 bar (moderate 5-10 bar)
- pH 3 – 11 (it may vary between 2-12 for short periods of time)

3.10.5.4. Cost data

CAPEX is around 200 € /m³/day filtrate (for a 400 m³/day installation) excluding membranes but will increase to around 1000 € /m³/day filtrate in case of small installations (50 m³/day). Membrane modules that will produce between 0,3-1,5 m³/day (per m² membrane) will add another 20-45 € /m² to the cost.

Energy costs are related to the pressure drop of the system and the recycle rate, and are usually around 0,15 kWh/m³. Only very little attention by staff is required.

Total costs (OPEX and CAPEX) for water are: 0,2-1 €/m³ depending on the scale of the installation.

3.10.5.5. Technological bottlenecks

Nanofiltration is a relatively new membrane technology but is already well-known in different applications. Its operational characteristics compare well with Reverse Osmosis. Pre-treatment is often required to prevent fouling and plugging of the membrane. Hard water treated by NF will need pre-treatment to avoid precipitation of scale on the membrane.

Rinsing/flushing may be required when the pressure drops is too large or when the permeate flow decreases too much; this is usually an automated process. Chemical cleaning is periodically applied to remove more resilient scaling and fouling from the membrane modules.

Suppliers are trying to develop more selective membranes for a better separation of certain ions as well as cheaper materials, in order to improve the market potential of NF.

3.10.5.6. Benefit for the grower

Advantages

- Reliable water quality
- Disinfection (full removal of bacteria/viruses)
- Easily automated
- Continuous water supply
- May replace RO membranes (no full removal of ions)
- Multivalent ions are separated (sulphates, phosphates, calcium, metals, etc.); monovalent ions are partially removed; partial separation of P versus N and K ions
- Reduction of colour and turbidity
- Water softening possible
- Little or no chemicals required
- NF results in less aggressive water than RO (but still some aggressiveness remains)
- Smaller volume of retention water than RO, with lower concentrations of ions
- Operation pressure may be lower than RO (usually around 5-10 bar)
- Low operating pressure; low energy consumption in comparison to NF and RO (but higher than ultrafiltration and microfiltration).

- Disinfection of bacteria; it completely removes viruses, bacteriophages and macromolecules
- No chemicals required (except cleaning activities)
- Few manual actions required (only module replacements)

Disadvantages

- Pre-treatment may be required (pre-filtration 0,1-20 µm). Spiral wound modules always require pre-treatment
- Sensitive to fouling
- Handling of reject water and rinsing water required
- Limited retention of monovalent ions.
- NF membranes are usually more expensive than RO membranes.
- Energy consumption higher than ultrafiltration or microfiltration (common range: 0,02-0,4 kWh/m³).
- Membranes may be sensitive to oxidative chemicals (e.g. sodium hypochlorite).

3.10.5.7. Supporting systems needed

The removal of rinsing water could require temporary storage.

When water recycling is applied, buffering tanks will be required. When using groundwater, a well for groundwater extraction is needed.

NF is usually applied in a treatment sequence. NF may be applied to obtain partial separation of ions or to reduce the load for subsequent treatment steps.

3.10.5.8. Development phase

Commercialised: is used in many installations, e.g. whey treatment, wastewater treatment, drinking water production.

3.10.5.9. Who provides the technology

Several suppliers, for instance, DOW, Koch, GE Osmonics, X-Flow/Pentair, TriSep provide membranes and installations. Several system suppliers as well, for example, Lenntech, Prominent and Degrémont offer a wider range of technologies.

3.10.5.10. Patented or not

Patents have been granted for specific applications and specific membrane types. However, NF is a generic technology available for application in horticulture.

Although, system suppliers build specialised systems using NF membrane modules from one or more membrane manufacturers. Some membrane suppliers have their own systems.

3.10.6. Which technologies are in competition with this one

The selectivity of ions is quite unique to NF, making it difficult to compare to other technologies. The best alternative is a column of (weak) ion exchangers, in combination with carbon filter as pre-filter to remove organics. Electrodialysis membranes have selectivity towards either cations or anions, which is different from the more generic NF selectivity.

A relatively new alternative is Capacitive Deionisation, which aims at removing a substantial part of the ions and which will work somewhat more effectively on multivalent ions than monovalent ions.

3.10.7. Is the technology transferable to other crops/climates/cropping systems?

The system is widely applicable for all types of water streams and is easy to upscale because it is a modular system. Pre-treatment is an important issue in most applications.

3.10.8. Description of the regulatory bottlenecks

3.10.8.1. Implementation at the regional level

In general, the discharge of concentrates from membrane installations is restricted in a number of countries.

3.10.9. Brief description of the socio-economic bottlenecks

There are no specific socio-economic bottlenecks for the use of NF itself. The technology has a high level of retention, except for small molecules and monovalent ions; the produced water is usually safe to use.

3.10.10. Techniques resulting from this technology

Not known.

3.10.11. References for more information

[1] Dutch Policy Document, November 2012: Beleidskader: Goed gietwater glastuinbouw,
[2] Delft Blue Water project, http://www.delftbluewater.nl/
[3] Van Os, E. A., Jurgens, R., Appelman, W., Enthoven, N., Bruins, M. A., Creusen, R., ... & Beerling, E. A. M. (2012). *Technische en economische mogelijkheden voor het zuiveren van spuiwater* (No. 1205). Wageningen UR Glastuinbouw. Retrieved from https://www.glastuinbouwwaterproof.nl/content/3Onderzoek/GW_Substraat_WP5_Businesscase.pdf on 06/02/2018

3.11. Modified Ion Exchange

(Authors: Ockie van Niekerk[16], Wilfred Appelman[22], Willy van Tongeren[22])

3.11.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge
- Nutrient recovery
- In-line water treatment (in closed-loop or semi-recycling production systems)

3.11.2. Region

- All EU regions
- South Africa

3.11.3. Crop(s) in which it is used

All crops.

3.11.4. Cropping type

- Soil-bound
- Soilless
- Protected

3.11.5. Description of the technology

3.11.5.1. Purpose/aim of the technology

Modified Ion Exchange (MIX) is a technology designed to remove dissolved salts from irrigation water, producing a high percentage of demineralised water, a very small volume of concentrated saline water, and solutes containing usable fertilisers. This means that unlike other methods of demineralisation, the saline concentrate produced by MIX does not have to be discharged, but can be evaporated so that the salt does not re-enter the water cycle.

Treating groundwater until it becomes irrigation water

For high yield agricultural production, the sodium content has to be kept low. In addition, some crops are also sensitive to high chlorine content. In many irrigation practices where groundwater is used, salts can accumulate since there are more dissolved salts than can be absorbed by the crops.

Treating recycled greenhouse water to prevent salt accumulation (semi-selective)

In greenhouses where water is continuously recycled, salts can accumulate. Regularly removing all the salt from a portion of greenhouse water prevents unwanted ions like sodium from accumulating. When used in a pre-treatment step, mainly sodium is removed from the system.

Recovery of nutrients from greenhouse runoff

Water discharged from greenhouses often contains large amounts nutrients such as nitrate. MIX can be used to recover these from the water before it is discharged to a natural water body.

Treating drain water for reuse

Unlike membrane-based technologies, MIX has a low fouling potential and can be used to treat water with a higher biological content. MIX removes the salts from treated drain water, and makes it suitable for irrigation.

3.11.5.2. Working Principle of operation

Modified Ion Exchange uses the principle of the widely-used ion exchange process to remove cations and anions from water producing highly concentrated solutions. This can also be used in pre-treatment steps to separate unwanted ions like sodium and chloride. The ion exchange resin can be regenerated with specific chemicals to become a fertiliser as a final product. An advantage of this technique is that the value of those fertilisers largely covers or exceeds the costs of the chemicals that are required for regeneration.

In MIX, water passes through a bed of resin, similar to the sand bed in a sand filter. The resin is preloaded with another ion for which the resin has a lower selectivity than the ions to be removed from the water being treated. In MIX we want to remove all the ions from the water so both a cation and an anion exchanger are used, respectively, preloaded with hydrogen and hydroxide ions. Once displaced from the resins, the hydrogen and hydroxide ions combine to form water. This results in water with 99% of its salts removed, this process can be seen in the figure below.

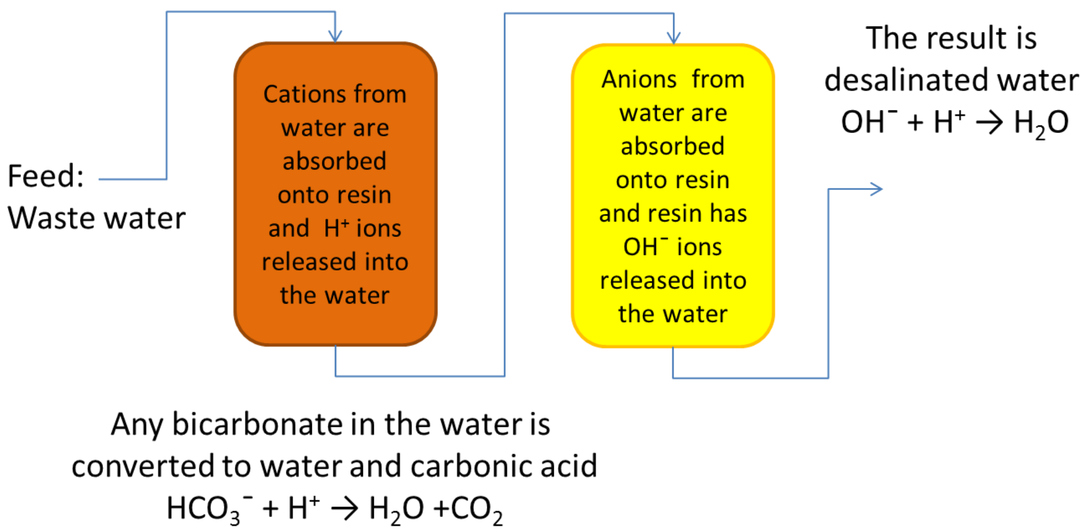

Figure 3-20. The loading process of MIX, where dissolved ions are removed from the water

3.11.5.3. Operational conditions

For groundwater with high concentrations of bicarbonate, a pressure of 2 bars is required to ensure that the produced CO_2 stays in the solution, otherwise, MIX has a pressure drop similar to some sand filters. The process can easily be scaled up for larger flow rates.

Fertilisers are produced in direct proportion to the amounts of salts removed, which means the higher the salt content the more fertiliser is produced. The amount of water that can be treated using MIX maybe limited by the amount of fertiliser that can be used on-site or sold to users close by, because transporting the fertiliser material produced can be costly and possibly uneconomical.

3.11.5.4. Cost data

The cost of the unit to treat 120 m^3/day would be 50000-100000 € per unit, installation included. The resin needs to be replaced once every 5-10 years (cost 1000-5000 €). Costs could vary depending on the specific conditions of the individual grower.

The cost of chemicals used is expected to be covered by the value of the fertiliser materials produced.

Energy costs (electric): 0,1-0,3 kW/m^3.

3.11.5.5. Technological bottlenecks

The amount of water that can be treated is limited to the marketing opportunity of the produced fertiliser. If the combination of the volume of water to be treated and its salt content produces too much fertiliser (in case all the water is treated using MIX) that may create a problem for the grower who would then need to find suitable, legally correct way to dispose of the fertiliser material.

3.11.5.6. Benefit for the grower

Advantages

- Increases the quality of the water
- The by-product is a locally-produced fertiliser
- The cost of potassium chloride, potassium hydroxide and nitric acid used as inputs is claimed to be less than the value of the potassium nitrate that is produced by the process
- Salt from irrigation water can be removed from the water cycle and possibly be sold or discharged into the sewer
- Low fouling potential, the resin is very robust and can handle undissolved solids
- Can be used in-line in a crop production system where it can remove sodium and chloride from recycling solutions

Disadvantages

- A complex system is needed on the farm
- Chemicals can be dangerous; extra safety precautions are necessary

- The fertilisers that are generated are liquid fertilisers. It is costly to store them or transport them over long distances. Therefore, they are preferably used in the greenhouse where they are produced

3.11.5.7. Supporting systems needed

- Evaporation ponds or multi-stage flash distillation units to treat the salt concentration
- A system where a solution containing a fertiliser mixture can be integrated
- A sand filter in case the water contains suspended solids (pre-treatment)
- The chloride solution that contains the Na still contains some plant protection products (PPP's). In the Netherlands, it is, therefore, necessary to treat the solution to meet the current legal requirements in terms of PPP's

3.11.5.8. Development phase

- Research: Use of treated sewage water for high-level irrigation practices
- Commercialised: Groundwater desalination, Nutrient recovery, In-line semi-selective treatment of recycled greenhouse water to prevent salt build-up

3.11.5.9. Who provides the technology

The technology is being provided by: Optima Agrik (Pty) Ltd., Horticoop and Verhoeve Milieu & Water.

3.11.5.10. Patented or not

This technology was developed by Optima Agrik (pty) Ltd, several processes and/or parts are patented.

3.11.6. Which technologies are in competition with this one

Widely used technologies to produce desalinated water or reduce salts in water are mostly membrane-based technologies. These require extensive pre-treatment to prevent fouling of the membranes, which are often susceptible to hard water and bioproducts in the water, but they require fewer chemicals These membrane technologies mostly use electrical power to separate dissolved salts from the water. These systems often have a lower capital cost, but the net running cost is higher than MIX if one takes into account the value of the fertiliser produced. Furthermore, these technologies produce a higher volume of brine, which can be discharged into the ocean, but cause soil salinisation or salinisation of groundwater and when disposed of inland.

Practically, these technologies can be used to treat water with higher concentrations than is possible with MIX. Even though MIX is more robust, it is limited by the amount of fertiliser that can be marketed. For very brackish water, the most economical option would be a combination of MIX and a membrane-based technology such as reverse osmosis.

3.11.7. Is the technology transferable to other crops/climates/cropping systems?

The technology is transferable to any crop, climate and cropping system, as long as the water is of such quality that the amount of fertiliser produced can be used by the farmer or others in the region.

3.11.8. Description of the regulatory bottlenecks

3.11.8.1. Implementation at the country level

MIX can produce highly concentrated salt solutions and fertiliser solutions. Large quantities of chemicals, used as inputs, have to be stored. The management of the solutions produced and the chemicals used as inputs, may be regulated depending on the region.

The discharge of highly concentrated brine is restricted in many countries, but MIX provides the opportunity for different handling of the brine. Since MIX produces the smallest volume of brine of any desalination technology, the brine can be evaporated economically (either using evaporation ponds, multi-stage flash distillation etc.) providing the salts in solid form, which has economic value as well as reducing pressures on the environment.

3.11.9. Brief description of the socio-economic bottlenecks

The system is complex and requires knowledge of chemistry to fully understand it. It is a new technology, so farmers are not yet used to it and maybe reluctant to implement a complex solution that they do not fully understand.

The small volume of highly concentrated brine that is produced provides an opportunity to evaporate the water of the brine solution and to recover the salt in a solid form; thereby avoiding that salt is discharged to the environment. This adds extra complexity to the process, which can make producers unenthusiastic to apply MIX.

For a grower, the slightly higher capital costs, increased complexity, the relative newness of MIX and a lack of understanding by potential users may outweigh the advantages and smaller operational costs for water desalination offered by MIX, at the moment.

3.11.10. Techniques resulting from this technology

MIX allows for closed-loop irrigation by removing salts that can build up:

Sodium Removal Unit (SRU)

This process can only be used when the water contains a sufficiently low Cl concentration.

For greenhouses where water is recirculated, it is very suitable for crops where the Cl uptake of the crops is equal to the Cl concentration in the feed water.

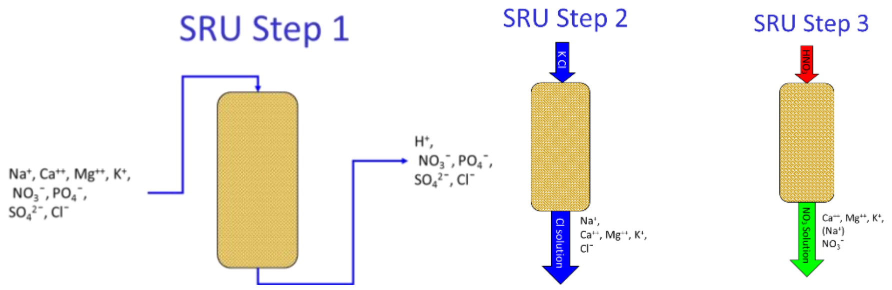

Figure 3-21. The three steps in a sodium removal unit

For water with a high bicarbonate concentration, this option is also ideal since the bicarbonate will be converted to water and carbon dioxide.

Step 1 Pump water (drain water for recirculation or groundwater) with low chloride concentration through cation exchange resin

All cations in the water are adsorbed onto the resin in a process where it is exchanged for hydrogen. As a result, the water leaving the resin column contains all the anions that were in the feed water but only hydrogen as a cation. The pH of the solution is too low for use on crops and is corrected to the most optimal level for the specific crop with calcium carbonate ($CaCO_3$), calcium hydroxide or potassium hydroxide.

Step 2 Remove Na from the column by pumping a potassium chloride solution through the column

The amount of cations other than Na, that is Ca, Mg, and K, that end up in the Cl solution will depend on the composition of the feed water. Also the requirement of Na that needs to be removed is a determining factor. The higher the percentage of Na removed, the more other cations will also be in the solution.

Step 3 Regenerate the resin with nitric acid

An excess of about 70% acid is required for the regeneration step. The excess must be neutralised with $CaCO_3$, calcium hydroxide or potassium hydroxide.

Additional information about the SRU

When this process is applied on greenhouse drain water, the Na concentration is lowered. While for most of the nutrients the recovery is 100%, for some other nutrients there can be losses up to 30% for example for Cu.

The table below illustrates the percentages of nutrients that are recovered.

Table 3-2. Recovery of nutrients in the sodium removal unit

Nutrient	Recovered
K	100%
NO_3	100%
PO_4	100%
SO_4	100%

Fe	100%
B	100%
Mo	100%
Ca	±97%
Mg	±86%
Mn	±90%
Zn	±80%
Cu	±70%

Between 50% to 70% of the Na is removed from the treated solution.

The nitric acid that is used in the process is neutralised with potassium hydroxide, $CaCO_3$ or calcium hydroxide. In The Netherlands, the cost of the potassium hydroxide and nitric acid is lower than the value of the potassium nitrate that is generated. This makes it an economic process.

The volume of discharge from the greenhouse is reduced by 80% to 90%.

Although only a percentage of the cost of the potassium cloride that is used to remove the Na from the resin is recovered, the impact on the cost of the process is limited.

3.11.11. References for more information

[1] Dąbrowski, A., Hubicki, Z., Podkościelny, P., & Robens, E. (2004). Selective removal of the heavy metal ions from waters and industrial wastewaters by ion-exchange method. *Chemosphere*, *56*(2), 91-106

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3.12. pH change/ adjustments

(Authors: Ockie van Niekerk[16], Esther Lechevallier[4])

3.12.1. Used for

Preparation of irrigation water.

3.12.2. Region

All EU regions.

3.12.3. Crop(s) in which it is used

All crops.

3.12.4. Cropping type

All cropping types.

3.12.5. Description of the technology

3.12.5.1. Purpose/aim of the technology

Adjusting the pH before use of water in the irrigation system is done to ensure that the pH is within the pH range of 5,5 to 6,5 which is acceptable for most crops. pH adjustment is sometimes necessary ensure that the irrigation water is within this acceptable range of pH values. Generally, the pH of a water source is stable; there are differences between rainwater and groundwater. In some cases, such as groundwater, often the pH will need to be lowered. In some cases, it may need to be increased.

Maintenance of pH within an optimal range is necessary for fertigation systems to allow optimal uptake of nutrients, especially micronutrients and to keep the irrigation system free from clogging.

3.12.5.2. Working Principle of operation

1) Acid or carbonate injection

Acid:

In order to lower the pH when it is too high, acid is injected into the water. A consistent pH will be ensured when the rate of injection is controlled by an inline controller or the pH is corrected in the storage tank with an automatic controller.

Water which contains a low concentration of bicarbonate can be treated with Nitric acid and/or Phosphoric acid; care needs to be taken to ensure that that the N or P added is considered when adding fertilisers. Water with a high concentration of bicarbonate is best treated with sulphuric acid to reduce the possibility of excess application of N or P to the crop.

Carbonates:

For water with a low pH, the pH can be increased with a carbonate-containing chemical such as potassium bicarbonate, potassium carbonate, calcium carbonate ($CaCO_3$), calcite or limestone. The bicarbonate also serves to buffer the water. Water with a low pH normally has no buffering capacity; using carbonate to neutralise the water will, therefore, provide the buffering capacity to enable in-line pH control.

Another aspect that should be considered is the solubility of the carbonate. Potassium carbonate is available in a solution that will make it easy to pump with a dosing pump. The addition of K should be taken into account for the nutrient supply.

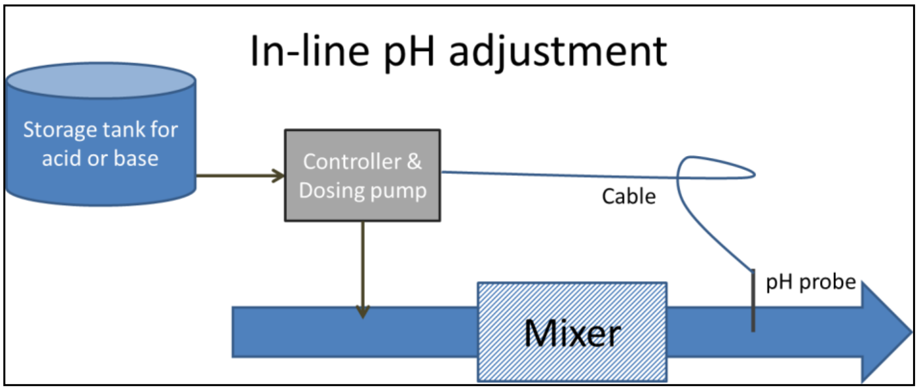

Figure 3-22. Schematics of In-line pH adjustment

Several injectors for acids or carbonates are available on the market. These systems consist of a flow meter, injector and pH meter to automatically adjust the amount of acid used.

2) Contact with calcium carbonate bed

A low-tech way to increase the pH of water is to let it flow through a bed of lime or $CaCO_3$. The low solubility of the $CaCO_3$ makes the process self-regulating. As long as the pH of the water is low, the water will dissolve the $CaCO_3$; as the pH rises, the rate at which the $CaCO_3$ dissolves decreases, stabilising at a pH of around 6. Any excess CO_2 will dissociate from the water, typically resulting in a bicarbonate concentration of 0,5 mmol/L.

It is used to neutralise/re-mineralise water which has a low cation level and an acidic pH.

3.12.5.3. Operational conditions

When using acid and carbonate injection, pumps and injection systems should be dimensioned depending on the scale of the system and water flow.

For a good contact with the $CaCO_3$ bed, the size of the bed will have a diameter of 2 m for a flow of 10 m^3/h.

Alkalinity must be taken into account for pH stabilisation. A certain level of alkalinisation can be reached to ensure better pH stability. However, high alkalinity can cause the precipitation of nutrients in concentrated fertiliser solutions and increases the pH of the growing medium (which in turn reduces the availability of micronutrients).

3.12.5.4. Cost data

1) Acid and carbonates injection

The cost of a unit will greatly depend on size, but costs start from around 3000 €.

The pH probe must be calibrated monthly, which will require 15-30 min/month.

Storage tanks of neutralisation chemicals must be kept full.

The amount of acid needed is dependent on the bicarbonate concentration of the water and is calculated as follows:

- Example neutralisation with nitric acid (38%):
- $[HCO_3]$ mmol/L X Volume (m^3/day) X 63 gr/mole ÷ 0,38 = nitric acid (kg/day)

2) Contact with calcium carbonate bed

The level of the $CaCO_3$ powder or granules must be kept at a sufficient depth to ensure neutralisation. Due to the many factors that will influence the final pH, the user will have to determine the optimal level of $CaCO_3$ in the tank.

3.12.5.5. Technological bottlenecks

Acid injection: nutrients added in an acidic form should be considered in the fertigation program. In cases where the bicarbonates concentration in the feed water is very high, the dosage of N and/or P may be excessive. The consequence is that the dosage level of N or P (in kg/hectare or millimole/L) will be reached before the pH is reduced to its optimal level.

Carbonates injection: high alkalinity can cause the precipitation of nutrients in concentrated fertiliser solutions and increases the pH of the growing medium (which in turn reduces the availability of micronutrients).

3.12.5.6. Benefit for the grower

Advantages

- Easy-to-use and to adjust
- Calcium carbonate does not need electricity
- Easily scalable

Disadvantages

Acids are dangerous products and need to be handled and stored safely.

3.12.5.7. Supporting systems needed

Automatic control of acid injection/carbonate injection is preferable to maintain a relatively constant pH over time.

3.12.5.8. Development phase

- Field tests: Some field tests have been conducted with the $CaCO_3$ bed
- Commercialised: Acid and carbonate injection systems are commercialised

3.12.5.9. Who provides the technology

Several injectors of acids are available on the market. These systems consist of a flow meter, injector and pH meter to automatically adjust the amount of acid used.

3.12.5.10. Patented or not

This technique is very general and not patented.

3.12.6. Which technologies are in competition with this one

Carbonate injection competes with the use of a $CaCO_3$ bed.

3.12.7. Is the technology transferable to other crops/climates/cropping systems?

Injection pumps for acid/carbonates are transferable to other crops/climates/cropping systems. Optimal pH has to be targeted, and the alkalinity and pH of supply water have to be taken into account.

3.12.8. Description of the regulatory bottlenecks

3.12.8.1. Implementation at the country level

Regional safety regulations on the handling of acids should be observed.

3.12.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks that we know of.

3.12.10. Techniques resulting from this technology

The Maërl filter is a specific version of the carbonate addition process that uses, as a source of $CaCO_3$, a substrate which is a lime deposit resulting from marine algae, lithothamnion, which contains crystallised mineral elements of sea water. It is particularly used in systems using rainwater.

Decision support systems to manage pH in irrigation water have been developed.

3.12.11. References for more information

[1] Whipker, B. E., Bailey, D. A., Nelson, P. V., Fonteno, W. C., & Hammer, P. A. (1996). A novel approach to calculate acid additions for alkalinity control in greenhouse irrigation water. *Communications in Soil Science and Plant Analysis*, *27*(5-8), 959-976

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Chapter 4. Optimising water quality – Particle removal

Coordinators: Rodney Thompson[23], Peter Melis[18], Ilse Delcour[19]

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4.1. Introduction

4.1.1. These techniques concern the issue

- Preparation of irrigation water
- More efficient use of water

4.1.2. Regions

All EU regions.

4.1.3. Crop(s) in which the issue is relevant

All fertigated crops.

4.1.4. Cropping type

All cropping types.

4.1.5. General description of the issue

Removal of particles present in the irrigation water is a fundamental requirement for drip irrigation to avoid clogging problems (taking into account the small size of the dripper outlet), which reduces irrigation uniformity and can provoke a decrease of water and nutrient use efficiency and of crop yield. As a general rule, it is recommended to install a filtration system after the fertigation equipment with a maximum gap size of 1/10 of the dripper outlet. However, special attention must be paid to closed soilless growing systems using organic substrates because drain water tends to contain organic particles and can be discoloured which can interfere with some disinfection techniques such as UV disinfection.

The challenges related to the removal of particles are the following:

4.1.5.1. Sub-Issue A: Particles in drain water interfere with recirculation

Drain water from horticulture using organic substrate often contain an appreciable amount of organic particles. When drain water is collected for recirculation, commonly disinfection step is used. Disinfection units require that the drainage water entering the disinfection unit does not contain in order particles to guarantee a sufficient light transmission and to prevent continuous backflushing.

4.1.5.2. Sub-Issue B: Flush water with nutrients and/or pesticides cannot be discarded

European law and the national laws in the member states pursue the re-use of drain water in horticulture. However, many systems used for the removal of particles generate backflush water containing nutrients and/or pesticides; the grower is required to collect this water and process it according to legislation.

4.1.6. Brief description of the socio-economic impact of the issue

In several regions in Europe, water quality and quantity are becoming a major issue in horticulture. Rainwater is by far the optimal source to use, but quantity is often a limiting factor. Drain coming from cultivations on the substrate can be collected, being available for reuse, although its disinfection is recommended in multiple crops before being used due to the presence of possible diseases. The water will contain nutrients which need to be considered. The drain water will also have a significant content of organic particles when organic substrates are used, which will interfere with the disinfection capacity. Therefore, effective previous filtration is required.

Some growers with smaller operations prefer to install filtration systems with manual instead of automatic cleaning systems because of their lower cost. However, commonly with manual cleaning systems, the selected gap size (of the filter mesh) tends to be relatively large to avoid frequent blockage of the filter and therefore frequent cleaning; this increases the risk of dripper clogging.

4.1.7. Brief description of the regulations concerning the issue

4.1.7.1. European level

Wash water from cleaning filter can contain nutrients and organic materials that can pollute natural water resources. European Union (EU) Directives such as the Water Framework Directive provide guidelines regarding the discharge of contaminating materials to water bodies such as rivers, lakes and aquifers. With time, there is increasingly strict implementation of these Directives at national and regional level.

4.1.7.2. Country level

The European Union Directives are translated into national law in the European Union member states. National governments have the obligation to organise control entities for the quality of natural water bodies. There are differences between member states in the details of the legislation, but in the general terms, the legislation should be similar. There are clear differences between member states in the implementation of the legislation. Generally, countries (and regions) in North West Europe have the strictest implementation within the EU. For example, The Netherlands is working towards zero emission of water contaminants from horticulture by 2027.

4.1.7.3. Regional level

At the regional level, the regulations are generally very similar to the national regulations.

4.1.8. Existing technologies to solve the issue/sub-issues

The general approaches of the existing technologies can be organised into the following categories:

Specific or crude filtration

- Sieve bend screen filtration

Crude filtration

- Hydrocyclone

Fine filtration with backwash

- Rapid sand filtration
- Cloth filtration
- Disc filtration
- SAF filtration
- Drum filtration (without vacuum pump)
- Microfiltration

Fine filtration not using backwash

- Paper band filtration
- Drum filtration (with vacuum pump)

4.1.9. Issues/sub-issues that cannot be solved currently: bottlenecks

All the technologies listed above have a waste product. In most cases, this is filthy water originating from back flushes. It can also be a soiled paper band or organic substrate contaminated with fungal spores and nutrients. Thus, it is necessary to find a solution for these residues.

4.1.10. References for more information

[1] Wen-Yong W., Yan H., Hong-Lu L. & Yong N. (2015). Reclaimed water filtration efficiency and drip irrigation emitter performance with different combinations of sand and disc filters. *Irrigation and Drainage*, *64*, 362-369

[2] Roncancio M. G., Pinilla P.A.F. & Martinez Q. F. (1989). Evaluación de filtros de arena y de malla para riego por goteo. *Ingeniería e Investigacíon*, *19*, 52-62

[3] Ruadales R. E., Fisher R. P. & Hall C. R. (2017). The cost of irrigation sources and water treatment in greenhouse production. *Irrigation Science*, *35*, 43-54

[4] Adin A. & Alon G. (1986). Mechanisms and process parameters of filter screens. *Journal of Irrigation & Drainage Engineering*, *112*(4), 293-304

[5] Niu W., Liu L. & Chen X. (2013). Influence of fine particle size and concentration on the clogging of labyrinth emitters. *Irrigation Science*, *31*, 545-555

4.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions

Technology	Characteristics		Strengths	Weaknesses	Additional comments; residual product
	Filtering force, Type and size of particles removed	Flow rate			
Specific filtration					
Sieve bend screen filtration	Gravity Larger particles Dependent on slot size (150 µm - 5 mm)	36-1000 m³/h (dependent on the scale and the selectivity of the screen)	Very simple principle Reliable Easy to install Purely physical action based on gravity All filtered water can be used (there is no backflush) Very high capacity	Only filtration of larger particles Additional filtration necessary to get water suited for disinfection The sludge has to be captured in a container Cleaning is mostly done manually with a garden hose (although models with automatic cleaning exist)	Often chosen as first filtering step for drain water loaded with organic material and substrate particles. Residual product: crude substrate
Crude filtration					
Hydrocyclone	Centripetal force + gravity Particles heavier than water > 50 µm	2 m³/h (0,08 m diameter) - 360 m³/h (0,8 m diameter)	Quick and effective removal of heavy particles No production of wastewater There are no moving parts	Only removes sand and heavy particles No removal of organic matter Not sufficient for filtration and preparation for disinfection by ultrafiltration, slow sand filtration or UV disinfection	Residual product: Sand + heavy particles
General fine filtration					
Band filtration	Gravity All particles Dependent on mesh width (min. 5-10 µm)	2-50 m³/h (dependent on contamination of water, selectivity and fleece width)	No backwash All water can be reused after disinfection Makes disinfection of all sorts of drain water possible Self-cleaning function available	Dirty band as rest product If the screen is flat and does not form a large cup, filthy drain water will flow over the borders and can get underneath the screen without filtration	Can remove very fine particles due to the small maze width Residual product: Dirty paper band
Rapid sand filtration	Pressure All particles	4-12 m³/h.m²	Simple technology Flow rate adjustable to requirements Self-cleaning function available	A lot of space required for the filter Periodic replacement of the sand Production of large amounts of concentrated water Dealing with backwash water	Not favourable technology because there are smaller and more efficient alternatives available Residual product: Backwash waste

Technology	Characteristics		Strengths	Weaknesses	Additional comments; residual product
Disc filtration	Pump pressure All particles Dependent on disc separation 55-400 µm	0,2 - 30 m³/h (each individual disc filter)	Small installation with high throughput Self-cleaning function available	Production of backflush water Cannot deal with a high sand content in water	Residual product: Backwash waste
SAF filtration	Pump pressure water flow All particles 10-800 µm	7-400 m³/h	Reliable filtration of particles Continuous filtration, even during the automatic backflush Automatic cleaning Limited maintenance needed High capacity	Deal with backwash water	Residual product: Backwash waste
Cloth filtration	Water flow / Gravity / Vacuum pump All particles Dependent on mesh width (min. 5-10 µm)	Smaller versions (up to 6 vertical discs): 10-60 m³/h Large-scale (up to 12 vertical discs): 50-570 m³/h	Successful particle removal Recovery of high quantities of clear drain water Self-cleaning function available	Generation of small amounts of particle-enriched drain water	Technology not common in horticulture Residual product: Backwash waste
Drum filtration	Water flow / Vacuum pump All particles Dependent on mesh width (min. 5-10 µm)	10-3000 m³/h	Waste is limited to only the substrate in a model with a vacuum pump The throughput can be very high, but size will increase Self-cleaning function available	Models without a vacuum pump generate particle concentrated waste water	No back-wash water when model is based on vacuum pump Residual product: Backwash waste/solids
Microfiltration	Water flow (not under pressure) All particles 0,1-10 µm		No pressure required Higher flow rate than ultrafiltration Filters out more than only particles Self-cleaning function available	No removal of dissolved contaminants Less selective than ultrafiltration Particles cause multiple backflushes, interrupting the filtering activity Deal with backwash water	Residual product: Backwash waste
Ultrafiltration	Water flow (under pressure) All particles Up to 0,01 µm	3 m³/h per module	More selective than microfiltration Holds back bacteria and fungi Self-cleaning function available	Pressurized flow required Unsuitable for particles (clogging) Automatic cleaning function frequently interrupts the filtering activity Pre-filtering is required Need to deal with backwash water	Recommended in combination with band filtration Residual product: Backwash waste

4.3. Band Filtration

(Authors: Peter Melis[18], Rodney Thompson[23])

4.3.1. Used for

- Preparation of irrigation water
- More efficient use of water

4.3.2. Region

All EU regions.

4.3.3. Crop(s) in which it is used

Strawberry, ornamentals, greenhouse crops. All crops on organic substrates.

4.3.4. Cropping type

- Soilless
- Protected
- Open air

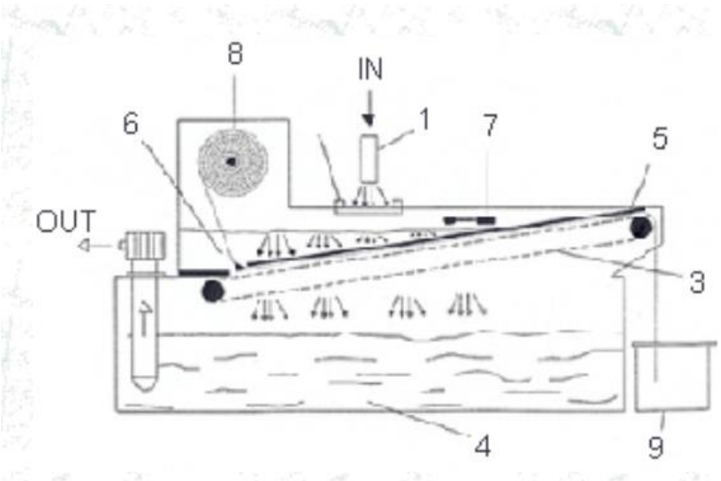
4.3.5. Description of the technology

4.3.5.1. Purpose/aim of the technology

Removing particles from irrigation, drainage or contaminated water. The filtration is dependent on the size of the mesh in the fleece which is the material that performs the filtration. The filtration can be as fine as 5 µm. This technique does remove nutrients or plant protection products.

4.3.5.2. Working Principle of operation

The band filter operates on the principle of gravitational filtering (Figure 4-1). The contaminated liquid to be filtered (1) is fed in through the liquid dispenser (2) onto an endless transport band (3) with filter fleece (8). Solid matter (dirt particles, sludge, etc.) is trapped (filtered-out) by the fleece. The more solid matter that is retained by the filter fleece, the less liquid is likely to flow through the filter fleece. As a result, the fleece can become clogged up. The cleaned liquid flows into filtrate holding tank (4) and can be reused. The sludge particles, remaining on the fleece, form a filter cake (5). If the density and thickness of the filter cake prevent an optimal flow the liquid through the filter or as soon as the filter cake (6) reaches a certain height (7, pre-set level-check), the dirty fleece is discharged into the sludge container (9). At the same time, replacement clean fleece is applied from a roll, and act as a new clean filtering material. The whole process occurs continuously and is fully automatic, and does not interrupt the filtering process.



1. Inlet liquid
2. Liquid dispenser
3. Filter fleece bed
4. Filtered liquid
5. Filter cake
6. Contaminated liquid
7. Level check
8. Filter fleece (100-250m)
9. Sludge container

Figure 4-1. Schematic picture of a band filtration unit (http://www.filtermat.be/EC/BandfilterEnglish.htm)

4.3.5.3. Operational conditions

The capacity of the technique is dependent on the degree of contamination of the incoming water, the mesh width of the filtration fleece, and the width of the fleece. Limitations vary from supplier to supplier. The finest fleeces can filter down to 10 µm. The flow rate through the system determines the size of the installation. The flow rate varies from 2 m^3/h in smaller installations up to 50 m^3/h. The dimensions of the systems providing these flow rates vary from 1,5 x 0,6 m to 5,5 x 1,0 m.

The fleece runs through the system with a cake of accumulated filtered material. When the cake gets too thick, the fleece is replaced and the dirty fleece is discarded. The rate of replacement of the fleece depends on the grade of contamination of the incoming water, the mesh size of the fleece and the width of the fleece.

4.3.5.4. Cost data

Band filtration units have a cost starting from 4000 €. Such a model has a “low” capacity of 10 m^3/h and a selectivity of 20 µm. A higher selectivity of the fleece towards 5 µm has a higher cost up to 10000 €. The unit can be set to roll the screen down to have a new cleaning surface in the unit, once the previous part is getting too filthy. Also, systems with higher capacities (flow rates) have higher costs.

The only maintenance is to remove and replace the filter screen when the screen is completely used. Prices differ strongly according to the mesh width.

At the moment there is no automatic cleaning function of the fleece. So waste in the form of a dirty fleece is unavoidable.

4.3.5.5. Technological bottlenecks

The filtration technique does not produce backflush water, but it does produce dirty fleece material which needs to be disposed of. There is no machine yet with a self-cleaning function of the fleece used in the filtering activity.

4.3.5.6. Benefit for the grower

Advantages

- No discharge of backflush water
- All water can be reused after disinfection
- Its use a pre-filtration treatment is useful for where disinfection is used

Disadvantages

If the screen is flat and doesn't form a large cup, dirty drain water can flow over the edges of the screen and pass underneath the screen without filtration. This is more likely when the cake is forming on the screen.

4.3.5.7. Supporting systems needed

None.

4.3.5.8. Development phase

Commercialised

4.3.5.9. Who provides the technology

Agrozone, AquaDNS, Royal Brinkman, ECOfilter, etc.

4.3.5.10. Patented or not

The paper band filtration technology is patented.

4.3.6. Which technologies are in competition with this one

The band filtration uses the same principle as techniques like cloth filtration and drum filtration. Also, disc filtration, microfiltration, SAF filtration, rapid sand filtration and sieve bend screen filtration can filter out particles. The band filtration, however, can remove very fine particles due to the small mesh width.

4.3.7. Is the technology transferable to other crops/climates/cropping systems?

Climate does not matter; of course, the unit has to be installed indoors when the top is open. Temperature does not matter. The crop should produce soil/substrate contaminated drain water to have a benefit from the installation.

4.3.8. Description of the regulatory bottlenecks

As there is no backflush water to discharge of, the water quality regulations regarding discharge do not apply.

4.3.9. Brief description of the socio-economic bottlenecks

None.

4.3.10. Techniques resulting from this technology

It is a stand-alone technology; no secondary techniques have been developed.

4.3.11. References for more information

[1] http://www.filtermat.be/EC/BandfilterEnglish.htm
[2] https://search-proquest-com.kuleuven.ezproxy.kuleuven.be/docview/1956077671?rfr_id=info%3Axri%2Fsid%3Aprimo
[3] https://emis.vito.be/en/techniekfiche/fabric-filter

4.4. Cloth Filtration

(Authors: Peter Melis[18], Rodney Thompson[23])

4.4.1. Used for

- Preparation of irrigation water
- More efficient use of water

4.4.2. Region

All EU regions.

4.4.3. Crop(s) in which it is used

All crops on organic substrates.

4.4.4. Cropping type

All cropping types.

4.4.5. Description of the technology

4.4.5.1. Purpose/aim of the technology

Removing particles from contaminated or drain water.

4.4.5.2. Working Principle of operation

Several versions of the technique are available. All have a similar basis for the working principle. A cloth filtration unit has three activities: filtering, backwashing and removing solid waste.

- Filtering: Inlet wastewater enters the tank or basin, completely submerging the cloth media which is located on a number of vertically aligned discs. By gravity, liquid passes through the cloth media. As solids accumulate on and within the cloth media, a mat is formed and the liquid level in the tank or basin increases. The filtered liquid enters the internal portion of the disc where it is directed to the centre shaft for final discharge
- Backwash: At a predetermined water level in the filtration tank or after a specified period of time, the backwash cycle is initiated. Solids are backwashed from the surface of the cloth on the discs by liquid suction from both sides of each disc. During backwash, discs are cleaned in multiples of two, unless a single disc unit is used. Discs rotate slowly, allowing each segment to be cleaned. Backwash water is directed to the headworks (i.e. the initial stage of the treatment process). Filtration is not interrupted during the backwash cycle
- Solid waste: The filtration process requires no moving parts. Heavier solids settle in the lower part of the filter tank. These solids are then pumped on an intermittent

basis back to the headworks, digester or other solids collection area of the treatment plant

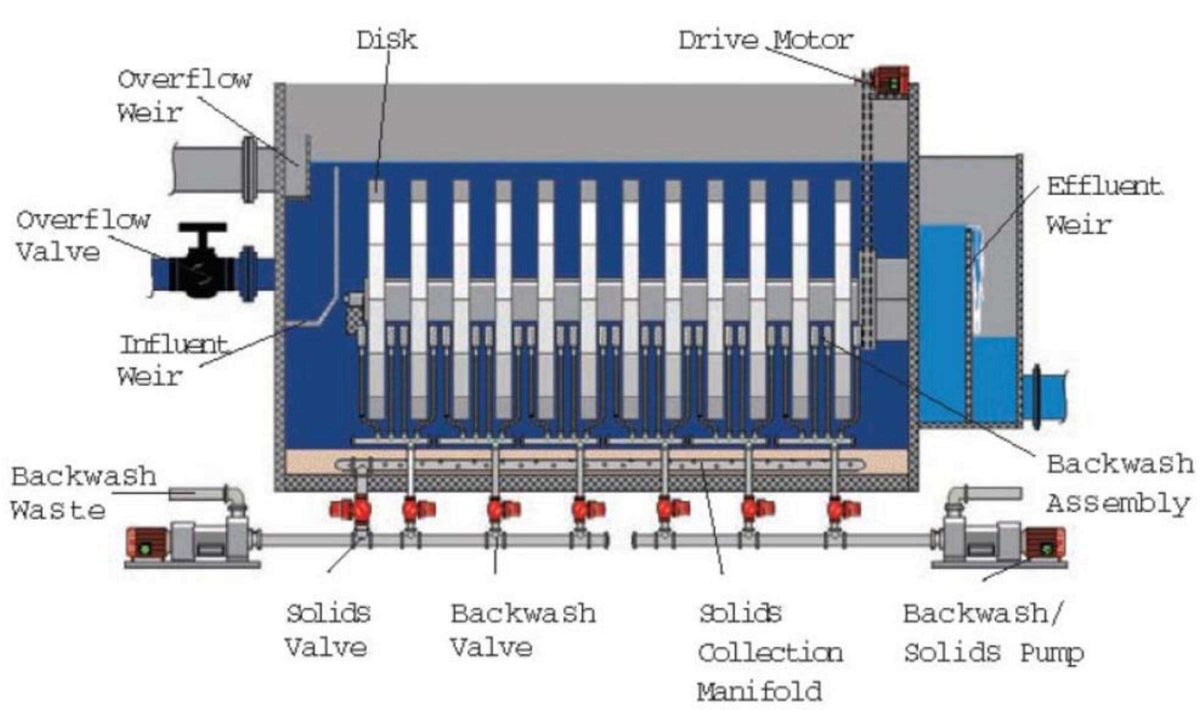


Figure 4-2. Disc-cloth filtration system (http://www.arwadh.com/engineering/wwt/filtration.asp)

The working principle of cloth filtration is demonstrated in two videos of different versions of the technique. The basic principle is the same to filter drain water and remove suspended particles. The backwash function is also shown in the two videos.

AquaDisk: https://www.youtube.com/watch?v=tyW_ZudaCTY

AquaDiamond: https://www.youtube.com/watch?v=vFtuFcG-C9k

4.4.5.3. Operational conditions

The surface area and characteristics of the cloth determine the filtering capacity. In a disc cloth filter, the number of discs increases the filtering surface and therefore the throughput of the system. A disc filter unit (large scale as the AquaDisk system) has a capacity of 50 to 570 m³/h and contains up to 12 vertically oriented discs; the discs can be 3 m in diameter. Smaller versions (like the mini-disc) contain up to 6 vertical discs per unit and can handle between 10 and 60 m³/h. In a traveling bridge version (like AquaDiamond) the surface is increased by the number of bridges in the filtration tank. Units can contain up to 8 vertically oriented laterals.

4.4.5.4. Cost data

Depending on the capacity and the set-up of the housing, the investment cost varies from 1000-13000 €. The filter material itself costs around 500-700 € for 1000 Nm³/h. The proportion of fabric material costs, as a percentage of total investment costs can vary from 10% to in excess of 50%.

The operating costs include:

- The personnel cost to maintain the installation. This would amount ca. 2 man hours per week
- Auxiliary and residual materials: 100-140 €/ year for 1000 Nm^3/h. Transport costs for the separated dust are determined by the type of residue.
  - Inert: ca. 75 €/ton
  - Chemical: 150-250 €/ ton
- Operational costs: 0,2-1,5 €/m^3/h

4.4.5.5. Technological bottlenecks

The unit often takes a lot of space. As an example, the Aqua MegaDisk system of Aqua Aerobics has a surface area of approximately 6 m x 2,4 m. They are not commonly used in horticulture. They are used more for industrial and municipal wastewater applications.

4.4.5.6. Benefit for the grower

Advantages

- Successful particle removal
- Recovery of high quantities of clear drain water

Disadvantages

- Generation of small amounts of particle enriched drain water by the backflush
- This water cannot be discarded either due to the presence of nutrients and/or pesticides
- Size, they are relatively large systems

4.4.5.7. Supporting system needed

No specific supporting systems required.

4.4.5.8. Development phase

Commercialised.

4.4.5.9. Who provides the technology

There are a number of suppliers. One of them is Aqua-Aerobics Inc.

4.4.5.10. Patented or not

Cloth materials and cloth filters are patented.

4.4.6. Which technologies are in competition with this one

The cloth filtration uses the same principle as techniques like band filtration and drum filtration. Also disc filtration, paper band filtration, microfiltration, SAF filtration, rapid sand filtration and sieve bend screen filtration can filter out particles. Cloth filtration is not widely used in horticulture.

4.4.7. Is the technology transferable to other crops/climates/cropping systems?

There are no limitations in climate or temperature. The crop should produce soil/substrate contaminated drain water to have a benefit from the installation.

4.4.8. Description of the regulatory bottlenecks

See section 4.1.7.

4.4.9. Brief description of the socio-economic bottlenecks

Mostly, the size and cost of the systems.

4.4.10. Techniques resulting from this technology

It is a stand-alone technology; no secondary techniques have been developed.

4.4.11. References for more information

[1] http://www.aqua-aerobic.com/index.cfm/products-systems/filtration/aquadisk/
[2] https://emis.vito.be/en/techniekfiche/fabric-filter
[3] Ribiero T., Paterniani J. Airoldi R. & da Silva M (2004). Performance of non woven synthetic fabric and disc filter for fertigation water treatment. *Scientia Agricola*, *61,* 127-133

4.5. Disc Filtration

(Authors: Peter Melis[18], Rodney Thompson[23])

4.5.1. Used for

- Preparation of irrigation water
- More efficient use of water

4.5.2. Region

All EU regions.

4.5.3. Crop(s) in which it is used

All crops on organic substrates.

4.5.4. Cropping type

All cropping types.

4.5.5. Description of the technology

4.5.5.1. Purpose/aim of the technology

Removing particles from contaminated or drain water.

4.5.5.2. Working Principle of operation

A disc filtration unit consists of the filtration system and an automatic cleaning function using backwash. The filtration is based on the compression of the discs inside the unit caused by a spring at the top. As dirty water is pumped into the filter and pressure increases, the water compresses the disc rings tightly together. The water is then forced to flow through the grooves of the disc rings, where debris is trapped, and releasing only clean water to the central shaft. After a set time or when the pressure difference reaches a set value, the backwash cycle starts. The inlet pipe is closed and the flow in the unit is reversed. Previously filtered water is pumped into the central shaft and the discs are loosened by compressing the spring at the top giving the discs the possibility to rotate and expel the particles. The trapped particles flow with the water towards the drain outlet. After the backwash cycle, the filtering activity re-starts after reopening the inlet pipe. A backwash takes up to 20 seconds and the water consumption should be less than 0,5% of the filtering capacity.

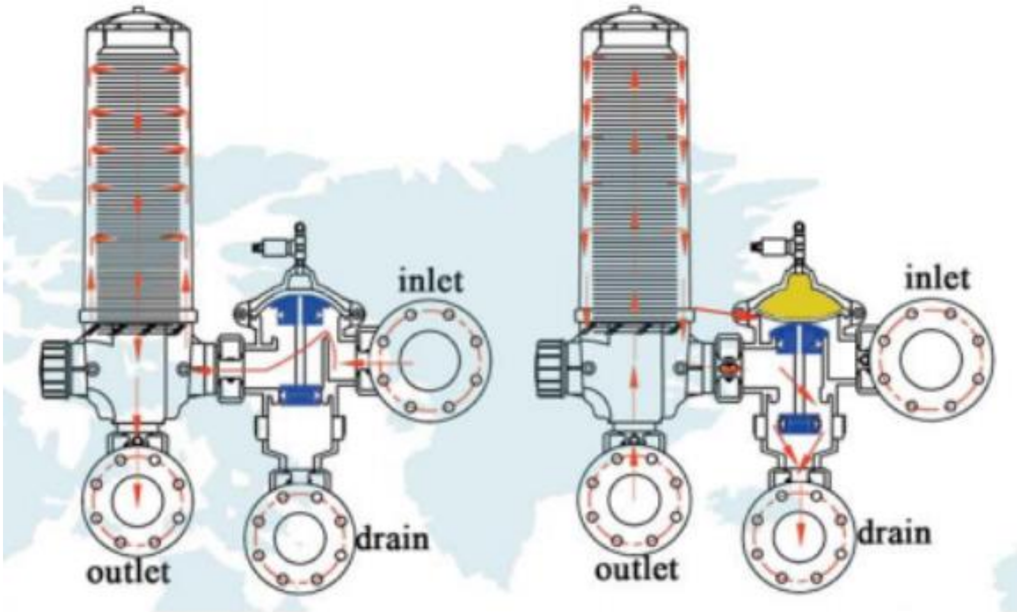


Figure 4-3. A disc filtration unit (http://www.czdlwater.com/content/?264.html)

4.5.5.3. Operational conditions

The capacity of the technique depends on the number of disc filters. Installations can contain up to 7 units in a row. There are also different sizes of disc filters, each with their own capacity. Individual disc filters can process from 0,2 up to 30 m^3/h. Also the characteristics of the disc rings determine how fine the filtration will be. Netafim for example offers different rings that can filter in the range of 55-400 µm; the mesh size is indicated by the colour of the rings.

4.5.5.4. Cost data

The prices of installation and maintenance are very dependent on the size of the installation. It is recommended to get estimates from the manufacturing companies or distributors.

4.5.5.5. Technological bottlenecks

During backwash, filtering activity is interrupted. Also sand particles can quickly damage the rings, requiring frequent replacement.

4.5.5.6. Benefit for the grower

Advantages

- Small installation with high throughput

Disadvantages

- Produces back flush water
- Cannot deal with a high sand content in drain water

4.5.5.7. Supporting systems needed

Pre-filtration when sand particles are an issue.

4.5.5.8. Development phase

Commercialised.

4.5.5.9. Who provides the technology

- Netafim
- UVAR Holland b.v.
- Amiad

4.5.5.10. Patented or not

It is possible in some systems, that some components are patented.

4.5.6. Which technologies are in competition with this one

A number of techniques can similarly filter out particles: band filtration, cloth filtration, drum filtration, rapid sand filtration, SAF filtration, sieve bend screen filtration, microfiltration, etc.

4.5.7. Is the technology transferable to other crops/climates/cropping systems?

There are no limitations in climate or temperature. The crop should produce soil/substrate contaminated drain water to have a benefit from the installation. It can be installed between a filthy drain silo and a disinfection unit.

4.5.8. Description of the regulatory bottlenecks

See section 4.1.7.

4.5.9. Brief description of the socio-economic bottlenecks

None.

4.5.10. Techniques resulting from this technology

It is a stand-alone technology; no secondary techniques have been developed.

4.5.11. References for more information

[1] Wen-Yong W., Yan H., Hong-Lu L. & Yong N. (2015). Reclaimed water filtration efficiency and drip irrigation emitter performance with different combinations of sand and disc filters. *Irrigation and Drainage*, *64*, 362-369

[2] Ribiero T., Paterniani J., Airoldi R. & da Silva M (2004). Performance of non woven synthetic fabric and disc filter for fertigation water treatment. *Scientia Agricola*, *61,* 127-133

4.6. Drum filtration

(Authors: Peter Melis[18], Rodney Thompson[23])

4.6.1. Used for

- Preparation of irrigation water
- More efficient use of water

4.6.2. Region

All EU regions.

4.6.3. Crop(s) in which it is used

All crops on organic substrates.

4.6.4. Cropping type

All cropping types.

4.6.5. Description of the technology

4.6.5.1. Purpose/aim of the technology

Removing particles from contaminated or drain water.

4.6.5.2. Working Principle of operation

Dirty drainage water flows into a drum that has a fine mesh. The drum is partly filled with water to be able to collect the particles that are being filtered out. The drum rotates and filters out the particles that remain on the inside of the drum. The rotating drum moves the particles upwards and nozzles at the top of the drum wash out the particles as a sludge. The sludge water is collected through an outlet.

Drum filters can also work with a vacuum pump in the centre. Dirty drain water is collected in a tank and a drum rotates in the tank. Due to the vacuum, the water is sucked through the drum and the particles adhere to the outside of the drum. The filtered water flows out through a central duct in the drum. The particles form a cake on the drum surface and are scraped off to collect the solid waste.

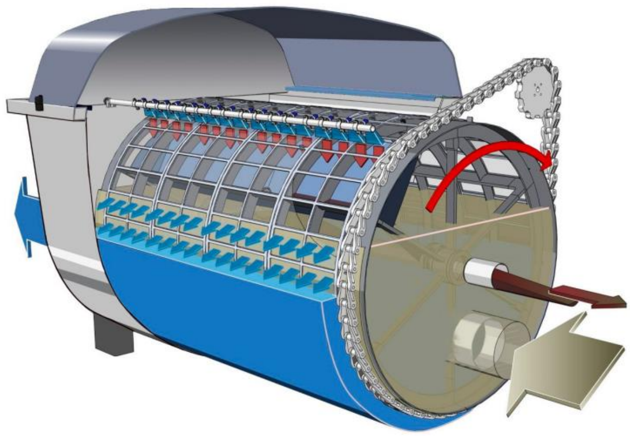


Figure 4-4. Drum filter without a vacuum pump (http://www.sklmineral.net/drum-filters.html#drum-filters)

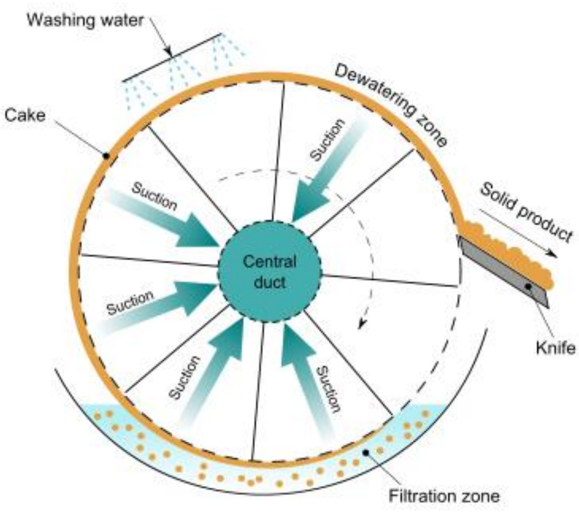


Figure 4-5. Drum filter with central vacuum pump (https://en.wikipedia.org/wiki/Rotary_vacuum-drum_filter#/media/File:Rotary_vacuum-drum_filter.svg)

4.6.5.3. Operational conditions

The larger the unit gets, the higher is the capacity. Also, the size of the mesh of the drum is a determining factor. The filtering surface can be as small as 0,5 m² and as large as 125 m². Typical flow rates are between 3-850 L/s, with mesh sizes varying between 0,25 and 2,5 mm.

4.6.5.4. Cost data

Prices in installation and maintenance vary depending on the size. It is recommended to obtain estimates from manufacturing companies or distributors.

4.6.5.5. Technological bottlenecks

For horticultural purposes, the relatively large size of the filter is a major bottleneck. This system is used in the paper industry and in laundries.

4.6.5.6. Benefit for the grower

Advantages

- Waste is limited to only the substrate in a model with a vacuum pump
- The throughput can be very high, but this requires larger systems

Disadvantages

- Models without a vacuum pump will generate higher particle concentrated waste water
- The wastewater cannot be discarded without treatment due to nutrients and/or pesticides

4.6.5.7. Supporting systems needed

No specific supporting systems are required.

4.6.5.8. Development phase

Commercialised.

4.6.5.9. Who provides the technology

A number of players are on the market. For example, Bokela. An overview can be found on www.environmental-expert.com/companies.

4.6.5.10. Patented or not.

Some of the technologies may be patented.

4.6.6. Which technologies are in competition with this one

A number of techniques can filter out particles: band filtration, cloth filtration, disc filtration, rapid sand filtration, SAF filtration, sieve bend screen filtration, microfiltration, etc.

4.6.7. Is the technology transferable to other crops/climates/cropping systems?

There are no limitations regarding climate or temperature. The crop should produce soil/substrate contaminated drain water to have a benefit from the installation.

4.6.8. Description of the regulatory bottlenecks

See section 4.1.7.

4.6.9. Brief description of the socio-economic bottlenecks

Size and cost.

4.6.10. Techniques resulting from this technology

It is a stand-alone technology; no secondary techniques have been developed.

4.7. Hydrocyclone

(Authors: Peter Melis[18], Wilfred Appelman[22])

4.7.1. Used for

- Preparation of irrigation water
- More efficient use of water

4.7.2. Region

All EU regions.

4.7.3. Crop(s) in which it is used

- All crops on organic substrates
- The technique is also used when water is drawn out of rivers with a sandy bottom

4.7.4. Cropping type

All cropping types.

4.7.5. Description of the technology

4.7.5.1. Purpose/aim of the technology

Removing sand and heavy particles from irrigation, drainage or contaminated water.

4.7.5.2. Working Principle of operation

A hydro cyclone filter uses centripetal force to separate particles from a liquid such as drainage or irrigation water. The water enters the hydro cyclone near the top of the unit in the cylindrical top. The water is pushed downwards in the conically shaped part and forms a circulating vortex. The heavier particles are pushed outwards and circulate near the outside; they move downwards and exit through the bottom outlet. The clean water moves to the middle of the vortex and rises towards the outlet at the top of the hydro cyclone. There are no moving parts, only a pump is necessary to create the necessary flow of the water.

4.7.5.3. Operational conditions

The capacity of the cyclone depends on the size. A small one (diameter 0,08 m) can handle 2-3,5 m^3/h. With increasing size, a hydro cyclone can treat deal with up to 230-360 m^3/h, in for this capacity; the hydro cyclone has a diameter of 0,8 m.

The hydro cyclone can only remove larger and heavier particles. Particles smaller than 50 µm are generally not removed. Also, organic matter is not removed because it is lighter than water.

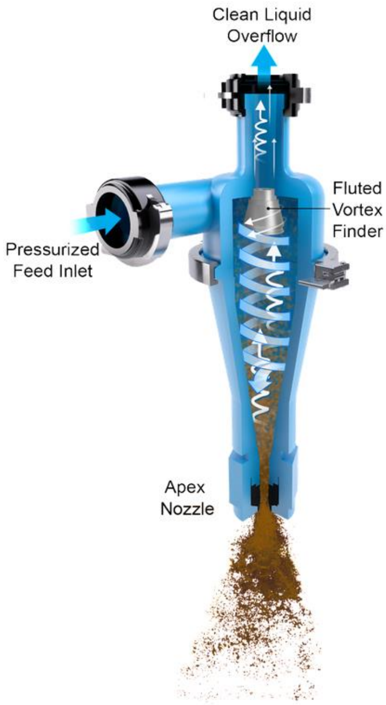


Figure 4-6. Illustration of a hydro cyclone (https://www.cccmix.com/urethane-vorspin-hydrocyclone/)

4.7.5.4. Cost data

Prices for the installation and maintenance vary depending on the size. It is recommended to obtain estimates from the manufacturing companies or distributors. An example of the installation cost is approximately 25000 € for a unit capable of filtering 1000 m^3/day or 50 m^3/h (https://emis.vito.be/en/techniekfiche/hydrocyclone).

4.7.5.5. Technological bottlenecks

None. The installation is small and quickly removes heavy particles.

4.7.5.6. Benefit for the grower

Advantages

- Quick and effective removal of heavy particles
- No production of wastewater
- There are no moving parts

Disadvantages

- The technique will only remove sand and heavy particles
- Generally, requires a subsequent finer filtration
- Not sufficient degree of filtration to prepare water for disinfection by ultrafiltration, slow sand filtration or UV disinfection
- No removal of organic matter

4.7.5.7. Supporting systems needed

The water entering must be under a suitable pressure provided by a pump. An additional finer filtration such as disc filtration is required after filtration with the hydro cyclone for horticultural applications because the hydro cyclone only removes heavier particles.

4.7.5.8. Development phase

Commercialised.

4.7.5.9. Who provides the technology

There are a number of producers that produce hydro cyclone filters such as Netafim, UVAR Holland b.v., Equova.

4.7.5.10. Patented or not

Some of these systems may be patented.

4.7.6. Which technologies are in competition with this one

A number of techniques can filter out particles: band filtration, cloth filtration, drum filtration, rapid sand filtration, SAF filtration, Sieve bend screen filtration, microfiltration, etc. Most of them will be able to filter out finer particles than the hydro cyclone.

4.7.7. Is the technology transferable to other crops/climates/cropping systems?

There are no limitations in climate or temperature.

4.7.8. Description of the regulatory bottlenecks

See section 4.1.7.

4.7.9. Brief description of the socio-economic bottlenecks

There are no such bottlenecks.

4.7.10. Techniques resulting from this technology

It is a stand-alone technology; no secondary techniques have been developed from this technology.

4.7.11. References for more information

[1] https://emis.vito.be/en/techniekfiche/hydrocyclone
[2] Yurdem H., Demir V. & Degirmencioglu A. (2010). Development of a mathematical model to predict clean water head losses in hydrocyclone filters in drip irrigation systems using dimensional analysis. *Biosystems Engeneering*, *105*, 495-506
[3] Soccol, O.J., & Botrel, T.A. (2004). Hydrocyclone for pre-filtering of irrigation water. *Scientia Agricola*, *61*(2), 134-140

4.8. Microfiltration and ultrafiltration

(Authors: Peter Melis[18], Wilfred Appelman[22])

4.8.1. Used for

- Preparation of irrigation water
- More efficient use of water

4.8.2. Region

All EU regions.

4.8.3. Crop(s) in which it is used

All crops grown on organic substrates.

4.8.4. Cropping type

- Soilless
- Protected
- Open air

4.8.5. Description of the technology

4.8.5.1. Purpose/aim of the technology

Removing particles and contaminants from contaminated or drain water.

4.8.5.2. Working Principle of operation

Microfiltration is a membrane filtration process which removes particle and contaminants from a fluid by a microporous membrane. The membrane pore size ranges from 0,1-10 µm. Microfiltration is different from reverse osmosis and nanofiltration because it does not require pressure and does not remove dissolved contaminants. Most systems are equipped with a cleaning function, based on a reverse flow to remove the filtered particles and organisms that collect on the membrane. Microfiltration removes bacteria.

Ultrafiltration is similar but is more selective and requires pressurised flow to operate. Membrane pore sizes can be as small as 0,01 µm and are sufficiently small to retain viruses and fungal spores. Modules can have a flow of 6 m^3/h. Ultrafiltration is not recommended to deal with particles because the filter will soon get clogged and the automatic cleaning function would interrupt the filtering activity too often. A pre-filtration is therefore recommended with a selectivity down to 5 µm (e.g. a paper band filter).

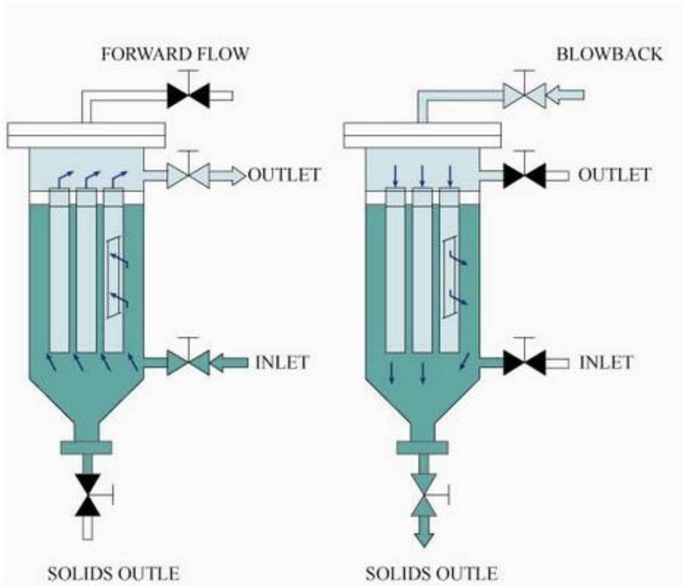


Figure 4-7. Scheme of a microfiltration unit (http://www.automaticselfcleaningfilters.com/sale-2960898-stainless-steel-water-filter-systems-filter-cartridge-for-ultra-pure-gas-filtration.html)

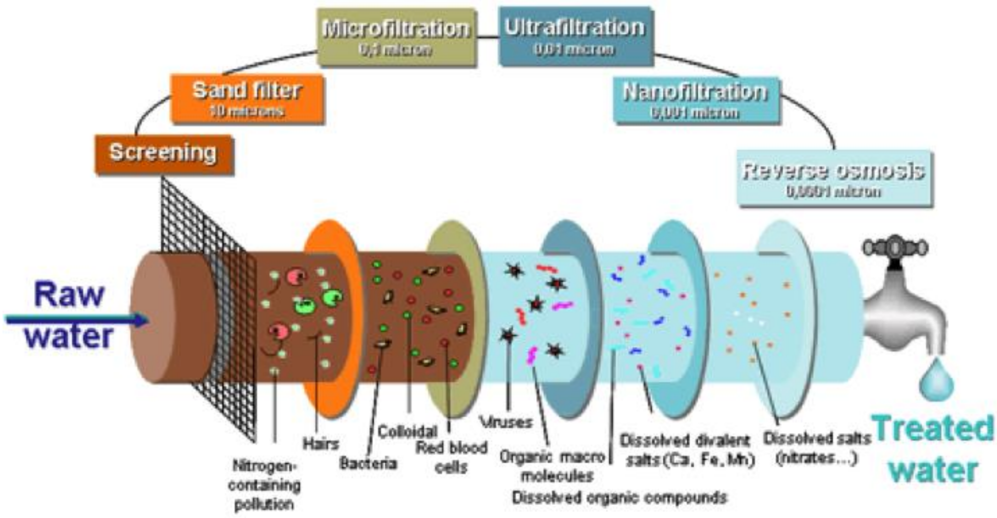


Figure 4-8. Removal of specific particles and contaminates by sequential filtration methods (http://www.pacificwater.com.au/product/kcw-1000-ultrafiltration/)

4.8.5.3. Operational conditions

Microfiltration has a higher flow rate than ultrafiltration due to the lower selectivity. The capacity of the installation is determined by the number of modules that are installed. Often, a single module will have a capacity of 3 m^3/h.

4.8.5.4. Cost data

Prices in installation and maintenance depend on the size. It is recommended to obtain estimates from manufacturing companies or distributors. In strawberry in Belgium, ultrafiltration is used at a capacity of 3 m^3/h in combination with a paper band filtration unit, the cost for this combination is 30000 €.

Typical installation costs for micro-filtration (tubular and poly(vinylidene fluoride) membranes) with a volume of 25 m^3/day, amount to between 25000 and 50000 € depending on the quality of the water supply. "Difficult to treat" supply water is more expensive to process due to the choice of membrane material, total membrane surface area and the special cleaning techniques needed for the membrane. For micro-filtration, average operating costs of 0,1-0,15 €/m^3 of produced permeate, should be assumed.

4.8.5.5. Technological bottlenecks

Microfiltration can operate without a pressure pump. Once a more selective membrane is chosen, such as in ultrafiltration, a pump is necessary to deliver the operating pressure.

The backflush interrupts the filtration/disinfection capacity and water rich in particles can result in frequent backflushing.

4.8.5.6. Benefit for the grower

Advantages

- Microfiltration:
  - No pressure required
  - Higher flow rate than ultrafiltration
  - Filters out particles and additional material
- Ultrafiltration:
  - More selective
  - Filters out bacteria and fungi

Disadvantages

- Microfiltration:
  - No removal of dissolved contaminants
  - Less selective
  - Excessive amounts of particles in incoming water can cause frequent backflushes, that interrupt the filtering activity
- Ultrafiltration:
  - Needs a pressurised flow
  - Pre-filtering is required
  - Unsuitable for particles (clogging)
  - Automatic cleaning function frequently interrupts the filtering activity

4.8.5.7. Supporting systems needed

A pre-filtration is needed to remove larger particles. Support aids like bleach, peroxide, acid, alkali or detergent can be used to chemically clean the microfiltration installation.

4.8.5.8. Development phase

Commercialised.

4.8.5.9. Who provides the technology

There are a number of producers, e.g. Lenntech and AquaDNS are among them.

4.8.6. Which technologies are in competition with this one

None, most other filtration systems filter out larger particles.

4.8.7. Is the technology transferable to other crops/climates/cropping systems?

For removal of particles, microfiltration is not a good choice in horticulture. Other techniques are cheaper and more effective. More suitable technologies for particle removal are band filtration, cloth filtration, drum filtration, rapid sand filtration, SAF filtration, sieve bend screen filtration etc.

4.8.8. Description of the regulatory bottlenecks

See section 4.1.7. The concentrate from micro and ultra-filtration has a high concentration of suspended matter and micro-organisms. This can be discharged together with wastewater if discharge norms are not breached. Rinse waters after chemical cleaning contain substances like bleach and peroxide, acid and alkali. These rinse waters can only be discharged to specific waste purification systems.

4.8.9. Brief description of the socio-economic bottlenecks

None apart from cost and requirement for pre-filtration.

4.8.10. Techniques resulting from this technology

It is a stand-alone technology; no secondary techniques have been developed.

4.8.11. References for more information

[1] https://emis.vito.be/en/techniekfiche/microfiltration
[2] https://emis.vito.be/en/techniekfiche/ultrafiltration
[3] Dogan, E. C., Yasar, A., Sen, U., & Aydiner, C. (2016). Water recovery from treated urban wastewater by ultrafiltration and reverse osmosis for landscape irrigation. *Urban Water Journal*, *13*(6), 553-568
[4] Zheng X., Mehrez R., Jekel M. & Ernst M (2009). Effect of slow sand filtration of treated wastewater as pre-treatment of UF. *Desalination*, *249*, 591-595
[5] http://watertool.inagro.be/interface/Technieken.aspx?techniekID=28

4.9. *Rapid sand filtration*

(Authors: Peter Melis[18], Rodney Thompson[23])

4.9.1. Used for

- Preparation of irrigation water
- More efficient use of water

4.9.2. Region

All EU regions.

4.9.3. Crop(s) in which it is used

All crops on organic substrates.

4.9.4. Cropping type

- Soilless
- Protected
- Open air

4.9.5. Description of the technology

4.9.5.1. Purpose/aim of the technology

Removing particles and contaminants from contaminated or drain water.

4.9.5.2. Working Principle of operation

Rapid sand filters use relatively coarse sand and other granular media to remove particles. The incoming water flows through the filter medium under gravity or under pumped pressure and the particles that were suspended in the water get trapped in the sand matrix. The sand filter can cope with flows ranging between 4 and 12 $m^3/h/m^2$ of surface of the sand bed. Regular backwashing is needed to clear the sand bed from accumulated particulate matter, and to reduce the risk of clogging. Every backwash interrupts the filtering activity and takes several minutes. The drain water resulting from the backwash needs to be discarded or used for other purposes. In some EU countries, it cannot be directly discharged into natural water bodies.

4.9.5.3. Operational conditions

The capacity is determined by the diameter of the surface area of the sand filter. Per square meter of surface, between 4 and 12 m^3/h can be filtered. A filter has a height of 1,5-2,0 m. With dirty drain water, several backwashes per day are needed, producing a larger volume of sludge water compared to alternative techniques. Usually, pre-treatment with chemicals is applied to coagulate or flocculate the suspended particles.

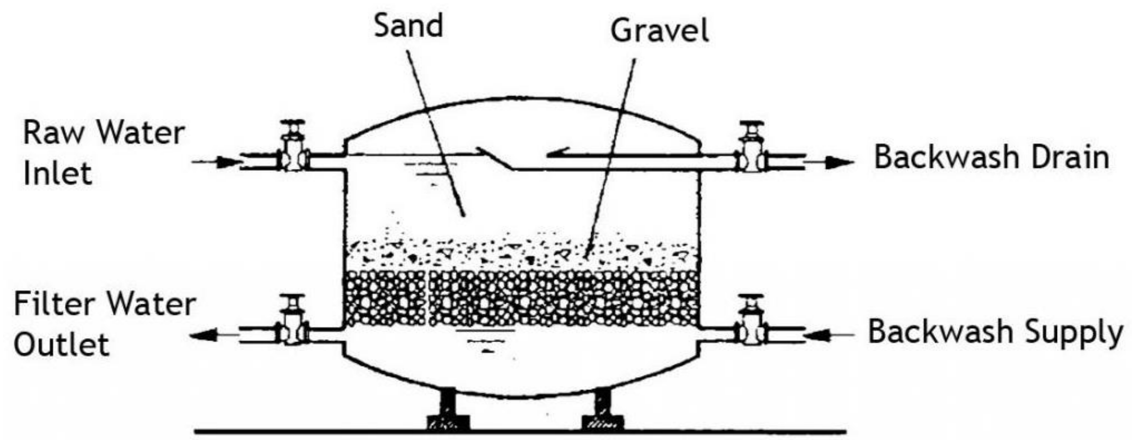


Figure 4-9. Illustration of a rapid sand filter(https://www.sswm.info/print/2852?tid=1268)

4.9.5.4. Cost data

Prices in installation and maintenance depend on the size. It is recommended to obtain estimates from the manufacturing companies or distributors. The technique is regarded as a relatively cheap form of filtration because of its simple design.

The investment cost for a small polyester sand filter of 12 m³/h for a swimming pool (48- 60 m³) costs 550-600 €. An industrial continuous sand filter of 5 m² for approximately 50 m³/h costs around 50000 €. Running costs are very low due to its simplicity and limited maintenance.

4.9.5.5. Technological bottlenecks

The major bottleneck is the backflush which interrupts the filtering activity and produces a large amount of concentrated sludge water.

4.9.5.6. Benefit for the grower

Advantages

- Simple technology
- Flow rate adjustable to the needs of horticulture

Disadvantages

- Backflush is the needed
- Maintenance costs: sand replacement after 3-5 years
- A lot of space is needed for the filter
- Production of large amounts of concentrated sludge water
- Issue of disposing of or treating backflush water in countries/regions where there are strict relevant regulations

4.9.5.7. Supporting systems needed

No particular supporting systems are required.

4.9.5.8. Development phase

Commercialised.

4.9.5.9. Who provides the technology

There are a number of producers among them is UVAR Holland b.v.

4.9.5.10. Patented or not

Probably not, this a long-established and widely used technology.

4.9.6. Which technologies are in competition with this one

A number of techniques can also filter out particles: band filtration, cloth filtration, drum filtration, disc filtration, SAF filtration, sieve bend screen filtration, microfiltration, etc.

4.9.7. Is the technology transferable to other crops/climates/cropping systems?

There are no limitations in climate or temperature. The crop should produce soil/substrate contaminated drain water to have a benefit from the installation. It can be installed on the bridge between a filthy drain silo and a disinfection unit.

4.9.8. Description of the regulatory bottlenecks

See section 4.1.7. There are regulations controlling the release of backflush water into water bodies that are implemented in countries/regions such as The Netherlands and Belgium.

4.9.9. Brief description of the socio-economic bottlenecks

None.

4.9.10. Techniques resulting from this technology

It is a stand-alone technology; no secondary techniques have been developed.

4.9.11. References for more information

[1] https://emis.vito.be/en/techniekfiche/sand-filtration

[2] Wen-Yong W., Yan H., Hong-Lu L. & Yong N. (2015). Reclaimed water filtration efficiency and drip irrigation emitter performance with different combinations of sand and disc filters. Irrigation and Drainage, *64*, 362-369

[3] http://watertool.inagro.be/interface/Technieken.aspx?techniekID=6

[4] Berckmoes E., Dierickx M. (2012). Wat met het spoelwater van filters? *Sierteelt & Groenvoorziening*, *17*, 35-37

[5] Berckmoes E., Van Mechelen M., Mechant E., Dierickx M., Vandewoestijne E. & Decombel A. (2013). Quantification of nutrient wastewater flows in soilless greenhouse cultivations, *Proceedings of NUTRIHORT conference*, September 16-18 2013, Ghent, Belgium

4.10. Automatic self-cleaning filters

(Authors: Peter Melis[18], Rodney Thompson[23])

4.10.1. Used for

- Preparation of irrigation water
- More efficient use of water

4.10.2. Region

All EU regions.

4.10.3. Crop(s) in which it is used

All crops on organic substrates.

4.10.4. Cropping type

- Soilless
- Protected
- Open air

4.10.5. Description of the technology

4.10.5.1. Purpose/aim of the technology

Removing particles from irrigation, drainage or contaminated water.

4.10.5.2. Working Principle of operation

Dirty water enters the automatic self-cleaning filter (SAF) at the bottom. Particles accumulate on the filter screen and form a cake. The filtered water passes out through the exit. The SAF filter is equipped with an automatic cleaning function that works without interrupting the filtering process. When the cake forms, pressure inside the filter screen builds up. At a certain moment (usually 0,5 bar) the cleaning function starts. The cleaning valve at the top opens and the pressure inside drops instantly. This pressure drop causes the particles to be sucked into a cylindrical tube in the centre of the SAF filter. A rotor moved by a hydraulic pump rotates the cylinder and moves it upwards. Two tubes attached to the cylinder will clean the entire filter screen and dirty water is pressed out the draining valve. A cleaning round lasts a number of seconds (5-60 seconds depending on the model) and because the removal of the cake doesn't use the entire filter screen surface at once, the filtering action is not interrupted.

4.10.5.3. Operational conditions

The size of the machine determines the capacity. SAF filters can manage flows from 7-400 m^3/h. A minimal working pressure of 2 bar (30 psi) is needed. The mesh width of the screen can be chosen and ranges from 10-800 µm.

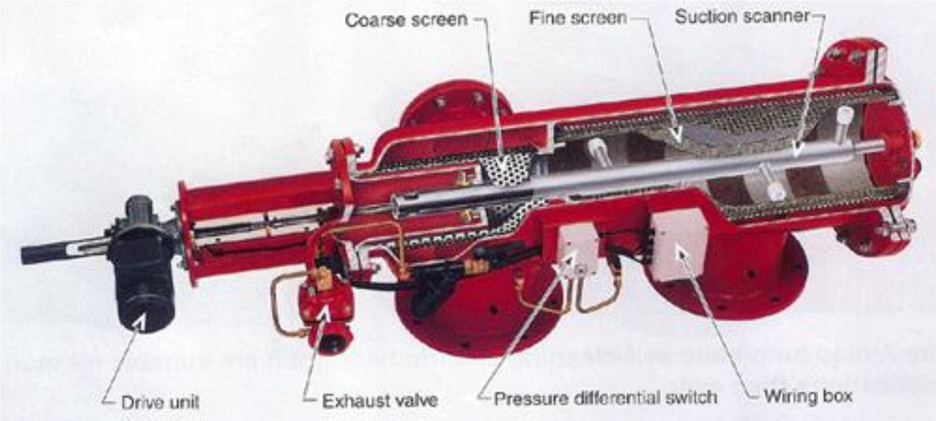


Figure 4-10. Illustration of a SAF filter (http://www.filtermat.be/FM/SAF/AutomaticFilters.htm)

4.10.5.4. Cost data

On average the cost of an installation is 4000-5000 € per unit. These units will be able to work with flows of around 10 m³/h. The installation is self-cleaning and maintenance is therefore limited. Where maintenance is required, it would require a technician.

4.10.5.5. Technological bottlenecks

It is a technically advanced filter system that will require specialist technical staff for maintenance operations.

4.10.5.6. Benefit for the grower

Advantages

- Reliable filtration of particles
- Continuous filtrations, even during the automatic backflush
- Automatic cleaning
- Limited maintenance needed
- High capacity

Disadvantages

Backflushes create drain water that has to be discarded or treated. See section 4.1.7. on regulatory bottlenecks.

4.10.5.7. Development phase

Commercialised.

4.10.5.8. Supporting systems needed

The water entering the system must be under pressure.

4.10.5.9. Who provides the technology

As an example some of the providers are listed below:

- UVAR Holland b.v.
- Amiad
- Aytok

4.10.5.10. Patented or not

Some of the technology is likely to be patented

4.10.6. Which technologies are in competition with this one

A number of techniques can filter out particles: band filtration, cloth filtration, drum filtration, rapid sand filtration, disc filtration, sieve bend screen filtration, microfiltration, etc.

4.10.7. Is the technology transferable to other crops/climates/cropping systems?

There are no limitations regarding climate or temperature.

4.10.8. Description of the regulatory bottlenecks

Compared to fast sand filters, the SAF filters produce only very limited amounts of wash water.

4.10.9. Brief description of the socio-economic bottlenecks

None.

4.10.10. Techniques resulting from this technology

It is a stand-alone technology; no secondary techniques have been developed.

4.10.11. References for more information

[1] Berckmoes E., Van Mechelen M., Mechant E., Dierickx M., Vandewoestijne E. & Decombel A. (2013). Quantification of nutrient wastewater flows in soilless greenhouse cultivations, *Proceedings of NUTRIHORT conference*, September 16-18 2013, Ghent, Belgium

[2] https://www.lenntech.com/filtratie/english/filtrationtechnologies/hydraulic-selfcleaning-screenfilter.htm

[3] http://www.revaho.nl/products-and-services/filtration/saf-filters/?lang=en

[4] Berckmoes E., Dierickx M. (2012). Wat met het spoelwater van filters? *Sierteelt & Groenvoorziening*, 17, 35-37

[5] https://www.youtube.com/watch?v=J2EhhKoPopA

4.11. Sieve bend screen filtration

(Authors: Peter Melis[18], Wilfred Appelman[22])

4.11.1. Used for

- Preparation of irrigation water
- More efficient use of water

4.11.2. Region

All EU regions.

4.11.3. Crop(s) in which it is used

All crops on organic substrates.

4.11.4. Cropping type

- Soilless
- Protected
- Open air

4.11.5. Description of the technology

4.11.5.1. Purpose/aim of the technology

Removing particles from drainage or contaminated water.

4.11.5.2. Working Principle of operation

Drain water is pumped into the inlet of the filter. The water flows over the top onto the sieve. Water pours through, while the solids are held back. The filtered water leaves at the bottom. The particles and substrate are caught from the bottom of the sieve. The sieve has slots ranging between 150 µm and 5 mm. The selectivity is much finer because of the vertical position of the screen filter. The capacity can go up to 1000 m^3/h and is dependent on the scale and the selectivity of the screen. Models with automatic cleaning exist, but mostly cleaning is done manually with a garden hose.

4.11.5.3. Operational conditions

The sieve bend screen filter is often chosen as the first filtering step for drain water loaded with organic material and substrate particles. The crude particles are filtered out. The flow rate of smaller models can cope already with 36 m^3/h with a filtering mesh of 0,5 mm.

The wastewater must only contain 10-50% rough particles. If loads are too high, it becomes impossible to clean the sieves. In this case, sieves can also be set up in a series – from rough to fine.

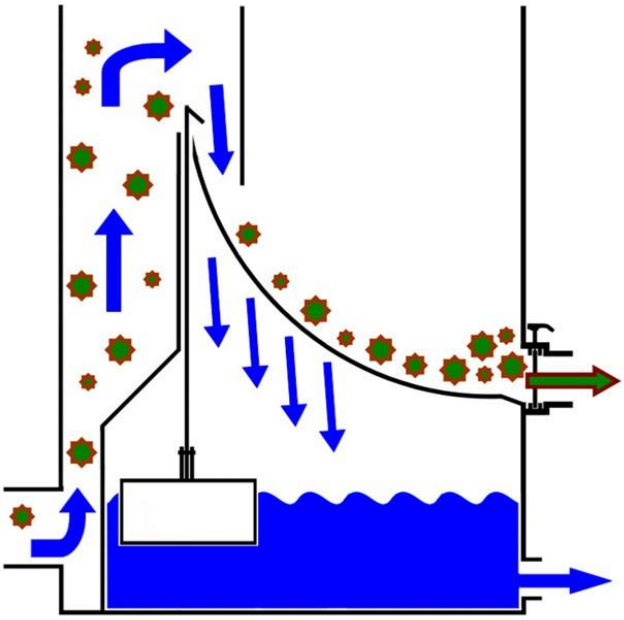


Figure 4-11. Scheme of sieve bend screen filtration (https://ariskoi-products.com/winkel/vijver/aquaforte-ultrasieve-extra-breed-3-ingangen-zwaartekracht-zeefbochtfilter/)

4.11.5.4. Cost data

The smallest unit will cost around 5000 € with complete installation for example on top of a filthy drain silo.

The investment costs for a manually cleaned grid with a capacity of 10-100 m^3/d are estimated at 1700-3000 €. For volumes 500-5000 m^3/d, this will be 5000-10000 €. Operational costs are estimated between 0,005 (for non-automated systems) to 0,15 €/m^3 (for automated systems).

Investments costs for a curved sieve are estimated at between 8500 and 25000 € for a volume of 50 to 500 m^3/d. Operational costs amount to between 0,01-0,35 €/m^3.

4.11.5.5. Technological bottlenecks

None.

4.11.5.6. Benefit for the grower

Advantages

- Very simple principle
- Reliable
- Easy to install
- Purely physical action based on gravity
- All filtered water can be used, there is no backflush
- Very high capacity

Disadvantages

- Only filtration of larger particles
- Additional filtration necessary to get water suited for disinfection
- The sludge has to be captured in a container
- No automated cleaning possible

4.11.5.7. Supporting systems needed

No specific supporting systems are needed.

4.11.5.8. Development phase

Commercialised.

4.11.5.9. Who provides the technology

In North-West Europe, the major manufacturer is REKO.

4.11.5.10. Patented or not

Some of the technology is likely to be patented.

4.11.6. Which technologies are in competition with this one

A number of techniques can filter out particles: band filtration, cloth filtration, drum filtration, disc filtration, SAF filtration, rapid sand filtration, microfiltration, etc.

4.11.7. Is the technology transferable to other crops/climates/cropping systems?

There are no limitations regarding climate or temperature. The crop should produce soil/substrate contaminated drain water to have a benefit from the installation. It can be installed on a filthy drain silo.

4.11.8. Description of the regulatory bottlenecks

See section 4.1.7

4.11.9. Brief description of the socio-economic bottlenecks

None.

4.11.10. Techniques resulting from this technology

It is a stand-alone technology; no secondary techniques have been developed.

4.11.11. References for more information

[1] https://emis.vito.be/en/techniekfiche/grids-and-sieves
[2] https://www.lenntech.com/curved-screen.htm

Chapter 5. Optimising water quality – Control of algae

Coordinators: Juan José Magán[9], Els Berckmoes[21], Ilse Delcour[19]

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5.1. Introduction to the control of algae

5.1.1. These techniques concern the issue

- Preparation of irrigation water
    - Storage of water - Algae control

5.1.2. Region

All EU regions.

5.1.3. Crops in which the issue is relevant

This technology is not related to specific crop since it considers irrigation water storage.

5.1.4. Cropping type

All crops where water storage occurs.

5.1.5. General description of the issue

One of the parameters affecting dripper and filter clogging is algae density in the irrigation water. Thus, control of algae development in the water is crucial for the optimal functioning of the irrigation system. The following issues must be considered when using technologies for algae control:

5.1.5.1. Sub-Issue A: lack of technological background on long-term algae control of water storages

Numerous methods are applied for long-term algae control, but most of them have major disadvantages:

- Addition of chemicals has a short-term effect, making repeated treatments necessary
- Addition of limestone at the bottom requires water removal during winter
- *Daphnia* spp. promotes a higher risk of filter clogging
- Covering the water storage is very expensive
- Water movement only has a local effect, which would require too many pumps or too much capacity to treat the storage as a whole
- Blue dye requires repeated treatments and provokes blue colour depending on dose applied
- Bacteria and enzymes can show reduced efficacy for algae control during summer

On the other hand, some tools used for algae control in large water volumes show still some technological knowledge gaps:

- Regarding algae control by using aquatic plants, there is not enough information about which species can be applied in specific regions and how to manage these plants as efficiently as possible

- There is big uncertainty regarding the efficacy of ultrasonic devices

5.1.5.2. Sub-Issue B: legislation restrictions regarding some interesting algae control tools

In case of algae control by fish and blue dye, some regulatory restrictions occur. Not all fish species are allowed for this purpose in the different member states. The same occurs regarding the use of blue dye. Although the latter technology meets the European Food Additive regulations and uses European Food Approved Colours, it is not clear if it can be applied as a water treatment/algaecide in all Member States.

5.1.5.3. Sub-Issue C: missing risk assessment regarding control of toxic blue-green algae

Most devices report their effectiveness regarding green algae. However, it is not always clear if those devices also include some risks when they are applied to blue-green algae, which can have toxic components.

5.1.5.4. Sub-Issue D: sociological/mental change of the growers

Application of blue dye, aquatic plants, bacteria, fish, etc. are all promising technologies to control algae bloom. However, it is clear that this might require a mental shift for the growers in some regions. Growers now want to make the water as clean as possible, whereas these technologies try to maintain a balance in algae population.

5.1.6. Brief description of the socio-economic impact of the issue

Algae tend to grow in the water stored in ponds for irrigation and must be controlled to avoid clogging problems in the fertigation system and an increased maintenance cost. If irrigation uniformity is reduced, crop development and/or water and nutrient use efficiency will be negatively affected.

Some technologies for algae control have a significant cost (e.g., pond covering), and growers frequently prefer alternative methods.

The application of technologies based on the maintenance of a balance in algae population requires a different mentality of the grower. This could be achieved by showcase events and exchanging knowledge between growers.

5.1.7. Brief description of the regulations concerning the issue

There are restrictions (which differ between countries) on the sale and use of fishes about their introduction, sale and stocking.

Annex of Commission Regulation (EU) No 1130/2011 amends Annex III to Regulation (EC) No 1333/2008 and includes the list of authorised food additives approved for use in food additives, enzymes, and flavourings. The Blue dye technology is in accordance with the European Food Additive regulations, but the patent may not have explicitly stated its use in food crops.

5.1.8. Existing technologies to solve the issues/sub-issues

The general approaches of the existing technologies can be organised into the following categories:

- Chemical methods
    - Phosphorous fixation
    - Lowering the pH
    - Dissolved copper
    - Oxidation (H_2O_2)
    - Cell wall damaging (NH_4)
    - Use of liming ($CaCO_3$)
- Biological methods
    - Use of *Daphnia* spp.
    - Use of straw bales
    - Use of bacteria and enzymes
    - Use of fish
    - Use of aquatic plants
- Physical methods
    - Use of water movement
    - Use of ultrasonic devices
    - Use of colourants like blue food dye
    - Covering the water storage

5.1.9. Issues that cannot be solved currently

Chemicals are currently applied to prevent algae blooms. However, chemical control has not been actively pursued because of the general feeling that it will be difficult, and perhaps impossible, to find an environmentally acceptable chemical that would target a particular algae species without adversely affecting other organisms or cultivated plants.

For small to large water storage systems, water covers and ultrasonic devices might be an option. However, the financial cost must be taken into account. An alternative strategy is a biological approach. There are a variety of organisms that could theoretically be used to control algal bloom; however, biological control of algae in ponds has numerous logistical issues and is not yet sufficiently developed for practical use. Additional experimental studies are still necessary. In assessing the practical use of such antagonists for control of algal blooms, aspects such as the frequency and timing of application, the mode of application (formulation and method of dispersal) are all important issues to be resolved.

Regarding legislation, this is uncertain for several technologies. More detail is required to see if colourants can be applied in the different Member States and which biological agents can be used in each Member State for which type of algae.

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5.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions (TDs)

TD title	Uses/Benefits		Cost	Technological requirements	Strengths	Weaknesses	Additional comments
	Algae control	Others					
Chemical methods							
Algae control by chemicals: phosphorus fixation	Preventive / Curative Green algae: yes Green-blue algae: not avail.		Maintenance: 0,04 €/100 m³	Protective clothes	No risk for damaging water storage	Temporally effect, vicious circle, insufficient efficiency, frequent addition needed, precipitation is formed	
Algae control by chemicals: lowering the pH	Curative Green algae: yes Green-blue algae: No (risk of toxin release)	Additional fertilisation (for Zwakal)	Maintenance: 1,6 €/100 m³ (H_2SO_4) 7,2 €/100 m³ (Zwakal)	Protective clothes pH monitoring		Temporally effect, vicious circle, insufficient efficiency, frequent addition needed, pH decrease, risk of toxicity to plants, risk for damaging water storage	Not to use acids containing N or P (first step in fighting algae and should precede any chemical treatment)
Algae control by chemicals: dissolved copper (Cu)	Curative Green algae: yes Green-blue algae: No (risk of toxin release)	↓[1] biofilm Additional fertilisation (Cu)	Maintenance: 1,6-3,6 € /100 m³	Protective clothes	No risk for damaging water storage	Temporally effect, vicious circle, oxygen decline, moderate efficiency, frequent addition needed, no environmentally friendly	No compatible with fish due to risk for decrease of the oxygen level Water pH < 7
Algae control by chemicals: oxidation (H_2O_2)	Curative Green algae: yes Green-blue algae: not avail.	↓ bacteria ↓ biofilm ↑ oxygen	Maintenance: 9,87 €/100 m³	Protective clothes	Environmentally friendly	Short-term effect (1 month), frequent addition needed, moderate efficiency, unstable if exposed to light, risk of damaging water storage	Prolonged effect on pipes, tanks, greenhouse equipment. Peroxide strips give an indication, a digital peroxide meter is more accurate

TD title	Uses/Benefits		Cost	Technological requirements	Strengths	Weaknesses	Additional comments
	Algae control	Others					
Algae control by chemicals: cell wall damaging (NH_4)	Curative Green algae: yes Green-blue algae: No (risk of toxin release)	Additional fertilisation (NH_4)		Protective clothes	Efficient for red algae on floors (foam)	Temporally effect, vicious circle, insufficient efficiency, frequent addition needed, risk of toxicity to plants	
Algae control by use of liming ($CaCO_3$)	Preventive Green and green-blue algae: yes		Maintenance: 0,08-2 €/100 m²	Protective clothes for hydrated lime	Long-term effect (change each year), good efficiency, no toxicity effects, reduce toxic effects of metals, availability all over Europe, environmentally friendly, compatible with fish (except for hydrated lime)	Liming the bottom requires removal of the water from the pond, hydrated lime is extremely corrosive	Dose of lime is highly related to pH
Biological methods							
Algae control by use of *Daphnia* spp.	Preventive / Curative Green and green-blue algae: small species		Installation: 0-12 €/L of water with live *Daphnia*	Pumps, protection equipment	Long-term effect, high efficiency, no toxicity effects, availability all over Europe, user and environmentally friendly	Risk for clogging of filters and irrigation systems	Sensitive to pH, O_2 fluctuations, presence of heavy metals, no compatible with fish
Algae control by use of straw bales	Preventive / Curative Green and green-blue algae: not all?		Maintenance: 0,25–0,75 €/100 m² (increase 3 times in ponds with heavy algae growth)	None	No risk for damaging water storage, availability all over Europe, refuge for water fleas, environmentally friendly and compatible with fish	Short-term effect (1,5 months), gradual removal, pH decline, risk of presence of pesticide residues in the straw	Dry barley straw seems to have the highest effect

TD title	Uses/Benefits		Cost	Technological requirements	Strengths	Weaknesses	Additional comments
	Algae control	Others					
Algae control by use of bacteria and enzymes	Preventive / Curative Green algae: yes Green-blue algae: not avail.		Maintenance: ≈ 70 €/100 m^3 per application (depending on the product)	None	Long-term effect, no toxicity effects, availability all over Europe, user and environmentally friendly	Risk for clogging of filters, increase of water temperature in summer can disrupt the aerobic process	These products should be applied preventatively at a sufficiently high temperature of the water (12°C) to be efficient
Algae control by use of fish	Preventive / Curative Green algae: yes (filamentous algae) Green-blue algae: not avail.	↓ aquatic plants Additional fertilisation	Installation: 0,5-1,0 €/100 m²	Some knowledge regarding fish	Long-term effect, high efficiency, no toxicity effects, no risk for damaging water storage, environmentally friendly	Nutrient-rich excrements of the fish, some species are restricted in some European Member States, harvesting of fishes may be desirable after some time	Cease feeding below 10°C. Some species are not desired as they dig the bottom and stir up mud while eating Low salinity tolerance, fish performance affected by differences in water quality
Algae control by use of aquatic plants	Preventive Green and green-blue algae: yes	↓ bacteria (up to 7 times)	Maintenance: Harvest of aquatic plants (if necessary)	Selection of adequate species, how to grow it	Long-term effect, high efficiency, refuge for water fleas, no toxicity effects, no risk for damaging water storage, environmentally friendly and compatible with fish	Species growing out of water to lead to O_2 reduction and sealing problems, plant harvesting can be required, species-specific per climatic region	Important knowledge gaps regarding optimal maintenance and implementation of aquatic plants
Physical methods							
Algae control by use of water movement	Preventive Green and green-blue algae: yes	↑ oxygen	Installation: Oloïd: 4000-7500 € Energy cost: Oloïd: 25-150 W/h	None	Long-term effect, availability all over Europe (in case of pumps), ice prevention, compatible with fish, user and environmentally friendly	Moderate efficiency, moving particles can clog filters	Oloïd is no longer available

TD title	Uses/Benefits		Cost	Technological requirements	Strengths	Weaknesses	Additional comments
	Algae control	Others					
Algae control by use of ultrasonic devices	Preventive / Curative Green algae: yes Green-blue algae: yes	↓ biofilm	Installation: 900 € (A), 1650-1950 € (B), 1950-2540 € (C) Maintenance: energy cost	None	Long-term effect, no risk of damaging water storage, user-friendly, availability all over Europe, compatible with fish	Not all devices turned out to work effectively in the past, toxicity effect if combining of blue-green algae and high-power devices (not in case of low power devices), high-power devices could harm fish and zooplankton	Evaluation of all the equipment. Devices only act in a radius of 180°. Aquatic plants might influence wave transmission, action radius 10-200 m
Algae control by use of blue dye	Preventive / Curative Green and green-blue algae: yes		Maintenance[2]: 0,9 € (A), 0,6 € (B), 0,5 € (C) per 100 m³	None	Good efficiency, compatible with fish, user and environmentally friendly	Short-term effect (2-3 treatments per year), blue colour of the water, availability restricted to the UK	Water quality and aquatic life not affected, except a deepening of the watercolour
Algae control by covering the water storage	Preventive / Curative Green and green-blue algae: yes	↓ aquatic plants	Installation: 4000 €/100 m²	None	Long-term effect, high efficiency, reduction of evaporation losses, user and environmentally friendly, availability all over Europe	Reduced oxygen level	See chapter 2

[1] ↑ Increase, ↓ Decrease

[2]Type A: < 750 m³ or < 150 m², Type B: 750 - 5000 m³ or 150 – 250 m², Type C: > 5000 m³ or > 250 m²,

5.3. Algae control by chemicals

(Authors: Ilse Delcour[19], Juan José Magán[9], Els Berckmoes[21], Dolors Roca[8])

5.3.1. Used for

Preparation of irrigation water.

5.3.2. Region

All EU regions.

5.3.3. Crop(s) in which it is used

All crops.

5.3.4. Cropping type

All cropping types.

5.3.5. Description of the technology

5.3.5.1. Purpose/aim of the technology

The addition of chemicals to water storages aims to prevent or inhibit algae growth. Some chemicals even have an algacidal effect.

5.3.5.2. Working Principle of operation

Addition of chemicals can initiate different working principles:

Based on phosphorus fixation: addition of chemicals is often based on the artificial suppression of the phosphorus availability due to fixation of the present phosphorus. A direct relationship exists between the amount of phosphorus in a reservoir and the amount of algae growing in it. As phosphorus levels increase, the amount of algae increases too. At very high levels of phosphorus, other nutrients or light may limit the growth of algae. Removal of phosphorus sources of the water body forms a key element in the long-term control of algae. Different chemicals can be used for the fixation of phosphorus:

1) Iron chloride: phosphorus binds easily with, for example, iron chloride. This occurs naturally in locations where water emerges. Rust-Coloured precipitation that settles on the bottom of the pond is formed
2) Aluminium: Based on lowering the pH of the water body: this technology is based on lowering the pH of the pond water to a pH of 4. Increased acidity changes the ability to obtain certain minerals. All photosynthetic organisms require carbon dioxide. Aquatic plants get it from the water and acidity affects both the amount and chemical form of the oxidised carbon that is present
3) Dissolved copper: consists of chelated univalent copper. The algae absorb the copper and die

4) Based on oxidation: hydrogen peroxide (H_2O_2) is a strong oxidant. This characteristic makes it a disinfectant which is effective against organic contamination (algae, bacteria, etc.). It is assumed that the activity of 5,5 ppm active chlorine is equivalent to 10 ppm hydrogen peroxide, although the peroxides require more time to kill, for example, bacteria
5) Based on cell wall damaging: some chemicals damage the cell walls of algae and bacteria and this way kill them. This is mostly the case for quaternary ammonium compounds

5.3.5.3. Operational conditions

This technology can be used on a large scale in (sewage)-water treatment companies and can be applied in garden ponds. However, in case of the addition of aluminium, the risk for side-effects/environmental risks should be considered (it leaves aluminium hydroxide and flocculated sludge on the bottom, which can interfere with fish reproduction, beneficial bacteria and insects that naturally feed on organic muck).

Depending on the product, specific recommendations are made regarding the dosage (see Table 5-1 and Table 5-2).

5.3.5.4. Cost data

Installation cost

The addition of the chemical compounds is applied manually. Therefore, no installation costs are required. However, different dosing systems are commercially available:

- A pulse dosing system: the cost is estimated around 1700-1820 € (water meter not included)
- A system for continuous dosing at set times: a system consisting of a pump, a volume counter, measuring cup costs around 1360-1560 €

Figure 5-1. Dosage pump (the pump, tubes, etc. have to be resistant to the corrosive character of the chemicals)

Maintenance

The final cost is closely related to the dosage that is required. Therefore, also the dosage is included in Table 5-1.

Table 5-1. Dosage and prices per chemical for algae removal

Product	Principle	Dosage	Frequency	Price indication per single treatment	Remarks
Cu/Fe preparates	1				Insufficient for water basins in horticulture
Alg-Stop	1	3,65 g/100 m³	Every 10 days	0,04 €/100 m³	
Algen-stop	1	10 L/100 m³		130 €/100 m³	Preventive, micro-organisms consume the nutrients in the water to prevent algae growth
Zwakal ($KMgSO_4$)	2	12 kg/100 m³		7,2 €/100 m³	
Proteck – van Iperen, Westmaas NL	3	1 L/ 250 m³	3-weekly or when fresh water is added	273 €/year per greenhouse	The product also chelates Mg and Ca, so these nutrients are unavailable for the algae (similar to principle 1)
H_2O_2 (35%)	4	5 mL/ m³		9,87 €/100 m³	With fish: dilute before adding to the water
Sulfuric acid (H_2SO_4)	2	2 L (37%) / 100 m³		1,6 €/100 m³	
Alum	1			4,9-12,35 €/100 m² depending on the dosage requirements and costs to mobilise equipment	Increases concentrations of free Al, sulphate and nitrous oxide, which could play a significant role in damaging the microbial and invertebrate communities that inhabit the bottom zone of freshwater bodies

Table 5-2. Weight (kg) per litre and content of S and acid (mole/L) of different fertilisers

Acid	Weight (kg)	Sulphate	Acid (H^+)	K	Mg
Zwakal (Yara Benelux)	1,32	3,96	3,96	0,79	1,6
H_2SO_4 44,1% (van Iperen)	1,35	6,07	12,15		
Sulfacid (Biofeed)	1,4	7,14	14,28		
KZZ (Fertigro)	1,2	2,4	3,0	1,8	
ZZ30 (Fertigro)	1,22	3,66	7,32		

5.3.5.5. Technological bottlenecks

- In the case of phosphorus fixation, rust-coloured precipitation is formed
- Products that do not easily dissolve in water could accumulate on the bottom of the water storage or cause technological failures of pumps or filters when extracted from the water body
- The products should be applied homogeneously to avoid local damages as higher concentrations of the chemicals might harm basin foils, glues, etc.

5.3.5.6. Benefit for the grower

Advantages

- Lowering the pH by addition of acids:
    - Since rainwater has a low buffer capacity, only little acid is needed.
    - Easy to apply
    - Cheap
    - Acid can be applied by use of the substrate unit (in case of greenhouses)
    - Nutrients added to the water can be subtracted from the nutrient solution and do not have to be purchased separately, so it is no additional cost
- Adding copper:
    - Curative
    - Prolonged effect: also has an effect on algae in the pipes and greenhouse, so that trays stay clean
    - The water does not become toxic to fish or plants; however, the addition of copper can lead to a temporally decrease of the oxygen level, which is harmful to fish
    - Is an efficient copper-fertiliser which can easily be applied by pouring into the corners of the basin
- Hydrogen peroxide (H_2O_2):
    - Instant effect
    - In small basins: a single manual application with a stable peroxide is sufficient for 1 month
    - Stability in packaging: 2 years
    - Quick degradation with organic matter after application (slower than Reciclean)
    - No residues
    - No effect on fertilisers
    - Safe for plants
    - Environmentally friendly
    - Has also an effect on bacteria and viruses
    - In combination with UV, it is useful for removing pesticide residues from the water (due by 2018 in the Netherlands)

Disadvantages

- General disadvantages:
    - As the algae die and decay, nutrients are released back into the water column, where new algae growth occurs. This re-growth then requires another treatment and starts a series of growth-kill cycles involving numerous chemical treatments

  - Oxygen levels decrease rapidly after chemical treatments and many sources indicate that excessive chemicals can do more harm than good
  - Chemicals can also kill off beneficial bacteria that help remove and control organic bottom muck. Copper compounds add new toxic sediment to the bottom of a pond or lake
  - Some forms of algae also become resistant to chemicals over time
- Specific disadvantages for adding copper:
  - If copper sulphate is applied to treat blue-green algae, cellular lysis (membrane collapse) occurs, and toxins contained in algae are released
  - As blue-green algae become increasingly resistant to copper sulphate, continuously larger doses (thousands of pounds per week) are required for effective control
  - Impacts on zooplankton and other life forms have led to increasingly stringent permitting requirements for its use
  - Only gradual removal of algae
  - Cannot be applied to basins with fish (strong decrease in oxygen level during cleaning of the basin)
  - If the pH of the basin is higher than 7, it has to be lowered by sulfuric acid
- Specific disadvantages for lowering the pH by addition of acids:
  - Selective: only for green algae
  - Continuous monitoring of the pH is needed
  - Shock-effect needed to be efficient
  - Phytotoxicity is possible (especially for flowering plants)
  - Can affect the material the basin is made of, may cause leaks if applied in one dose at one point
  - The amount of acid applied to the basin has to be subtracted from the nutrient solution, so the amounts have to be checked and recalculated
  - Do not use acids with N or P
  - Insufficient efficiency
- Specific disadvantages for hydrogen peroxide (H_2O_2):
  - Moderate efficiency
  - Short-term effect
  - Expensive when applied on large scale
  - Strong reaction to contact with metals
  - Protective clothing required
  - Results only visible after 5 weeks
  - Causes a decline in pH of the water
  - Basins made of poly-olefin dissolve (latex can stand H_2O_2)
  - Needs a stabiliser to inhibit its degradation

- o Low temperatures needed to inhibit its degradation
- o H_2O_2 disappears due to reaction with the organic matter in the water

5.3.5.7. Supporting systems needed

- In general, the products are applied manually. Still, a boat or a distribution system can be used to guarantee a homogeneous spread of the product avoiding local damage to the water storage materials
- To control the water quality parameters such pH, measuring equipment is required
- Protection equipment (safety glasses, gloves, etc.)
- Tools to measure the reduction of the algal bloom
- Tools to measure the presence of the chemicals, for example in case of H_2O_2, measuring strips are commercially available

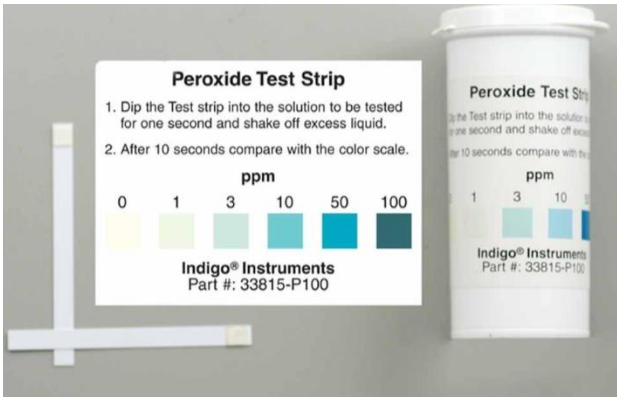

Figure 5-2. Measuring strips to assess the concentration of hydrogen peroxide in the water (https://www.indigoinstruments.com)

5.3.5.8. Development phase

All chemicals are commercially available.

5.3.5.9. Who provides the technology

Numerous suppliers provide these chemicals. Below, some examples are listed:

- Yara Benelux: Zwakal
- Van Iperen: proteck
- Hortiplan: dosing system H_2O_2
- Prayon – Hortipray (the Netherlands): H_2O_2
- Kemira (the Netherlands): H_2O_2
- Airedale Chemical (United Kingdom): H_2O_2

5.3.5.10. Patented or not

These chemicals are not patented.

5.3.6. Which technologies are in competition with this one

Algae control by use of fish competes with the application of chemicals as serious oxygen decrease may occur, leading to the death of the fish. Other chemical treatments (e.g. chlorination or biobeds/biofilters would kill the biofilm which is active within them).

5.3.7. Is the technology transferable to other crops/climates/cropping systems?

This technology is not related to specific crop, climate or cropping conditions.

5.3.8. Description of the regulatory bottlenecks

5.3.8.1. Brief description of the European directive and implications for growers at European level

Impacts on zooplankton and other life forms have led to increasingly stringent permitting requirements for the use of chemicals in water.

Zwakal: conform Regulation (EG) No. 1907/2006 (REACH), Annex II.

Hydrogen peroxide: Commission Implementing Regulation (EU) 2015/1730 of 28 September 2015 approving hydrogen peroxide as an existing active substance for use in biocidal products for product-types 1, 2, 3, 4, 5 and 6.

5.3.8.2. Implementation at the country level

Regulation (EG) No. 453/2010 (Belgium): the Belgian legislation requires that products for disinfection of irrigation water are authorised as biocides type 4, for use in food or feed. Not all hydrogen peroxides that are commercially available are authorised, so this needs attention when purchasing a product.

The Netherlands: biocide registration process started in 2010 with Authorisation of Plant Protection Products and Biocides.

The U.S. Food and Drug Administration approved hydrogen peroxide for use in bottled drinking water in 2005: "Addition to Food for Human Consumption (21 CFR part 172), to provide for the safe use as an antimicrobial agent in bottled drinking …" (U.S. Federal Register; Department of Health and Human Services; FDA; 21 CFR Part 172; Docket No. FDA-2005-F- 0505).

5.3.8.3. Implementation at the regional level

Not applicable.

5.3.9. Brief description of the socio-economic bottlenecks

- Possible food safety issues when the water is used in vegetables
- Environmental issues when using chemicals
- Expensive because constant inputs are needed

5.3.10. Techniques resulting from this technology

- Products based on phosphorus fixation (Alg-stop, Aqua Forte, ammonium compounds, etc.)
- Products based on lowering the pH (Zwakal, Yara; H_2SO_4, Royal Brinkman)
- Products that act in an algaecidal way (Proteck, Van Iperen; etc.)
- Products based on oxidation, hydrogen peroxide (Huwa-San, Royal Brinkman; DelgoSan, Delgeco nv, etc.)
- Products that damage the cell walls and contain quaternary ammonium (Clean special, Greenstop Pro, Quatam, Lema, Dimanin, Virocid, etc.)

Figure 5-3. An example of an algaecide: hydrogen peroxide

5.3.11. References for more information

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5.4. Algae control by liming

(Authors: Justyna Fila[6], Els Berckmoes[21])

5.4.1. Used for

Preparation of irrigation water.

5.4.2. Region

All EU regions.

5.4.3. Crop(s) in which it is used

All crops.

5.4.4. Cropping type

All cropping types.

5.4.5. Description of the technology

5.4.5.1. Purpose/aim of the technology

Liming is used to prevent algae bloom in ponds and water reservoirs.

5.4.5.2. Working Principle of operation

Liming is the addition of limestone (calcite), primarily calcium carbonate ($CaCO_3$), to neutralise acid waters and soils and buffer them from rapid fluctuations in pH. Limestone is typically applied to lawns, gardens, pastures and croplands to supply calcium, an essential plant nutrient, and to decrease soil acidity. Limestone can also be applied to lakes, ponds and their surrounding watersheds to protect them from acidification, to add calcium and to restore their important ecological, economic and recreational values. Adding limestone to maintain a near-neutral pH (pH 7) keeps lake and pond water safe for aquatic life.

Traditionally, copper sulphate and reward treatments have been used to provide short-term control of algae blooms. However, the use of hydrated lime is a more complete and longer lasting method of improving water quality in ponds.

Hydrated lime (calcium hydroxide) is mixed into the pond water and allowed to settle. Phosphate precipitation will result in fewer algae growth over the following season. Experience has also shown that the lime treatment will reduce the growth of most rooted water plants, such as Richardson's pondweed due to the reduction of nutritive elements.

To limit algae bloom in ponds, lime can be used in both ways:

- Liming the bottom of the pond: liming the bottom of the pond gives the best results. The recommended period is just before winter
- Introduction directly into the water: the recommended period for ponds liming is autumn or early spring

For liming ponds, we can use lime in different forms, such as calcium oxide, alcium carbonate and alcium hydroxide. All these three forms of lime are more often used at the bottom and rarely introduced directly into the water.

Figure 5-4. Liming the bottom of a pond in February 2016 (www.wksbogaczowice.pl/pierwsze-zarybienie/194)

Figure 5-5. Liming of the bottom of the ponds does not require any special equipment (www.wksbogaczowice.pl/pierwsze-zarybienie/194)

Lime doses introduced into the water are 25% lower than used for the bottom. To properly apply liming in ponds, pH of the water should be marked in advance. The optimal frequency of use of liming is once a year.

Figure 5-6. A pond divided in two to demonstrate the efficacy of the addition of lime in order to control algal bloom. The picture shows the situation before the treatment (http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex706)

Figure 5-7. A pond divided in two to demonstrate the efficacy of the addition of lime in order to control algal bloom. The picture shows the situation after the treatment. The left side shows the treated water volume, the right side shows the untreated water (http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex706)

Lime is most often applied with a custom applicator. The hydrated lime is mixed into wet slurry and sprayed evenly over the entire water surface of the pond. Concentration is needed on the deeper areas of the pond and on any rooted plants along the edge. The hydrated lime must be thoroughly mixed with the pond water. Aerating the dugout during the first few days after treatment improves the settling of the lime. Wave action created by a windy day will also improve the mixing.

After a treatment, it is recommended to wait until the water surface clears (3-7 days) before using the water for any purpose.

5.4.5.3. Operational conditions

The correct determination of the level of pH of the water is a basis to determine the proper doses of lime.

The required quantity of lime will generally be independent of the amount of phosphate present. It will depend primarily on the alkalinity of the wastewater. The lime dose required can be approximated at 1,5 times the alkalinity as $CaCO_3$. Neutralisation may be required to reduce pH before subsequent treatment or disposal. Recarbonation with carbon dioxide is used to lower the pH value.

Table 5-3. Dose of CaO depending on the water pH

Water pH	CaO dose (t/ha)		
	Sands	Clay sands	Heavy clays
<4,0	1,45	2,2	4,2
4,0-4,5	1,45	1,7	3,2
4,5-5,0	1,2	1,45	2,7
5,0-5,5	0,7	1,2	1,7
5,5-6,0	0,45	0,7	1,2
6,0-6,5	0,2	0,7	0,7

The technology is not recommended for crops where water should be stored year-round to fulfil the crops water demand (for example in greenhouse crops) as the water has to be discharged once per year.

5.4.5.4. Cost data

Prices vary between regions and dealers. In Mazovia region (Poland) lime cost, on average, 40 €/ton in 2016.

5.4.5.5. Technological bottlenecks

Introducing lime directly into the pond is less efficient than liming its bottom although it requires the annual discharge of the water before the application of lime.

5.4.5.6. Benefit for the grower

Advantages

- Cost-effective
- Counters acidification and its effects
- Enhances the abundance and diversity of aquatic life
- Reduces the toxic effects of metals (Al, Cu, Cd, Pb, Ni, Zn)
- Improves reproduction and survival of aquatic life
- Promotes healthy, balanced fish populations
- Can be used simultaneously with herbivorous fish (except for hydrated lime)
- Preventative method against algae
- Environmentally friendly
- Reduces growth of submerged rooted plants

Disadvantages

- Liming of the bottom of the ponds requires removal of the water in advance
- Hydrated lime increases the pH of the water
- Hydrated lime may result in the death of plants and fish
- Waiting period of three days required before reintroducing fish or fauna into the pond
- Hydrated lime is extremely corrosive
- Safety equipment is required
- Change in the taste of the water

5.4.5.7. Supporting systems needed

- Pumps to remove the water in case the bottom of the pond is limed
- Equipment to achieve a homogeneous spread of the product (in most cases, the manual application is enough)
- Safety equipment in case hydrated lime is applied

5.4.5.8. Development phase

Lime is commercially applied.

5.4.5.9. Who provides the technology

Any company does not presently provide this technology but this is not a limiting factor because the grower himself can lime ponds if having the adequate knowledge.

5.4.5.10. Patented or not

This technique is not patented.

5.4.6. Which technologies compete with this one

- Control of algae by fish
- Addition of copper/iron to remove phosphorous from water (chemical treatment)

5.4.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this technology is widely transferable as it can be used in each climate and cropping system. Better results are achieved when lime is applied at the bottom of the pond.

However, the technology could not be recommended for crops where water should be stored year-round to fulfil the crop water demand (for example in greenhouse crops) as the water has to be discharged once per year.

5.4.8. Description of the regulatory bottlenecks

None.

5.4.9. Brief description of the socio-economic bottlenecks

The loss of water is an important cost in case of discharging water storage during winter. The decision on discharging or not depends on various factors like climate conditions, growers needs and possibilities.

5.4.10. Techniques resulting from this technology

Not applicable.

5.4.11. References for more information

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5.5. Algae control by Daphnia spp.

(Authors: Ilse Delcour[19], Els Berckmoes[21], Dolors Roca[8])

5.5.1. Used for

Preparation of irrigation water.

5.5.2. Region

All EU regions.

5.5.3. Crop(s) in which it is used

All crops.

5.5.4. Cropping type

All cropping types.

5.5.5. Description of the technology

5.5.5.1. Purpose/aim of the technology

Slow removal of algae by feeding *Daphnia spp*.

5.5.5.2. Working Principle of operation

Daphnia or water fleas are species that feed on algae so that the water is cleared. *Daphnia* feeds on small algae, which includes some species of cyanobacteria (blue-green) algae.

Figure 5-8. Picture of *Daphnia* with the cyanobacterium *Mycrocystis*. Algae cells are too large to be consumed by *Daphnia* (www.ag.auburn.edu)

5.5.5.3. Operational conditions

- Temperature: in northern Germany, *Daphnia magna* starts to hatch at < 4 °C in years with mild winters when the ponds are not frozen although temperature rises rapidly to 10-15°C, being maximum in summer with approximately 20-23°C

- In a temperate pond, populations take full advantage of the longer growing season by producing plenty of offspring. When temperatures decline, resting eggs are produced which show dormancy. *Daphnia* can reproduce asexually when the temperature is above 16°C
- Although they prefer temperatures between 18-22°C, they can tolerate a much broader range, with averages of 40 days at 25°C and 56 days at 20°C
- The absence of fish because fishes feed on *Daphnia*
- Type of algae: *Daphnia* feeds on small algae, which includes some species of cyanobacteria (blue-green) algae. It was found that from the spectrum blue-green, flagellates and green algae, *Daphnia* performed best on a diet of cryptomonads, *Rhodomonas minuta* and *Cryptomonas* sp
- *Daphnia* is extremely sensitive to metal ions. For this purpose, it is used as an indicator of pollution

5.5.5.4. Cost data

Installation cost

A population of *Daphnia* that can feed on the algae and reproduce in the pond is only necessary. *Daphnia* spp. are present in natural lakes, rivers, etc. *Daphnia* spp. can be collected from natural ponds, lakes or rivers and introduced into the water storage.

Some stores also sell *Daphnia* spp.:

- In a British fish food trade store: 50 bags or 1 dm^3 of water with live *Daphnia magna* costs 60 €
- A British online store: 1,19 €/100 mL or 2,25 €/300 mL

Maintenance

Daphnia will die if there is no food left but this will rarely be the case in a large pond. *Daphnia* has a lifespan of 7-10 weeks and the first eggs appear when *Daphnia* is 1,5 weeks old. Otherwise, it is necessary to maintain the population by adding extra food or a new population of *Daphnia* when the development of algae occurs again.

5.5.5.5. Technological bottlenecks

- Practical information like the minimal number of *Daphnia* to be inserted is not known yet
- It has not been applied on a large scale yet, so the optimal conditions for light, temperature, acidity, etc. still have to be investigated

5.5.5.6. Benefit for the grower

Advantages

- Very effective
- Very cheap
- Little or no maintenance

- Biologically friendly

Disadvantages

- The population has to be kept alive when all the algae have been consumed
- The water temperature has to be high enough for the daphnids to stay active and reproduce (16°C)
- Daphnids are sensitive to chemicals in the water
- The flees can cause clogging of filters, especially in case of an overpopulation
- Fish eat daphnids
- Daphnids probably only remove the floating algae
- Some green-blue algae have an inhibitory and even toxic effect on *Daphnia*
- It has not been applied on a large scale

5.5.5.7. Supporting systems needed

A fine filter for all pipes connected to the pond to keep the daphnids in the water.

5.5.5.8. Development phase

- Research has been carried out on a limited scale in Belgium
- Field tests have been conducted but were not successful when combined with a sand filter
- Commercialised for small ponds, aquaria, etc.

5.5.5.9. Who provides the technology

No specific suppliers. In general, these organisms can be found at specialised aquarium shops.

5.5.5.10. Patented or not

This technique has not been patented.

5.5.6. Which technologies are in competition with this one

Algae-eating fish, blue pond dye (this technology prevents algal growth, so alternative food sources for *Daphnia* should be provided).

5.5.7. Is the technology transferable to other crops/climates/cropping systems?

This technology is not related to specific crop, climate or cropping conditions.

5.5.8. Description of the regulatory bottlenecks

Not applicable.

5.5.9. Brief description of the socio-economic bottlenecks

No specific bottlenecks.

5.5.10. Techniques resulting from this technology

Not known.

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[13] Ebert, D. (2005). *Ecology, epidemiology, and evolution of parasitism in Daphnia*. National Library of Medicine

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5.6. Algae control by straw bales

(Authors: Ilse Delcour[19], Dolors Roca[8], Justyna Fila[6], Els Berckmoes[21])

5.6.1. Used for

Preparation of irrigation water.

5.6.2. Region

All EU regions.

5.6.3. Crop(s) in which it is used

All crops.

5.6.4. Cropping type

All cropping types.

5.6.5. Description of the technology

5.6.5.1. Purpose/aim of the technology

Gradual removal of the algae by limiting the proliferation of algae.

5.6.5.2. Working Principle of operation

When straw bales are submerged in the water storage, the degradation or rotting process of the straw is initiated. During this process, algae-toxic exudates are produced. The actual toxins or mode of action is not known but might be due to free oxygen radicals. The straw is also a good shelter for water fleas (daphnids) and amoebas that can easily reproduce in such an environment and suppress lower organisms such as algae.

Research mentions an improved efficiency of the system when a net with loose straw is put at the entrance point of the water. Barley seems to be the most efficient type of straw.

Figure 5-9. Barley straw in nets being sunk below the surface of the water to assist control Algae (www.adlib.everysite.co.uk)

5.6.5.3. Operational conditions

- The most common application is about two to three bales per surface acre of the pond (or about 10-25 g of straw per m^2 of pond area). The depth of water in the pond is not essential. In ponds that are frequently muddy or those that have a history of heavy algae growth, two or three times this recommended dose may be required for the initial treatment
- Fresh and old bales are needed at the same time for an optimal effect
- No fresh material can be used; it has to be dry straw
- The recommended amount of straw differs from region to region (see Table 5-4)

Table 5-4. Overview of recommended amounts of straw for the control of algae in ponds found in the literature

Source	Amount of straw ($kg/1000\ m^3$)	Amount of straw ($kg/1000\ m^2$)
DLV (the Netherlands)	50	-
Centre for Ecology and Hydrology (United Kingdom)	8-125	25-50
Rutgers (United States of America)	1200	25
Swistock (USA)		10-25

5.6.5.4. Cost data

Installation cost

Installation costs are low as only straw has to be bought:

- In Belgium, 200 kg of straw costs about 20 €
- In Poland, 200 kg of straw costs about 16,70 €

Additionally, jute bags (e.g. 80-litre bags) can be used to reduce straw sinking to the bottom of the pond.

Maintenance

The old bales have to be replaced several times per year:

- Belgium: the advice is the replace the bales 2 or 3 times per year and remove all bales in August
- In Poland: growers noticed that they have to be replaced every 1,5 months

5.6.5.5. Technological bottlenecks

This system is applied at a domestic scale, and this is not widespread (i.e. small ponds in gardens). This technique is less interesting to improve the quality of water in irrigation ponds - generally of large volumes (from 10000 m^3) in short times. Also, little is known about this technique, so recommended doses of straw differ strongly from region to region.

Other possible problems are the clogging of filters if the straw spreads in the water and a small risk of water contamination with pesticide residues from the straw.

5.6.5.6. Benefit for the grower

Advantages

- Very cheap
- Environmentally friendly
- Ecological

Disadvantages

- Barley might not control the growth of all species of algae
- Optimal functioning after 6 months in the water
- Preventive adding of straw necessary to be sufficiently effective
- Temporary solution: it does not treat the cause of the problem (excessive levels of nutrients)
- Causes a decline in water pH: additives needed
- Results can be seen after 6-8 weeks
- Risk of water contamination with pesticide residues

5.6.5.7. Supporting systems needed

- Jute bags (e.g., 80-litre bags) can be used to reduce straw sinking to the bottom of the pond
- A sieve or supporting system to ease the removal of the straw

5.6.5.8. Development phase

Field tests have been carried out in different countries (the Netherlands, Poland, UK, etc.).

5.6.5.9. Who provides the technology

Straw itself is widely available.

5.6.5.10. Patented or not

This technique is not patented.

5.6.6. Which technologies are in competition with this one

The use of blue dye is also an ecological solution to combat algae.

5.6.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this technology is not crop specific since it considers irrigation water storage.

5.6.8. Description of the regulatory bottlenecks

Not applicable.

5.6.9. Brief description of the socio-economic bottlenecks

Not applicable.

5.6.10. Techniques resulting from this technology

Not applicable.

5.6.11. References for more information

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5.7. Algae control by bacteria and enzymes

(Authors: Ilse Delcour[19], Juan José Magán[9], Els Berckmoes[21], Dolors Roca[8])

5.7.1. Used for

Preparation of irrigation water.

5.7.2. Region

All EU regions.

5.7.3. Crop(s) in which it is used

All crops.

5.7.4. Cropping type

All cropping types.

5.7.5. Description of the technology

5.7.5.1. Purpose/aim of the technology

The aim of using bacteria and enzymes is to reduce the algal activity by decomposition of the algae.

5.7.5.2. Working Principle of operation

Enzymes, bacteria and nutrients all have an effect on algae. Calcium and magnesium carbonate have a precipitative effect on all organic matter present in the water. Enzymes (cellulases and proteases) dissolve the organic molecules from algae, rotting leaves and organic sediments.

Once settled at the bottom of the pond or lake, the bacteria begin to mineralise the organic matter that causes odours and turbidity. Thus, bacteria (such as *Pseudomonas* and *Bacillus*) are responsible for the biological reactions related to an aerobic decomposition of all present plant materials. The phosphorus assimilated by the bacteria is discharged in the form of an insoluble precipitate that remains attached to the porous support. This breaks the eutrophication cycle and restores the natural balance of the water.

These components live on porous beads/pearls made of the mineral skeletons of marine algae colonies and should be spread evenly in the water.

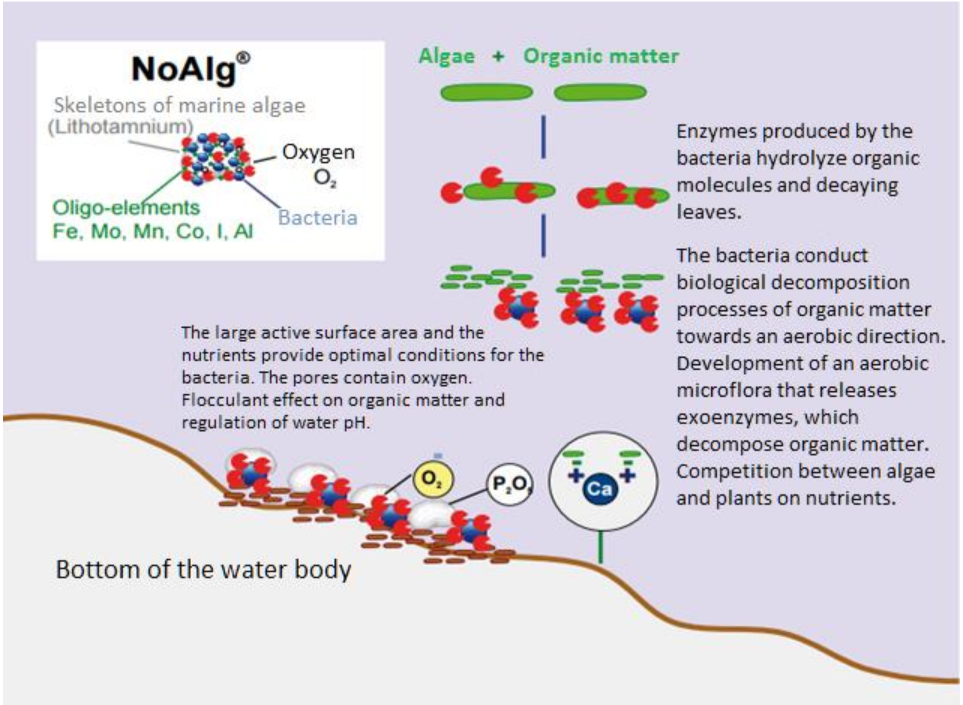

Figure 5-10. Mode of action of enzymes and bacteria against algae in water bodies

5.7.5.3. Operational conditions

The pH of the water should be monitored for some of these products (between 5 and 9 when applying Aquaclear).

These products should be applied preventatively at a sufficiently high temperature of the water (12°C) to be efficient. Applications can take place twice a year: in April (Belgium) at a dose of 40-60 g/m² to fight the algae in the current year; or in October to treat the water body preventively for the next year. When algae bloom takes place in summer, an extra treatment can be justified. For Belgium, a dose of 40-60 g/m² is then advised in June. One to three treatments a year are advised.

5.7.5.4. Cost data

A starting dose of the product is needed:

- Aquaclear: 12 kg/100 m³ of water at a price of 6 €/kg or 72 €/100 m³. For maintenance, one to three applications per year is required
- Fixaflor Equilibre: 600 kg/ha in spring or fall for maintenance or as a preventive measure (12,2 €/kg)
- Fixaflor Flash: 1500 kg/ha in summer for a direct effect

Prices are variable and depend on the product that is used (Table 5-5).

Table 5-5. Dosage and prices of the products based on enzymes and bacteria

Product	Dosage		Price (per 100 m² or m³)
	First application	Maintenance	Per application
Fixaflor Equilibre (Lobial, France)	600 kg/ha		73,2 €/100 m²
Fixaflor Flash (Lobial, France)		1500 kg/ha	Not avail.
Aquaclear (Greenhouse Holland, Benfried, Netherlands)	12 kg/100 m³		72 €/100 m³
NoAlg (Kali AG, Switzerland)			72 €/100 m³
Poly A + Biocure (Agrimor)	0,02 kg/100m³ 0,08 L/100m³	0,01-0,100 L/100m³	3,24 €/100 m³ 0,9 €/100 m³
Clean & Clear Concentrated Enzymes (CleanFlo, USA)	3,8 L/100m³		62,5 €/100 m³

5.7.5.5. Technological bottlenecks

The efficiency of the bacteria might be influenced by the water temperature, certainly in summer when water level drop and the water temperature increases. As the water temperature increases, the oxygen level decrease, which disrupts the aerobic process of the bacteria.

There might be a risk of the beads/pearls, used to apply these products, getting into the pumps or filters when extracting the water from the pond.

The beads have to be spread evenly, which is not easy on a large pond.

Since little literature has been found, we do not know what happens with the beads/pearls. They might pile up after years of using them, or they might dissolve eventually since they are in essence made of calcium.

5.7.5.6. Benefit for the grower

Advantages

- Has no effect on the fish in the basin
- Efficient
- Has a lasting effect
- Good price/quality
- No manual or mechanical cleaning needed
- No side effects
- Fish and plants can stay in the pond during application

Disadvantages

- In large basins, a boat is needed to spread the pearls/beads evenly in the water
- Possible accumulation of the pearls/beads at the bottom after a few years because the rate of decomposition is not known

- Visible effect only after 2-3 weeks
- Reduced efficiency between half of July and August because the bacteria do not succeed in competing with the algae at this time of the year
- Variable efficiency due to currents in the water
- Doses sometimes have to be the 10-fold of the advised dose to be efficient
- UV lamps are harmful to the bacteria in this product

5.7.5.7. Supporting systems needed

- A boat to spread the beads/pearls in case of larger ponds
- Additional filters to prevent aspiration of the beads when water is extracted from the ponds/water storage (especially when water levels are low). A solution here could be the installation of floating pumps

5.7.5.8. Development phase

- Research: applied in Belgium and France in 1998
- Field tests: applied in a natural pond in France

5.7.5.9. Who provides the technology

Fixaflor: fa. Lobial.

5.7.5.10. Patented or not

Fixaflor is patented (FR2659645A1) by laboratories SOGEVAL.

5.7.6. Which technologies are in competition with this one

The use of bacteria can be combined with:

- Fish
- Aeration (as we are talking about an aerobic process)

The use of bacteria should be avoided when the following technologies already are applied:

- Ultrasonic
- Water movement
- Chemicals with bactericidal effect
- Aquatic plants (competition for nutrients)

5.7.7. Is the technology transferable to other crops/climates/cropping systems?

This technology is not related to specific crop, climate or cropping conditions.

5.7.8. Description of the regulatory bottlenecks

No legislation found at present.

5.7.9. Brief description of the socio-economic bottlenecks

These products are considered "biological" and "ecological" so they are widely accepted.

Prices vary strongly and depend on the product that is used.

5.7.10. Techniques resulting from this technology

- Fixaflor Equilibre (fa. Lobial France): Fixaflor Equilibre consists of harmless bacteria attached to a porous, nutritive medium (12,2 €/kg)
- Fixaflor Flash (fa. Lobial France): This product is only different from Fixaflor Equilibre in size of the beads and concentration of bacteria. It is used in summer when an instant effect is needed
- Aquaclear (Greenhouse Holland, Benfried, Netherlands): to be able to use the product, it is necessary to map all water streams/flows at the company and maybe adapt them or even change the composition of the feed water
- NoAlg (Kali AG, Switzerland)
- CLEAR&CLEAR CONCENTRATED ENZYMES is a special blend of non-toxic vegetable enzymes from nature that acts as a catalyst to biodegrade non-living organic matter and reduces available nutrients in the water, thus improving water quality
- Poly A + Biocure (Agrimor) are microorganisms (*Bacillus subtilis*, *Bacillus megaterium*, *Saccharomyces*, *Bacillus thuringiensis israelensis*) and an enzyme bacteria catalyser

5.7.11. References for more information

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5.8. Algae control by fish

(Authors: Justyna Fila[6], Els Berckmoes[21])

5.8.1. Used for

Preparation of irrigation water.

5.8.2. Region

Central-East Europe.

5.8.3. Crop(s) in which it is used

All crops.

5.8.4. Cropping type

All cropping types.

5.8.5. Description of the technology

5.8.5.1. Purpose/aim of the technology

Control of algae in ponds using fishes as an environmentally friendly method of preparing water for irrigation.

5.8.5.2. Working Principle of operation

The use of grass carp (*Ctenopharyngodon idella*) is the most common method used in the purification of the ponds, mainly because it can purify the most contaminated tanks. Silver carps (*Hypophthalmichthys molitrix*), which feed on plankton, are also commonly used for this purpose. They can consume 2 or 3 times their weight of plankton each day. Additionally, a common nase (*Chondrostoma nasus*) can be used. This species dwells near the bottom where it feeds on algae and other aquatic plants. Undesired species are *Cyprinus carpio, Carassius carassius,* and *Tinca tinca* because they dig at the bottom of the pond and stir up mud while eating.

The grass carp (*Ctenopharyngodon idella*) is the species of fish with the largest reported production in aquaculture globally (over five million tons per year). It is a large herbivorous freshwater fish. The grass carp multiplies fastly. Young fish stocked in spring at 20 cm will reach over 45 cm by fall. The average length is about 60-100 cm. The maximum length is 1,4 m, and they gain 40 kg. This fish belongs to the family *Cyprinidae* native to eastern Asia, with a native range from northern Vietnam to the Amur River on the Siberia-China border.

Figure 5-11. Adult grass carp, *Ctenopharyngodon idella* (Source: Jeffrey E. Hill, University of Florida)

Silver carp were imported and stocked for phytoplankton control in eutrophic water bodies and also as a food fish. The silver carp is a filter feeder and possesses a specialised feeding apparatus capable of filtering particles as small as 4 µm. The gill rakers are fused into a sponge-like filter, and an epibranchial organ secretes mucus which assists in trapping small particles. A strong buccal pump forces water through this filter. Silver carp, like all *Hypophthalmichthys* species, have no stomachs; they are thought to feed more or less constantly, largely on phytoplankton. They also consume zooplankton and detritus. Because they feed on plankton, they are sometimes successfully used for controlling water quality, especially in the control of harmful blue-green algae (cyanobacteria). Certain species of blue-green algae, notably the often toxic *Microcystis*, can pass through the gut of silver carp unharmed, picking up nutrients in the process. Thus, in some cases, blue-green algae blooms have been exacerbated by silver carp. *Microcystis* has also been shown to produce more toxins in the presence of silver carp. These carp, which have natural defences to their toxins, sometimes can contain enough algal toxins in their systems to become hazardous to eat.

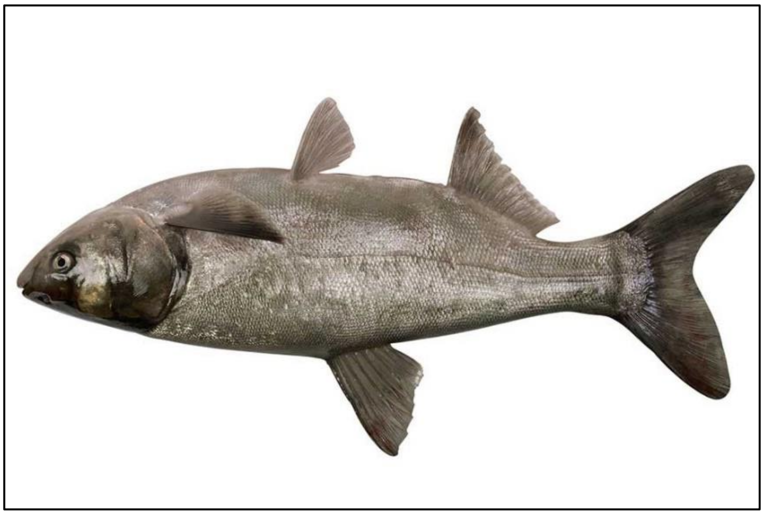

Figure 5-12. Silver carp (www.medianauka.pl/tolpyga-biala)

5.8.5.3. Operational conditions

Grass carp will tolerate a wide range of temperatures and oxygen concentrations. However, their feeding behaviour is strongly influenced by the water temperature:

- At about 10°C, they will almost cease to feed
- At 14°C, they will eat preferred species
- Between 20-23°C, they feed intensively (100% of their body weight per day in young fish)
- At 25°C, they will eat almost any weed species available

Other preferences of the grass carp are:

- Shallow waters (under 3 m) but they generally avoid water less than 30 cm in depth
- Freshwater, they have low salinity tolerances
- Differences in the water chemistry between sites can also influence their preferences for certain plant species

Effects on water quality:

- There may be a reduction in water clarity if aquatic plant density is greatly reduced or eliminated
- Use of grass carp is renowned for resulting in the total removal of aquatic plants. If you are planning to use grass carp for weed control you will need to assess whether complete plant removal is acceptable. After the total cleaning of the tank, fish harvesting is recommended

Stocking:

- Stocking rates vary considerably and calculating how many grass carp to stock will depend on a range of factors such as the type of water body, the aquatic weed species, water temperature, etc.
- The average advised stocking rates for aquatic plant removal are based on a standard fish size of 250 mm fork length (measured from the tip of the snout to the fork in the tail fin):
    - 3-5 years old fish: 20-30 grass carp per hectare
    - 2 years old fish: 50-100 grass carp per hectare
- A higher stocking rate is normally used in agricultural drains than lakes and ponds as drains usually have more vigorous weed growth
- Grass carp stocking densities are based on the maximum expected weed coverage and the feeding preference ratings from Table 5-6. Stock 10, 15 or 20 fish per acre depending on whether the target weed species is high, moderate or low on the feeding preference list, respectively

Table 5-6. Feeding preferences of grass carp on some common aquatic plants

High preference	Moderate	Low
American elodea Hydrilla Musk-grass Naiads	Bladderwort Coontail Duckweeds Fanwort Filamentous algae Pondweeds Water pennywort Water primrose	Alligator weed Cattail Eel grass Maidencane Milfoil Parrot feather Reeds Sedges Spatterdock Torpedo grass Water hyacinth Waterlily Watermeal Watershield Yellow cowlily

Several studies have demonstrated the effectiveness of grass carp for aquatic plant management.

Figure 5-13. A pond in Southeast Florida before (top) and one year after (bottom) stocking with grass carp at 40 fish per acre (0,4 ha) (Source: David Sutton, University of Florida)

5.8.5.4. Cost data

Prices vary considerably depending on availability, fish size, season and dealer. The estimated price is approximately 1 € per piece of 10-15 cm juvenile fish. The costs of feeding fish are not present. It is recommended not to feed the fish throughout the period of treatment. After the total cleaning of the tank/pond, fish harvesting is recommended.

5.8.5.5. Technological bottlenecks

Using fish is subject to compliance with the principles of stocking and removal.

5.8.5.6. Benefit for the grower

Advantages

- Cheap
- Ecologic
- Preservation of biodiversity
- Improves the landscape in environmentally degraded areas
- Alternative for organic farms
- Removes a wide range of weed species
- Adaptable to a wide range of environmental conditions
- 60-70% of the nutrients in the aquatic plants they consume are digested
- Effective for a long period of time over large areas
- Complete eradication of aquatic weeds is possible
- Grass carp do not distinguish between native and introduced species of aquatic plants
- Selective decrease or elimination of aquatic plant biomass and the release of nutrient-rich excrements into the water

Disadvantages

- Various restrictions on the sale and use of grass carp, different in different countries
- Strictly defined grass carp stocking rates
- Fish removal is slow (predation, fishing, and natural mortality)
- Fish removal requires a permit

5.8.5.7. Supporting systems needed

None.

5.8.5.8. Development phase

Commercialised, applied at some medium-size farms.

5.8.5.9. Who provides the technology

This technology is not presently provided by any company, but this is not a limiting factor because the grower himself can inoculate his pond with grass carp if having the adequate knowledge.

5.8.5.10. Patented or not

This method is not patented.

5.8.6. Which technologies compete with this one

Liming ponds.

5.8.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this technology is transferable but mainly dependent on environmental conditions.

5.8.8. Description of the regulatory bottlenecks

There are various restrictions on the sale and use of grass carp that differ in different countries and are related to the introduction, sale, and stocking of grass carp. In some countries, there are penalties for improper management, e.g., in New Zealand and the USA.

5.8.9. Brief description of the socio-economic bottlenecks

Not known.

5.8.10. Techniques resulting from this technology

Not applicable.

5.8.11. References for more information

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[5] Lewis, W. G. Use of sterile grass carp to control aquatic weeds. The University of Georgia College of Agricultural & Environmental Sciences Cooperative Extension Service.

[6] Grass carp control weeds in ponds and lakes. Missouri Department of Conservation. Pond Management series. http://mwands.com/pdf_files/pond_care/grass-carp-weed-control.pdf

[7] http://entnemdept.ufl.edu/creatures/BENEFICIAL/MISC/Ctenopharyngodon_idella.htm#top

5.9. *Algae control by aquatic plants*

(Authors: Juan José Magán[9], Els Berckmoes[21], Justyna Fila[6])

5.9.1. Used for

Preparation of irrigation water.

5.9.2. Region

Mediterranean.

5.9.3. Crop(s) in which it is used

Crops irrigated from ponds.

5.9.4. Cropping type

All cropping types.

5.9.5. Description of the technology

5.9.5.1. Purpose/aim of the technology

To reduce algae development and total suspended solids content in the water of irrigation ponds by the proliferation of submerged aquatic vegetation (SAV) to decrease dripper clogging risk. Furthermore, some species of aquatic plants are effective controlling aquatic phytopathogens existing in the irrigation water.

5.9.5.2. Working Principle of operation

Phytoplankton usually grows well in stagnant water bodies and competes for light and nutrients with SAV, which is a disadvantage because of its growth at the bottom. For that reason, a lot of SAV species have developed mechanisms of competition against microalgae, being capable of producing allelopathic substances which inhibit their development. In addition, SAV serves as a refuge to algae-eating zooplankton (e.g., *Daphnia*) against potential predators. Zooplankton indirectly helps SAV by consuming suspended microalgae and clarifying the water, thus allowing more radiation to reach the bottom. On the other hand, many species of invertebrates (larvae of insects, snails and crustaceans) find food and refuge on the leaves or thalli of SAV, consuming deposited particles or microalgae stuck to the surface, which contributes to the improved photosynthetic activity of SAV. Therefore, the maintenance of sub-aquatic meadows of certain plant species in the irrigation ponds can induce high levels of biodiversity, together with clear water, which is essential in localised irrigation systems to minimise clogging risk.

5.9.5.3. Operational conditions

Ponds are suitable environments for SAV development because they are shallow aquatic ecosystems and enough radiation usually reaches the bottom of the system where this vegetation takes root. In South-Eastern Spanish conditions, almost 50% of ponds in commercial farms develops SAV despite the application of biocides to the water and pond dredging during summer (carried out every 8,6 years on average). *Potamogeton pectinatus* (Figure 5-14) and *Chara* (Figure 5-15) are the most important SAV groups found in such ponds.

Figure 5-14. Picture of *Potamogeton* with high development reaching the water surface in a pond (Source: Melchor Juan Cazorla and J. Jesús Casas Jiménez)

Figure 5-15. Picture of *Chara* (Source: Melchor Juan Cazorla)

According to the study carried out by Bonachela et al. (2013), SAV development in ponds improves water clarity by decreasing the concentration of chlorophyll a from an average value of 23,2 µg/L in open ponds without SAV to 7,2 µg/L in open ponds with SAV. About the total suspended solids, average values are 10,3 mg/L and 9,2 mg/L, respectively in open ponds without SAV and with SAV. In both cases, ground or surface water was used. However, SAV does not grow well in covered or in recycled urban waste-water fed ponds, which is likely due to light limitation and harsh water quality conditions. No significant differences in water quality parameters were found regarding the predominant SAV species; however, the development of *Chara* in ponds causes fewer problems than *Potamogeton* and can have additional advantages.

Chara fragilis has demonstrated to be the best option among the different SAV species adapted to the environmental conditions of South-Eastern Spain because of its development at the bottom of the pond, high survival and inhibitory effects on bacteria and *Pythium* viability.

5.9.5.4. Cost data

Installation cost

Inoculation of SAV in the pond can be done by the grower. However, the optimal management is unknown.

Maintenance:

Periodical mechanical harvest of SAV can be necessary with species growing vertically (e.g., *Potamogeton*), to avoid sealing problems of the suction pipe of the irrigation pump. There is a reduced risk with species developing a dense meadow at the bottom of the pond (e.g., *Chara*) and a lower need for maintenance.

5.9.5.5. Technological bottlenecks

There are still some gaps in knowledge about this technology. For example, how to achieve an optimal installation and development of *Chara* has not been studied, as well as the way of promoting *Chara* when existing *Potamogeton* in the pond.

5.9.5.6. Benefit for the grower

Advantages

- Cheap
- Environmentally friendly strategy
- It allows biodiversity preservation
- It can improve the landscape in environmentally degraded areas
- Some SAV species, such as *Chara fragilis*, *Potamogeton pectinatus* and *Najas marina* have shown antibacterial properties
- Less dripper clogging due to flocculants produced by bacteria
- Better plant quality due to limited phytopathogenic bacteria in the water
- *Chara fragilis* inhibits *Phytium* propagule viability
- *Chara* has high capacity to withstand pond desiccations

Disadvantages

- Reduced radiation and oxygen concentration in the water if SAV grows vertically out of the water (e.g. *Potamogeton pectinatus*)
- Plants can block the irrigation system
- Evaporation causes water losses from the pond (8,3% of the total irrigation water used in South-Eastern Spain). This disadvantage is also present with other methods of algae control, excepting if the pond is covered

- Low efficiency in recycled urban waste-water
- Little knowledge about the processes of establishment and growth of these plants in the ponds to develop effective management protocols

5.9.5.7. Supporting systems needed

None.

5.9.5.8. Development phase

Commercialised, successfully applied in some commercial farms in South-Eastern Spain.

5.9.5.9. Who provides the technology

At present, this technology is not provided by any company, but this is not a limiting factor because the grower himself can inoculate his pond with SAV.

5.9.5.10. Patented or not

This method is not patented.

5.9.6. Which technologies are in competition with this one

- Application of biocides to the irrigation water
- Shading of the pond
- Ultrasonic sound emission

5.9.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, but the species of SAV developing in the pond will probably have to be different in each region for a better adaption to the local environmental conditions. This should be studied in advance.

5.9.8. Description of the regulatory bottlenecks

5.9.8.1. Implementation at the regional level

In Andalusia (Spain), the law regulating the integrated production of horticultural protected crops recommends not applying copper in uncovered reservoirs to allow the proliferation of aquatic plants involved in best quality and oxygenation of the water, including the control of pathogens.

5.9.9. Brief description of the socio-economic bottlenecks

Many growers do not know about the benefits of SAV development in the ponds and think that the best way to avoid clogging problems is maintaining the pond as sterile as possible. For that reason, they usually apply chemicals to the pond water, which can affect SAV development. Growers frequently have a negative opinion about the presence of SAV in the pond because of the risk of sealing of the suction pipe of the irrigation pump. Hence, a change of mentality of the growers is necessary for a large application of this technology.

5.9.10. Techniques resulting from this technology

Not applicable.

5.9.11. References for more information

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5.10. Algae control by water movement

(Authors: Els Berckmoes[21], Ilse Delcour[19])

5.10.1. Used for

Preparation of irrigation water.

5.10.2. Region

All EU regions.

5.10.3. Crop(s) in which it is used

All crops.

5.10.4. Cropping type

All cropping types.

5.10.5. Description of the technology

5.10.5.1. Purpose/aim of the technology

The aim of using aeration and water movement is to prevent algae in big water reservoirs.

5.10.5.2. Working Principle of operation

This is based on three principles.

First, the algae are continuously moved through the water storage, preventing them to stay at the surface layers of the water storage. When the algae are in the darker areas, their growth is inhibited since they depend on photosynthesis.

Secondly, since algal blooms are often caused by an increase in nutrients (due to decomposing organic matter and aquatic organisms in the ponds, which cause a significant drop of the natural oxygen levels and simultaneously a rise in nitrogen and phosphate levels), increasing the oxygen content of the water body is also a solution. This provides a natural control of the nitrogen and phosphate levels in the pond by the dissolved oxygen.

Third, when you increase oxygen levels in the pond, the existing beneficial aerobic bacteria can also thrive and are better able to compete with algae for nutrients.

The continuous water movement also results in:

- A homogeneous spread of oxygen-rich water throughout the body of water
- A homogenous water quality and temperature throughout your reservoir or tank, resulting in more stable growing conditions for the crop
- Improved decomposition of the organic matter

5.10.5.3. Operational conditions

In Table 5-7, the operational conditions for some existing aeration/water movement devices are shown.

Table 5-7. Operational conditions for aeration and water movement devices

Device	Volume	Depth	Diameter of the storage
Oloïd 200x	Max 1000 m^3	Max 2-3 m	Max 30 m
Oloïd 400x	Max 12000 m^3	Max 4-5 m	Max 130 m
Fountain	No data	No data	No data
Water pumps	Variable	Variable	Not applicable

5.10.5.4. Cost data

The costs for installation and maintenance of the different devices for aeration and water movement are presented in Table 5-8.

Table 5-8. Cost data for aeration and water movement devices

Device	Installation cost	Energy cost	Maintenance cost
Oloïd 200x	3950 €	25-60 W/h	Once per 2 years
Oloïd 400x	7500 €	150 W/h	Once per 2 years
Fountain	No data	No data	No data
Water pumps	800 € for 18 m^3/hour	Not known	Not known

5.10.5.5. Technological bottlenecks

Fountains only have a very local effect compared to Oloïds. On the other hand, water pumps can have a similar effect as Oloïds but they require much more energy to obtain a similar result.

5.10.5.6. Benefit for the grower

Advantages

- Simple techniques
- Low maintenance requirements
- No extra space needed, the devices are in or on the water

Disadvantages

- Moving particles can clog filters
- Organic material cannot settle on the bottom to decay
- Mud can be present in extracted water
- Low efficiency
- No curative effect

Table 5-9. Advantages and disadvantages of the different aeration and water movement devices

Device	Advantages	Disadvantages
Oloïd	Low power demand Higher oxygen content Homogeneous water quality (pH, EC, temperature, oxygen) Keep the water storage frost free	Too expensive for small ponds Availability of the technology
Fountain	Keep the water storage frost free	Only local effect High energy demand in comparison with Oloïd
Water pumps	Higher oxygen content Homogeneous water quality (pH, EC, temperature, oxygen) Keep the water storage frost free	High energy demand

5.10.5.7. Supporting systems needed

Curative technologies can be necessary as the moving of the water body only has a preventive effect.

5.10.5.8. Development phase

Commercialised, several suppliers provide the technology.

5.10.5.9. Who provides the technology

- Oloïd: Hortiplan
- Fountains: general suppliers
- Water pumps: general suppliers

5.10.5.10. Patented or not

Oloïd is patented, the other devices are not.

5.10.6. Which technologies are in competition with this one

CLEAN-FLO: this technique oxygenates an entire body of water from top to bottom. This oxygenation helps purge the water of carbon dioxide, which is a primary nutrient necessary for aquatic plant photosynthetic growth and productivity. Other gasses such as hydrogen sulphide and ammonia are also purged from the sediments. Oxygenation enables beneficial microorganisms to feed on bottom organic sediment. It enables aquatic insects to feed on the microorganisms and fish to inhabit the bottom waters and feed on the insects, providing a valuable natural food source to improve fish growth and health.

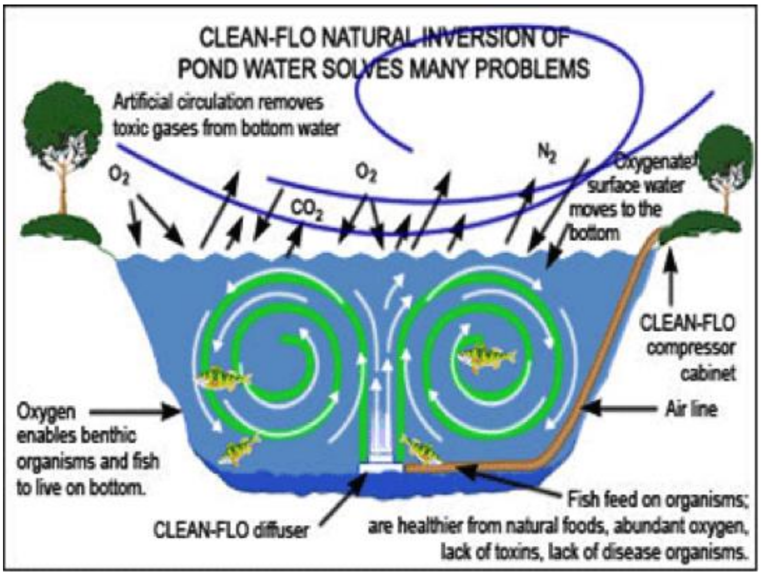

Figure 5-16. Mode of action of the Clean-Flo technology (www.clean-flo.com)

Other oxygenation techniques, e.g. http://lake-savers.com/how-inversion-oxygenation/.

5.10.7. Is the technology transferable to other crops/climates/cropping systems?

This technology is not related to specific crop, climate or cropping conditions.

5.10.8. Description of the regulatory bottlenecks

Not applicable.

5.10.9. Brief description of the socio-economic bottlenecks

There are no direct socio-economic bottlenecks.

5.10.10. Techniques resulting from this technology

Oloïd is equipped with an electrically-driven agitating body, which has a unique geometric shape and drive mechanism. The rotating, agitating body causes a pulsating and unidirectional water current, which efficiently stirs great quantities of water. This current flows throughout the reservoir or tank, not just at the surface. As a result, oxygen-enriched water is spread homogeneously throughout the body of water. Oloïd is adjustable to different depths. In its highest position, the device is partly above the water surface, mixing air (and therefore oxygen) into the water. In its lowest position, Oloïd is mostly submerged, increasing the water current. This position is used in winter to prevent the water surface from freezing solid. This position also prevents biodegradable matter and waste from collecting at the bottom of the reservoir.

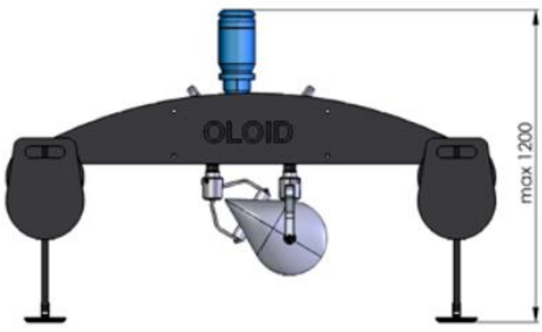

Figure 5-17. Schematic representation of an Oloïd (left) and an Oloïd in a pond (right) (http://www.hortimax.com)

5.10.11. References for more information

[1] http://www.hortimax.com/uploads/editor/Leaflet%20GB009%20v1_1%20Oloid%20.pdf

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5.11. Algae control by ultrasonic devices

(Authors: Els Berckmoes[21], Dolors Roca[8], Justyna Fila[6], Juan José Magán[9], Ilse Delcour[19])

5.11.1. Used for

Preparation of irrigation water.

5.11.2. Region

All EU regions.

5.11.3. Crop(s) in which it is used

All crops.

5.11.4. Cropping type

All cropping types.

5.11.5. Description of the technology

5.11.5.1. Purpose/aim of the technology

The use of ultrasonic devices makes it possible to control algae bloom both in a preventive and curative way.

5.11.5.2. Working Principle of operation

1) Based on sound barriers (low-power device): the ultrasonic devices emit specific ultrasonic parameters that create a sound barrier. Blue-green and some green algae are capable of travelling through the water vertically due to their possession of gas vesicles. The ultrasonic sound waves create an ultrasonic pressure in the top layer of the water. This ultrasonic sound barrier prevents the algae from rising to the surface and absorbing light for photosynthesis, preventing their growth. In this way, the algae will die while the cell wall remains intact, preventing the release of toxins from the algae into the water. The algae will sink to the bottom of the water reservoir and are degraded by bacteria
2) Based on oscillation (low-power device): these devices are based on high-frequency pulses that strike algal cells, causing the cells to oscillate. If the algae, such as the blue/green algae, have a gas vacuole (for buoyancy), then the vacuole also starts to resonate – to such an extent that it starts to increase in size. There then comes the point when the vacuole becomes unstable and collapses, making the algae sink to the bottom of the pond

   Algal species which do not have gas vacuoles react differently. The vibrations from the ultrasound cause the inner cell wall of the algal cell (plasma lemma) to become detached from the outer cell wall – this means that water, gases, and nutrients can neither be absorbed nor expelled and as a result, the algae die

3) Based on cavitation (high-power device): these devices are based on the phenomenon where high-power ultrasound causes the formation of micro-bubbles that implode, causing intense heat pressure. These processes can destroy the gas vesicles of algae. The VitaFloat, for example, sends its ultrasonic waves vertically in the water

5.11.5.3. Operational conditions

Low power devices can act in a radius of minimum 5 m to maximum 200-500 m, in case of bigger ponds, several devices can be combined to cover the complete area.

High-power devices can act in volumes of max 6000 m³ (VitaFloat 500) to 15000 m³ (VitaFloat 1000).

The combination of different devices makes it possible to achieve an action radius of 360°.

5.11.5.4. Cost data

Installation cost

- Smart Sonic pond/lake: 858-2233 €
- VitaFloat: 4100-6100 €
- Aquasonic/LG Sonic: 1650 € for basin up to 150 m
- Algasonic: 1950 € for basin up to 150 m
- Unspecified device: 2540 € (covering the same pond would cost 6800-9075 €)
- Ultrasound detector: this equipment makes it possible to measure the presence of the ultrasound in the water volume: 350 €

Maintenance

- Energy cost: In the case of ultrasonic devices, energy costs should be taken into account. In the case of low-power devices, the energy demand is low (<60 Watt). In the case of high-power devices, the energy demand can increase to 1,1 kW/hour.
- Other maintenance costs: not applicable according to the providers

5.11.5.5. Technological bottlenecks

The size of the area covered will depend on several factors including the type of algae being controlled. Other factors such as pond shape, the presence of fountains/aerators, water clarity, weed growth, etc. will also affect coverage size. In larger ponds having complex shapes, more than one device may be required or the placement of a transduces might be essential.

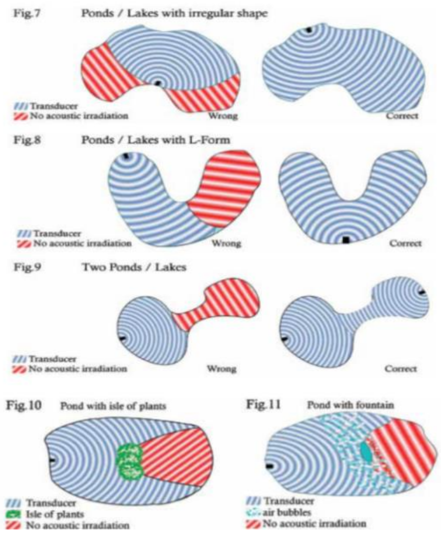

Figure 5-18. The location of the device is essential to assure the maximum action radius is achieved (www.ethosaeration.com)

The emitted ultrasound waves are absorbed as they travel through the water. In essence, they become weaker the further they travel from the transducer. As a result, easy to control algae types can be controlled far out into the pond while harder to control strains, like *Chara*, will only be controlled in close ranges. Submerged plant growth will influence the transduction of the sound waves in a negative way.

The ultrasonic waves are emitted in a narrow range of 180°. Several ultrasonic emitters are needed to cover the full area (of 360°). This increases the costs of the equipment.

If the ultrasound is generated in regular pulses, it will be reflected back by pond edges or obstructions such as rocks or islands. As a result, the outgoing and returning waves can "cancel" each other out creating "quiet" areas where algae will be unaffected. With Smart Sonic units, the ultrasound is generated at irregular intervals to guarantee maximum effectiveness.

The right frequency of ultrasound is fundamental. This frequency has to be between 20000 and 60000 Hertz. The sound intensity is also an important parameter. If the intensity of the sound is too low, the algae can adapt by growing thicker walls, and therefore the effect of ultrasound will diminish. The selected sound intensity of the VitaFloat is such that the algae cannot adapt themselves.

5.11.5.6. Benefit for the grower

Advantages

- No release of toxins of blue-green algae with low-power devices
- Safe for humans, fish, plants and insects
- Possibility to adapt the device to the specific type of algae
- Easy and fast to install
- Large action radius (200-500 m)
- Low energy consumption

- Removal/prevention of biofilm
- Cheaper than a floating obscuration cover

Disadvantages

In case of low-power devices:

- Only a few devices have shown to be effective
- Several ultrasonic emitters are needed to cover the full area (of 360°)
- Costs increase for irregular or large water basins

In case of high-power devices:

- Release of toxins (blue-green algae)
- Might harm fish and zooplankton due to cell destruction

5.11.5.7. Supporting systems needed

- Additional aeration: in the case of high organic contamination (leaves of trees, soil particles, etc.) or high algae pressure, additional aeration may be necessary to support the degradation of the algae
- Additional water movement: in the case of the high-power devices the ultrasound is sent out in a vertical direction. Water movement improves the efficacy significantly.
- Ultrasonic detector: with the detector, one can measure whether the signal is present anywhere in the water
- Optional: a water quality monitoring system: it is possible to combine online water quality monitoring and ultrasound technology to provide a complete and cost-effective algae control solution in lakes and reservoirs. This control unit makes it possible to adapt the specific parameters of the emitted sound to the specific algae

5.11.5.8. Development phase

Commercialised, several devices are available for sale.

5.11.5.9. Who provides the technology

- LG sonic
- Smart Sonic
- Hortimax
- BE De Lier
- Thomas Electronics

5.11.5.10. Patented or not

Yes, some devices are patented.

5.11.6. Which technologies compete with this one

- Obscuration (smaller scale water storages only)
- Aeration

- Water movement (smaller scale water storages only?)

5.11.7. Is the technology transferable to other crops/climates/cropping systems?

This technology is not related to specific crop, climate or cropping conditions. Therefore, it can be applied in a broad range of crops, regions and storage systems.

5.11.8. Description of the regulatory bottlenecks

Not applicable.

5.11.9. Brief description of the socio-economic bottlenecks

Ultrasonic devices could harm zooplankton and fish (in case of high-power devices).

5.11.10. Techniques resulting from this technology

- Low-pressure devices:
    - LG-sonic E-line (10-200 meters, producer LG sonic)
    - MPC-BUOY (200-500 meters, producer LG sonic)
    - Smart Sonic Pond (15-40 meters, Smart Sonic)
    - Smart Sonic Lake (50-+400 meters, Smart Sonic)
    - SS 100- SS600 (40 Watt, 120-180 meters, Sonic Solutions)
    - Algasonic
- High-pressure devices:
    - VitaFloat (550 Watt-1kWatt, provider Hortimax)
    - AquaSonic (100Watt, provider BEDeLier)

5.11.11. References for more information

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[3] https://www.lgsonic.com/product/control-monitor-algae-mpc-buoy/
[4] http://www.ultrasonicalgaecontrol.co.uk/product-range/the-smart-sonic-range/
[5] http://vandingsgrossisten.dk/vejledning/1293449650_VitaOlod_VitaFloat_GB.pdf
[6] http://www.ethosaeration.com/ultrasonic-algae-control-system-up-to-82-x-41/
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[9] Maestre-Valero, J. F. & Pedrero, F. (2014). Evaluación del efecto de los ultrasonidos en balsas de riego que almacenan aguas regeneradas procedentes de un tratamiento terciario. CEBAS-CSIC. http://www.crcc.es/wp-content/uploads/2012/11/informe-CRCC-ULTRASONIDOS.pdf
[10] Personal conversation with Thomas, H. (Thomas Electronics) and Peeters, Y. (Innovative and ecological Solutions) on March 21st, 2017

5.12. Algae control by blue food dye

(Authors: Georgina Key[1], Els Berckmoes[21], Justyna Fila[6])

5.12.1. Used for

Preparation of irrigation water.

5.12.2. Region

North-West Europe.

5.12.3. Crop(s) in which it is used

Ornamental crops.

5.12.4. Cropping type

All cropping types.

5.12.5. Description of the technology

5.12.5.1. Purpose/aim of the technology

The aim of using blue dye is to reduce the algae growth in water storages to keep water clear for irrigation use. Removing algae from the water will reduce the chance of filters becoming blocked.

5.12.5.2. Working Principle of operation

Adding the blue dye to the water results in a light blue colour which filters light to disrupt the process of photosynthesis. More precisely, the infra-red part of the spectrum that fuels photosynthesis is filtered out, preventing submerged weeds and algae from growing. It can also help in situations where algae and weeds have already become established.

Products like "Pond Blue" should be added to the reservoir water two to three times per year. Pond Blue is free of chemicals, algaecides and herbicides.

Figure 5-19. Lake and fisheries with blue dye (www.dyofix.co.uk)

Figure 5-20. Blue dye being dispersed into the water via a pump (www.dyofix.co.uk)

5.12.5.3. Operational conditions

Manufacturer recommendations say that a 5 kg bottle of liquid concentrate will treat 28,75 million litres of water. A British grower has found that if he adds 1 litre to their reservoir, he can treat 1 million litres of water for up to 4 months with no algae problems. There is no effect of the product on water quality or pH. It is designed to be used as a preventative measure but can be used as a solution to more advanced algal problems. It does not prevent normal decomposition of organic matter in the pond or reservoir.

5.12.5.4. Cost data

- No installation costs
- Will require top-up applications every 3-4 months

Table 5-10. Examples of blue dye and the cost for application in 1000 m³ of water

Product	Form	Volume treated (m³)	Cost (€)	Cost (€) per treated 1000 m³
Dyofix Pond Blue	1 kg soluble sachets	10000	47,65	4,8
	1 kg liquid concentrate	5750	35,74	6,2
	5 kg liquid concentrate	28750	148,91	5,2
Dyofix Lake Shadow	1 kg soluble sachets	4000	35,74	8,9
Dyofix C Special	1 kg soluble sachets	4000	35,74	8,9

5.12.5.5. Technological bottlenecks

Technologically there are none but the prices include postage and packaging, which would not apply to areas outside the UK mainland. However, growers can phone/email the sales department and discuss delivery outside this area.

5.12.5.6. Benefit for the grower

Advantages

- Good quality water with very little cost
- Environmentally-friendly product: products are safe for humans, animals, fish or insects
- The effects are long lasting
- Savings can be made on filters and labour cleaning the filters
- The product has a long shelf life
- There is no effect on pH or water quality
- It does not interfere with normal processes within the water

Disadvantages

May require an extension of legislation if it is going to be used on food crops.

5.12.5.7. Supporting systems needed

None in case the growers already have water reservoirs.

5.12.5.8. Development phase

- Field tests: "C Special" is being trialed to control *Crassula helmsii* and *Chara*. Early indications are very positive
- Commercialised: it is an established product used by growers, landscape gardeners, commercial fishing lakes, local authorities and golf clubs

5.12.5.9. Who provides the technology

Dyofix (Townsend Ltd.)

5.12.5.10. Patented or not

This method is patented.

5.12.6. Which technologies compete with this one

Growing *Lemna minor* on a reservoir to suppress algal growth.

5.12.7. Is the technology transferable to other crops/climates/cropping systems?

Although by the European Food Additive regulations, the patent may not have explicitly stated that it can be used with food crops.

5.12.8. Description of the regulatory bottlenecks

All the dyes that the company uses comply with the European Food Additive regulations and use European Food Approved Colours, with no effect on wildlife, fish or domestic animals. Therefore, it could potentially be extended for use on food crops.

5.12.9. Brief description of the socio-economic bottlenecks

None as it is a very economically priced product.

5.12.10. Techniques resulting from this technology

- Addition of feed colour dyes (Pond Blue, Lake shadow, by Dyofix Townsend Ltd)
- In case of Pond Blue, a blue food colourant is added to the water
- In case of Lake Shadow, a special blend is added to the water of the three primary colours, red, yellow and blue, so that anyone looking at the water would not know that any colour had been used at all

5.12.11. References for more information

[1] http://www.dyofix.co.uk/pond-lake-blue.html

Chapter 6. Optimising water quality – Disinfection

Coordinators: Julia Model[20], Claire Goillon[2], Benjamin Gard, Ilse Delcour[19]*

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6.1. Introduction to Optimising water quality - Disinfection

6.1.1. These techniques concern the issue

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

6.1.2. Regions

All EU regions.

6.1.3. Crops in which the issue is relevant

All crops with a special focus on substrate grown crops.

6.1.4. Cropping type

All cropping types.

6.1.5. General description of the issue

This chapter describes the different technical possibilities to disinfect intake water like rain or surface water as well as drain water to avoid crop contamination with the waterborne pathogen. Recirculation of drain water in soilless cultivation systems is a good method to avoid water and nutrient discharge to the environment and to increase water reuse in order to save water and nutrients. In closed cultivation systems, the quality of water is important for recirculation in a safe way.

6.1.6. Brief description of the socio-economic impact of the issue

Under the framework of the nitrate directive, water and nutrient discharge is strictly supervised. In some countries, it is forbidden for nurseries with soilless cultivation systems to discharge drain water to surface waters over a maximum nitrate limit. Therefore, disinfection of drain water becomes a necessity.

Growers may not implement the technologies for recirculation due to several socio-economic factors:

- Risk-benefit: technological improvements should be reached without compromising crop yield and quality
- Cost-effectiveness: technologies can significantly contribute to improving the quality of irrigation water while saving costs when water is recirculated. Depending on the technology, investment costs can be very high, but earn back times are relatively fast
- Critical size: depending on the size of the nursery and the technology, investment and maintenance costs may be too high to reuse drain water
- Awareness: growers are not always convinced of the use/benefit of a technology

6.1.7. Brief description of the regulations concerning the problem

6.1.7.1. European level

The Water Framework Directive and the Nitrate Directive (91/676/EEC) supervised the protection of water resource at the European level from agricultural nitrate polluting sources. For the soilless growing system, growers can reuse water to avoid nutrient discharge to surface waters. In this case, water quality is crucial for recirculation.

With regards to chemical disinfection, the use of oxidative compounds is regulated by the Biocidal Products Regulation (BPR) EU 528/2012, which concerns the availability on the market and use of biocidal products. For instance, Chlorine, Sodium Hypochlorite and Calcium Hypochlorite are listed under BPR. Besides, regulations may also require continuous monitoring of oxidative compounds in the effluents. The maximum residue level must be respected in treated water.

Some chemical compounds like nitric acid, phosphorous acid, are classified under REACH registration as toxic. Hence, special guidance for safe use must be followed.

6.1.7.2. Country level

Those Europeans directives have been acknowledged in each European country. Limits of the nutrient quantity that could be discharged are set in national rules according to the acknowledgement of the European Directive. In some countries, regulation on chemical compounds may hinder the use of several oxidants.

6.1.8. Existing technologies to solve the issue/sub-issues

Several variants of chemical oxidation technologies are available that belong to one of the following two main groups:

- Chemical oxidation (non- AOP), involving the addition of a chemical reagent, such as ozone (O_3), hydrogen peroxide (H_2O_2), sodium hypochlorite (NaClO), chlorine dioxide, persulphates (e.g. persulfate), peroxyacetic acid or combinations thereof
- Advanced oxidation processes (AOP), involving the generation of highly reactive, short living hydroxyl radical (OH) by using UV-C light (e.g. H_2O_2/UV), peroxone (combination of H_2O_2/O_3) or a catalyst (Fe^{2+} in Fentons Reagent; titanium dioxide (TiO_2) in photocatalytic oxidation)

Physical treatment technologies rely on the action of heat or light to destroy microorganisms present in water:

- UV-C light, thermal disinfection

Biological treatment technologies rely on the action of antagonist microorganisms, biofilm formation and filtration (mechanical action), which are able to control pathogens:

- Biofiltration or slow sand filtration

Some of those technologies may be combined to increase their efficacy to control pathogen in irrigation and drain water.

6.1.9. Issues that cannot be solved currently

Chemical oxidation and physical treatments are non-selective techniques, i.e. almost all organics are degraded. Treatments with non-AOP's will often end up in carboxylic acids; these are much more difficult to remove by O_3or hydrogen peroxide alone. Non-AOP's are very suitable for treatment of aromatic and unsaturated compounds.

Restrictions are found in the following situations:

- high COD content (> 500 mg/L), resulting in high dosages and hence high treatment costs
- high amounts of radical scavengers, like bicarbonates, resulting in higher dosages (relevant for all AOP's)
- toxicity of the treated water (formation of unwanted breakdown by-products) when the insufficient oxidant is used (e.g. nitrosamides)
- toxicity of the oxidant itself, especially O_3
- formation of chloride derivatives, dichloramine and trichloramine

The high toxicity and the risk linked to the use of some oxidative compounds, like O_3, in a working people area can be a problem that may remain unsolved.

Concerning biological disinfection, factors that affect the biological community of the filter also impact filtration and disinfection effectiveness. Biological effectiveness depends on the microbial species and species diversity present in the microbial community of the filter. Some research has demonstrated that is possible to inoculate biofilters with specific beneficial microorganisms to speed-up the commissioning.

Finally, for physical disinfection, UV is the most used and reliable technique nowadays, but it has high investment costs that can be earned back within 2-3 years. Thermal disinfection is effective against fungi bacteria and viruses, but it has a poor reliability and high energy consumption. Furthermore, these technologies may have a negative impact on the nutrient present in the treated water.

To conclude, two main options are competing: using highly efficient disinfection systems causing a crawlspace in the treated water with the risk of recontamination with pathogens, or using biological treatment based on the monitoring of a balance between beneficial and pathogenic microorganisms.

6.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions (TDs)

Technology		Costs (starting at)		Required technological knowledge	Weaknesses	Strengths	Limitations
		Installation	Maintenance				
Chemical oxidation (non-AOP)	Chlorination	Sodium hypochlorite: 4583 € Calcium hypochlorite: 2837 €	Sodium and Calcium hypochlorite: 1701 €/year	Moderate level	Toxic to both plant and human, risk of organochlorine formation, corrosive, risk of precipitation with ammonium, iron and manganese	Simple to install and maintain, residual disinfectant activity, keeps pipework and irrigation system clean	Chlorate concentration is regulated by maximum residue level, non-convenient for water with high organic matter concentration (risk of organochlorine formation)
	Ozonisation	40000 €	2000 €/year	High level	High toxicity of this oxidant, high risk of toxic by-product formation, corrosive, high investment costs	Strong disinfection efficacy, partial removals of organics (growth inhibitors) and pesticides, increases the amount of dissolve oxygen	Necessity of controlled process conditions and installation by a specialised company
	Peroxide	Installation: €2500 Peroxide liquid: 0,73 €/m³	Not avail.	Low level	Significant risk of root damage if oxidant concentration is too high, needs a system for trapping oxidative compounds	Effective against biofilm, easy to use, requires only a dosing pump	Efficacy and dose depend on water quality and crop sensitivity, needs close monitoring of the dosing volume
Advanced oxidation processes (AOP)	Copper/Silver ionisation	7700 €	0,09 €/m³	Moderate level	Resistance to silver ions can occur, silver is ineffective against *Alternaria, Fusarium* and Tobacco mosaic virus, copper-silver affectivity depends on water pH	Large residual effect, effectively deactivate *Legionella* and biofilm, non-corrosive, no transport and storage difficulties	Deactivation rate is lower than that of ozone or UVC-light, for effective disinfection, copper and silver ions should be present in the whole water system, water analysis is required
	ECA water	17000 €	0,047 €/m³	High level	Formation of by-product, corrosive to metal, high investments costs	No chemical used, oxidant produced on site. low energy usage, no resistance build-up by pathogens, residual effect, protect dripper and pipes from biofilm (no clogging)	Softening of water is often necessary

Technology		Costs (starting at)		Required technological knowledge	Weaknesses	Strengths	Limitations
		Installation	Maintenance				
Advanced oxidation processes (AOP)	Photocatalytic oxidation	Not avail.	Not avail.	Moderate level	Risk of toxic byproduct formation, corrosive, phytotoxicity on fine roots of young plants, space consuming	Effective against pathogens, chemical (pesticides), and organic compound (growth inhibitors)	Needs controlled process conditions, filtration system for catalyst is required for water reuse
Physical processes	UV-C light	18000 €	1800 €/ 10000 operation hours	Moderate level	High investment costs	Effective and reliable, automated water treatment	Treatment is highly dependent on water transmission
	Thermal disinfection	25000 €	Not avail.	Moderate level	High energy consumption, poor reliability of the heaters due to mineral deposits, high investment costs	Automation of the water treatment, suitable for small greenhouses	Poor reliability of the heaters and quick equipment deterioration, treated water requires acidification to avoid carbonate deposits and needs to be cooled down to avoid root damages, needs management of standby temperature between two disinfections to avoid waste of energy
Biological processes	Slow sand filtration	65000 €	0,13 €/m^3	Low level	High installation and investment costs	Solution to eliminate soil-borne pathogens, green technology	*Fusarium*, virus and nematodes are only partly removed by this technology
	Biofiltration	18000 €	0,04 €/m^3	Low level	Slow filtration flow, large storage volume, poor knowledge about efficacy on *Clavibacter* and viruses, high investment costs	Effective against fungi but less against bacteria, preserve microbiological balance in reuse water, no influence on treated water (pH, nutrient content), green technology	Tank must be seeded to improve disinfection, takes a lot of space if treated volumes are high, optimum temperature for biological activity of filtration ranges from 15 to 25°C
Preparation of irrigation water	Airlift	Not avail.	0,07 €/m^3	Low level	None	Increases level of dissolved oxygen in the water, improves water quality, simple system, reliable	For all crops with water storage, poor knowledge on the benefits of aerating storage water due to lack of experience and research

6.3. Chemical oxidation

(Authors: Jan Willem Assink[22], Willy Vantongeren[22], Nico Enthoven[20])

6.3.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

6.3.2. Region

All EU regions.

6.3.3. Crops in which it is used

All crops.

6.3.4. Cropping type

All cropping types.

6.3.5. Description of the technology

6.3.5.1. Purpose/aim of the technology

Chemical oxidation processes convert hazardous contaminants into non-hazardous contaminants or less toxic compounds that are more stable, less mobile, and/or inert.

At horticulture growing companies, chemical oxidation is mainly used for reuse of drain water and can also be used for the reduction of crop protection agents in discharge water to fulfil on local legislation.

6.3.5.2. Working Principle of operation

The oxidising agents most commonly used are O_3, H_2O_2, NaClO, chlorine dioxide, persulphates (e.g. persulfate), peroxyacetic acid or combinations thereof.

Other oxidising agents may have important restrictions in terms of costs, sludge formation and/or high risk of toxic by-product formations. The description focuses on the removal of dissolved organics and disinfection. A combination of other techniques is often applied for partial removal of contaminants.

Most chemical oxidation processes are established technologies within the process industry; like drinking water production, treatment of contaminated groundwater, swimming pools as well as other applications.

Chemical oxidation involves the controlled addition and generation of oxidising agents to water. A sufficient contact time is needed to disinfect, but also to transform pollutants. Most of the times, this takes 10-30 minutes, occasionally up to 60 minutes or more. It is a temperature depended process that will be faster at higher temperatures and slower at lower temperatures.

The installation consists of a buffer tank, a tank or pipe reactor with a static mixer, a dosing unit for the oxidant as well as a storage tank for the oxidant or an O_3 generator. One or more sensors like transparency or mass flow may be used to control the right dosage of an oxidant.

It is relatively expensive to remove high concentrations of organic compounds just by chemical oxidation. Therefore, this technology is often applied in combination with others.

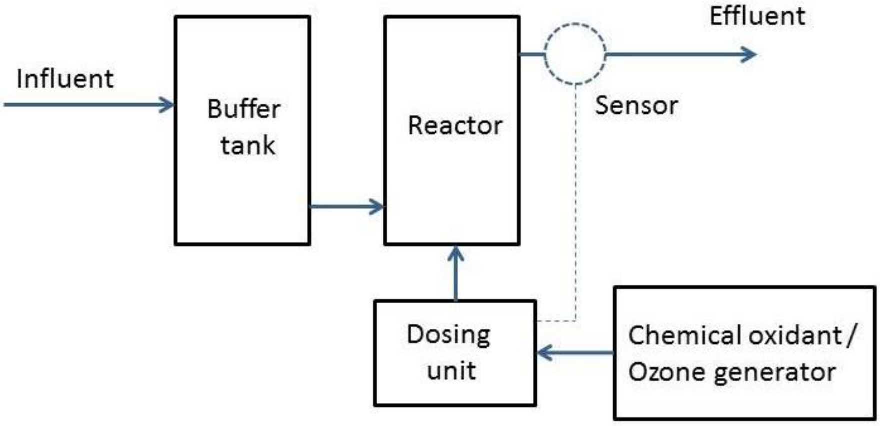

Figure 6-1. General operating scheme of chemical oxidation technology

6.3.5.3. Operational conditions

Consultation with the supplier, installer or crop advisor is usually required to define the best oxidising agent and process conditions; like the amount of dosage, retention time, preferred pH value or required pre-treatment. Pre-treatment for removal of suspended particles is important for an effective oxidation process. This can be done with for example sand, band or cartridge filtration.

Disinfection requires a certain "time*concentration" value to obtain a certain kill-off of micro-organisms. Spore-forming organisms require the highest "time*concentration" values.

Chemical disinfection with O_3 can be achieved by bringing water in contact with gaseous O_3. Ozone is usually on-site produced from (dry) air or pure oxygen. Concentrations vary between 5-12wt%. Ozone is best applied at low Chemical Oxygen Demand (COD) streams (< 100 mg COD/L), because of its low solubility in water (< 30 mg O_3/L).

Hydrogen peroxide is often delivered as a 30-50wt% solution and may be applied at higher COD concentrations (typically < 500 mg COD/L).

Values between approximately 0,01 and 5 mg/L*min are reported for $\log_2$ removal of micro-organisms and viruses. Nevertheless, oxidants will differ in effectiveness. For instance, cysts and spores are difficult to remove, whereas rotaviruses and *Escherichia coli* are very easily removed.

Ozone is more effective than H_2O_2 because certain types of organism possess peroxygenase to guard themselves against oxidation.

6.3.5.4. Cost data

Operation costs for hydrogen peroxide differ between 0,4-1,0 €/kg pure H_2O_2 but vary per country. Ozone requires approximately 6-15 kWh/kg O_3 produced (high values are reported for insufficiently dry feed gasses or very high O_3 concentrations). These values increase to 17-30 kWh/kg O_3 in the case of adding air. Oxygen costs are approximately 140-200 €/ton.

An investment cost of roughly 100000 € is required for an O_3 generator with a capacity of 1,5 kg O_3/h (i.e. a generator for treating approx. 1-2 kg COD/h).

6.3.5.5. Technological bottlenecks

Chemical oxidation processes will often end up in carboxylic acids; these are much more difficult to remove by O_3 or hydrogen peroxide alone. They are very suitable for treatment of aromatic and unsaturated compounds.

Restrictions are found in the following situations:

- High COD content (> 500 mg/l), resulting in high dosages and hence high treatment costs
- High amounts of radical scavengers, like bicarbonates, resulting in higher dosages
- Toxicity of the treated water when insufficient oxidant is used (e.g. nitrosamides)
- Toxicity of the oxidant itself, especially O_3
- Toxicity of the oxidant for the plant, especially the roots

6.3.5.6. Benefit for the grower

Advantages

- Effective disinfection (however, it requires threshold levels and contact time)
- Partial removal of organics, including growth inhibitors and pest control chemicals
- No removal of inorganics, such as potassium (K), nitrogen (N) and phosphorous (P). Phosphorous may harm fertilisers like iron chelates

Disadvantages

- Some selectivity in the removal of contaminants (aromatics and unsaturated compounds are quickly removed)
- Need for controlled process conditions and tests on residues
- Relatively high risk of toxic by-product formation (e.g. chlorate)
- Relatively high investments for an O_3 generator
- Corrosiveness of oxidants (materials for reactor and piping should be carefully selected, such as PVC, glass-lined reactors or other corrosive-resistant materials)
- Installation by a specialised company, especially required when O_3 is used

6.3.5.7. Supporting systems needed

Pre-treatment will be necessary or economically attractive when the water contains high amounts of dissolved organics (> 100 mg COD/L) or suspended particles (> 10 mg/L). Flocculation and filtration are commonly considered techniques. In case of O_3, safety measures need to be considered on the exhaust gas to prevent the escape of O_3 to the surroundings (for example carbon filters or heat). Also drying of air or reused oxygen may be needed for a high efficiency of the O_3 generator (cooling, compression, absorption).

In the case of hydrogen peroxide, one may need to remove the excess dose of hydrogen peroxide. This is done by a large inert, but the still reactive area, such as activated carbon filters. Also, a UV treatment or a pH-change could achieve this. In the case, a limited conversion of contaminants occurred (i.e. at low oxidant dosage), a post-treatment may be required for “polishing” (i.e. membrane filtration or biological treatment) before discharge to the environment is possible. Low concentrations of organics may also be adsorbed on carbon filters.

6.3.5.8. Development phase

Commercialised for different applications.

6.3.5.9. Who provides the technology

- Wedeco - Xylem (http://www.xylem.com/treatment/us/brands/wedeco)
- Degremont (http://www.degremont-technologies.com/~degremon/-Ozonia-68-)
- Enviolet (http://www.aquaconcept.de/en/uv-technology/uv-reactors-for-uv-oxidation.html)
- Logisticon (http://www.logisticon.com/en/technologies)
- Van Remmen (http://www.vanremmen.com/aop-advanced-oxidation-process-en)
- AgroZone (http://www.agrozone.nl/producten-p24lm)
- Priva (https://www.priva.com/products/vialux)

6.3.5.10. Patented or not

System suppliers build their own systems. Special aspects may be patented, such as minor improvements in the O_3 generator, but usually, chemical oxidation is a well-known concept, which has been applied to many aqueous streams for several decades.

6.3.6. Which technologies are in competition with this one?

Major competitors for water with high COD’s are biological conversion and membrane separation technologies (ultrafiltration, nanofiltration, possibly reversed osmosis). The first alternative may be hindered by the variability (and toxicity) of the water and the second alternative by the fact that membrane fouling may occur, so there is a need to dispose or treat its waste. Carbon adsorption may be considered when the stream has low COD levels. More information can be found on the corresponding technology sheets.

6.3.7. Is the technology transferable to other crops/climates/cropping systems?

The system is broadly applicable for all types of water but requires that the subjects under "bottlenecks" and "disadvantages" are considered.

6.3.8. Description of the regulatory bottlenecks

It should be considered that discharge water can be toxic and retains nutrients. Discharge should only take place when parameters like COD or biological oxygen demand are within the usual limits set by local, national or European regulations. Regulations may also require continuous monitoring of oxidants in the effluent.

6.3.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks.

6.3.10. Techniques resulting from this technology

A variety of technology combinations can be done, including chemical oxidation or advanced chemical oxidation:

- Dosing of hydrogen peroxide to an UV-circuit for advanced oxidation
- Addition of O_3 and hydrogen peroxide to a ceramic filtration system for drain water disinfection and crop protection agent removal in discharge water

6.3.11. References for more information

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[5] Water treatment selection system (WASS), 2010 (https://emis.vito.be/en/node/33467)

6.4. Chlorination

(Authors: Ronald Hand[24], Marinus Michielsen[20])

6.4.1. Used for

Preparation of irrigation water.

6.4.2. Region

All EU regions.

6.4.3. Crops in which it is used

All crops.

6.4.4. Cropping type

All cropping types.

6.4.5. Description of the technology

6.4.5.1. Purpose/aim of the technology

Growers, packers and processors in the horticulture and agriculture industry require fresh water, free of human and plant pathogens. This method is used to kill certain bacteria, viruses and fungi. It is applied to irrigation and fertiliser dosing purposes, post-harvest washing, hydro-cooling, surface and equipment cleaning.

6.4.5.2. Working Principle of operation

Chlorine is added to water as either sodium hypochlorite (NaClO), calcium hypochlorite or as chlorine gas. The form used most frequently in Europe is sodium hypochlorite. Sodium hypochlorite is purchased as a liquid concentrate that is injected into water using a simple electric dosing pump, see figure below. Calcium hypochlorite is normally purchased as solid granules that need to be dissolved into a water solution prior to injection by a liquid pump or a dosing channel using a venturi. When chlorine is added, it reacts with water by hydrolysis to form a hypochlorous acid – the main active ingredient of chlorination.

Dissolved, the disinfectant will break down to form active (free) chlorine: hypochlorite acid (HOCl) and hypochlorite ions (OCl). In the case of sodium hypochlorite:

$$NaClO + H2O \leftrightarrow Na^{+} + OH^{-} + HOCl$$

$$HOCl \leftrightarrow H^{+} + OCl^{-}$$

HOCl is a stronger oxidising agent than OCl, and is more effective as a disinfectant. Therefore, a lower pH (more acidic) is favourable to achieve a more effective disinfection.

Figure 6-2. Sodium hypochlorite injection system using an electric pump and reservoir water at a UK ornamental nursery

6.4.5.3. Operational conditions

The extent of disinfection required for the water depends on its organic matter and microbial loading and its origin (i.e. reservoir and surface water are commonly treated, but well and mains water are not often treated, depending on water quality). Hypochlorous acid (HOCl) and hypochlorite ion (OCl) exist in equilibrium depending on water pH. At a pH of 7,5, 50% of the HOCl is dissociated to OCl^-. At pH 6 the HOCl is only dissociated to 3% of OCl^-. Hypochlorous acid is 80-100 times more effective as OCl^-. Therefore, the ideal pH to disinfect water tends to pH 6.

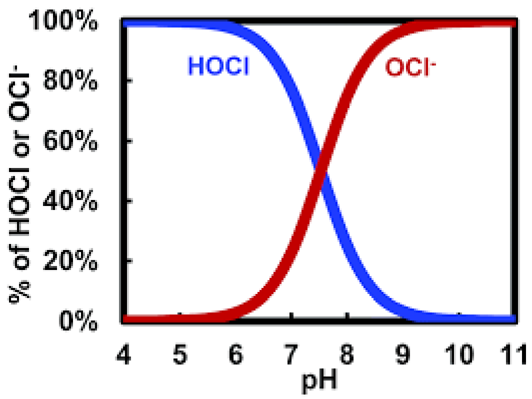

Figure 6-3. Hypochlorous acid and Hypochlorite Ion effectiveness at a certain pH (Qin et al. 2015)

The effective concentration of HOCl depends on the type of the waterborne microorganisms. For instance, a treatment with 0,6 mg/L of NaClO during 10 minutes is enough to inactivate 100% of *Botrytis cinerea* propagules but for *Phytophthora spp.,* the effective treatment is 5 mg/L of NaClO during 1 minute to inactivate 100% of the propagules. A complete list of chlorine efficacy on waterborne microorganisms is available in the review article wrote by Raudales*et al.* (2014).

6.4.5.4. Cost data

- Installation costs: Very little information is available regarding costs. The calculated costs below are based on work by one person in the United States, working with growers. The amounts have been converted to Euros and metric measurements (Table 6-1). The estimated installation costs are 2837 €, including establishment costs of wells, ponds or rainwater systems and the purchase price of pumps
- Yearly maintenance or inputs needed: The costs of chlorine dioxide did not change between 10000-100000 L of water per day suggesting that chlorine dioxide may be more cost-effective for large volumes of water. Looking at the costs for 10000 L in Table 6-1, UV disinfection may be more cost-effective

Fund-intensive technologies with lower consumable costs have advantages from economies of scale where large volumes of water are treated.

Table 6-1. Capital and running costs for chlorination systems based on several growers in the USA

	Capital total cost	Annual total cost	Marginal cost in €/1000 L (percentage from total cost)			
			Capital	Consumables	Labour	Total cost
Calcium hypochlorite	2837 €	1701 €	0,08 (22%)	0,15 (44%)	0,11 (33%)	0,34
Sodium hypochlorite	4583 €	1701 €	0,11 (33%)	0,11 (33%)	0,11 (33%)	0,34

6.4.5.5. Technological bottlenecks

It may not be an appropriate treatment for waters containing high concentrations of dissolved organic matter. It is important to pre-filter water before treatment.

An electric dosing pump or a venturi driven dosing channel are required to inject the sodium hypochlorite liquid concentrate into the irrigation water. The materials have to be resistant to corrosion.

6.4.5.6. Benefit for the grower

Advantages

- Relatively simple to install and maintain
- Long record of successful use
- Creates environment hostile to algae growth
- Keeps pipework and irrigation system clean
- Economic installation
- Residual disinfectant activity

Disadvantages

- High rates could cause phytotoxicity
- Chlorate is a competitive inhibitor of iodine uptake in the thyroid
- Risk of organochlorine formation
- Chlorine reacts with ammonia and cannot be used with nitrogen fertilisers (precipitation occurs). Pure chlorine gas may react vigorously with ammonia gas. An excessive mix of the two gases in the air can produce hazardous compounds such as the explosive nitrogen trichloride. In facilities that use chlorination, the pure chlorine and ammonia need to be stored in separate, sealed rooms or buildings
- The hypochlorite reacts with (soluble) iron or manganese to form insoluble precipitants, like mineral fouling of irrigation lines. The chelated iron is much less affected
- Corrosive
- Chlorates can build up in edible products
- Depending on the concentration, dosed water needs to be stored for a time to allow dissipation of chlorine

6.4.5.7. Supporting systems needed

Filtration systems to remove organic matter and other particulates are needed.

6.4.5.8. Development phase

This technology is commercialised.

6.4.5.9. Who provides the technology

- Netafim
- Mazzei
- Swimming pool supply stores (calcium hypochlorite)
- Industrial chemical suppliers
- Farm suppliers

6.4.5.10. Patented or not

This technique is not patented.

6.4.6. Which technologies are in competition with this one?

- Dioxychloration and chlorination
- Alternative technologies such as O_3, copper salts, hydrogen peroxide, iodine

6.4.7. Is the technology transferable to other crops/climates/cropping systems?

The system is broadly applicable for all types of water but requires that the subjects under "bottlenecks" and "disadvantages" are considered.

6.4.8. Description of the regulatory bottlenecks

Chlorine, Sodium Hypochlorite and Calcium Hypochlorite are listed in the BPR EU 528/2012 which concerns the making available on the market and use of biocidal products.

6.4.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks.

6.4.10. Techniques resulting from this technology

There are no techniques resulting from this.

6.4.11. References for more information

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[2] Raudales, R. E. (2014). Characterization of water treatment technologies in irrigation. University of Florida http://ufdc.ufl.edu/UFE0046234/00001

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[5] Qin, Y., Kwon, H. J., Howlader, M. M., & Deen, M. J. (2015). Microfabricated electrochemical pH and free chlorine sensors for water quality monitoring: recent advances and research challenges. *RSC Advances*, *5*(85), 69086-69109

6.5. Ozonisation

(Authors: Ronald Hand[24], Benjamin Gard[*])

6.5.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

6.5.2. Region

All EU regions.

6.5.3. Crops in which it is used

All crops.

6.5.4. Cropping type

All cropping types.

6.5.5. Description of the technology

6.5.5.1. Purpose/aim of the technology

This technology aims to treat drain water from pathogens, which allows recirculation of the drain water. Ozone (O_3) is used for disinfection by ozonisation that is produced by an O_3 generator. Ozone is injected directly into the drain water and induces oxidation of microorganisms (fungi, microorganisms and viruses) and organic matter leading to their destruction.

6.5.5.2. Working Principle of operation

Disinfection by ozonisation is based on the oxidation of organic compounds. The oxidative action of O_3 is twofold: a direct oxidation of organic compounds by O_3 and an indirect oxidation due to the production of free radicals (O-H) coming from the decomposition of O_3 in water.

Chemical oxidation processes like ozonisation involve the controlled addition and generation of oxidants to the wastewater. A sufficient contact time is needed to disinfect, but also to transform the pollutants (typically 10-30 minutes, occasionally up to 60 minutes or more). The kinetics of the deactivation of microorganisms (disinfection) is comparable to a chemical reaction. The most commonly used model to describe water disinfection by O_3 is a first-order reaction (Chick-Watson law):

$$k = C * t$$

- k = reaction-constant, dependent on the type of microorganism and the disinfectant
- C = dissolved O_3 concentration (mg/L)
- t = contact time, a period of time that the disinfectant is in contact with water

Values for k may widely vary; values between 0,01 and 5 mg/L*min are reported for log_2 removal of micro-organisms and viruses. Variations are mainly depending on the resilience of the organisms against oxidation. For instance, cysts and spores are difficult to remove, whereas rotaviruses and *Escherichia Coli* are very easily removed. In order to obtain a certain ozone*time level, a lead time should be given for other dissolved contaminants that quickly react with O_3, before the actual disinfection begins. Ozone is more effective than H_2O_2, also because certain types of organism pose peroxygenase to guard themselves against oxidation. Suppliers can provide more detailed information.

Ozone treatment of discharge and drain water is approved in the Netherlands to be used as treatment technology at horticulture growing companies to meet the requirement of more than 95 % reduction of crop protection agents.

The installation for chemical oxidation based on O_3 consists of a buffer tank, a reactor (tank or pipe reactor with static mixer), and a dosing unit for the oxidant as well as a storage tank for the oxidant or an O_3 generator.

Chemical oxidation like ozonisation is often operated in a process train because it is relatively expensive to remove high concentrations of organic compounds by this technology alone. Therefore upstream treatments are used to remove the bulk of pollutants or interfering compounds (e.g. particles and some specific radical). Downstream processing may be applied to remove residues of the added oxidant and incompletely converted pollutants; this may be biological treatment in the case of partial conversion or active carbon filtration for polishing of streams. Membrane treatment may also be considered.

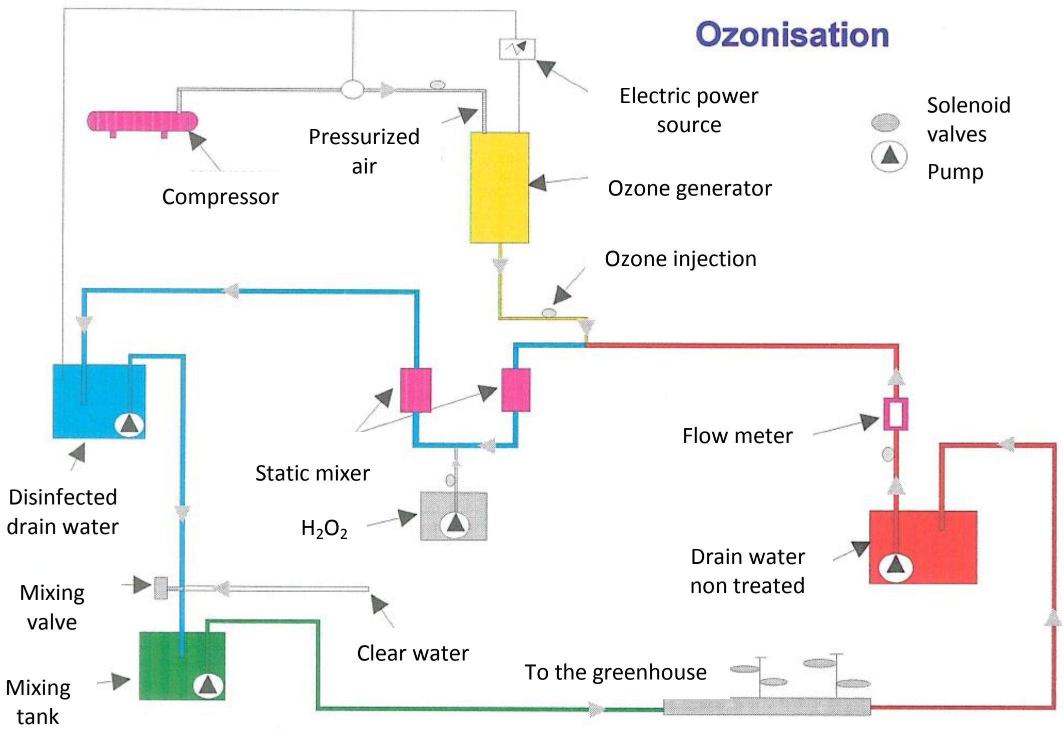

Figure 6-4. Operating scheme of disinfection of drain water by ozonisation, using air (source: CATE, 1997)

6.5.5.3. Operational conditions

Ozone is a very unstable gas and very toxic to human health (lethal at a concentration of 4 ppm). Besides, it is very corrosive for irrigation network equipment. Hence, it must be produced directly on site, on demand and immediately mixed into the water to treat in order to lower the concentration and avoid any undesirable effect. Ozone generators use O_2 present in the atmosphere to produce O_3. The efficacy of disinfection is dependent on various factors: the concentration of organic matter in the drain water, the flow, the contact time and the concentration of O_3 in the solution. Recommendations for a complete disinfection are 8-10 g O_3/m^3 of treated water, for a contact time of 1-2 seconds. Ozone is best applied on low COD streams (< 100 mg COD/L), because of its low solubility in water (< 30 mg O3/L). When coupled with peroxide, the ideal ratio is 0,15 g H_2O_2/g O_3. These parameters allow 2-6 m^3/h of the solution to be treated.

6.5.5.4. Cost data

The Table 6-2 gives the capacity and costs for O_3 standing water, tides with phenol removal and tides with a full purification treatment.

Table 6-2. Cost data for installation and maintenance of an ozone disinfection system

System	Capacity	Investment	Maintenance/year	Consumption
Ozone standing water	10 - 100 m^3/day	40000-100000 €	2000 €	10 m^3 = 1,5 kwh (0,5 kwh for installation, 1 kwh for pump); 100 m^3 = 6,2 kwh
Tides, only fenol removal	4 - 10 m^3/h	30000-40000 €	1000 €	
Tides, full purification treatment	10 - 66 m^3/h	40000-100000 €	2000 €	

Chemical oxidation requires approximately 0,5-2,0 kg O_3 per kg COD or 0,8-5,0 kg H_2O_2 per kg COD, for partial conversion of organics. These data relate to 100% purity of the oxidant; O_3 is usually produced on-site from (dry) air or pure oxygen (concentrations O_3 between 5-12wt%) and hydrogen peroxide is often delivered as 30-50wt% solution. In all cases, the actual dosages are different for each nursery.

- Capex costs for an installed process: an investment cost of roughly 100000 € is required for an O_3 generator with a capacity of 1,5 kg O_3/h (i.e. a generator for treating approximately 1-2 kg COD/h)
- Opex costs: hydrogen peroxide costs vary between 0,4 and approximately 1 €/kg pure H_2O_2, depending on the distance and size of the truck delivery. Ozone requires 6-15 kWh/kg O_3 produced (high values are reported for insufficiently dry feed gasses or very high O_3 concentrations). These values increase to 17-30 kWh/kg O_3 in case of air. Oxygen costs are 140-200 €/ton

6.5.5.5. Technological bottlenecks

The high toxicity and the risk linked to the use of O_3 in a space with working people can be a bottleneck. Chemical oxidation is a non-selective technique, i.e. almost all organics are degraded; treatment with non-AOP's will often end up in carboxylic acids, these are much more difficult to remove by O_3 or hydrogen peroxide alone. Non-AOP's are very suitable for treatment of aromatic and unsaturated compounds.

Restrictions are found in the following situations:

- high COD content (> 500 mg/L), resulting in high dosages and hence high treatment costs
- high amounts of radical scavengers, like bicarbonates, resulting in higher dosages (relevant for all AOP's)
- toxicity of the treated water when the insufficient oxidant is used (e.g. Nitrosamides)
- toxicity of the oxidant itself, especially O_3

6.5.5.6. Benefit for the grower

Advantages

- Destroys bacteria, fungi and viruses
- Partial removal of organics and growth inhibitors
- Removal of pest control chemicals like atrazine
- Increased dissolved oxygen concentration
- Reduction of iron and manganese concentrations
- No removal of inorganic minerals such as K, N and P
- pH can be kept constant when combined with hydrogen peroxide

Disadvantages

- Toxicity (of by-products)
- Sufficient contact time of the O_3 and the water required to be effective
- Dangerous manipulation
- Risk for working people
- Perfect sealing necessary to avoid gas leaks
- Strictly controlled process conditions required
- No immediate control of the efficiency possible
- Some selectivity in the removal of contaminants
- High investments needed for the O_3 generator
- Corrosiveness of oxidants (materials for reactor and piping should be carefully selected, such as PVC, glass-lined reactors or other corrosive-resistant materials)
- Installation by a specialised company is required when O_3 is used

Figure 6-5. Ozone installation for horticultural water treatment (https://www.glastuinbouwwaterproof.nl/)

6.5.5.7. Supporting systems needed

Pre-treatment will be necessary or economically attractive when the water contains high amounts of dissolved organics (>100 mg COD/L) or suspended particles (>10 mg/L). Flocculation and filtration are commonly considered techniques.

In the case of O_3, one needs safety measures on the exhaust gas to prevent the escape of O_3 to the surroundings (carbon filters, heat). Also drying of air or the reused oxygen may be needed for high efficiency of the O_3 generator (cooling, compression, absorption). To lower the concentration of O_3 involved in the disinfection treatment, it is possible to couple ozonisation with H_2O_2 injection. The addition of 0,15 g of H_2O_2 per g of O_3 allows the concentration of O_3 to be reduced by half for an equivalent action of disinfection.

In the case, a limited conversion of contaminants occurred (i.e. at low oxidant dosage), a post-treatment may be required for "polishing" (i.e. membrane filtration or biological treatment) before discharge is possible to the environment. Low concentrations of organics may also be adsorbed on carbon filters.

One or more sensors (UV transparency, mass flow) may be used to control the right dosage of oxidant.

6.5.5.8. Development phase

This technology is commercialised.

6.5.5.9. Who provides the technology

Many suppliers provide the technology, for example:

- Wedeco - Xylem (https://www.xylem.com/en-us/products-services/treatment-products-systems/disinfection-and-oxidation/ozone-systems/)
- Degremont - Suez (http://www.degremont-technologies.com/-Ozone-)
- Logisticon (http://www.logisticon.com/en/disinfection)
- PRAXAIR (http://www.praxair.com/industries/water-and-wastewater-treatment/disinfection)
- AGROZONE (http://www.agrozone.nl/aquazone)

6.5.5.10. Patented or not

The technology is patented, several patents exist for the different parts of the process (O_3 production, mixing with water, distribution, excess O_3 removal).

6.5.6. Which technologies are in competition with this one?

All technologies based on advanced oxidation process such as: UV-C disinfection, chlorination, peroxide disinfection, photocatalytic oxidation, etc.

Other major competitors for streams with moderate-high COD are biological conversion and membrane separation (ultrafiltration, nanofiltration, possibly reversed osmosis). The first alternative may be hindered by the variability (and toxicity) of the water stream and the second alternative by the fact that membrane fouling may occur and the need to treat its retentate. Carbon adsorption may be considered when the stream has (very) low COD levels (high COD levels will lead to frequent replacements of the filter volume that increases costs).

6.5.7. Is the technology transferable to other crops/climates/cropping systems?

This technology works for all crop types with no climate restriction.

6.5.8. Description of the regulatory bottlenecks

Regulatory bottlenecks are inherent to the use of a toxic gas in an area with working people around. Hence, there is a restriction on use and storage. At the European level, O_3 is registered as a biocide and the use is under the Biocidal Products Regulations (EU) 528/2012 framework (see for more details, http://www.euota.org).

Discharge of both AOP and non-AOP treated water is likely to be addressed in terms of toxicity and remaining nutrients, assuming the other parameters (COD, biological oxygen demand, etc.) are within the usual limits set in local, national or European rules. Regulations may also require continuous monitoring of oxidants in the effluent.

6.5.9. Brief description of the socio-economic bottlenecks

No socio-economic bottlenecks have been identified so far. However, O_3 toxicity for employees may hinder the use of this technology.

6.5.10. Techniques resulting from this technology

Many variants, treatment trains and applications may be considered, in which O_3 is useful. Further treatment of discharges by membrane separation can be considered. The simplest and most effective alternatives for horticulture can be the treatment of retentates from membrane techniques, in order to reuse nutrients and avoid discharges. The concentrations in the retentate should not be too high in order to avoid slow degradation (e.g. caused by radical scavengers).

6.5.11. References for more information

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[2] Martinez, S. (2005). Procédé d'optimisation de la gestion du recyclage des effluents des serres (PR.O.G.R.E.S). Institut National Polytechnique de Toulouse. Ph-D thesis

[3] Cees de Haan, Agrozone, cdh@agrozone.nl

[4] Pieter Duin, Proeftuin Zwaagdijk, personal communication

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[6] Derden, A., Schiettecatte, W., Cauwenberg, P., Van Ermen, S., Ceulemans, J., Helsen, J., … Hoebeke, L. (2010). Water treatment selection system (WASS). VITO, Boeretang, Belgium (https://emis.vito.be/en/node/33467)

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6.6. Peroxide

(Authors: Ilse Delcour[19], Benjamin Gard[*])

6.6.1. Used for

- Preparation of irrigation water
- More efficient use of water by recirculation

6.6.2. Region

All EU regions.

6.6.3. Crops in which it is used

All crops.

6.6.4. Cropping type

All cropping types.

6.6.5. Description of the technology

6.6.5.1. Purpose/aim of the technology

This technology aims to treat drain water and irrigation tubes against pathogens, allowing recirculation on the crop. Peroxide induces a chemical oxidation in the treated water, which kills bacteria, fungi, algae, viruses and removes biofilm.

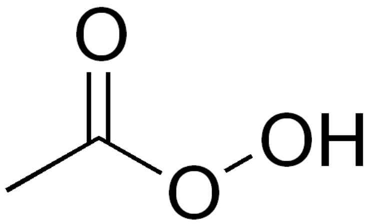

Figure 6-6. Peracetic acid

6.6.5.2. Working Principle of operation

The peroxide ion consists of a single bond between two oxygen atoms: $(O\text{-}O)^{2-}$. The bond between the two oxygen atoms of the peroxide ion, the so-called peroxide bond, is very unstable and easily splits into radicals with strong oxidative activity. Several chemical compounds contain the peroxide ion (O_2) such as peracetic acid or H_2O_2, the latter being the most economically important peroxide.

Decomposition of chemical compounds containing a peroxide ion produces H-O radical forms (also called free radicals). These radicals quickly react with other substances, while new radicals are formed and a chain reaction takes place. H-O radical is a strong oxidiser and a good disinfectant. H-O radical induces an oxidation of proteins, membrane lipids and DNA of microorganisms, resulting in their destruction. It will then disintegrate into hydrogen and water, without the formation of by-products.

Peroxides are unstable; therefore stabilisers like silver nitrate or peroxyacetic acid are added. The efficiency of hydrogen peroxide depends on several factors, such as pH, catalysers, temperature, peroxide concentration and reaction time. For water treatment, concentrations of 30-50wt% H_2O_2 are used. Peroxides are added to the water in calculated doses, dependent on the water quality and the sensitivity of the crop.

6.6.5.3. Operational conditions

The dose is dependent on the crop sensitivity and the water quality, which have to be closely monitored. A dosing system is required.

6.6.5.4. Cost data

Only costs of the product are needed, these vary among the commercially available products, a good average price is 0,73 €/m³ of water to disinfect.

6.6.5.5. Technological bottlenecks

No technological bottleneck has been identified so far.

6.6.5.6. Benefit for the grower

Advantages

Oxidative compounds are also effective against biofilm and allow irrigation lines to be kept clean from it.

Disadvantages

The risk of root damage is significant if the concentration of the oxidative compound is too high in the solution recirculated on the crop. Systems for trapping oxidative compounds are needed to avoid this risk.

6.6.5.7. Supporting systems needed

A dosing system like a venturi driven dosing channel or a dosing pump is required.

6.6.5.8. Development phase

This technology is commercialised.

6.6.5.9. Who provides the technology

- Certis (http://www.certiseurope.co.uk/products/miscellaneous/detail/article/jet-5.html)
- Yara (http://www.yara.co.uk/?home=1)
- Hortiplan (http://www.hortiplan.com/en/home/)
- Brenntag: (http://www.brenntag.com/france/fr/index.jsp)
- Priva (https://www.priva.com/products/vialux)

6.6.5.10. Patented or not

This technique is not patented.

6.6.6. Which technologies are in competition with this one?

Electrolysis, chemical disinfection with hypochlorite and all advanced oxidative processes that produce peroxide.

6.6.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this technology is transferable to all crops.

6.6.8. Description of the regulatory bottlenecks

In the USA, H_2O_2 was registered as a pesticide by the Environmental Protection Agency in 1977.

Hydrogen peroxide is not mentioned in the European Drinking Water Standard 98/83/EC. Hydrogen peroxide is a biocide according to EU legislation (http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015R1730&from=EN).

In France, it is not allowed to treat drain water with peroxyacetic acid.

6.6.9. Brief description of the socio-economic bottlenecks

No socio-economic bottleneck has been identified so far.

6.6.10. Techniques resulting from this technology

- Jet 5: 10 g/L peroxide + 55 g/L peractic acid as stabiliser, produced by Certis
- Antibloc Organic (by Yara): 45-50wt% peroxide + 0,5-5,0% peractic acid as stabiliser,
- Hydroclean (by Hortiplan): 50wt% peroxide + 0,36 g/L Ag as stabiliser
- Brenntag (by Brenntag): 27,5wt% peroxide
- Reciclean (by Kemira) W1+W2: 35wt% = 395,5 g/L in W1 + 15% performic acid in W2
- Ecoclearprox (by ABT): 42wt% peroxide + Sorbitol as stabiliser
- Chlorinated Ecoclearprox (by ABT): 42wt% peroxide + Sorbitol + 2% Cl as stabiliser

6.6.11. References for more information

[1] Wikipedia (https://en.wikipedia.org/wiki/Peracetic_acid)
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6.7. Copper/Silver ionisation

(Author: Ilse Delcour[19])

6.7.1. Used for

- Preparation of irrigation water
- More efficient use of water by recirculation

6.7.2. Region

All EU regions.

6.7.3. Crops in which it is used

All crops.

6.7.4. Cropping type

All cropping types.

6.7.5. Description of the technology

6.7.5.1. Purpose/aim of the technology

High concentrations of copper can bind to protein prosthetic groups and disrupt normal cellular protein structure, negatively affecting microbial and plant metabolism. Copper-silver ionisation can deactivate *Legionella* bacteria and other microorganisms in slow-running water and still water. Copper-silver ionisation also takes care of biofilm.

6.7.5.2. Working Principle of operation

Metals such as copper and silver can be used for water disinfection if they are ionised. Electrically charged copper ions (Cu) in the water search for particles of opposite polarities, such as bacteria and fungi. Positively charged copper ions form electrostatic compounds with negatively charged cell walls of microorganisms. These compounds disturb cell wall permeability and cause nutrient uptake to fail. Copper ions penetrate the cell wall and as a result, they will create an entrance for silver ions. These penetrate the core of the microorganism. Silver ions bond to various parts of the cell, such as the DNA and RNA, cellular proteins and respiratory enzymes, causing all life support systems in the cell to be immobilised. As a result, there is no more cellular growth or cell division, causing bacteria to no longer multiply and eventually die out. The ions remain active until they are absorbed by a microorganism. Silver ions disrupt membranes of microorganisms, resulting in cell lysis.

Copper and silver ions can be generated either through electrolysis or as a dissolved salt.

Figure 6-7. Mini-Aquahort (http://www.aqua-hort.dk)

6.7.5.3. Operational conditions

The required concentration of Cu and silver ions is determined by the water flow, the volume of water in the system, the conductivity of the water and the present concentration of microorganisms. The electrodes should be in good condition. When the water is hard or fouling takes place, as a consequence of water hardness and quality, there will be a decrease in electrode release and the additional effect will decrease. By using pure silver and pure copper, the supply of Cu and silver ions can be regulated separately. These electrodes suffer from less limestone formation and fouling. When pH values are high, Cu is less effective. When the pH value exceeds 6, insoluble copper complexes will precipitate. When the pH value is 5, copper ions mainly exist as copper(II) hydrogen carbonate; when the pH value is 7 as Copper(II) carbonate and when the pH value is 9 as $Cu(CO_3)_2$. Copper-silver ionisation affectivity is determined by the presence of chlorine. Chlorine causes silverchlorine complex formation. When this occurs, silver ions are no longer available for disinfection. The effective dose to control microorganisms by copper supplied via electrolysis ranged between 2 and 4 mg/L for several microorganisms. Greenhouses and nursery growers typically apply 1 mg Cu/L of ionised copper to prevent algae build up and control plant pathogens.

6.7.5.4. Cost data

The installation costs of some devices that are based on these principles are given in Table 6-3.

Table 6-3. Installation costs for ionisation devices

Type	Capacity (m^3/hour)	Dimension (L*H*B in m)	Investments (€)	Variable costs (€)
AH 75 Mini	1-15	1,2x1,5x0,4	6615	1058
AH 90 Standard	1-30	1,7x1,4x0,6	8900	1266
AH 75 Tank	3-75	variable	15632-17760	1920

These devices use about 7200 m^3 of water per year. Variable costs are the replacement of the copper, the use of electricity and overhead. The yearly maintenance costs and needed inputs for difference disinfection methods are compared in Table 6-4.

Table 6-4. Maintenance costs for different disinfection methods

Type	Area (m^2)	Type	Cost (€/m^3)
Vegetables	2000	Slow filter	0,70
		Biofilter	1,13
		UV treatment	1,61
		BenRad oxidation	1,08
		Heat Treatment	1,87
Pot plants	1600	Ebb/flood Slow filter	0,29
		Ebb/flood Bio filter	0,53
		Ebb/flood Aqua-Hort	0,09

6.7.5.5. Technological bottlenecks

There are no regulatory bottlenecks.

6.7.5.6. Benefit for the grower

Advantages

- Very suitable for fishpond disinfection
- Large residual effect when compared to most other disinfectants
- Water quality improvement
- Residual effect of copper in the biofilm

CuAg ionisation:

- Effective deactivation of Legionella bacteria and biofilm
- Effective throughout the entire water system, even in dead-end points and parts of the system that contain slow-running water
- Independent of water temperature

- Non-corrosive
- Little maintenance to the water system required
- Little chemical use (no contamination of/effect on lids, pumps, shower heads, tanks and taps)
- No transport and storage difficulties

Disadvantages

Copper:

- Phytotoxicity in a hydroponic system 0,08 mg/L in taro (Colocasiaesculenta) and 5,0 mg/L in woody ornamentals
- Growth/flowering reduction in Calla lilies (*Zantedeschia* spp.) overhead irrigated with water

Silver:

- Precipitation in case of high concentrations
- Reacts easily with chlorines and nitrates in the water
- Resistance of some species of microorganisms
- Ineffective to control *Alternaria*, *Fusarium* spp. and Tobacco mosaic virus
- Potential impact on plant health (inhibits ethylene responses, reduces the number of staminate flowers, reduces petal abscission and plant height)

Combination:

- Lower deactivation rate than O_3 or UV
- Affectivity depends on the pH value of the water
- Water analysis and tests must be conducted to prove system affectivity
- Ions should be present in the entire water system to effectively kill pathogenic microorganisms

6.7.5.7. Supporting systems needed

There is no supporting system needed.

6.7.5.8. Development phase

This technology is commercialised.

6.7.5.9. Who provides the technology

Aqua Hort, Aksel De Lasson (http://www.aqua-hort.dk/).

6.7.5.10. Patented or not

Aqua-Hort is internationally patented.

6.7.6. Which technologies are in competition with this one?

Disinfection with chlorine or UV light.

6.7.7. Is the technology transferable to other crops/climates/cropping systems?

The system is applicable in recirculation systems.

6.7.8. Description of the regulatory bottlenecks

European level

The European Union does not dictate any standards considering silver concentrations in the water. Copper, however, has a maximum value of 20 µg/L, because it corrodes waterworks. Copper concentrations should be measured in taps (EU Drinking water directive 98/83/EC, 1998).

Country level

Copper formulations are regulated by US-Environmental Protection Agency pesticides (1999). Based on the Safe Drinking Water Act, the maximum contaminant level goals for copper in water is 1,3 mg/L (US- Environmental Protection Agency, 2013).

6.7.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks.

6.7.10. Techniques resulting from this technology

Aquahort from Denmark provides a controlled addition of copper-ions and an electromagnetic water treatment with liquid fertiliser.

6.7.11. References for more information

[1] Raudales, R. E., Parke, J. L., Guy, C. L., & Fisher, P. R. (2014). Control of waterborne microbes in irrigation: A review. *Agricultural Water Management*, *143*, 9–28
[2] Lenntech BV (2016) (http://www.lenntech.com/processes/disinfection/chemical/disinfectants-copper-silver-ionization.htm#ixzz4W7WzFkAE)

6.8. *Electrochemically Activated (ECA) water*

(Authors: Ilse Delcour[19], Benjamin Gard[*])

6.8.1. Used for

- Preparation of irrigation water
- More efficient use of water by recirculation

6.8.2. Region

All EU regions.

6.8.3. Crops in which it is used

All crops.

6.8.4. Cropping type

All cropping types.

6.8.5. Description of the technology

6.8.5.1. Purpose/aim of the technology

ECA water is used to clean and disinfect complete water systems.

6.8.5.2. Working Principle of operation

The heart of an ECA unit is the electrolytic cell in which potassium chloride is converted to active chlorine. The unit must be connected to tap water that has been decalcified. At the entrance of the Unit, potassium chloride is added. A current is being sent through the water, which initiates the electrolysis process and forms ECA water with free chlorine radicals in it. The ECA water can be added to the irrigation water by a dosing or injecting pump, preferably at a concentration of 8 ppm.

Table 6-5. Characteristics of Electrochemically Activated (ECA) water

Characteristics	Aquaox	Hortiplan
pH	6,5-8,0	> 8,5
Free Chlorine (FAC)	50-500 mg HOCl/L	4250 mg HOCl/L
EC	<15 mS	45-50 mS
Oxidation / reduction potential		+ 800- 850 mV

Figure 6-8. Installation for ECA water (Hortiplan)

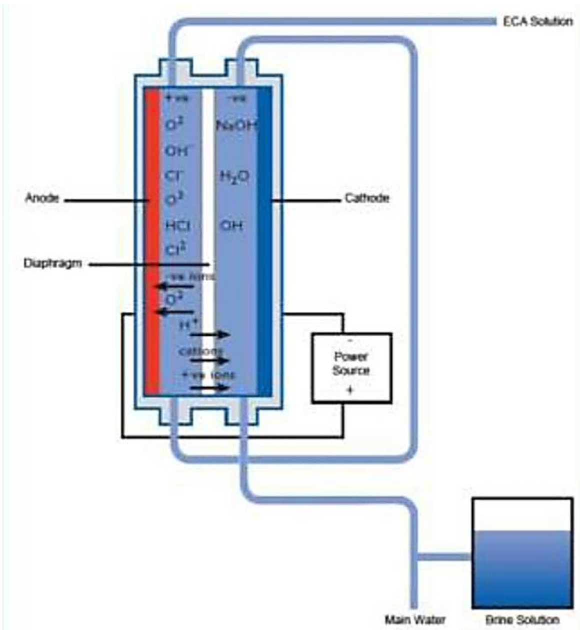

Figure 6-9. Operating principles of ECA technology (Hortiplan)

6.8.5.3. Operational conditions

Making ECA water is strongly influenced by the hardiness, pH and conductivity of the water. Therefore, it is in most cases necessary to pre-treat the water (softening).

Table 6-6. Disinfection capacity of different ECA systems (Hortiplan)

Type	ECA water production (L/ 22 h)	Disinfection capacity per day	
		1‰	2‰
Wafer 80	22 h x 8 L = 176 L	176000 L	88000 L
Wafer 160	22 h x 16 L = 352 L	352000 L	176000 L
Wafer 240	22 h x 24 L = 528 L	528000 L	264000 L
Wafer 320	22 h x 32 L = 704 L	704000 L	352000 L
Wafer 2-50	22 h x 50 L = 1100 L	1100000 L	550000 L
Wafer 2-100	22 h x 100 L = 2200 L	2200000 L	1100000 L
Wafer 2-150	22 h x 150 L = 3300 L	3300000 L	1650000 L
Wafer 2-200	22 h x 200 L = 4400 L	4400000 L	2200000 L

6.8.5.4. Cost data

For a horticultural company with an average of 78500 L of processing water a day: with a WAFER 80, 176 L of ECA water can be produced per day. At 2‰ (8 ppm), 88000 L of processing water can be disinfected every day.

Including the ECA WAFER 80 unit, salt-tanks, magnetic pump and connection materials for the mixing tank, a supply tank of 850 L, a flow meter, the PVC materials, a test kit and the installation, the estimated costs are 17000 € (excl. VAT).

Table 6-7. Costs for producing 1 L of ECA water in case of a Wafer 80

Input	Amounts	Price
KCl salt (99% without anti caking)	20-25 g	0,0290 € for 25 g
Salt for hard water (Broxo or comparable)	Depending on hardiness water ± 4,5 g	0,0027 €
Tap water	1 L	0,0024 €
Electricity	50 Watt	0,0030 €
Longevity cell	2 – 3 years	
Replacement costs cell	0,01 €/L of ECA water produced (undiluted)	0,010 €
TOTAL		0,047 €/L of ECA water produced (undiluted)
	Example horticultural company	3274 L/m²/year => 0,15 €

6.8.5.5. Technological bottlenecks

There are no technological bottlenecks.

6.8.5.6. Benefit for the grower

Advantages

- Production of ECA water on site
- No use of chemicals
- Low energy use (50 Watt/L of ECA water)
- Clears mixing tank, silo's and basements
- Drippers are no longer clogged by organic matter
- Tubes and pipes are free of biofilm
- Eliminates *Phytophthora*, *Pythium*, algae, biofilm, etc.
- No resistance build-up by pathogens
- Higher crop yields
- Green technology
- Efficient
- Pre-treatment for cut flowers
- The technical lifespan of the units is 15 years
- Complies with ISO 9001, CE and ATEX 95 so it is safe

Disadvantages

- Softening of the water is often necessary before ECA water can be made
- Due to scale on the electrodes, the technique requires a lot of maintenance
- Formation of by-products
- Effect on scent and taste at higher chlorine concentrations
- The ECA water is corrosive to metal

6.8.5.7. Supporting systems needed

There are no supporting systems needed.

6.8.5.8. Development phase

Commercialised.

6.8.5.9. Who provides the technology

- Hortiplan (www.hortiplan.com)
- Newtec water systems: no addition of salts. Based on the naturally present salts in the water
- Royal Brinkman: Chlorinsitu
- Spranco: Aquaox

6.8.5.10. Patented or not

Radical Waters (Pty) Ltd has spent over 20 years focused on developing and commercialising its patented green ECA technology. The company has installed operating devices on six continents and in 27 countries primarily for blue-chip companies. Radical Waters' products are used in a wide range of markets formerly dependent on chemicals for controlling contamination and bacterial infection. The company has a focus on markets that include beverage production, meat & seafood, sauce manufacture, milling & starch and hospitality. Radical Waters (Pty) Ltd produces devices in its factory outside Johannesburg, South Africa. Radical Waters International (UK) LLP in London is responsible for international distributor relationships.

List of patents for ECA water production:

- Sterilox Medical (Europe) Limited, Electrochemical treatment of an aqueous solution (EP1074515A2, EP1074515A3, US6632347, US7303660)
- Radical Waters International Ltd., Method for electrochemical activation of water (US9533897)

6.8.6. Which technologies are in competition with this one?

Chlorine dioxide (Di-Ox Forte), Aquahort (copper ions by electrolysis), Reciclean (peracetic acid).

6.8.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this technology is transferable. One limit can be the sensitivity of the crop to chlorine.

6.8.8. Description of the regulatory bottlenecks

The BPR (Regulation (EU) 528/2012) deals with the placing on the market of biocidal products, which are used to protect humans, animals, materials or articles against harmful organisms like pests or bacteria, by the action of the active substances contained therein. This regulation aims to improve the functioning of the biocidal product market in the EU while ensuring a high level of protection for humans and environment.

6.8.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks identified by now.

6.8.10. Techniques resulting from this technology

There are no techniques resulting from this technology.

6.8.11. References for more information

[1] Royal Brinkman (2017). De nieuwe generatie ECA-Units van Royal Brinkman (http://www.royalbrinkman.nl)

[2] Gruwez, J. (2003). Alternatieve desinfectietechnieken voor Legionella: pro en contra's. Studiedag Legionella, 3 april 2003

[3] Spranco-matic. Aquaox Electrolyzed Water (ECA). Folder

[4] Scheers, E. (2003). Ontsmetting met ECA-Technologie. Studiedag Legionella, 3 april 2003
[5] Vissers, M. (2013). Vergelijking waterontsmettingssystemen 2012-2014. PCS

6.9. Photocatalytic oxidation

(Authors: Wilfred Appelman[22], Benjamin Gard[*])

6.9.1. Used for

- Preparation of irrigation water
- More efficient use of water by recirculation
- Minimising the environmental impact by discharge prevention

6.9.2. Region

All EU regions.

6.9.3. Crops in which it is used

All crops.

6.9.4. Cropping type

All cropping types.

6.9.5. Description of the technology

6.9.5.1. Purpose/aim of the technology

The aim of chemical oxidation technologies, such as photocatalytic oxidation is to:

- Remove organic pollutants in water flows by means of chemical conversion into harmless (or less dangerous) substances. Organic substances may be completely degraded to CO_2 and H_2O and possibly inorganics, like hydrochloric acid, HNO_3 and sulphuric acid
- Disinfect water
- Improve colour, smell and/or taste of a water flow
- Remove certain inorganic components (e.g. cyanide and hydrogen sulphide)
- Improve the performance of downstream processes, for instance, biological treatment. The partial oxidisation of organic components (i.e. “cracking” of difficult compounds) makes them more suitable for biodegradation and reduces the bio-toxicity of the water stream. Chemical oxidation may also reduce the amount of sludge by partly oxidising the formed sludge and return it to the bioreactor

6.9.5.2. Working Principle of operation

In Photocatalytic oxidation (PCO) processes, inert, non-toxic, inexpensive catalysts (such as TiO_2) are used in combination with oxygen (from the air), water, and solar light (or another source with UV-A light) to generate OH radicals. The radicals have a strong oxidative effect and can purify water and break down germs and pesticides. TNO research, in collaboration with Productshap Tuinbouw, Priva, TTO, and WUR, has demonstrated that daylight-driven PCO can break down more than 90% of pesticides and removes 99% of pathogens.

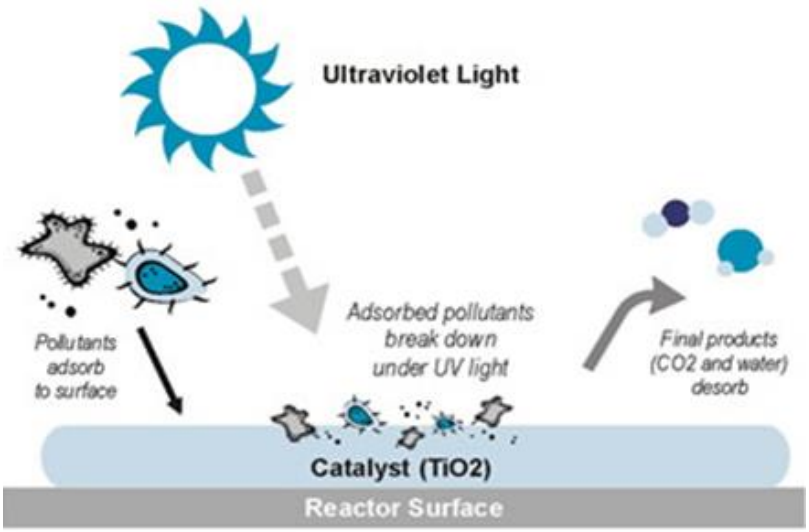

Figure 6-10. Working Principle of Photocatalytic oxidation (http://www.airocide.co.uk/science.htm)

To determine the degradation rate of the crop protecting agents laboratory experiments are conducted (relatively starting concentration of 50-780 ng/ml of each) over time. Figure 6-11 demonstrates the degradation of plant protection products in time. After 10 minutes, an average removal of > 80% (ln c/c 0 < -1,6) of resources is achieved.

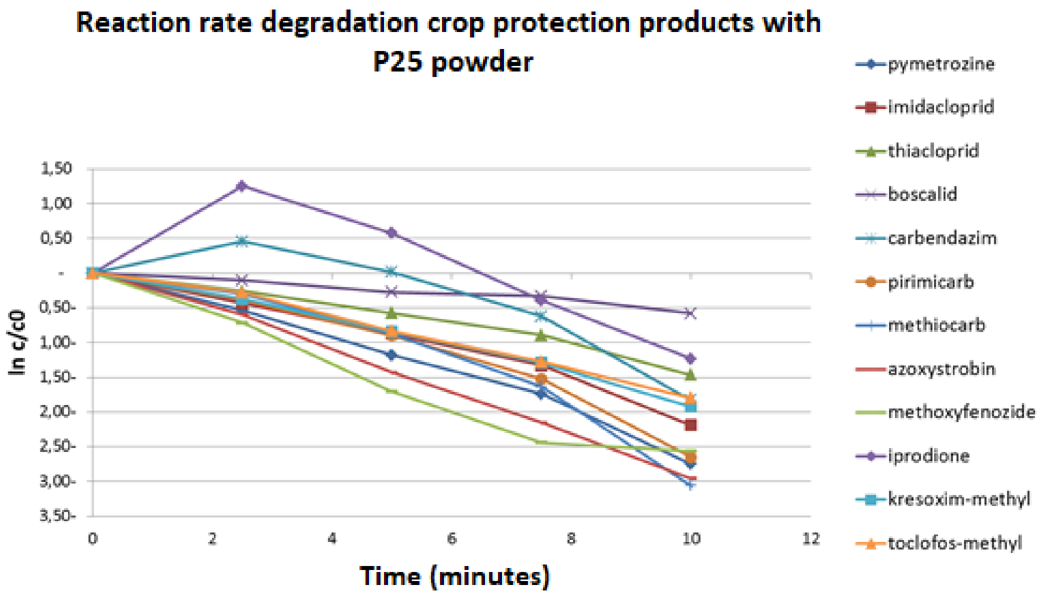

Figure 6-11. Degradation of plant protection products (start concentration 50-780 ng/ml; 10 W/m^2 UV-A) (Jurgens & Appelman 2013)

6.9.5.3. Operational conditions

Restrictions for PCO mainly refer to a load of contaminants per m^2 of the area with a photocatalytic coating. Also, light may be blocked by suspended particles or strong colour.

One of the main preconditions for the feasibility of PCO in horticulture is the availability of light in and around the greenhouse. The amount of natural light, and thus the amount of UV-A radiation, is decisive for the surface of TiO_2 which is necessary for effecting the required/desired degradation.

Conversion rates in PCO are relatively low because both the amount of UV light in daylight and the Quantum Yield (the effective usage of UV light for one oxidation step of the pollutants) are low, a few percent respectively less than 1%.

Figure 6-12. Space utilisation and light availability for tomato (left) and Gerbera (right) (Jurgens & Appelman 2013)

6.9.5.4. Cost data

Effectiveness and costs are competitive with conventional techniques. The costs for PCO utilising daylight (Solar-PCO) for treating 10 m^3/day wastewater are preliminarily estimated between 1,10-3,60 €/m^3 water with a selected number of pesticides. This price includes a preliminary removal of TOC (approx. 0,30 €/m^3). Solar-PCO may be considered for low COD levels (<10 mg/L) and where enough time and space is available [Jurgens and Appelman, 2013].

6.9.5.5. Technological bottlenecks

A suspension of TiO_2 particles requires downstream removal of the catalysts (filtration) for reuse. This needs to be done in order to avoid growth inhibition and regulatory violations.

6.9.5.6. Benefit for the grower

Advantages

- Effective disinfection
- Removal of all organics, including growth inhibitors and pest control chemicals
- Elevates the amount of dissolved oxygen

Disadvantages

- No selectivity in the removal of contaminants (in case of water recycling)

- Needs controlled process conditions
- Risk of toxic by-products formation
- Careful selection of materials for reactor and piping such as PVC, glass-lined reactors or other corrosive-resistant materials is necessary
- No removal of inorganics, such as K, N, P
- Installation by a specialised company required

6.9.5.7. Supporting systems needed

None supporting systems are needed. However, specialised knowledge is needed to apply the coating.

6.9.5.8. Development phase

- Research: In horticulture, the technology is at moment not available and research and development is being performed to assess the potential. TNO (the Netherlands) is, for example, developing PCO as a possible new, sustainable water treatment and purification method for greenhouse horticulture
- Experimental phase: For recycling drain water and wastewater treatment plant effluent. TNO is developing photocatalytic oxidation (PCO) as a possible new, sustainable water treatment and purification method for greenhouse horticulture. In PCO processes, inert, non-toxic, inexpensive catalysts (such as TiO_2) are used in combination with oxygen (from the air), water, and UV-A light to generate OH radicals. The radicals have a strong oxidative effect and can purify water and break down pesticides
- Commercialised: PCO is a well-known technology. Examples include the use of TiO_2 in self-cleaning glass and decontamination of water with photocatalysis

6.9.5.9. Who provides the technology

Several suppliers are available for a catalyst containing materials such as TiO_2 powders and coatings. At the moment, the technology is still in development and there are not yet suppliers who deliver market-ready systems or solutions.

6.9.5.10. Patented or not

No, not for the process itself in general. The different photocatalytic products and materials can be protected by the suppliers.

6.9.6. Which technologies are in competition with this one?

Other technologies that are in competition are other oxidation technologies as ozone (O_3), Advanced Oxidation Processes (AOP) with UV (H_2O_2/UV and O_3/UV). All these technologies may have important restrictions in terms of costs, sludge formation and/or high risk of toxic by-products formation.

Most variants of chemical oxidation and AOP are proven technologies in the process industry, drinking water production, treatment of contaminated groundwater, swimming pools and other applications. They are however not (yet) common in horticulture, except the disinfection of return water by O_3.

6.9.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, with the condition that there is enough UV radiation available. PCO also has a wide range of applications in the greenhouse and therefore opens the way for new additional sterilisation/decomposition concept. Use of artificial light reduces the required surface areas.

6.9.8. Description of the regulatory bottlenecks

On a European level, there can be issues on special measures to contain the TiO_2 catalyst within the company and avoiding emission. Catalysts like TiO_2 are unwanted in the environment.

6.9.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks identified.

6.9.10. Techniques resulting from this technology

Promising concepts are:

- Integration of TiO_2 in concrete growing floors
- Use of immobilised TiO_2 as a temporarily deployable additional aid for the breakdown of pesticides and/or sterilisation (e.g. as roll-out film or additive)
- Use of optical fibres (light at any desired location) and innovative reactor concepts (more compact systems)

6.9.11. References for more information

[1] Jurgens R.M., Appelman W.A.J. (2013). Fotokatalytische oxidatie in de glastuinbouw: Fase 1 – Ontwikkelingen en evaluatie van technologieconcepten voor desinfectie en afbraak van middelen in de kas. TNO-rapport, TNO 2013 R11269

[2] Dutch Policy Document (2012). Beleidskader: Goed gietwater glastuinbouw

6.10. Ultraviolet disinfection

(Authors: Claire Goillon[2], Ilse Delcour[19], Nico Enthoven[20], Benjamin Gard[*])

6.10.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

6.10.2. Region

All EU regions.

6.10.3. Crops in which it is used

All crops.

6.10.4. Cropping type

All cropping types.

6.10.5. Description of the technology

6.10.5.1. Purpose/aim of the technology

UV disinfection is a well-known technology from the drinking water industry. For horticultural purposes, ultraviolet disinfection (UV) is used to disinfect water sources like a drain, surface or rainwater. Pathogens like fungi, bacteria, nematodes or even viruses can be made harmless to allow water usage in a safe way. It is done with UV-C light, that damages the DNA of microorganisms either killing them or ensuring that they can no longer reproduce.

6.10.5.2. Working Principle of operation

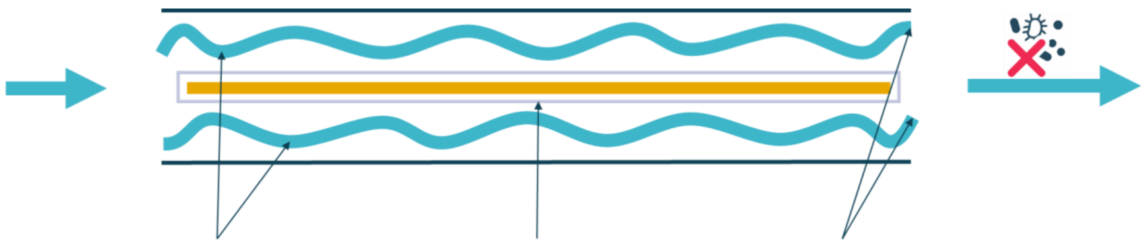

Figure 6-13. Scheme of a UV chamber

UV-C light is produced by a lamp and fitted in a quartz tube in the middle of a cylindrical UV chamber. The quartz tube protects the UV lamp against the water and allows the UV light through (normal glass would shield practically all UV-C light). The water to be disinfected flows through the UV chamber. The high speed brings the water flow into complete turbulence. As a result, an equal average dose of UV-C is administered to each part of the water flowing through the chamber. UV disinfectors for the horticultural industry are specially designed and calculated for water with low T10 values (T10 value is the transmittance of UV-C light at 254 nm over a distance of 10 mm water expressed in percentage).

UV-C dose: The dose of UV-C is the total quantity of energy of UV-C light to which the water is exposed, expressed in millijoules per square centimetre (mJ/cm²). The dose of UV-C depends on two factors:

- The average intensity with which the water in the UV chamber is illuminated
- The detention time of the water in the UV chamber
- To determine the dose of UV-C received by the water, the T10 value of the water must be known
- Minimum and maximum flow rate
- For a reliable disinfection, it is important that the flow of water in the UV chamber should be turbulent. This ensures that all parts of the water flowing through the chamber are exposed to the UV-C light for an equal amount of time and are illuminated at the same average intensity. To guarantee sufficient turbulence of water in the UV chamber, a minimum value applies for the flow rate through the UV chamber. On the other hand, a maximum value also applies to the flow rate. This is determined by the minimum detention time that is necessary to be able to guarantee the desired minimum dose of UV-C

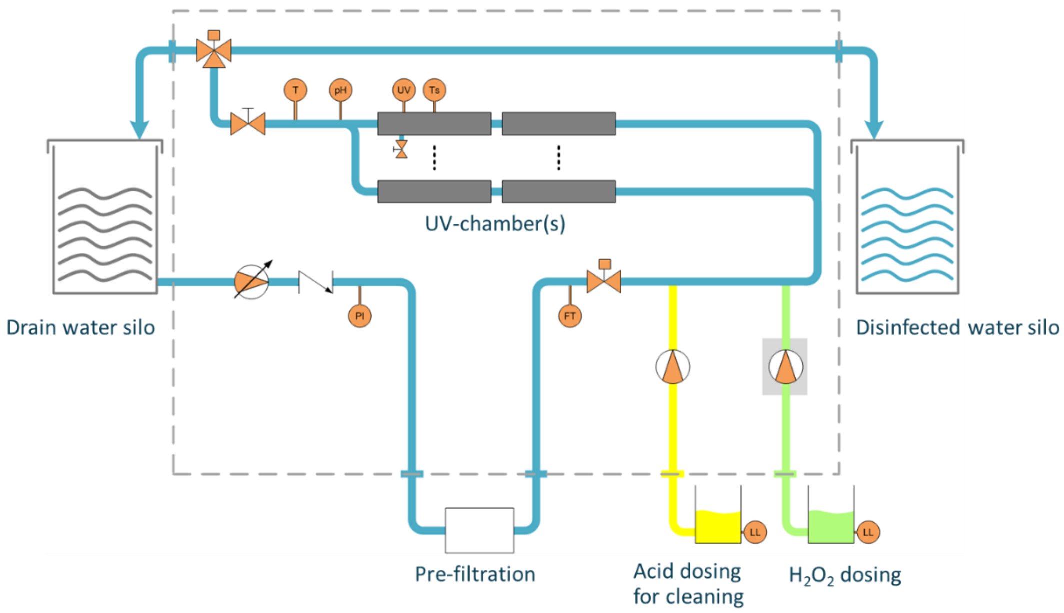

Figure 6-14. Operating scheme of drain water disinfection with UV radiation

There are 3 systems of UV disinfection: low pressure (LP), mid pressure (MP) and high pressure (HP) (Table 6-8). The difference is the wavelength of radiation produced. In LP and MP systems, the wavelength is fixed at 254 nm whereas, in HP system, wavelengths are available between 200 nm and 300 nm. LP UV lamps are less powerful than HP lamps.

Hence, in the LP UV system, lamps are connected in series, whereas in HP system, only one lamp is needed and power can vary. Lamp lifetime is longer for LP and MP systems than for HP system. Effective UV output reduces upon lamp age, this should be taken into account. Also, other losses of UV output should be taken into account, like the UV absorbed by the quartz tube.

Table 6-8. Characteristics of UV systems

System	Low-Pressure UV	Mid-Pressure UV	High-pressure UV
Number of lamps	Many lamps	Fewer lamps	1 lamp
Power per lamp	200 - 300 W	800 W	3000 - 12000 W
Wavelength UV	254 nm	254nm	200-300 nm
Effective UV dose required for eliminating bacteria, algae, fungi	80-100 mJ/cm²	80-100 mJ/cm²	80-100 mJ/cm²
Effective UV dose required for eliminating mosaic viruses	250 mJ/cm²	250 mJ/cm²	250 mJ/cm²
System performance (proportion of electric energy converted to effective UV radiation	± 35%	± 33%	± 12%
UV sensors	1 per system	1 per max 8 lamps	each lamp

6.10.5.3. Operational conditions

A minimum UV transmittance is given by the supplier of the equipment. UV treatment is highly dependent on water clarity (T10 value). Particulate matter suspended in the water causes shadows, while the particles can also carry pathogens. Therefore, pre-filtration with for example sand- or screen filtration is necessary. Particles should not be bigger than 25 µm and the maximum quantity of particles should not exceed 5 mg/L.

6.10.5.4. Cost data

Cost data for installation of a UV-disinfection unit are listed in Table 6-9.

Table 6-9. Costs for disinfection with UV per m^3 at different scenario's (€)

	Irrigation mat	Irrigation mat	Low/high tide	Low/high tide
General	10% drain	30% drain	90% drain, 10% disinfection	90% drain, 100% disinfection
Volume to disinfect (m^3/ha/year)	11110	14286	11000	110000
Drain per 24 hours (m^3/ha)	30	39	39	300
Capacity (m^3/h)	4,9	4,9	4,9	29,0
Nominal power (kW)	2,5	2,5	2,5	7,0
Investment (€) (including installation costs)	22000	22000	22000	32000
Fixed costs				
Depreciation (€)	3143	3143	3143	4571
Interest (€)	770	770	770	1120
Maintenance (€)	660	660	660	960
Variable costs				
Electricity (€)	249	320	246	1760
Pump energy (€)	178	229	176	1760
Aging lamp (€)	177	228	175	391
Annual costs (€)	5177	5350	5170	10562
Costs per m^3 (€)	0,47	0,37	0,47	0,10

Costs are very dependent on:

- the volume of water to be treated
- the required UV-C dose (usually between 80-250 mJ/cm^2) to effectively remove the potential plant pathogens
- the transmittance (T10) of the water to be treated. This can vary during the crop season. One should take into account: the highest volume of water to be treated per day (usually on sunny days in spring/summer) and the UV transmittance at that time

Yearly maintenance or inputs needed: As the quartz tube is hot, deposits of fertilisers will form, which hamper UV light entering the water. These deposits should be removed by acid injection (usually lower pH with nitric acid to pH 2-3). HP UV systems have a mechanical cleaning system which needs yearly maintenance. UV lamp needs to be replaced regularly, normally after 10000-16000 hours of functioning. An alarm generally warns the grower. Annual maintenance costs are approximately 900-1800 €.

6.10.5.5. Technological bottlenecks

With organic substrate (coconut or wood fibres) the water has too low transmittance (T10) to assure a good disinfection, especially at the start of the season. Hence, the addition of clear water is needed to optimise UV disinfection. Iron fertilisers reduce transmittance. Standard amounts should not be a problem.

6.10.5.6. Benefit for the grower

Advantages

- Efficient
- Reliable
- Fully automated solution
- Possibility to add clear water to improve transmittance and disinfection efficacy
- Effectiveness is not pH dependent

Disadvantages

- Destruction of iron chelates, especially at high pH
- Destruction of both pathogen and antagonist micro-organisms
- Efficacy depends on water clarity

6.10.5.7. Supporting systems needed

There are not supporting systems needed.

6.10.5.8. Development phase

This technology is commercialised.

6.10.5.9. Who provides the technology

Several companies provide the technology in Europe.

- Hortimax commercialised the VitaLite CXL system (http://www.hortimax.com/4/3/25/en/products/water-and-nutrition/hortimax-vitalite-cxl.html)
- PRIVA commercialised the VIALUX system (https://www.priva.com/products/vialux)
- Infatechniek (http://www.infatechniek.nl/)
- Smaller companies also provide this kind of equipment. This is the case for the French constructor UVRER-ANEMO (http://www.uvrer-anemo.com/)

6.10.5.10. Patented or not

This technique is not patented.

6.10.6. Which technologies are in competition with this one?

Biofiltration, thermal disinfection, chemical disinfection (chlorination, ozonisation, etc.).

6.10.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this technology is applicable to most greenhouses.

6.10.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

6.10.9. Brief description of the socio-economic bottlenecks

Investments costs are high but have an earn back time of around 2-3 years. The system needs a good support from retailers to be operative. The investment should be optimised based on the amount of water to be treated, the required UV dose and the transmittance (T10) of the water.

6.10.10. Techniques resulting from this technology

Removal of organic chemicals like plant protection agents can be reached by adding an oxidiser like hydrogen peroxide to the UV installation. This enables Dutch growers to fulfil the discharge legislation from 1-1-2018. Other EU countries will follow.

6.10.11. References for more information

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6.11. Thermal disinfection

(Authors: Alain Guillou[4], Esther Lechevallier[4])

6.11.1. Used for

- Preparation of irrigation water
- More efficient use of water by recirculation

6.11.2. Region

All EU regions.

6.11.3. Crops in which it is used

All crops.

6.11.4. Cropping type

All cropping types.

6.11.5. Description of the technology

6.11.5.1. Purpose/aim of the technology

This technology aims to treat drain water against pathogens, allowing recirculation on the crop. Thermal disinfection is physical disinfection of water. Water is heated to a certain temperature during a certain period of time to inactivate pathogens.

6.11.5.2. Working Principle of operation

Heat treatment is a technology that uses the principle of pasteurisation, which consists of heating drain water to a specific temperature that inactivates microorganisms. This affects the different pathogens (viruses, bacteria, fungi) and their forms (spore, mycelium, conidia, etc.). Usually, in horticultural use, the solution is heated to reach 95°C during 30 seconds, passing through a heat exchanger in which the transfer of heat is done by conduction.

The solution is first acidified with nitric acid to reach pH 4 in order to avoid calcium carbonate deposits into the heat exchangers. Then it is filtrated at 75 µm to suppress organic and mineral debris. The preheating of the solution is done by a first heat exchanger at 90°C, by energy exchange with the leaving solution that is cooled. A second heat exchanger, coupled with a heater or a hot water tank, heats the solution to disinfect until 95°C. The temperature is maintained at 95-97°C during a period of 30 seconds by passing the solution into a thermally insulated pipework system. Water is cooled through the first plate's exchanger by an energy transfer between the disinfected solution and the non-disinfected solution. The temperature of the leaving solution is about 25-30°C, which is 5°C more than the entering solution. Water should sometimes be cooled down before it is sent to the irrigation area. Treatment flow is between 2-15 m^3/h.

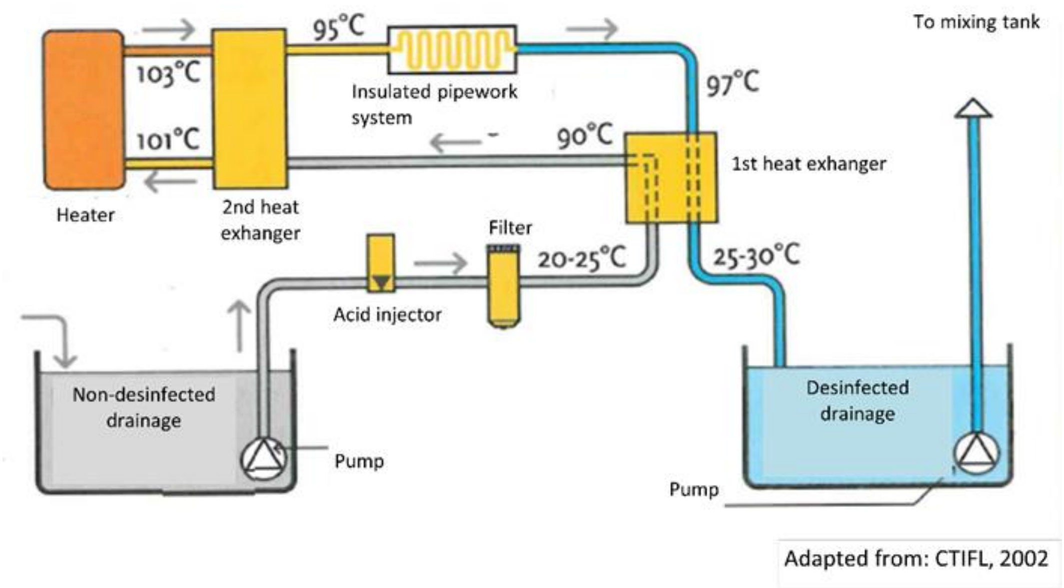

Figure 6-15. Operating scheme of thermal disinfection of drain water (CTIFL, 2002)

6.11.5.3. Operational conditions

Pasteurisation does not have any residual impact on plants (unless the solution has not been cooled after having been heated). The main limitation is that pasteurisation requires a high amount of energy to heat the water. The heat treatment is expensive for production facilities that use large volumes of water and therefore better for nurseries that operate with smaller volumes of water. If the water is not acidified, calcium carbonates deposits can occur at the heat exchangers.

6.11.5.4. Cost data

Installation costs for a thermal disinfection functioning with gas are shown in Table 6-10.

Table 6-10. Costs estimation for thermal disinfection functioning with gas (adapted from Ctifl, 2002)

	Investment costs		Operating costs	
Pasteurisation	95°C for 30 seconds	85°C for 180 seconds	95°C for 30 seconds	85°C for 180 seconds
15000 m^2 greenhouse Treatment flow 2-3 m^3/h	20400 €	18300 €	36 €/100 m^3	34 €/100 m^3
30000 m^2 greenhouse Treatment flow 4-6 m^3/h	25300 €	22800 €	24 €/100 m^3	22 €/100 m^3

Due to the use of acid and heat, the thermal disinfection system needs a monthly cleaning of heaters and filters. The system also needs a good management of the standby temperature between the two disinfections to avoid waste of energy.

6.11.5.5. Technological bottlenecks

The reliability of the heaters is one of the important bottlenecks. High maintenance is often required for the heaters. This is one of the reasons for which this system is not commonly used nowadays. When the heaters have to be replaced and are manufactured abroad, it is a huge problem for the grower who cannot treat the drainage for a long time.

6.11.5.6. Benefit for the grower

Advantages

- Efficient and reliable disinfection against bacteria, fungi, viruses
- Easily scalable
- Automation of pasteurisation
- No risk of phytotoxicity
- More suitable for small greenhouses

Disadvantages

- Requires high maintenance of the heaters
- No removal of ions: ion accumulation is still possible
- Highly energy-consuming
- Destruction of both pathogens and antagonist microorganisms

6.11.5.7. Supporting systems needed

There are not supporting systems needed.

6.11.5.8. Development phase

This technology is commercialised.

6.11.5.9. Who provides the technology

Van Dijk Heating

(http://www.vandijkheating.com/en/horticulture_products/drainwater_disinfectors/).

6.11.5.10. Patented or not

This technique is not patented.

6.11.6. Which technologies are in competition with this one?

This technology is in competition with several other technologies used to disinfect drain water: UV-C disinfection, chlorination, ozonisation, biofiltration (see the relevant TDs).

6.11.7. Is the technology transferable to other crops/climates/cropping systems?

This technology is suitable for all protected soilless crops, with no climate restriction.

6.11.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks identified yet.

6.11.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks identified yet.

6.11.10. Techniques resulting from this technology

Studies showed that a lower temperature at various time periods can be used to get rid of most of the pathogens. The temperature and time of treatment should be adapted depending on the pathogens considered. The literature states that heating irrigation water to 60°C for an exposure time of 2 minutes should be sufficient to suppress most greenhouse pathogens. Compared to the commonly used method, this would reduce energy use by 42%. However, if viruses are found to be a problem, the heating water of 85°C during 180 seconds is recommended. This combination suppresses *Fusarium oxysporum*. This principle (85°C/ 180°C) has been later proposed for energy savings.

6.11.11. References for more information

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6.12. Slow sand filtration

(Authors: Federico Tinivella[7], Ilse Delcour[19])

6.12.1. Used for

- Preparation of irrigation water
- More efficient use of water by recirculation
- Minimising the environmental impact by discharge prevention

6.12.2. Region

All EU regions.

6.12.3. Crops in which it is used

All crops.

6.12.4. Cropping type

All cropping types.

6.12.5. Description of the technology

6.12.5.1. Purpose/aim of the technology

Slow sand filtration is a reliable, low-cost solution to eliminate soil-borne pathogens in greenhouse horticulture in soilless cultivation systems. *Phytophthora* and *Pythium* can be effectively controlled by this method, but *Fusarium*, viruses and nematodes are only partly removed by this technology. The principle is based upon a supernatant water layer, which trickles slowly through a sand layer. The mechanism of elimination is not only filtering (mechanical) as the size of the pores is generally larger than the pathogens eliminated. The formation of a biologically active layer up on top of the sand in the filter is of great importance since it is composed by a resident microflora that suppresses the soil-borne pathogens above mentioned. The application of selected strains of antagonistic fungi (mainly *Trichoderma* spp.) can further enhance such natural suppresses of the microflora developed on the sand filter. Finally, slow sand filtration can be combined with UV treatment as an active method of disinfection.

6.12.5.2. Working Principle of operation

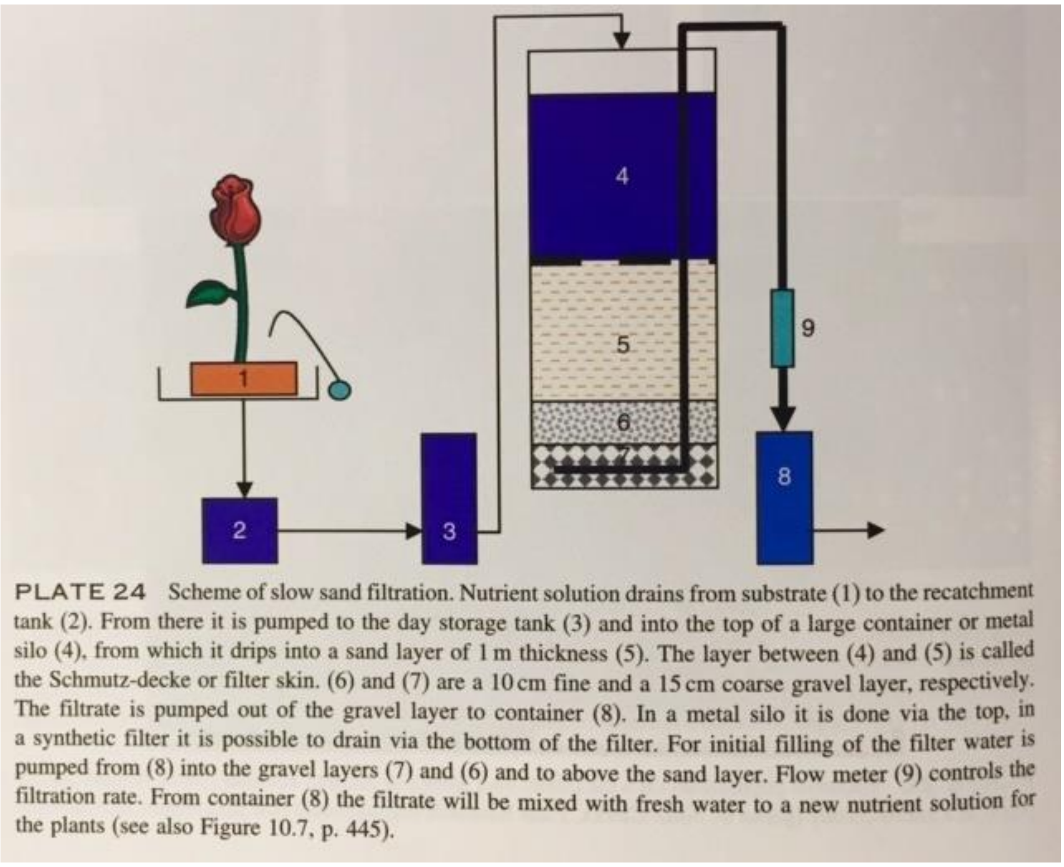

Figure 6-16. Basic operational scheme of slow sand filtration (from Soilless Culture, Raviv and Lieth Eds., Elsevier, San Diego, Ca, USA, p.445)

Figure 6-17. Picture of a slow sand filter (Belgium) with a sieve bend to get rid of coarse organic material before disinfecting it with the slow sand filter

As presented in the previous figures the key components of a slow sand filter are as follows:

- Water layer: Provides hydraulic head (pressure) to push water through the sand filter below. In order to prevent the dirt layer (Schmutzdecke) from being exposed to temperature and moisture fluctuations, the water layer should be around 0,9 m deep

- Schmutzdecke: This layer is a biofilm of microorganisms (as well as other organic and inorganic materials) that develops towards the surface of the sand bed over time, potentially to a depth of around 40 cm. The Schmutzdecke is the main source of biological pathogen control in the sand filter. Antagonistic organisms that make up this layer include fungi, bacteria, nematodes, protozoa and others
- Sandbed: The sand bed provides a medium for the Schmutzdecke and the microorganism community, in general, to grow on, as well as providing physical filtration. Sand grain texture will affect the porosity and ultimately biofilm creation. It is recommended sand grains be round to avoid packing and about 0,3 mm in diameter to maximise surface area. Media depth should be a minimum of 80 cm
- Supporting gravel**:** This layer allows water to drain freely from the sand bed while preventing sand from escaping to the outlet tank. The layer may be around 0,15 m and should be composed of gravel, or some other material that will allow free drainage. Gravel may range from fine (2-5 mm) to coarse (7-15 mm); either mixed together or in separate layers
- Control valve**:** A system of control valves allows regulation of flow rate and adjustment of the depth of the water layer above the sand bed
- Outlet tank**:** The outlet tank contains a weir that serves to prevent the water layer in the filter from dropping below the sand bed (maintains a minimum water depth in the filter). Ventilation of the outlet tank allows absorption of oxygen and release of other gases before filtered water flows to irrigation

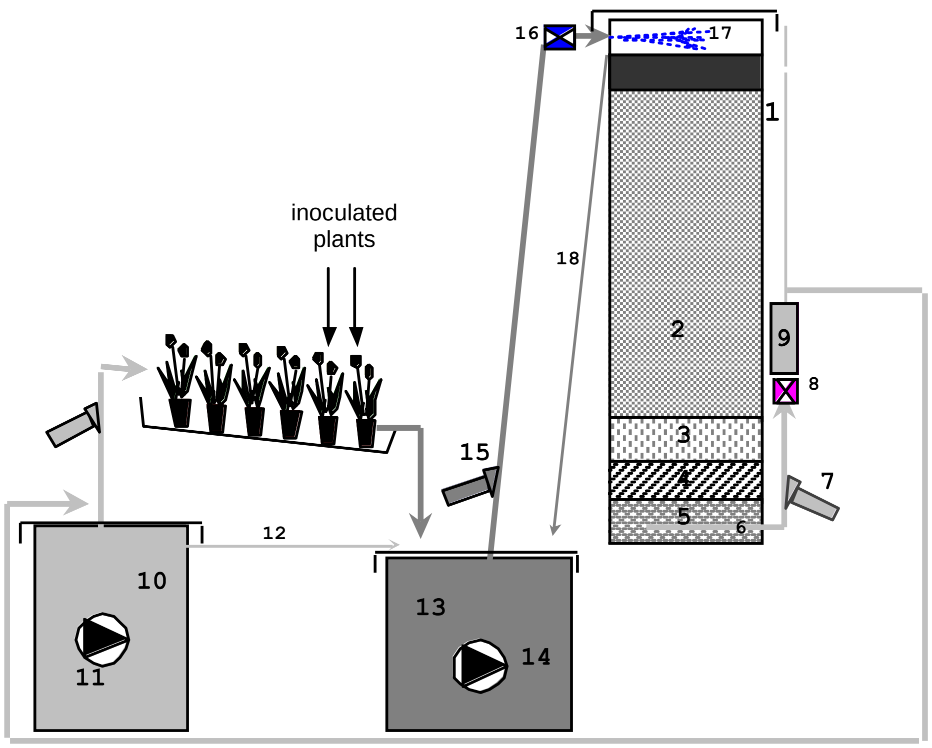

Figure 6-18. Scheme of the slow sand filtration plant installed at Cersaa's premises in the frame of the project "Microbial Optimisation to Prevent Root Diseases" (MIOPRODIS), years 1999-2003

A scheme of the slow sand filtration plant installed at Cersaa's premises is shown in Figure 6-18. The numbers in the picture indicate:

1 = Sand filter container, PVC pipe, 1,5 m high, 0,4 m diameter

2 = Filtering layer 80-100 cm, sand size 0,2-2,0 mm; effective grain size (d10 - sieve opening through which 10% by weight of the grains will pass) 0,08678 mm; uniformity coefficient (UC - d60/d10) 3,0617; density 2,6 g/cm^3; SiO_2 > 96%

3 = Drain layer 15-20 cm, sand size 2-3 mm; absolute density 2,6 g/cm^3; SiO_2 > 94%

4 = Drain layer 15-20 cm, sand size 8-12 mm; absolute density 2,6 g/cm^3; SiO_2 > 94%

5 = Drain layer 15-20 cm, sand size 20-40 mm; absolute density 2,6 g/cm^3; SiO_2 > 99%

6 = PVC (diameter 19 mm) output diffuser (effluent) 35 cm length with 140 holes diameter 2 mm

7 = Filter to remove inorganic (quartz) dust from sand filter layers (diameter 19 mm)

8 = Stainless steel adjust (diameter 12.7 mm) valve for flow meter

9 = Flow meter min-max flow rate 6,5-65 L/h (connection with pipe diameter 8 mm for filter water level monitoring)

10 = Polyethylene storage tank of effluent from the sand filter (200 L)

11 = Irrigation pump (effluent) connected with pipe PN 4 diameter 20 mm with water emitter diameter 0,9 mm of 50 cm length and a height with a maximum of 16 m. Valve between pump and water emitter pipe to avoid flow back

12 = Polyethylene (PN 6 diameter 16 mm) storage tank of effluent overflow

13 = Polyethylene storage tank of drain water from the gerbera crop (200 L)

14 = Input pump (influent) connected with input pipe PN 6 diameter 16 mm and a maximum height of 6,5 m

15 = Disk filter to remove organic and inorganic dust from the gerbera crop (diameter 19 mm, 120 mesh, 130 μm)

16 = Polyethylene adjust valve (diameter 12.7 mm) for input diffuser (influent)

17 = Polyethylene (PN 6 diameter 16 mm) input diffuser (influent) 35 cm length with 40 holes diameter 2 mm

18 = Polyethylene (PN 6 diameter 32 mm) input overflow (influent)

6.12.5.3. Operational conditions

The filter must be filled with water through the drain to remove all air. Then the filter is ready to be used.

The rate of water flow through the sand filter is possibly the main variable determining filter effectiveness. Flow rate should be slow to allow for proper filtration and allow a sufficient microbial community to develop and act on pathogens. Slower flow rates allow for adequate disease control even in the presence of high pathogen populations or small pathogen propagules (e.g. of *Fusarium* spp.). A flow rate of around 100 L/h/m^2 maximises performance. However, if disease presence appears to be less of an issue, a higher flow rate may be allowable. Flow rates of less than 300 L/h/m^2 can successfully remove *Pythium* spp. and *Phytophthora* spp. and may be successfully implemented if disease pressure is not high.

Deciding on the construction specifics of a filter requires balancing the trade-off between improved filtration vs. slower flow rate. The slower the flow rate used, the larger (in surface area) the filter will need to be to filter a certain amount of water. The low flow rate will allow optimal pathogen filtration, however, a very large filter may be required if large amounts of water must be treated per day. The size of the filter can be decreased if the allowed flow rate is increased, but this may lead to less successful pathogen suppression. After determining the desired flow rate (based on which pathogens needs to be controlled), it is possible to determine the size of the required filter (square metres), based on how much water has to be treated. To determine the size of the filter, the calculation is as follows: dividing the amount of water the facility uses in an hour by the desired flow rate (in L/h/m^2). The Table 6-11 below gives some examples of filter capacity (volume of water filtered/day) of different sized filters at various flow rates.

Table 6-11. Filter capacity expressed in litres of water filtered per day for different filter surfaces and various flow rates

Surface Area (m²)	Flow rate 100 L/h	Flow rate 200 L/h	Flow rate 300 L/h
1	2400 L	4800 L	7200 L
5	12000 L	24000 L	36000 L
10	24000 L	48000 L	72000 L
15	36000 L	72000 L	108000 L

In addition to flow rate, some other factors may play a role in determining filter efficacy. Increased organic matter content of the filter may serve to improve surface area available to adsorb microbes and decrease pore size, while also providing a food source for beneficial microorganisms to use.

6.12.5.4. Cost data

Normally slow sand filtration plants are supplied "keys in hands" therefore the total costs depend on the company who provides the technology.

Case study: A calculation of the different costs supported by four German nurseries producing mainly rhododendron and ornamental conifers in containers and adopting a big scale slow sand filtration plant is reported in Table 6-12.

Table 6-12. Cost of construction and operation of a slow sand filtration system (adapted from Ufer et al, 2008)

Factors		Slow sand filtration
Construction costs		65200 €
Construction + operating costs	Per year	11200 €
	Per day	31 €
Proportion of the fixed costs	Per year	8800 € (79%)
	Per day	24 €
Proportion of the variable costs	Per year	2400 € (21%)
	Per day	6 €
Construction + operating costs for 1 m^3 filtrated water based on:	Design flow rate	124 €/m^3
	Annual filtrated volume	0,13 €/m^3

6.12.5.5. Technological bottlenecks

Factors that affect the biological community of the filter also impact filtration effectiveness. Low temperatures will stunt microbial activity and as such decrease effectiveness (optimal activity at 10-20°C). Oxygen deficiency may also decrease effectiveness. Most importantly, biological effectiveness depends on the microbial species and species diversity present in the microbial community of the filter. Research suggests certain specific species may be more beneficial in filters than others. As such, filtration effectiveness could, in theory, be improved by directly inoculating these species into the filter rather than waiting for a natural community to develop. However, there is currently too little information available in this area to encourage any inoculation of this sort. Alternatively, it is also possible that just using the natural microflora that develops over time may maximise pathogen control. The type of algae predominating in the schmutzdecke may also influence filtration. A predominance of filamentous algae will increase the filtration rate, decrease resistance and potentially hurt filtration performance. Therefore it is advisable to cover your filter. When more organic material is present in the drain water, the filter needs more maintenance because the impurities accumulate in the filter and diminish the volume of the pores.

6.12.5.6. Benefit for the grower

Advantages

- Relatively simple technology
- Reduced operating costs
- Reduced maintenance costs compared to active treatment system applied to fertiliser solution
- Little technical monitoring required
- Reduced use of pesticides

- Especially useful for crops suffering from fungi (e.g.: *Pythium*, *Phytophthora*, *Olpidium*, *Cylindrocladium*, *Thielaviopsis*) or bacteria (e.g. *Xanthomonas*, *Pseudomonas*, *Erwiniaen Corynebacterium*)
- Removes organic material, impurities and suspended particles
- Might be used as a water storage

Disadvantages

- High installation cost
- Require a large amount of space and infrastructure
- The porosity of the filter is not uniform throughout
- Large variability in the filter decreases filtration performance
- Efficacy breakdowns may occur occasionally (e.g. a drop in pathogen propagule removal rate from 100% to 80-90%)
- Maintenance may need to be performed relatively frequently due to the potential for clogging
- Levels of Legionella should be monitored to prevent harm to workers
- It takes 2-4 weeks before the biological activity in the filter settles
- The efficiency is temperature dependent
- Inefficient for nematodes or viruses

6.12.5.7. Supporting systems needed

Normally slow sand filtration plants are provided “keys in hands” together with control units (desktop computer). In some crops (*Azalea*, hardy nursery stock) it is necessary to do a pre-filtering to remove coarse organic materials like leaves and small branches.

6.12.5.8. Development phase

This technology is commercialised.

6.12.5.9. Who provides the technology

Different private companies are specialised in supplying this technology. Hereby some examples:

- River Sands Pty Ltd, Australia
- AS Filtration, LLC, USA
- Everfilt Water Filtration, USA
- Blue Future Filters, Inc., USA
- Bluewater Filter Clear Limited, UK
- Warden Biomedia, UK
- Lenntech Water Treatment, The Netherlands
- Colloide Engineering Systems, Northern Ireland

- Filtralite Saint-Gobain Byggevarer As, Norway
- Bilfinger Water Technologies GmbH, Germany
- KAMPS s.a., Belgium
- METAWATER Co., Ltd., Japan
- Pure Water Technology, United Arab Emirates
- Haixing Wedge Wire Co,. Ltd, China
- Interecos.n.c, Italy
- EMWG s.r.l., Italy
- Rolland Sprinklers, France

6.12.5.10. Patented or not

The technology itself is not patented either the single elements used to build the plant. Plants considered as a whole and supplied by a specific company could be patented.

6.12.6. Which technologies are in competition with this one?

This technology is in competition with biofiltration, but especially with all active water treatments adopted in soilless cultivation for drain water treatment such as UV filtration, chlorination and thermal disinfection.

6.12.7. Is the technology transferable to other crops/climates/cropping systems?

The technology is mainly applied in the soilless cultivation of vegetables and ornamentals. It can be transferred to other crops and climates, but there the composition of the biofilm might differ, influencing the efficiency of the filter. This should be evaluated case by case.

6.12.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

6.12.9. Brief description of the socio-economic bottlenecks

The main socio-economic bottlenecks are represented by the high investment costs related to the installation of the slow sand filtration plant.

In addition, *Legionella* bacteria have been found to make up a significant portion of the bacterial population in slow sand filters. Some species of *Legionella* are human pathogens. As such, it is recommended that the sand filter not to be kept inside the greenhouse where high temperatures can lead to a proliferation of *Legionella.*

6.12.10. Techniques resulting from this technology

There are no techniques resulting from this technology.

6.12.11. References for more information

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6.13. Biofiltration disinfection

(Authors: Claire Goillon[2], Alain Guillou[4], Esther Lechevallier[4], Benjamin Gard[*])

6.13.1. Used for

- Preparation of irrigation water
- More efficient use of water by recirculation
- Minimising the environmental impact of discharge prevention

6.13.2. Region

All EU regions.

6.13.3. Crops in which it is used

All crops.

6.13.4. Cropping type

All cropping types.

6.13.5. Description of the technology

6.13.5.1. Purpose/aim of the technology

This technology aims to treat drain water against pathogens allowing recirculation into the crop. The technology of biofiltration combines two processes in the filter: a process based on the filtration, sedimentation and adsorption of organic matter and a biological process based on predation and antagonism by specific micro-organisms.

6.13.5.2. Working Principle of operation

The filter (Figure 6-19) is filled with an inert and porous support, in general pozzolana. Filtration takes place when drain water passes the pozzolana. Biological cleaning operates through the action of a bacterial biofilm which develops naturally on the pozzolana. This biofilm consists of *Pseudomonas* and *Bacillus* bacteria which are well known for their antagonistic actions against phytopathogenic fungi and bacteria. To accelerate the germicidal efficacy of the filter, the tank can be seeded with a selected biofilm. This technology is called static biofiltration. Finally, the filtered solution is collected at the bottom of the filter and pumped to a "Filtered drain water" tank.

To enhance the efficacy of bio filtration and to improve the flow of treated water, an air circulation is set up in the tank. This increases the time of contact with the microorganisms in the drain water and therefore, the efficacy of the biofilm. This technology is called dynamic or activated biofiltration. The use of biostimulants increases the efficacy of biofiltration as well. To reach an optimal efficiency, the flow should be slow (100-350 L/m² of filtering surface/hour, depending on whether the biofilter is equipped with air circulation or not).

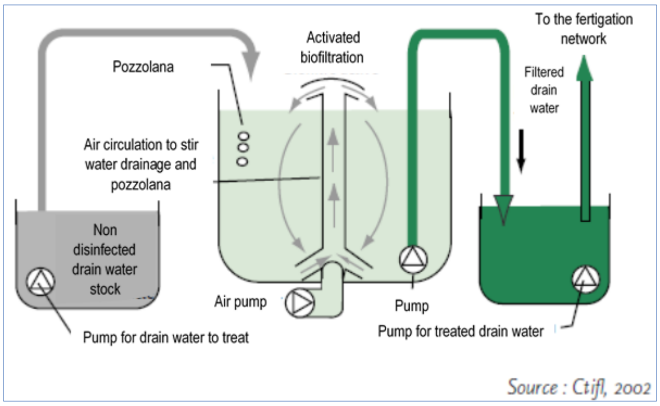

Figure 6-19. Functional diagram of the activated biofiltration technology for drain water disinfection (Ctifl, 2002)

6.13.5.3. Operational conditions

The capacity of the biofilter to treat drain water is directly linked to the diameter and volume of the tank. For the treatment of drain water of a 4 ha greenhouse of soilless tomato crops, a biofilter of 22 m^3, with a diameter of 4 m, containing 23 tons of pozzolana, is needed.

Table 6-13. Characteristics of activated biofilter related to the quantity of drain water to treat

Filtration capacity (m^3/hour)	Diameter of the biofilter (m)	Electrical power (kW)	Number of tubes for air circulation
2,5	3,10	0,55	4
3,5	3,55	0,75	5
4,5	4,00	0,75	7
5,0	4,40	0,75	7
7,0	5,10	1,10	9
9,5	5,95	1,10	13
13,4	7,04	2,20	19

6.13.5.4. Cost data

Table 6-14. Estimation of investment and operating costs of static and dynamic biofiltration technologies

	Investment costs		Operating costs	
	Static biofiltration	Dynamic biofiltration	Static biofiltration	Dynamic biofiltration
1,5 ha greenhouse Treatment flow 2 - 3 m^3/h	11600 €	18300-20000 €	Low cost	4 €/100 m^3
3,0 ha greenhouse Treatment flow 4 - 6 m^3/h	16100 €	24400-25600 €	Low cost	3,8 €/100 m^3

Additional costs include the purchase of appropriate UV resistant tanks (14215 € for a standard 1000 L unit) and if organophosphate compounds are present, disposal charges can be up to 455 €.

6.13.5.5. Technological bottlenecks

The biofilter must be installed in a temperate and protected area that can be a problem in hotter regions like the Mediterranean. The optimum temperature for biological activity of the biofilm ranges from 15-25°C and needs to be covered with black plastic to avoid algae development. To protect the activity of the biofilter, drain water should not contain pesticide residues and chemical disinfection substances. Also, dry out must be prevented and the water level must be kept above the pozzolana layer. Between seasons, the biofilter must function a couple of hours per day in a closed system to maintain biological activity. Air circulation must be regular, as well as the flow of non-disinfected drain water. In static filtration, regular cleaning by backflushing is needed.

6.13.5.6. Benefit for the grower

Advantages

- Easy to implement
- Low level of control and maintenance
- Low operating costs
- Little influence on the treated solution (pH, iron, nutrient composition, temperature)
- Selective method of drain water disinfection which helps to preserve a microbiological balance

Disadvantages

- Poor knowledge about the efficacy against *Clavibacter michiganensis*, pathogens and viruses of tomato crop; mid efficacy against total bacterial flora
- Low disinfection flow for static biofiltration
- High storage capacity required for the slow filtration flow; large size of the biobed
- Space inside a building needed to control temperatures
- Operation within the growing season to keep the biofilm activated

6.13.5.7. Supporting systems needed

None supporting systems are needed.

6.13.5.8. Development phase

- Field tests
- Commercialised

6.13.5.9. Who provides the technology

- Access Irrigation(http://www.access-irrigation.co.uk/)

- Eden irrigation
- Laterlite (http://www.laterlite.fr/applications/vegetalisations-et-environnement/filtration/
- Rotorflush self-cleaning filters (https://www.rotorflush.com/
- Lusseau Squiban (http://www.squiban.com/)

6.13.5.10. Patented or not

A couple of patents exist for this technology:

- Holder, J. L. and McKinley R. S., 2013, Recirculating aquaculture systems and biofilters, therefore, US20130247832
- van Toever, J. W., 2007. Bio-filter with low-density media and toroidal media stirring configuration. US20070264704 A1

6.13.6. Which technologies are in competition with this one?

Technologies such as biobed filtration, UV disinfection, and thermal disinfection, chemical disinfection like chlorination or ozonisation are in competition with biofiltration.

6.13.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, the technology is applicable to most substrates.

6.13.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

6.13.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks.

6.13.10. Techniques resulting from this technology

There are no techniques resulting from this.

6.13.11. References for more information

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[9] Runia, W. T. (1995). A review of possibilities for disinfection of recirculation water from soilless cultures. *Acta Horticulturae*, *382*, 221–229

6.14. Airlift for horticultural water storage

(Author: Matthijs Blind[24])

6.14.1. Used for

Preparation of irrigation water.

6.14.2. Region

All EU regions.

6.14.3. Crops in which it is used

All crops.

6.14.4. Cropping type

All cropping types.

6.14.5. Description of the technology

6.14.5.1. Purpose/aim of the technology

This technology intends to increase the oxygen level of the stored water. The oxygen level of stored water is very important for different reasons:

- Dissolved oxygen is a major contributor to water quality. Not only do fish and other aquatic animals need it, but oxygen breathing aerobic bacteria decompose organic matter. When oxygen concentrations become low, anoxic conditions may develop, which can decrease the ability of the water body to support life
- When anoxic conditions (this is the absence of oxygen) arise in water storage systems, noxious gasses such as carbon dioxide, methane or hydrogen sulphide can be formed. This should be avoided

Oxygen is very important for healthy roots. By using aerated storage, water plants are not only provided with water but also with oxygen.

Figure 6-20. Airlift installation

6.14.5.2. Working Principle of operation

In general, aeration techniques are based on the principle of creating a large contact surface between air and water. This can be done by bringing water in the air (waterfall, fountain) or bringing air in water in the form of bubbles. For all of these techniques water pumps and a lot of energy is needed.

The airlift technique is based on the same principle but very energy efficient. The only energy that is required, is provided by compressed air. This air is usually compressed by a blower (can be used in water depths ≤ 2,5 m) or a compressor (can be used in water deeper than 2,5 m). The air is injected into the lower part of a pipe that transports the water. The air, which has a lower density than water, rises quickly by buoyancy. By fluid pressure, the liquid is taken in the ascendant air flow and moves in the same direction as the air. The calculation of the volume flow of the liquid is possible thanks to the physics of two-phase flow.

Fine bubble aeration is an efficient way to transfer oxygen to a water body. A blower on shore pumps air through a hose, which is connected to an underwater aeration unit. Attached to the unit are a number of diffusers. These diffusers come in the shape of perforated membrane discs. Air pumped through the diffuser membranes is released into the water. These bubbles are known as fine bubbles. This type of aeration has a very high oxygen transfer efficiency.

Fine bubble diffused aeration is able to maximise the surface area of the bubbles and thus transfer more oxygen to the water per bubble. Additionally, smaller bubbles take more time to reach the surface, so not only is the surface area maximised but so is the time each bubble spends in the water, allowing it more time to transfer oxygen to the water. As a general rule, smaller bubbles and a deeper release point will generate a greater oxygen transfer rate.

However, almost all of the oxygen dissolving into the water from an air bubble occurs at the time the bubble is being formed. Only a negligible amount occurs during the bubbles transit to the surface of the water. This is why an aeration process that makes many small bubbles is better than one that makes fewer larger ones. The breaking up of larger bubbles into smaller ones also repeats this formation and transfer process.

6.14.5.3. Operational conditions

Both classical system and Airlift are applicable on any scale.

6.14.5.4. Cost data

The use of the airlift technique in water storages is relatively new. Therefore, data on costs are scarce and the following example must be regarded as an indication: Based on a water storage capacity of 14000 m³, the installation costs for a conventional system are estimated to be 1,10 €/m³ and for the airlift system 0,57 €/m³. The yearly energy costs for a conventional system (based on a compressor) are about 0,56 €/m³ and for an airlift system (based on a blower) about 0,07 €/m³.

6.14.5.5. Technological bottlenecks

Technological bottlenecks have not yet been identified.

6.14.5.6. Benefit for the grower

Advantages

- High levels of dissolved oxygen in the aerated water
- Low investment and energy use compared with the conventional method
- The pump is very reliable
- Based on a very simple principle
- The liquid is not in contact with any mechanical elements
- Acts as a water aerator and can, in some configurations, lift stagnant bottom water to the surface (flow creation)
- Solids up to 70% of the pipe diameter can be reliably pumped, there are no mechanical pump parts
- Improves water quality

Figure 6-21. Measurement of the dissolved oxygen of the water storage of Proeftuin Zwaagdijk (The Netherlands) where a floating Airlift is installed

Disadvantages

No disadvantages have been identified so far.

6.14.5.7. Supporting systems needed

None supporting systems are needed.

6.14.5.8. Development phase

- Field tests: At present, there are several aerator systems (Airlifts) implemented in Hydroponic ponds at the Research Centre Zwaagdijk in The Netherlands
- Commercialised: The optimising phase (e.g. optimal dimensions of the system) has still to be passed through (based on experience and measurements)

6.14.5.9. Who provides the technology

Botman Hydroponics B.V. (www.botmanhydroponics.com) in The Netherlands introduced and developed the Airlift technique for use in water storage and hydroponics in 2015.

6.14.5.10. Patented or not

This technology is not patented.

6.14.6. Which technologies are in competition with this one?

On the bottom of the water storage fixed diffuser systems in combination with compressors.

6.14.7. Is the technology transferable to other crops/climates/cropping systems?

It can be used in all crops with water storage systems.

6.14.8. Description of the regulatory bottlenecks

No regulatory bottleneck has been identified so far.

6.14.9. Brief description of the socio-economic bottlenecks

The benefits of circulating and aerating storage water are not yet generally accepted, due to a lack of experience and research. Because of this, a lot of growers are not yet convinced that investments in this system will be paying off.

6.14.10. Techniques resulting from this technology

The airlift from Botman Hydroponics is resulting from this technology.

6.14.11. References for more information

[1] Proeftuin Zwaagdijk (www.proeftuinzwaagdijk.nl)
[2] Botman Hydroponics B.V. (www.botmanhydroponics.com)
[3] Plant Nursery Gitzels (www.gitzels.nl)

6.15. Airlift for aeration of nutrient solutions used in combination with Deep Flow Technique

(Author: Matthijs Blind[24])

6.15.1. Used for

- More efficient use of water by recirculation
- Minimising the environmental impact by discharge prevention

6.15.2. Region

All EU regions.

6.15.3. Crops in which it is used

- Leafy vegetables
- Herbs
- Ornamentals

6.15.4. Cropping type

- Soilless
- Protected
- Open air

6.15.5. Description of the technology

6.15.5.1. Purpose/aim of the technology

The technology is used to aerate and circulate nutrient solutions in production systems based on deep flow technique.

Figure 6-22. Trials with crops grown with deep flow technique, left: ornamentals, right: wild rocket

Trials at research stations as well as experiences in horticultural practice show that the growth and development of crops grown on deep flow technique (DFT) are enhanced by high (dissolved) oxygen concentrations and a good circulation of the nutrient solution. There are strong indications that some crops cannot complete the production cycle when oxygen concentrations are low. First experiences show that the airlift technology can aerate and circulate large production ponds with a low energy use.

6.15.5.2. Working Principle of operation

The principle of operation is explained in Figure 6-23.

The heart of the system is a 2 m long vertical positioned pipe below the basin which has to circulate and to be aerated. An aeration unit connected with a blower is fixed at the bottom of the pipe. Via a pipe system below the basin, the nutrient solution can flow in direction of this central pipe. The driving force of the flow is created by the blower. Above the aeration unit, air bubbles are formed. These bubbles lower the density of the water and as a result of that this “lighter” water rises and the whole water system will start to flow. The oxygen in the air bubbles dissolves in the nutrient solution.

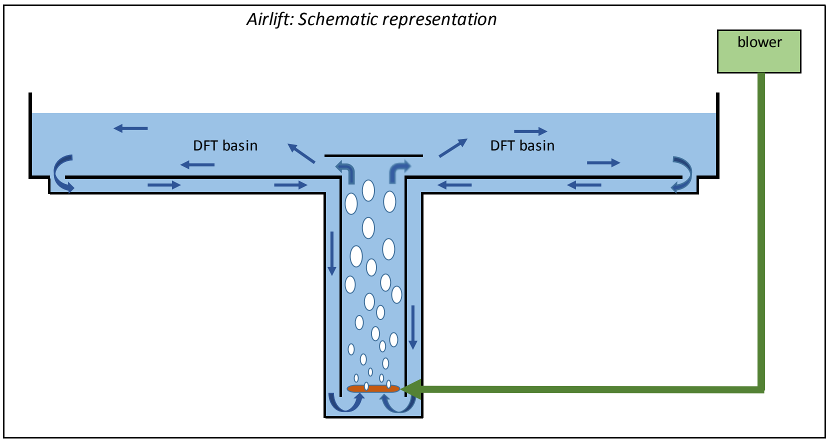

Figure 6-23. Airlift, schematic representation

The principle is used in fish farming and in water purification.

6.15.5.3. Operational conditions

Essentially, there are no limits. However, application of this technique in (large scale) DFT-systems is relatively new. In large production sites more units (vertical pipes/aeration units, supply tubes) must be installed (± 1 unit/300 m²).

6.15.5.4. Cost data

For installation:

Indication: Airlift - Blower – Tubes: as a start 7500 € to aerate (and circulate) 2500 m³ water.

Yearly maintenance or inputs needed:

- Changing the air filters of the blower
- Check regularly for leaking tubes

6.15.5.5. Technological bottlenecks

Technological bottlenecks are not known.

6.15.5.6. Benefit for the grower

Advantages

- Optimal growth and production
- Reduced risk of loss by diseases (vital crops)
- Simple and reliable technique in comparison with other circulation and aeration techniques
- Low energy demand

Disadvantages

In some (rocky) areas it might be difficult or too costly to install the central pipes and the tubes.

6.15.5.7. Supporting systems needed

None supporting systems are needed.

6.15.5.8. Development phase

- Research: At present, several airlifts are operational in trials at Proeftuin Zwaagdijk, a research centre in The Netherlands
- Field tests/Commercialised: The first larger scale application (about 8000 m²) was built in April/May 2016

6.15.5.9. Who provides the technology

- Botman Hydroponics B.V.(www.botmanhydroponics.com)
- Stan van Eekelen BV (www.stanvaneekelen.nl)

6.15.5.10. Patented or not

This technology is not patented.

6.15.6. Which technologies are in competition with this one?

Active aeration means using submersible pumps in combination with the venturi technique (below). The flow caused by the pump creates under-pressure and this sucks air (bubbles) into the nutrient solution.

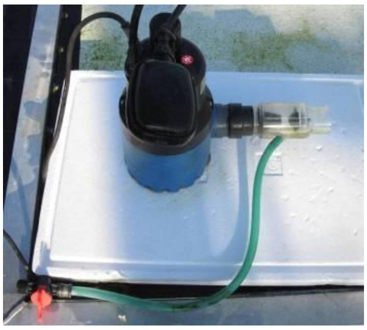

Figure 6-24. Submersible pump with an extension for aeration based on the Venturi principle

In one case a waterfall technique was used (Figure 6-25). In small-scale applications, aeration stones are used.

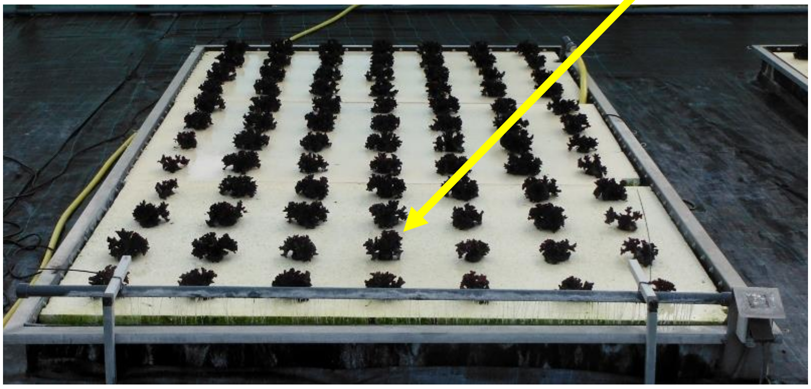

Figure 6-25. Aeration created by a waterfall

6.15.7. Is the technology transferable to other crops/climates/cropping systems?

It can be used in all crops produced with a system based on DFT. As the oxygen demand depends also on temperature, aeration is increasingly important when the average temperature is higher.

6.15.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks known for this technology.

6.15.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks known.

6.15.10. Techniques resulting from this technology

There are no techniques that result from this technology.

6.15.11. References for more information

[1] Proeftuin Zwaagdijk (www.proeftuinzwaagdijk.nl)
[2] Botman Hydroponics (www.botmanhydroponics.com)
[3] De Kruidenaer (www.dekruidenaer.nl)
[4] Jan van Eekelen BV (www.stanvaneekelen.nl)

Chapter 7. Fertigation equipment – Irrigation

Coordinators: Elisa Suárez-Rey [11], Miguel Giménez [11], Ilse Delcour [19]

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7.1. Introduction

7.1.1. These techniques concern the issue

- More efficient use of water
- More efficient use of fertiliser
- More efficient use of chemicals
- Minimising the impact to the environment by nutrient discharge

7.1.2. Regions

All EU regions.

7.1.3. Crops in which the problem is relevant

All crops.

For all crops and cropping systems, it is important to maximise water and nutrient use efficiency while minimising impacts. Proper design and management of the system are always necessary.

7.1.4. Cropping type

All cropping types.

As irrigation and fertigation systems for soil-grown crops are different from soilless systems, the demands for irrigation and good nutrient management are different, as well as the requirements for the design and management of the systems.

7.1.5. General description of the issue

Micro-irrigation is an irrigation method that slowly applies water to a small area or volume of growing medium (soil or substrate). Drip irrigation is the most widely used for of micro-irrigation; specialised sprinkler systems are another form. With micro-irrigation, water is generally applied close to the plants. A network of valves, pipes, and tubing transports water over the soil surface, or in some cases below the soil surface, to close to the plants where an emitter transfers the water to the soil surface or to the crop root zone.

The total surface area irrigated with drip irrigation for intensive vegetable and ornamental production and for fruit tree production systems in the European Union is continually increasing, particularly in the Mediterranean countries. For intensive vegetable and ornamental production, and the more intensive fruit production systems (e.g. stone fruits), drip irrigation and fertigation are used together. All substrate-grown and many open field crops are irrigated with drip irrigation on the expectation that yields may be higher and that water use will be reduced compared to other irrigation methods. The particular characteristics of the drip irrigation system adapted for an individual cropping situation depend on the type of cropping system (protected vs. open field; soil vs. soilless), the crop type (fruit, vegetable, ornamental), the crop species, and the water source.

Acceptable irrigation uniformity is an essential factor for the effective use of drip irrigation in intensive horticultural and fruit crops. Uniformity of application does not guarantee high irrigation efficiency, but water and fertiliser use efficiency decrease with reduced uniformity of application.

7.1.5.1. Sub-Issue A: Designing the irrigation system. Limitations and components selection

A relatively even distribution of irrigation within a crop is essential. Despite the theoretical benefits of micro-irrigation systems, correct design is necessary to evenly distribute irrigation on a field or in a greenhouse. For example, in open field, soil-grown vegetable crops, it is common to install drip irrigation systems on sloping fields. Special care should be taken with the design (e.g. following contour lines, length of laterals, etc.) and the selection of emitters, to avoid waterlogging at lower elevations. Pipe ageing also affects water distribution within a field. One possible solution is the use of thin-walled dripper lines which have a lower cost and are disposable, making it possible to use new dripper lines with each crop cycle.

Subsurface drip irrigation (SDI) may solve some of these issues. SDI applies water at some depth (depending on the crop) directly to the root zone. It is one of the most advanced methods currently in use and has several advantages, including the possibility of using treated wastewater since it is not applied to the soil surface thereby preventing possible contamination of fruit or vegetable crops. SDI also prevents water loss through evaporation. However, as the system is relatively complex, it is more suitable for medium to large-scale production.

Clogging of the emitters (both in surface drip and SDI) may be one of the limitations of drip irrigation due to the accumulation of particles, organic matter, bacterial slime, algae, or chemical precipitates. Root intrusion can be an added problem in SDI. Newly developed emitters with turbulent water flow may perform better than self-compensating emitters when using water with higher biological loads. Also, drip lines and emitters treated with chemical products to prevent root intrusion are being developed.

7.1.6. Brief description of the socio-economic impact of the issue

Some difficulties are faced when using more sophisticated irrigation methods, for example, SDI. Requirements for skilled labour, careful design of the system and good management of irrigation and fertilisation are required to maximise efficiency and to avoid emitter clogging. SDI has a high initial investment cost compared to some alternative irrigation systems. Such large investments may not be warranted in areas with uncertain water availability.

Additionally, as consumers, particularly those North-West European countries, become more environmentally conscious, they are likely to require that the products that they purchase are produced with minimal negative environmental impact.

The use of combined drip irrigation and fertigation systems can reduce fertiliser applications which will reduce growers' variable costs, and contribute to the profitability of their enterprises.

7.1.7. Brief description of the regulations concerning the issue

7.1.7.1. European level

The current European Union Directives for that affect crop water management (Nitrates Directive, European Water Framework Directive) demonstrate that the European Commission is moving towards agricultural systems in which reduced water use and enhancing the quality of natural water bodies are major priorities. These Directives have given rise to national and regional legislation to protect natural water bodies.

Growers are increasingly having to deal with legislation affecting on-farm water and nutrient management. In countries like The Netherlands, Germany, Belgium, etc., growers of soil-grown crops are being increasingly required to reduce fertiliser use to meet the national or regional criteria regarding contamination of natural water bodies. There is an on-going tendency, in these countries, to more strictly apply this legislation. Additionally, it is probable that there will be increasingly strict application in other EU countries, over time.

7.1.7.2. Country level

The European Union Directives have been transposed to national level since legal responsibility for agriculture and the environment are shared both by the EU and the member states' governments.

7.1.7.3. Regional level

In those countries with decentralised administration, regions have developed their own regulations for the use of water and fertilisers, in conjunction with national and EU legislation. At the regional level, authorities may limit water consumption for agriculture due to drought.

7.1.8. Existing technologies to solve the issue/sub-issues

The general approaches of the existing technologies can be organised into the following categories:

Irrigation equipment: materials

- Irrigation Pipes
- Drip emitters and drip lines
- Thin-walled dripper lines (irrigation tape)
- Drip pipes and drippers with anti-microbial and anti-roots functionalities

Irrigation equipment: design and management

- Installation of drip irrigation systems on sloping fields
- Adaptation of drip irrigation systems to water with high biological loads

Irrigation equipment: systems

- Subsurface drip irrigation (SDI)

7.1.9. Issues that cannot be solved currently

Growers that switch to pressurised irrigation systems (drip, sprinkler) from surface or ebb and flow systems have to ensure that they well-designed systems combined with an adequate selection of materials and equipment. Both the design and the materials used are critical to achieving good standards of water use efficiency and uniformity. Issues such as non-optimal water quality, coarse soils or topographical constraints can impede the adoption of pressurised irrigation. Additionally, the high investment costs and the necessary on-going maintenance of the equipment may be issues for some growers. Clogging of emitters and lack of uniformity of water and nutrient supply are two major issues in relation to irrigation materials. These can be important problems where design, component selection, maintenance, and management are inadequate. However, if these issues are adequately addressed, clogging and lack of uniformity can be minimised.

7.1.10. References for more information

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[2] Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., Scardigno, A. (2014). Improving water-efficient irrigation: Prospects and difficulties of innovative practices. *Agricultural Water Management*, *146*, 84-94

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7.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions (TDs).

	Technology	Cost		Required	Weaknesses	Strengths	Limitations
		Installation	Maintenance				
Materials	Irrigation pipes	Pipes + emitters between 3000 and 8000 €/ha	Evaluation of irrigation uniformity Anti-clogging treatments	Basic knowledge of pipe maintenance Pressure and flow measuring skills	High initial investment costs	Better control of water flows and pressures More efficient use of water and of fertilisers where fertigation used	Environmental issues regarding the recycling of PVC materials
	Drip emitters and drip lines	0,02-0,03 €/m for low-cost irrigation tapes to 0,2-0,4 €/emitter for pressure compensating emitters	Evaluation of irrigation uniformity Anti-clogging treatments	Maintenance of irrigation networks, good understanding of plant nutrition and water balance	High initial investment, complexity in the agricultural practice	Improvement of crop irrigation practices Increase in yields Very suitable for areas with a limited supply of water	Good quality of water Water pressurising pump, irrigation head unit
	Innovative pipes and drippers for micro-irrigation	Between 1,99 €/Kg (2% additive concentration) and 3,69 €/Kg (6% additive concentration)		Basic knowledge of maintenance of irrigation networks	Recycling of used pipes and drippers. Such service can be provided by the manufacturer company itself	Reduce the algae and diseases in irrigation water Reduce root clogging of drippers	Not yet commercialised
	Thin-walled dripper lines (irrigation tape)	600-750 €/ha		Maintenance of irrigation networks Good understanding of plant nutrition and water balance	Pressures above 0,2 MPa cause damage Not recommended for stony or coarse-textured soils	Low cost and disposable thin walled material	Short lifespan New equipment each crop cycle

	Technology	Cost		Required	Weaknesses	Strengths	Limitations
		Installation	Maintenance				
Design& management	Installation of drip irrigation systems on sloping fields	4 €/lm for pressure compensating drippers and 0,03 €/lm for irrigation tape	Periodic maintenance operations, such as chlorination and acid injection	Maintenance of irrigation networks A good understanding of plant nutrition and water balance	Cost, inefficient when medium to low-quality water is used	Compensates pressure changes and varying discharge rates Increased water and nutrient use efficiency	Irrigation water with high biological loads
	Adaptation of drip irrigation systems to water with high biological loads	Same as conventional turbulent emitters	Periodic maintenance operations, such as chlorination and acid injection	Basic knowledge of maintenance of irrigation networks good understanding of plant nutrition and water balance is required	Not suited for soilless culture facilities Does not allow small irrigation pulses	Suited drippers to avoid clogging or emitter´s flow unbalances	Yearly maintenance. Periodic evaluation of the irrigation uniformity
Systems	Subsurface drip irrigation (SDI)	900-2000 €/ha	Periodic maintenance operations, such as chlorination and acid injection	Basic knowledge of maintenance of irrigation networks Good quality water	Short lifespan No resale value	Water applied directly to the root zones Applicators placed below the ground surface	Investment not warranted in areas with uncertain water and fuel availability

7.3. *Irrigation pipes*

(Authors: Miguel Giménez[11], Rafael Baeza[11])

7.3.1. Used for

More efficient use of water.

7.3.2. Region

All EU regions.

7.3.3. Crops in which it is used

Vegetable crops, fruit crops, extensive crops.

7.3.4. Cropping type

All cropping types.

7.3.5. Description of the technology

7.3.5.1. Purpose/aim of the technology

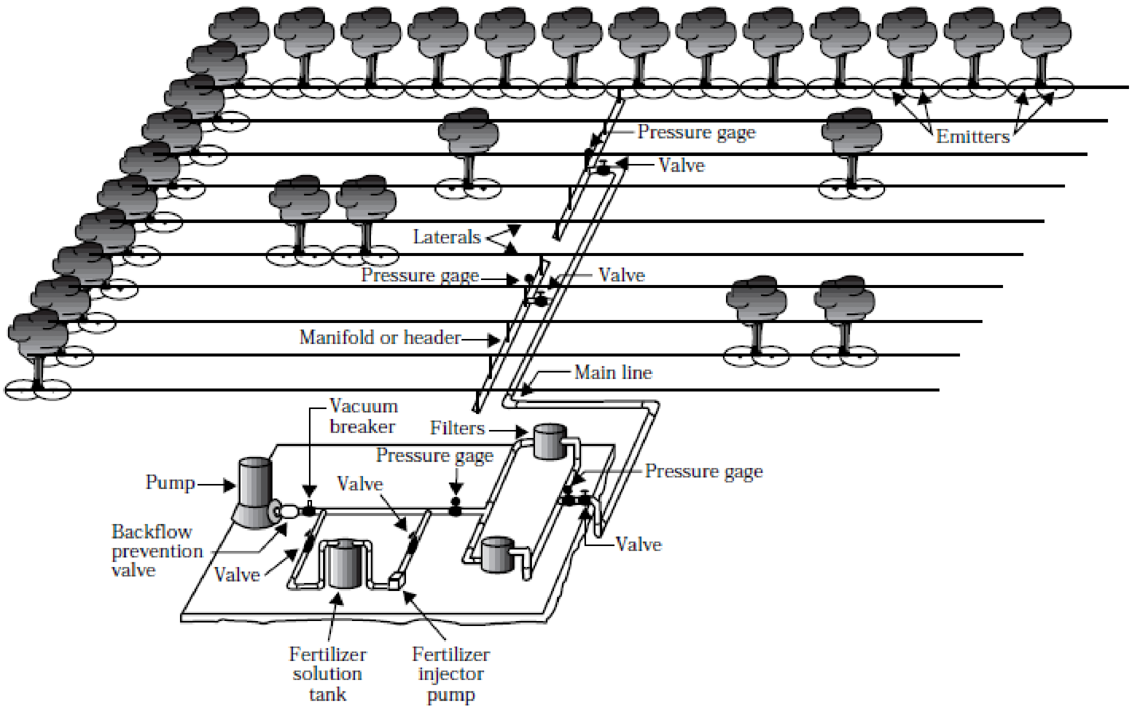

Figure 7-1. Schematic operation diagram of a pipeline irrigation distribution system (from http://www.gokulplast.com)

All drip irrigation systems consist of three components: 1) the irrigation head (the control equipment and filters), 2) the pipes that convey water to the crop, and 3) the drip emitters. The pipes convey filtered and treated water from the irrigation head to the emitters. Pipes and fittings form a distribution system that is adapted to the size, shape, and configuration of the irrigated plots. Depending on their function and position within the complete irrigation system, different terms are used to describe the component pipes. Mainlines are all the pipes (main, sub-main) between the irrigation head or water source and the control valves in the irrigation zone. Laterals are the pipes or tubes into which the emitters are inserted.

7.3.5.2. Working Principle of operation

Irrigation pipes are normally made of plastic derived materials, mainly polyvinyl chloride (PVC) or polyethene (PE).

Since PVC is a rather rigid and brittle material, its use is restricted to conditions free from impact or external sources of excessive pressure. It is normally used when the required outside diameters are >50 mm. It should be buried to avoid mechanical or sunlight damage. Because of these characteristics, it is normally used for mains pipes.

A development of PVC is Oriented PVC (PVC-O). PVC-O is made by realigning the PVC molecules when the PVC is produced. This greatly enhances the material properties giving around twice the strength and ten times the impact resistance compared to traditional unplasticised PVC (PVC-U) material. Using PVC-O enables the wall thickness of PVC-O pipes to be reduced by up to 50% while maintaining the same pressure as that of the traditional PVC- pipe. The result is that PVC-O has a larger internal diameter providing greater flow rates for an equivalent outer diameter.

Polyethylene is a flexible and easy-to-use material. Installation is much easier and faster than with PVC and can be mechanised. It is recommended for outside diameters of <50 mm. There are different classes of pipes according to the maximum working pressure (2,5, 4, 5, 6 bar). Pipes are manufactured with UV and oxidation protection, making them durable to solar radiation without significant damage for many years. PE pipes are resistant to saline water, acid, or alkaline solutions (excluding highly concentrated solutions) and to most substances employed in agricultural applications. Low-density polyethene is normally used for the drip lines in which the emitters located. The high flexibility of low-density polyethene is an important characteristic for drip lines. High-density polyethene can be used for other pipes.

The basic characteristics used to classify (plastic-derived) pipes are:

- Pressure rating: Maximum working pressure at 20°C
- Diameter: Outside diameter as stated by the manufacturer
- Wall Thickness: Thickness of the pipe wall as stated by the manufacturer

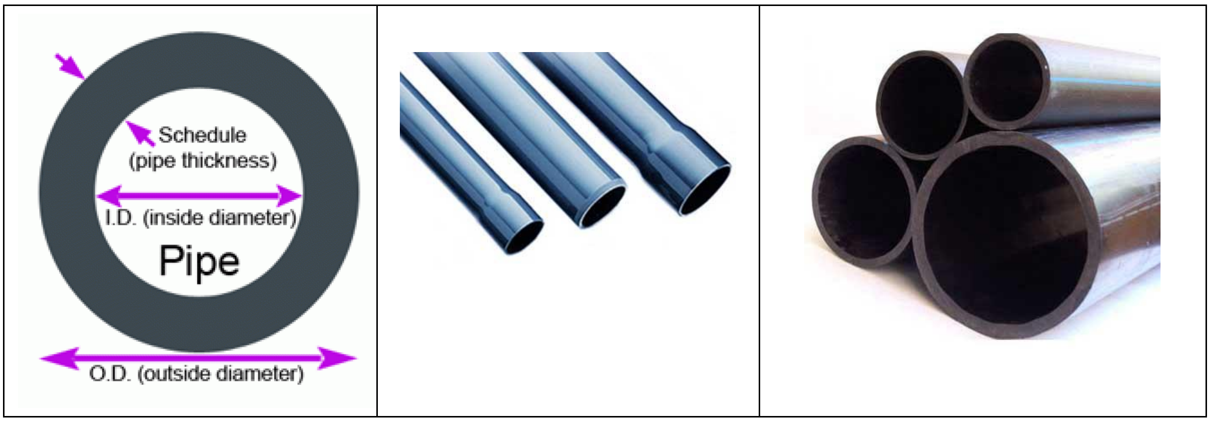

Figure 7-2. Schematic characteristics of an irrigation pipe, examples of PVC and polyethene pipes (http://www.novedades-agricolas.com; https://mathtab.com/app_id=4519)

7.3.5.3. Operational conditions

When using pipes for irrigation, the design of the irrigation system is a relevant aspect since it strongly influences the performance of the system. All pipes and fittings should be properly sized to withstand maximum operating pressures and to ensure that they convey water with the minimal loss of pressure. Crop irrigation requirements, soil type and water quality are some of the key factors that must be considered.

Consideration of the agronomic requirements determines the gross irrigation volume to be distributed by the network in periods of maximum demand and is equivalent to the maximum crop requirements modified by an application efficiency factor and a drainage factor. The hydraulic design establishes the dimension, distribution and optimal working conditions of the pipes and fittings to comply with the agronomic requirements. The calculation of the pipe diameters considers the emitters' working pressure and the pressure losses due to water transport friction along pipes and fittings. There are many spreadsheets available to enable such calculations. In addition to the pipe distribution system being designed to provide the flow rate necessary for normal irrigation, it must also have the capacity for a sufficient flow rate that ensures that the water velocity is sufficiently high for proper flushing velocities in the system (minimum 0,3 m/s).

In the Almeria region, the average irrigation sectors (maximum area irrigated in one single event) occupies an area of 5100 m^2, and the average area of irrigation subunits (maximum area in which irrigation pressure can be managed by closing or opening valves) occupies an area of 1034 m^2. The required maximum flow rates for irrigation sectors and subunits are 30,6 m^3/hour and 6,2 m^3/hour, respectively. Therefore, recommended diameters according to these flow rates are 90-110 mm for irrigation sectors and 50 mm for irrigation subunits.

Expansion and contraction that occurs under normal on-surface operating conditions should be considered to avoid possible damage. It is important to double check that all fittings are secure, particularly in subsurface distribution systems.

7.3.5.4. Cost data

The cost of an installation depends on the location, supplier, quality, size, crop, and plant density. A rule of thumb that is specific for the Almeria region is that the cost of pipes and emitters for one hectare of a greenhouse crop is approximately 3000-8000 for turbulent and pressure compensating emitters, respectively. Plant density should be around 2 plants/m^2 with one emitter/m^2. Additionally, the cost of pipes and fittings for the irrigation head unit would be between 1000 and 2000 €/ha.

7.3.5.5. Technological bottlenecks

No technological bottlenecks.

7.3.5.6. Benefit for the grower

Advantages

- Better control of water flows and pressures
- More efficient use of water and of fertilisers where fertigation used
- Easily installed and maintained

Disadvantages

- There are some environmental issues regarding the recycling of PVC materials
- More expensive installation costs compared with surface or furrow irrigation methods

7.3.5.7. Supporting systems needed

Irrigation head unit and pumps. Where a continuous supply of water is not available, water storage facilities on the farm may be required.

7.3.5.8. Development phase (delete as appropriate, add additional information if needed):

Commercialised.

7.3.5.9. Who provides the technology

Many distributors and suppliers.

7.3.5.10. Patented or not

This technique is very general and is not patented.

7.3.6. Which technologies are in competition with this one (can be referred to another technology sheet)

Surface irrigation.

7.3.7. Is the technology transferable to other crops/climates/cropping systems?

Already in general use in many regions.

7.3.8. Description of the regulatory bottlenecks

The adoption of more sustainable irrigation strategies is encouraged policy objectives at EU level, as expressed in the 6th and 7th Environmental Action Programmes and the Water Framework Directive. These policy objectives aim to promote that the rates of extraction from water resources are sustainable over the long term and to promote sustainable water use based on a long-term protection of available water resources; national, regional, and local authorities need, among other things, to introduce measures to improve the efficiency of water use and to encourage changes in agricultural practices necessary to protect water resources (and quality).

7.3.9. Brief description of the socio-economic bottlenecks

Pipes may be associated with high initial investment costs when initially installing the irrigation systems. Additionally, the use of pipes and pressurised water introduces complexity into farming practice which requires a good understanding of hydraulics and crop water requirements.

7.3.10. Techniques resulting from this technology (add as many needed)

Pipes are used in the sprinkler, drip, and subsurface irrigation.

7.3.11. References for more information

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7.4. Drip emitters and drip lines

(Authors: Rafael Baeza[11], Miguel Giménez[11])

7.4.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge
- More efficient use of fertiliser

7.4.2. Region

All EU regions.

7.4.3. Crop in which it is used

All crops.

7.4.4. Cropping type

All cropping types.

7.4.5. Description of the technology

7.4.5.1. Purpose/aim of the technology

Drip irrigation is the high-frequency application of small volumes of water in localised areas forming "wetted bulbs" along crop lines. When these wetted bulbs overlap they form a "wetted strip". With good management, drip irrigation provides high application efficiency of irrigation water. Other advantages of drip irrigation are high uniformity of water distribution, improved control of water content in the root zone, enhanced capacity to manage salinity in the root zone enabling better crop performance with poorer quality water, reduction of labour costs and improved fertiliser use efficiency when combined with fertigation. The core elements in drip irrigation are the drip emitters. The emitters are installed on the pipe and act as small throttles, assuring that a uniform rate of flow is emitted. Different models of drip emitters are available that enable use with large variations in crop types and cropping conditions. To ensure maximum irrigation uniformity and water use efficiency, it is necessary that the most appropriate emitters are selected for the crop type and local conditions. Pipe and emitter technical features and specifications determine what conditions and cropping are better applied. Parameters like length and shape of the labyrinth path, flow rate, presence of a pressure-compensating silicon diaphragm, anti-drain systems, or physical root barriers define their optimal range of applications. Normally emitters and drip lines are on-surface but in a much smaller percentage of crops, sub-surface drip irrigation (SDI) is used where the drip line is buried.

7.4.5.2. Working Principle of operation

Examples of common layouts of drip emitters and driplines have been explained in other sections of this chapter (see Irrigation Pipes or SDI). Mains, sub-mains, and laterals are installed, mostly on the soil surface, to convey water and nutrients to the crop in the most uniform and efficient way. Design of the irrigation layout should consider not only crop needs or issues related with the water quality of soil physical properties but also the hydraulic calculations to determine the most suitable materials for the required pressures and water flows.

Drip emitters 'manufacturers should provide information on the technical features of their range of products. Not every drip emitter is suitable for every situation. This information is, in the case of big manufacturers, well developed and available in their internet web pages. Information should include data about flow, working pressure ranges, recommended filtration, and some hydraulic parameters that express to what point the flow rate changes with pressure. Besides, information on the maximum recommended lateral length at different inlet pressures and different slopes might also be very useful. The hydraulic design of dripper and pipes determines to what crops or cropping systems are more suitable. As an example, a dripline could be tagged as adequate for on-surface multi-seasonal row crops while a second one would be more suitable for sub-surface seasonal crops.

Type of drip emitters

Depending on how emitters are assembled to the lateral mains, they can be classified as:

- In-line emitters, driplines, or dripper lines: Emitters are inserted and welded into the pipe or tubing during the manufacturing process, so emitter and pipe form a single piece of equipment. The emitters are uniformly spaced along the tube, often several different spacing options are available. The primary advantage of drip lines is ease of installation due to the preinstalled emitters. However, in some cases, they are just inserted between short pipe sections (0,4 and 0,5 m distance) so they can be manually extracted by pulling apart both sections of the pipe where the emitter has been intercalated. This is good for maintenance because they allow manual de-clogging of the emitters but as they are fitted with barbed joints high temperatures may easily cause accidental split opening
- On-line emitters: Assembled and pinched on the lateral mains. To install the emitters a hole is made on the lateral piping and the barbed emitter inlet is pushed into the hole and the barb locks it in place. The diameter of the main does not limit the election of emitters of different sizes which makes the adoption of new emitters easier. This type of assembly is adequate for irregular plant densities since it is manually done. However, laterals with pre-installed on-line emitters are commercially available and are widely used in soilless and container cropping drip irrigation systems

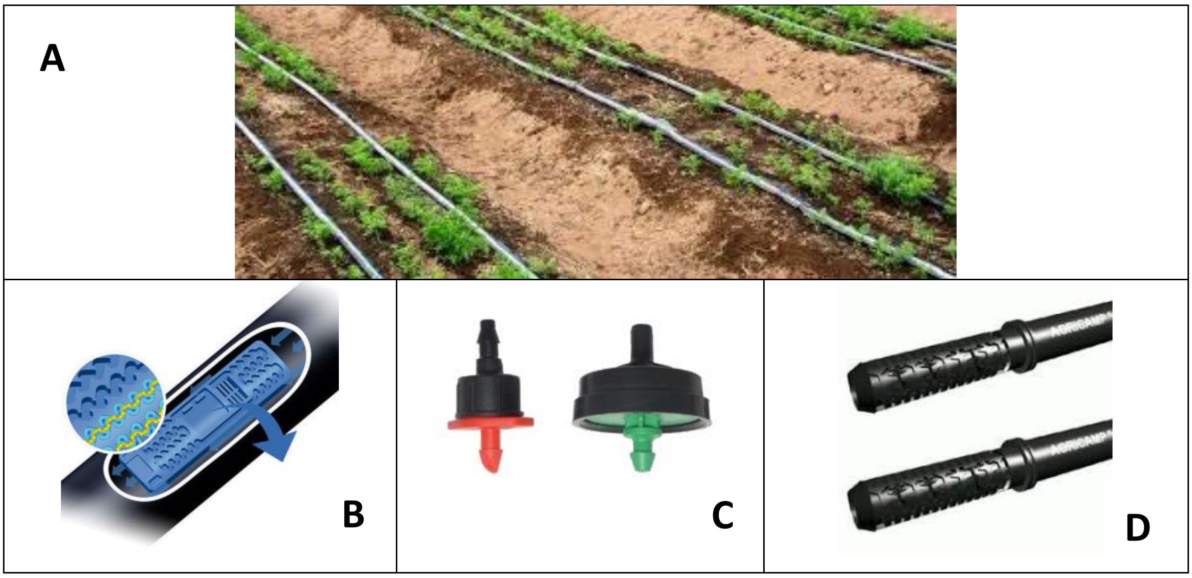

Figure 7-3. Wet bulb (A), dripline (B), on-line emitters (C) and intercalated emitters (D)

Other features also relevant to classify emitters:

- Length of the labyrinth path: Long path emitters are more expensive and maintain uniform and low flow rates. Short path emitters are cheaper and adequate for low-pressure systems where other types will not work at all. The latter is more due to clogging, especially if water quality is not good enough. Their flow performance is poorer
- Method to control flow rate and pressure: Turbulent-flow emitters work by running the water through a labyrinth resulting in water turbulence which reduces the flow rate and pressure, and clogging. Diaphragm emitters use some type of flexible diaphragm to reduce the flow and pressure. They wear out eventually, but they are much more accurate in controlling the flow rate and pressure. Besides, the show anti-leak properties so when the irrigation pulse stops irrigation water remains in the pipe and there is no extra flush of water. Combined emitters are commercially available and have the advantages of these two methods. Drip emitters with constant flow rates regardless changes of water pressure are called pressure-compensating
- Emitter sensitivity to clogging: Emitter sensitivity to clogging strongly depends on the minimum diameter of water passage inside. Emitters are then classified in:

Table 7-1. Classification of emitters according to sensitivity to clogging

Minimum diameter (mm)	Clogging sensitivity
< 0,7	High
0,7-1,5	Medium
> 1,5	Low

7.4.5.3. Operational conditions

Adequate uniformity and efficiency of irrigation can only be achieved if the technical features of emitters are suitable for the specific conditions of the crop. Firstly, the flow rate and layout of emitters should be considered in relation to the crop type and crop layout. The objective is to form wetted bulbs or strips that are adapted to the crop root system. The size of the wetted volume of soil will depend on soil texture and structure, the flow rate of the emitter, and the volume of each irrigation pulse.

There are different types of drippers commercially available. Pressure-compensating and anti-drain drippers are recommended for soilless crops or any other cropping systems requiring short and frequent irrigation pulses. On the contrary, if water used for irrigation presents high biological loads, emitters should allow complete drainage of the main circuit after each irrigation pulse. In this case, turbulent emitters, in which the applied water passes through a labyrinth structure, are recommended.

Water with high concentrations of suspended particles requires emitters specifically designed to prevent clogging, so that minimum diameter to ensure water passage should be considered.

Drip lines are recommended in layouts in which laterals are extended and retired in each cropping cycle. If this is the case and water presents high biological loads and/or suspended particles, one-use irrigation tapes may be the most suitable material.

Emitters with a low variability (measured as the “coefficient of variation”) should be selected to ensure maximum uniformity of irrigation.

7.4.5.4. Cost data

Investment costs depend much on the choice of material. Prices go from 0,02-0,03 €/m for low-cost irrigation tapes to 0,2-0,4 €/emitter for anti-drain pressure compensating emitters.

7.4.5.5. Technological bottlenecks

Most of the bottlenecks experienced are associated with the use of emitters with inadequate characteristics for the local conditions which can hamper their operation. Suitable materials have been developed to avoid the entrance of soil particles and roots, clogging due to low-quality water, or unwanted leakage causing irrigation inefficiency. However good maintenance practices are always recommended. In the case of continuous machinery passing cheaper materials made with thin walled PE are available if frequent replacement is required.

7.4.5.6. Benefit for the grower

Advantages

- Allows high-frequency irrigation
- Low pressure is sufficient
- Requires low volumes of water and fertilisers
- Suitable for using recycled water
- More uniform distribution of water and fertilisers
- Efficient and precise technique
- Reduces evaporation and runoff losses
- Easily adaptable to small and odd shaped parcels

- Requires minimal land grading
- Reduces the relative humidity in the crop canopy
- Reduces disease pressure
- Less groundwater contamination and leaching of nutrients
- Suitable for high return value crops such as vegetable and horticultural crops
- Can increase yields and decrease nutrient, pesticide, and labour requirements
- Limits deep water drainage
- Increases infiltration and storage of water on drier, less encased soils
- Possible on sloping or irregularly shaped land areas that cannot be flood irrigated
- High Fertiliser efficiency: application at any time and any dosage without wetting plant foliage; any water-soluble fertiliser may be injected
- Yields are typically increased

Disadvantages

- High initial system cost
- Power costs
- Difficulties with emitter uniformity
- Careful system design is essential
- Soil salinity issues must be addressed as well as the effects of excess calcium carbonate dissolved in the irrigation waters
- Emitter clogging will affect distribution uniformity
- Algae growth and scale build-up ($CaCO_3$) must be controlled
- Provisions must be made for utilising the flush water, same as with all systems that use filters
- Water must be available on a regular basis
- Problems with deficit irrigation strategies during the early stages of cultivation may result in limited bulb size and root entry in the dripper
- The depth of drip line installation limits soil tillage

7.4.5.7. Supporting systems needed

The irrigation system may need to be adapted to facilitate the application of this technology.

7.4.5.8. Development phase

Commercialised.

7.4.5.9. Who provides the technology

Manufacturing companies working in the irrigation sector.

7.4.5.10. Patented or not

This technology is not patented. SDI is a generic technology.

7.4.6. Which technologies are in competition with this one

Sprinkler irrigation systems and surface irrigation systems. Both provide less control of the wetted bulb and are less efficient in terms of water and fertiliser use.

7.4.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, when compared to rain-fed agriculture, irrigation can significantly increase and stabilise crop yields and farm incomes from season to season, reducing farming risk. It is a very suitable technology for arid, semi-arid, hot, and windy areas with limited water supply. Also for controlled environments like greenhouses. It is commonly used in situations including row crops, orchards, and vines.

7.4.8. Description of the regulatory bottlenecks

No relevant European directives or regulatory bottlenecks at European level. Being a system with a great efficiency in the applied water is integrated within the directive of efficient use of irrigation.

7.4.9. Brief description of the socio-economic bottlenecks

Drip lines may be associated with high initial investment costs when reclaiming or adapting land from rain-fed to irrigated agriculture. Besides, drip irrigation introduces complexity in the agricultural practice and a good understanding of plant nutrition and water balance is required.

7.4.10. Techniques resulting from this technology

Subsurface drip irrigation supplies irrigation water and nutrients directly to the root zone.

7.4.11. References for more information

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7.5. *Innovative pipes and drippers for micro-irrigation*

(Authors: Jadwiga Treder[12], Federico Tinivella[7])

7.5.1. Used for

More efficient use of water.

7.5.2. Region

All EU regions.

7.5.3. Crop in which it is used

- Vegetables
- Ornamentals
- Tree fruit

7.5.4. Cropping type

- Soil-bound
- Protected
- Open air

7.5.5. Description of the technology

7.5.5.1. Purpose/aim of the technology

The RIGA project (www.rigaproject.eu) funded in the frame of the CIP- Eco-innovation scheme has developed new irrigation systems with anti-microbial and anti-roots (trifluralin free) functionalities to pursue the following objectives:

- To reduce the algae and diseases in irrigation water, which may cause biofilm formation inside the tubes, by the addition of anti-microbial additives, according to the biocide standards: 98/8/CE and RD 1054/2002, in the extruded micro-irrigation pipes
- To reduce the clogging of the drippers by roots, using additives with low toxicity as an alternative to trifluralin. Drippers will be impregnated with these additives during the manufacturing process through injection

7.5.5.2. Working Principle of operation

Micro-irrigation, also known as drip irrigation (Figure 7-4) or trickle irrigation is an irrigation method that applies water slowly to the roots of plants. This is done by depositing the water either on the soil surface or directly to the root zone, through a network of valves, pipes, tubing, drippers, and emitters. Of the various forms of micro-irrigation, drip irrigation is the one most widely used because it can save water and reduces the use of agrochemicals.

Figure 7-4. A drip irrigation installation at PCS (Belgium)

Figure 7-5. Drip irrigation at PCS (Belgium)

Figure 7-6. Drip irrigation in Albenga (Italy)

However, despite the benefits that micro-irrigation systems present, there are some limitations:

- The clogging of the emitters. Soil particles, organic matter, bacterial slime, algae or chemical precipitates can easily clog the small openings. The micro-irrigation systems require very exhaustive filtration, even with a good quality water supply
- The prevention of root intrusion that leads to the collapse of the water emitters. Current systems with inbuilt anti-root chemical treatments are available. However, most of these chemicals are based on trifluralin which has a high toxicity to fish and

other aquatic organisms and is not approved for use as a plant protection product in Europe

Pipes and drippers already containing anti-root and antimicrobial additives that are added through the extrusion and the injection processes respectively, can ensure a constant flow during the crop cycle and avoid dripper clogging due to the formation of biofilms inside tubes or the penetration of roots into the drippers.

7.5.5.3. Operational conditions

The operational conditions are the same as the ones adopted for traditional pipes and drippers.

7.5.5.4. Cost data

Since the technology is still at a pre-commercialisation stage, costs are provided as €/Kg of the product according to manufacturers' calculations. Costs are referred to pipes already extruded with drippers (1 dripper every 15 cm). They vary between: 1,99 €/Kg (2% additive concentration) and 3,69 €/Kg (6% additive concentration).

7.5.5.5. Technological bottlenecks

No technological bottlenecks are encountered.

7.5.5.6. Benefit for the grower

Advantages

- Longer duration of pipes and drippers
- Reduction in water consumption
- Reduction of the amount of plastic waste to be collected and recycled
- Reduced environmental impact

Disadvantages

Slightly higher costs of the final product compared to traditional polyolefins.

7.5.5.7. Supporting systems needed

Mainly a service dedicated to the collection of used pipes and drippers in order to facilitate the recycling of plastic. Such service can be provided by the manufacturer company itself.

7.5.5.8. Development phase

Field tests.

7.5.5.9. Who provides the technology

- Galloplast, Spain (www.galloplast.com): additive masterbatches
- Irritec, Italy (www.irritec.com): pipes and drippers manufacturing

7.5.5.10. Patented or not

Both additives (antimicrobial and anti-root) are patented.

7.5.6. Which technologies are in competition with this one

Traditional pipes and dripper used for micro-irrigation based on standard polyolefin.

7.5.7. Is the technology transferable to other crops/climates/cropping systems?

With some adaptations/modifications, the technology can be easily transferred to plants grown in pots/containers.

7.5.8. Description of the regulatory bottlenecks

7.5.8.1. Brief description of the European directive and implications for growers at European level

- Directive 2008/98/EC on wastes
- Directive 1999/31/EC on landfill of wastes
- Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste

7.5.8.2. Implementation at the country level

- Directive 2008/98/EC adopted in Italy through the Legislative Decree n° 205 on 03/12/2010
- Directive 1999/31/EC adopted in Italy through the Legislative Decree n° 36 on 13/01/2003
- Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste adopted in Italy through the Legislative Decree n° 133 on 11/05/2005

7.5.8.3. Implementation at the regional level

- Resolution n° 14 on 25/03/2015 of the Regional Council with regards to waste management

7.5.9. Brief description of the socio-economic bottlenecks

The main issue related to the market introduction of the innovative micro irrigation pipes and drippers could be its cost compared to current polyethylene systems. The difference in the final cost is mainly attributed to the price of the new additives: it was demonstrated that the cost increase is around 10-15% regarding the final cost of the product. This could be a restraint in crops with short cultivation cycle (lower than 5 months) and where the pipe reuse is complex.

7.5.10. Techniques resulting from this technology

This technology is still in a pre-commercialisation phase. Therefore, the new pipes and drippers will be distributed according to the commercial agreements defined among project partners and on the basis of the commercial requests received by the manufacturers.

7.5.11. References for more information

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[7] www.irritec.com

[8] www.galloplast.com

7.6. Thin-walled dripper lines (irrigation tape)

(Authors: Rafael Baeza[11], Milagros Fernández[11], Elisa Suárez-Rey[11])

7.6.1. Used for

More efficient use of water and fertilisers.

7.6.2. Region

All EU regions.

7.6.3. Crop in which it is used

All crops.

7.6.4. Cropping type

- Soil-bound
- Protected
- Open air

7.6.5. Description of the technology

7.6.5.1. Purpose/aim of the technology

Counter deficient facilities that lack proper maintenance or aged irrigation networks with low cost and disposable thin walled dripper lines, making it possible to use a new material each crop cycle.

7.6.5.2. Working Principle of operation

An acceptable uniformity of irrigation distribution is an essential factor for the proper development of intensive horticultural crops. While the uniformity of distribution does not guarantee high irrigation efficiency, a lower uniformity decreases the efficiency of the applied water and fertiliser. Studies carried about by IFAPA on horticultural crops grown under Mediterranean greenhouses and conventional thick-walled dripper lines shown that a high percentage of facilities have no acceptable coefficients of uniformity (Figure 7-7).

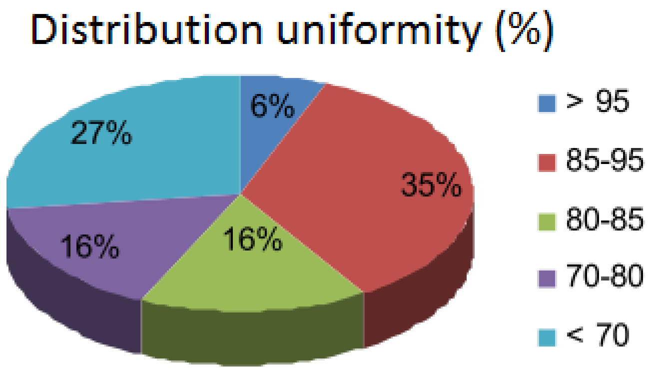

Figure 7-7. Distribution Uniformity (%) obtained in a sample of 80 grower facilities (Methodology Merriam and Keller) (Baeza et al. 2010)

Irrigation uniformity undergoes a progressive decrease because of chemical scaling and develops sedimentation with biological colonies. If the available material has a low cost and low coefficient of variation, you can use such materials for one or two growing cycles, thereby ensuring distribution uniformity. Currently, there are inexpensive irrigation tape types (0,03-0,06 €/m) on the market with a pretty good manufacturing quality. A recent study by IFAPA with a sample of 13 different irrigation tape types shows that there are types of high-quality manufacturing (Figure 7-8).

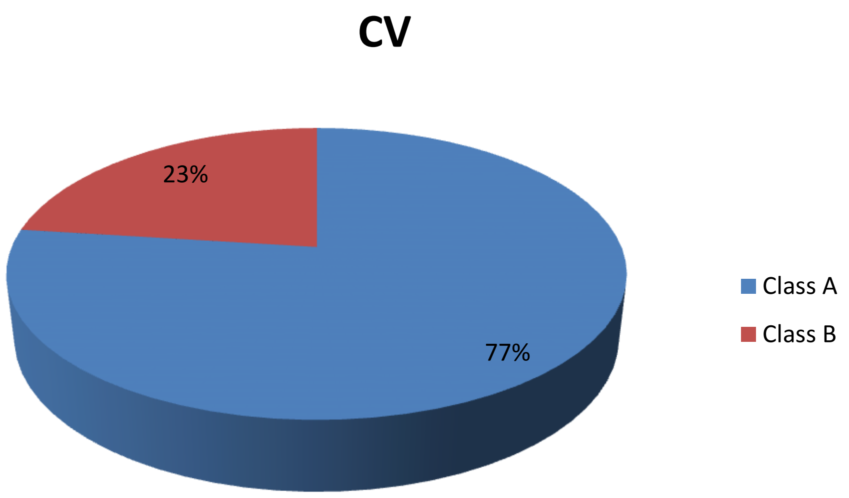

Figure 7-8. Classification of tapes studied as manufacturing coefficient of variation (CV). Class A (CV <5%), Class B (5 <CV <10) (Baeza et al. 2016)

7.6.5.3. Operational conditions

- These tapes do not allow for irrigation at high pressures (pressures above 0,2 Mpa can damage the material)
- Installing this type of materials is not recommended in farms with high presence of stones or other heavy elements

7.6.5.4. Cost data

The cost of these materials is about 20-25% of the cost of conventional irrigation pipes. The costs of labour, required to remove and replace the lines annually or biennially should, however, be considered together with a regular maintenance.

7.6.5.5. Technological bottlenecks

Not detected.

7.6.5.6. Benefit for the grower

Advantages

- Ensures high irrigation uniformity distribution
- Reduces initial investment
- No high levels of technical knowledge for handling required

- Technology developed widely and readily available

Disadvantages

- Not suited for soilless culture facilities
- Not suited for farms with high presence of stones or other coarse materials
- More sensitive to farm operations and machinery
- More sensitive to insects or animals damaged

7.6.5.7. Supporting systems needed

There are no supporting systems required.

7.6.5.8. Development phase

Commercialised.

7.6.5.9. Who provides the technology

Manufacturers and distributors of irrigation systems.

7.6.5.10. Patented or not

Yes, this technology is patented.

7.6.6. Which technologies are in competition with this one

Conventional irrigation pipes of a thick wall.

7.6.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

7.6.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

7.6.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks.

7.6.10. Techniques resulting from this technology

None.

7.6.11. References for more information

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7.7. Installation of drip irrigation systems on sloping fields

(Authors: Rafael Baeza[11], Elisa Suárez-Rey[11])

7.7.1. Used for

- More efficient use of fertiliser
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

7.7.2. Region

All EU regions.

7.7.3. Crop in which it is used

All crops.

7.7.4. Cropping type

Open air.

7.7.5. Description of the technology

7.7.5.1. Purpose/aim of the technology

Counter the pressure change and varying discharge rates along the drip line when this type of irrigation is applied on sloping fields.

7.7.5.2. Working Principle of operation

In open field vegetable production, it is common to install drip irrigation systems on sloping terrain. In these systems, the irrigation uniformity can be high when the system is evaluated when fully operating. However, an elevation change of 0,7 m will cause a 0,07 bar change in pressure in a drip line. For example, a drip tape on a 5% sloped plot, would have a change in pressure of about 0,4 bars along with a 91 m distance. Assuming the drip tape was medium flow tape (5 L/h/m) and the pressure at the manifold was 0,7 bar, then 25% more water would be applied at the lower end of the field compared to the top of the slope.

The land slope can have either a positive or a negative effect on the emitter discharge rate along the lateral drip line (Figure 7-10) in surface irrigation. Drip lines running uphill always result in increasing pressure losses along the drip line and thus lower system uniformity. When the downhill slope is too high, the emitter discharge rate at the end of the drip line becomes unacceptably high. In the example shown (Figure 7-9), the optimum slope is 1% downslope, but this will vary with drip line and emitter characteristics.

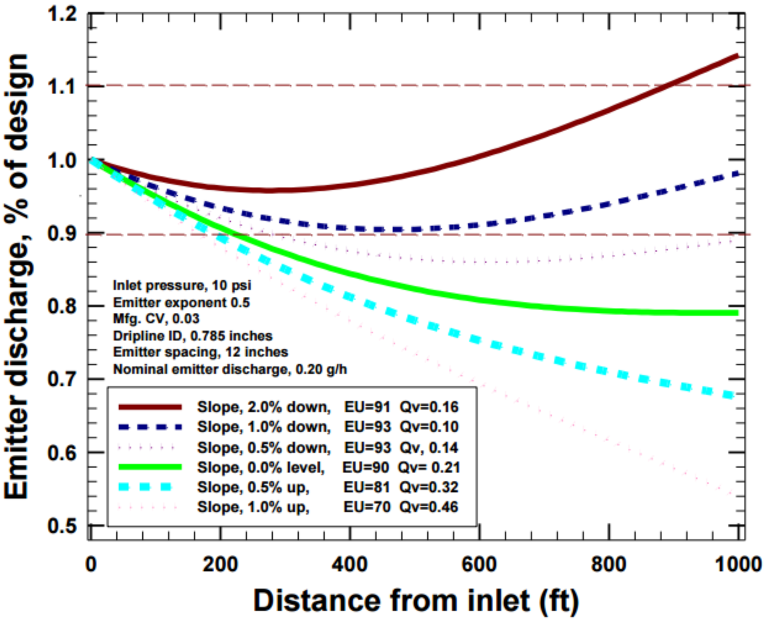

Figure 7-9. Calculated emitter discharge, emission uniformity and emitter discharge variation as affected by topography. Results for hypothetical drip line calculated with software from Roberts Irrigation Products (2003)

Irrigation Uniformity is normally measured when the flow rate from the drip emitters has become even (air flushed out and constant pressure). This method does not consider the charge/discharge periods. In case of short irrigation pulses (frequent in soilless culture) is common to find apparently good irrigation uniformity percentages whereas the situation is completely the opposite. It is strongly advised to consider the whole irrigation pulse when evaluating such irrigation systems.

In poorly designed and/or maintained irrigation systems irrigation uniformity can drastically decrease if the evaluation includes the processes of manifold water charge and discharge, as they may cause irregular water flow from the emitters when irrigation pulses finish. Those emitters at the bottom of the slope give higher outputs than those at the top since the irrigation system drains downwards. Furthermore, in sandy soils and to improve irrigation water use efficiency, it is necessary to increase the frequency of irrigation by using less volume of water per pulse. However, this increases the number of discharges from the irrigation pipes. The low uniformity in the distribution of irrigation water creates negative impacts on the crop and the environment because of waterlogging in the lowest ground levels of the farm as a consequence of the discharge of the lower emitters (due to drain off) whilst those at the top have stopped emitting water. Irrigation uniformity on sloping sites can be significantly improved by following some simple guidelines on design and maintenance.

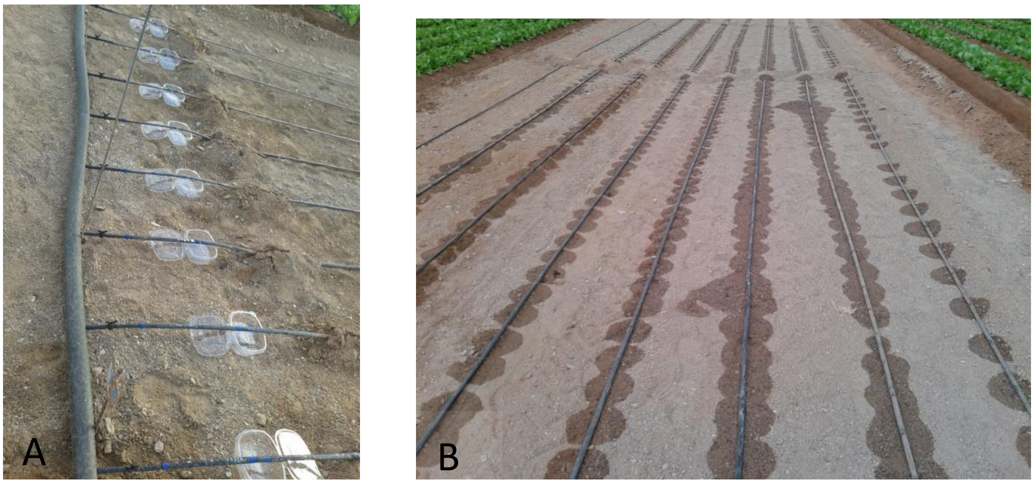

Figure 7-10 Determination of the Coefficient of Uniformity (A) and irrigation on sloping plots (B)

Possible solutions are:

- To install irrigation laterals following contour lines
- To increase the length of irrigation pulses and reduce frequency
- To install anti-leak emitters
- To reduce laterals' length
- To install electro valves; thus, avoiding the discharge of the irrigation pipes when irrigation has finished
- To bury tertiary lines, keeping them to a lower height than the first irrigating emitters, thus avoiding their discharge when irrigation is finished
- To use pressure compensating emitters in fields with elevation differences of 1,5 m or more within a zone. Pressure compensating emitters apply a more uniform rate of water on slopes and equalise pressure differentials created by the elevation differences when compared to a standard emitter
- Areas of a field at different elevations should operate as separate sub-units with separate pressure regulators
- To locate drip-lines parallel to the contour of slopes whenever possible
- Since subsurface runoff can occur in areas with a slope larger than 3%, consideration must be given to drip-line density from the top to the bottom of the slope. The drip-line on the top two-thirds of the slope should be placed at the recommended spacing for the soil type and plant material in use. On the lower one-third, the drip-lines should be spaced 25% wider. The last drip-line can be eliminated on slopes exceeding 5%. For areas exceeding 3 m in elevation change, zone the lower one-third of the slope separately from the upper two-thirds to help control drainage

7.7.5.3. Operational conditions

The use of anti-drain emitters is limited to the differences in height within the irrigation sector.

7.7.5.4. Cost data

Installation costs would be increased with the incorporation of electro-valves and anti-drain emitters. This cost is variable depending on the size and design of the irrigation system within the farm. An approximation could be 0,4 €/lm for pressure compensating drippers and 0,03 €/lm for irrigation tape. The cost of an electro-valve of 50 mm diameter is approximately 100 €.

Yearly maintenance or inputs needed are low. If anti-drain emitters are installed, periodic revision is needed since their failure may induce the discharge of water in some part of the irrigation network.

7.7.5.5. Technological bottlenecks

Anti-drain emitters may undergo reduction of their closing capacity after some time of use.

7.7.5.6. Benefit for the grower

Advantages

- Increased irrigation uniformity
- Increased water and nutrient use efficiency

Disadvantages

Cost, inefficient when medium to low-quality water is used.

7.7.5.7. Supporting systems needed

None.

7.7.5.8. Development phase

Commercialised.

7.7.5.9. Who provides the technology

Installation irrigation and fertilisation companies.

7.7.5.10. Patented or not

Not patented.

7.7.6. Which technologies are in competition with this one

Land levelling (high cost in large size farms).

7.7.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

7.7.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

7.7.9. Brief description of the socio-economic bottlenecks

High costs associated with land levelling for large size farms.

7.7.10. Techniques resulting from this technology

Not applicable.

7.7.11. References for more information

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7.8. Adaptation of drip irrigation systems to water with high biological loads

(Authors: Rafael Baeza[11], Elisa Suárez-Rey[11])

7.8.1. Used for

More efficient use of water and fertilisers.

7.8.2. Region

All regions.

7.8.3. Crop in which it is used

All crops.

7.8.4. Cropping type

All cropping types.

7.8.5. Description of the technology

7.8.5.1. Purpose/aim of the technology

This document aims to provide decision support to choose the best-suited drippers to avoid clogging or emitter´s flow unbalances when the quality of the irrigation water is low. Besides from suspended solids, agglomeration of inorganic or organic fine particles with microbial biomass and products developing inside pipes and emitters is a major problem in irrigation distribution systems. This problem is aggravated when nutrients are added to the irrigation water (fertigation) as these nutrients are a source of food for microorganisms in the water, thus increasing the biomass.

7.8.5.2. Working Principle of operation

Clogging occurs with the conjunction of the following circumstances:

- Presence of microorganisms in water
- Presence of nutrients in the water
- Water remnant in the irrigation pipelines

Drip Irrigation users can select from many different types of drippers to suit different watering needs. Drippers, also referred to as emitters, are the end devices which deliver water to plants in a specific manner. The type of irrigation emitter, the design of the irrigation network, operation and maintenance are thereof essential to achieve or avoid the previous three issues. Two major types of emitters may be distinguished. Turbulent flow emitters work by running the water through a path with all kinds of sharp turns and obstacles in it. These larger passages make the emitter less likely to clog up, but the flow is not constant since depends on water pressure. Pressure compensating drippers deliver a precise amount of water regardless of changes in pressure due to long tubing runs or changes in terrain elevations (Figure 7-11). Two works carried out by IFAPA with reclaimed wastewater have shown that emitters with turbulent regime perform better in these conditions than pressure compensating emitters. This is a result of the problems caused by the interference of bacterial colonies on the operation of the membranes in these pressures compensating emitters (Figure 7-12).

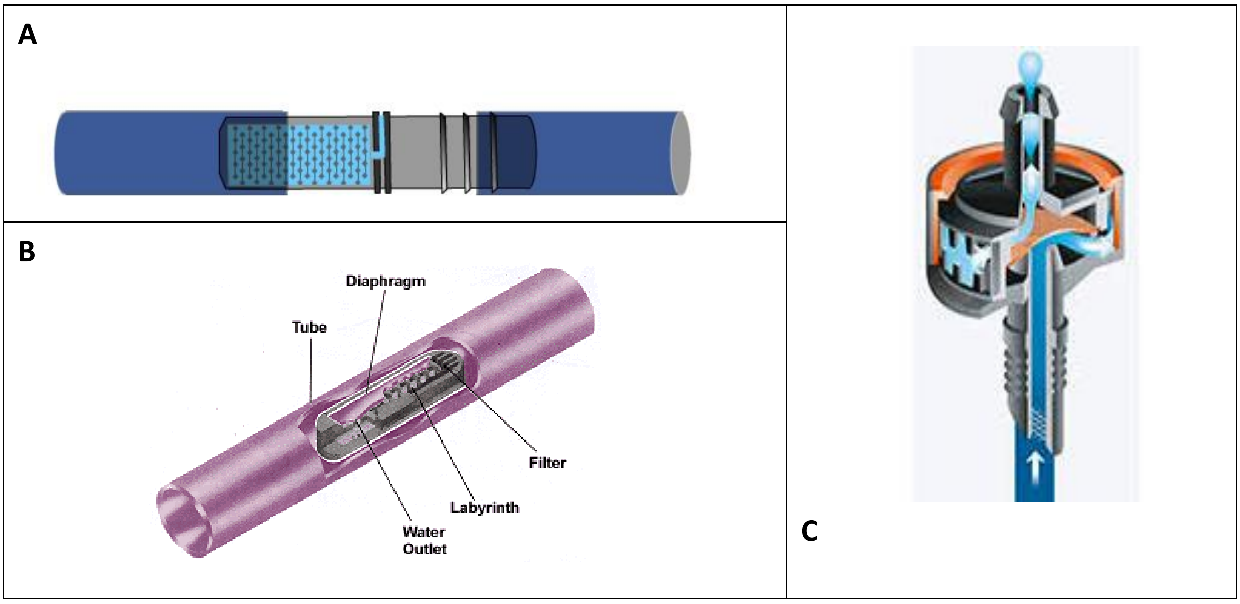

Figure 7-11. Turbulent (A) and pressure compensating drip emitters (B and C) emitters (http://www.anadoluparkbahceler.com; https://www.planetahuerto.es)

An irrigation network that provokes complete draining of the lines between irrigation pulses and this is the case when turbulent flow drippers are used, increases water transit velocity. A period of post-irrigation with no nutrients in each pulse helps to maintain irrigation uniformity. With regards to equipment maintenance, it is advised to frequently clean the end of irrigation laterals by opening end-line valves and the use bactericides.

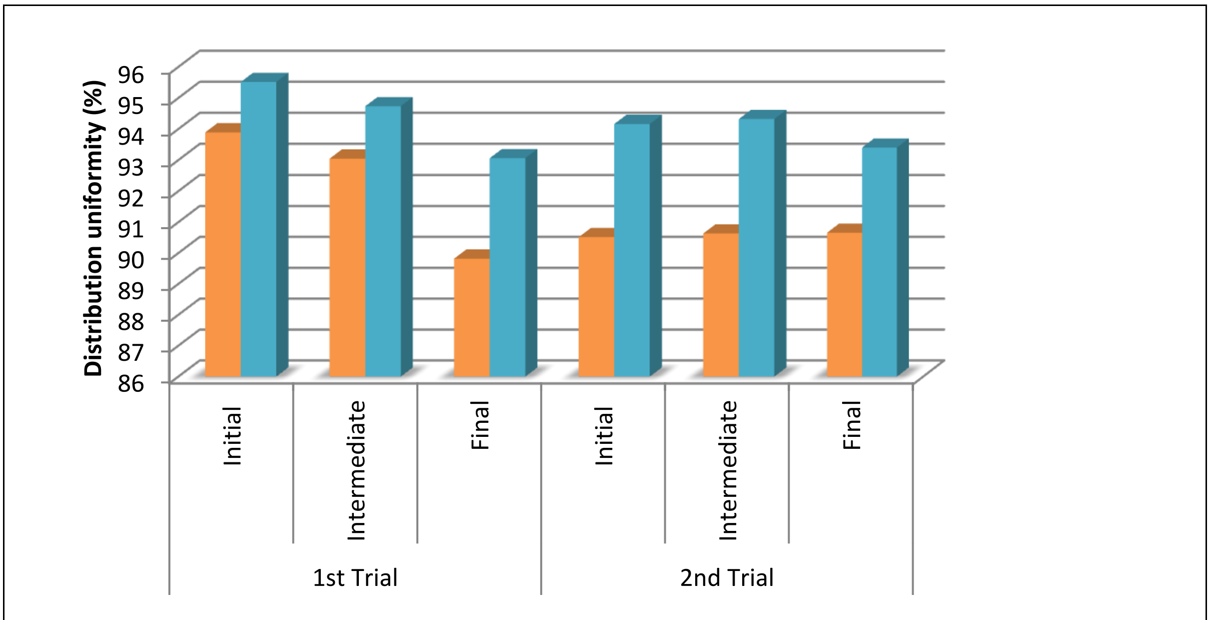

Figure 7-12. Distribution uniformity (%) and dripper type: pressure-compensating (membrane drippers) in orange, non-compensating (turbulent drippers without membrane) in blue

7.8.5.3. Operational conditions

Turbulent emitters do not perform well with short irrigation pulses. Emitters with a flow of 3 L/h and irrigation pulses of less than 1 L (thus 20´) show a drastic reduction of irrigation uniformity due to the time spent in charging or filling the irrigation manifolds. In the case of lateral pipes e.g. 180 m long and because of this charge/discharge process, 3 minutes are spent just in establishing the right operational pressure conditions. In soilless systems, in which short irrigation pulses are required, it is not recommended to follow these guidelines. Regarding increasing velocity of transit, it would require the design of smaller irrigation sectors to avoid excessive pressure head losses in the network.

7.8.5.4. Cost data

Following these design criteria, operation and maintenance of drip irrigation networks using reclaimed urban wastewater do not increase costs compared to conventional water sources.

- Yearly maintenance or inputs needed
- Periodic evaluation of the irrigation uniformity
- Regular cleaning of the irrigation network by opening the end of the drip lines (flushing)
- Application, if necessary, of bactericides and/or descaling

7.8.5.5. Technological bottlenecks

None.

7.8.5.6. Benefit for the grower

Advantages

- Increases irrigation network durability
- Reduces initial investment
- Reduces power consumption
- Not requiring high levels of technical knowledge for handling
- Widely developed technology and readily available

Disadvantages

- Not suited for soilless culture facilities
- Does not allow small irrigation pulses

7.8.5.7. Supporting systems needed

None.

7.8.5.8. Development phase

Commercialised.

7.8.5.9. Who provides the technology

Companies which install irrigation and fertigation.

7.8.5.10. Patented or not

Not patented.

7.8.6. Which technologies are in competition with this one

- Irrigation networks equipped with high-tech emitters
- Irrigation networks using drip tapes

7.8.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this decision tool can be applied in all regions when considering soil bound crops.

7.8.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

7.8.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks.

7.8.10. Techniques resulting from this technology

Not applicable.

7.8.11. References for more information

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7.9. Subsurface drip irrigation

(Authors: Elisa Suárez-Rey[11], Carlos Campillo[5], Mercedes Romero[11])

7.9.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

7.9.2. Region

All EU regions.

7.9.3. Crop in which it is used

All crops.

Currently on a wide range of grain forage and fibre crops including alfalfa, corn, cotton, tomatoes, sugar beets, potatoes, melons, soybeans and sugarcane and fruit crops.

7.9.4. Cropping type

- Soil-bound
- Protected
- Open air

7.9.5. Description of the technology

7.9.5.1. Purpose/aim of the technology

It is a planned irrigation system in which water is applied directly to the root zone of plants by means of applicators (e.g. orifices, emitters, and porous tubing) placed below the ground surface.

7.9.5.2. Working Principle of operation

A subsurface drip irrigation system (SDI) has a similar design as a common drip irrigation system. The correct design of the installation is one of the most important points due to the practically insurmountable difficulties to modify an installation that is mostly below the ground. A typical system layout consists of a settling pond (where possible), pumping unit, pressure relief valve, check valve or backflow prevention valves, hydrocyclone separator (if a settling pond is not feasible), chemical/fertiliser injection unit, filtration unit equipped with backflush valves, pressure regulators, air vent valves and PVC pipes delivering the water to the crop. The principal protection system for the drip lines is the filtration system (Figure 7-13).

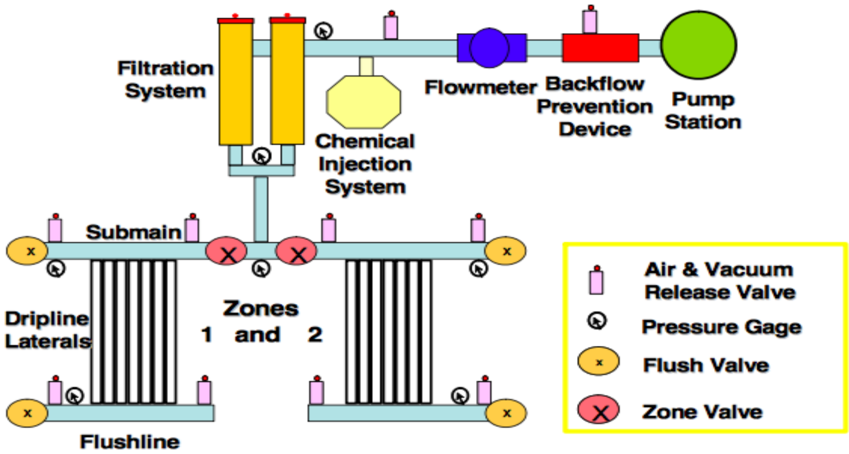

Figure 7-13. Schematic of Subsurface Drip Irrigation (SDI) System and Minimum Requirement components. (Rogers and Lamm, 2005)

The type of filtration system needed will depend on the quality characteristics of the irrigation water. The piping is 10-60 cm below the ground, depending on crop and soil (capillary attraction). As a rule, depths of between 40-45 cm are recommended in soils with clay texture and 25-35 cm in sandy loam soils. Clogging of drip line emitters is the primary reason for SDI system failure. As a water source, treated grey water or even black water is possible, with the risk of clogging being greater if the influent flow has not properly settled. Therefore, treatment of the water (e.g. a non-planted filter system, constructed wetlands or at least a septic tank) before the settling pond is necessary.

The drip tapes normally come in rolls and are buried with a customised shank that is attached to a tractor (Figure 7-14).

Figure 7-14. Equipment used to install the drip lines (Payero et al., 2006)

7.9.5.3. Operational conditions

SDI systems are highly efficient irrigation systems that apply accurate amounts of water directly to the root zone, preventing water loss through evaporation and other negative effects of surface irrigation. This is especially suitable for arid, semi-arid, hot, and windy areas with limited water supply. However, as the system is relatively complex and most likely automated, it is more suitable for medium to large-scale production.

In light textured soils without clay subsoil, deep drainage can be substantial and much closer drip tape spacing is required to ensure adequate irrigation of the areas between dripper lines and to avoid substantial water losses to deep drainage.

It is not advisable that the slope of the dropper lines is greater than 2%, in which case the use of self-compensating drippers will be necessary to minimise the differences in flow between the first and last dropper. This irrigation system is not recommended in plots with significant undulations.

7.9.5.4. Cost data

Investment costs of a subsurface drip irrigation system are between 900-2000 €/ha. The costs vary depending on the water source, quality, filtration needs, and choice of material, soil characteristics and degree of automation. Normal life expectancy is 12-15 years. With good maintenance and high-water quality, the system can be used even longer.

7.9.5.5. Technological bottlenecks

SDI systems are expected to last for many years. As a result, they must be designed, installed, operated, and maintained properly. Common challenges including emitter clogging, root intrusion, vacuum suction and insect, rodent and mechanical damage are difficult to find and repair, all of which may be successfully addressed with proper planning and management. Management time requirements for SDI can be higher than for other irrigation systems, especially the first couple of years when the learning curve is steep. This is because operating an SDI system requires special periodic maintenance operations, such as chlorination and acid injection, which are not required for other systems. Also, applying fertilisers and other chemicals using SDI requires special care and knowledge.

Preventing clogging requires regular preventive maintenance, including proper water filtration, injection of chemicals and flushing. Since the drip tape is buried, supplying water for crop germination can be a problem, especially in sandy soils. In the case of crops where medium-deep tillage is realised, to perform a perfect monitoring of the irrigation line placement to avoid drip line breakage is required. In this sense, to incorporate the lines, tractors with high-resolution GPS-RTK technology are necessary. The guidance systems will be necessary to monitor a correct drip line position to carry out the deep workings of the crop.

7.9.5.6. Benefit for the grower

Advantages

- Allows high-frequency irrigation
- Low pressure is sufficient
- Requires low volumes of water and fertilisers
- Suitable for using recycled water
- More uniform distribution of water and fertilisers
- Efficient and precise technique
- Reduces evaporation and runoff losses
- Easily adaptable to small and odd shaped parcels

- Requires minimal land grading
- Reduces the relative humidity in the crop canopy
- Reduces disease pressure
- Less groundwater contamination and leaching of nutrients
- Suitable for high return value crops such as vegetable and horticultural crops
- Can increase yields and decrease nutrient, pesticide, and labour requirements
- Limits deep water drainage
- Increases infiltration and storage of water on drier, less encased soils
- Reduced weed growth due to the dryer soil surface
- Possible on sloping or irregularly shaped land areas that cannot be flood irrigated
- High Fertiliser efficiency: application at any time and any dosage without wetting plant foliage; any water-soluble fertiliser may be injected
- Yields are typically increased
- Improved efficiency and management of agricultural operations: lower compaction and soil crusting

Disadvantages

- High initial system cost
- Power costs
- Difficulties with emitter uniformity
- Sizeable personal effort required to understand the anticipated outcome as well as the operation and maintenance
- Requires higher skilled labour than most other irrigation systems
- Difficulty in monitoring and evaluating irrigation events and management of the system
- Possible poor water distribution, infra- and over-watering areas, poor soil aeration, lower yields and high losses by deep percolation in case of bad management
- Careful system design is essential
- Difficulty of adaptation of crop rotations with different distance between lines at the fixed distance between the dripper lines
- Insufficient movement of water to the soil surface, especially in sandy soils, limiting germination and establishment of crops and increasing the application of water to achieve optimum moisture
- High cost of recovery and removal of tapes
- Soil salinity issues must be addressed as well as the effects of excess calcium carbonate dissolved in the irrigation waters
- Filtration is critical
- Emitter clogging will affect distribution uniformity
- Algae growth and scale build-up ($CaCO_3$) must be controlled

- Provisions must be made for utilising the flush water, same as with all systems that use filters
- Water must be available on a regular basis
- Problems with deficit irrigation strategies during the early stages of cultivation may result in limited bulb size and root entry in the dripper
- The depth of drip line installation limits soil tillage
- Necessary to use a tractor with GPS control systems RTK and automatic steering

7.9.5.7. Supporting systems needed

The irrigation system may need to be adapted to facilitate the application of this technology.

7.9.5.8. Development phase

- Research
- Experimental phase
- Commercialised

7.9.5.9. Who provides the technology

Several suppliers, e.g. Netafim, NaandanJain, Toro.

7.9.5.10. Patented or not

This technology is not patented. SDI is a generic technology.

7.9.6. Which technologies are in competition with this one

SDI is generally a high-tech, automatically operated technology. However, several low-cost and simple methods of subsurface (drip) irrigation like pitcher or bottle irrigation exist that are equally effective for small-scale farming. There are several subsurface techniques used for secondary wastewater treatment such as a leach field or evapotranspiration bed that also provide uncontrolled irrigation to fields.

Other water saving techniques such as regulated deficit irrigation (see relevant TD) or transient deficit irrigation which trigger similar effects on the plant but require different management can also be used.

7.9.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, when compared to dryland farming, irrigation can significantly increase and stabilise crop yields and farm income from season to season, reducing farming risk. This is especially suitable for arid, semi-arid, hot, and windy areas with limited water supply. It is commonly used in situations including row crops, orchards, and vines.

7.9.8. Description of the regulatory bottlenecks

7.9.8.1. Brief description of the European directive and implications for growers at European level

There are no relevant European directives or regulatory bottlenecks at European level. Being a system with a great efficiency in the applied water is integrated within the directive of efficient use of irrigation.

7.9.8.2. Implementation at the regional level

SDI allows the use of recycled water while complying with environmental and public health regulations which prohibit overhead irrigation of certain crops with recycled water.

7.9.9. Brief description of the socio-economic bottlenecks

SDI has a high initial investment cost compared to some alternative irrigation systems. In many cases, the system has no resale value or a minimal salvage value. Such large investments may not be warranted in areas with uncertain water and fuel availability, particularly if commodity price outlook is poor. SDI systems typically have a shorter design life than alternative irrigation systems which means the annualised depreciation costs must increase to provide for system replacement.

Management time requirements for SDI can be higher than for other irrigation systems, especially the first couple of years when the learning curve is steep. This is because operating an SDI system requires special periodic maintenance operations, such as chlorination and acid injection, which are not required for other systems. Also, applying fertilisers and other chemicals using SDI requires special care and knowledge.

7.9.10. Techniques resulting from this technology

SDI is a specialised sub-set of drip irrigation where drip line or drip tape "lateral lines" (tubes buried beneath the crop rows) and supply and flushing "submains" (pipes supplying water to the lateral lines) are buried beneath the soil surface for multi-year use. The technique of burying Bi-Wall drip tape laterals beneath field crops was pioneered in the American Southwest decades ago and has since been implemented by researchers and growers alike.

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Chapter 8. Fertigation equipment – Nutrient addition

Coordinators: Juan José Magán[9], Ilse Delcour[19]

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8.1. Introduction on fertigation equipment for nutrient addition

8.1.1. These techniques concern the issue

Preparation of the nutrient solution to be supplied to the crop.

8.1.2. Regions

All EU regions. The accuracy of fertiliser injection is a relevant issue in every region since it must always be taken into account when managing fertigation.

8.1.3. Crops in which the problem is relevant

All fertigated crops.

8.1.4. Cropping type

All cropping types.

As buffer capacity of the soil is not available in soilless culture, the preparation of the nutrient solution is more critical in this growing system (especially in closed systems). However, the accuracy of fertiliser injection must also be considered in soil cropping when optimising fertigation.

8.1.5. General description of the issue

In fertigation, nutrients are supplied to the crop together with the irrigation water as a nutrient solution. For the preparation of this solution, fertilisers have to be previously dissolved in one or several concentrated solutions, which are injected into the irrigation water by using one of the different fertigation systems available. In the primitive systems, the objective was to supply absolute quantities of nutrients to the crop, not a stable nutrient solution. However, a lot of modern fertigation systems that are frequently used nowadays are based on EC and pH measurements and can make a balanced nutrient solution. The idea is to maintain adequate nutrient concentrations at the root level. This criterion is typically for soilless culture but is applied as well in soil-grown crops. In any case, it is essential to achieve accurate injection of fertilisers for adequate control of crop nutrition, avoiding crop development to be affected.

The different issues related to the preparation of the nutrient solution are the followings:

8.1.5.1. Sub-Issue A: Accurate addition of nutrients to the irrigation water about the established fertigation

When preparing the final nutrient solution, the objective is to add exact quantities of fertilisers to the irrigation water in relation to the nutrient requirements to reduce as much as possible deviations between desired and supplied fertigation. This deviation can be significant if using inadequate technology or if it is not well managed.

8.1.5.2. Sub-issue B: Determination of the nutrient quantity supplied to the crop

The current trend in fertigation is to supply a balanced nutrient solution to the crop, which is frequently prepared with Venturi injectors based on EC and pH. In this way the exact quantity of nutrients supplied per sector is unknown. It is possible to install a flow meter per injector, but the measurement is not exact because the flow of the injected solution is not continuous. Deviations amount at least 5-10%. Automatic systems based on injection pumps are more appropriate for this objective. However, their price is frequently a limiting factor. Furthermore, injection pumps tend to block or fail easily if fertilisers are not well dissolved, thereby provoking higher maintenance requirements.

8.1.5.3. Sub-issue C: Automatic addition of fertilisers with a low effect on EC

Fertilisers that only have a small effect on EC are frequently used in organic production. When applying them with automatic injection systems, based on EC measurement, it can be difficult to quantitatively manage fertiliser addition because the precision of EC measurement is insufficient. Quantitative injection is a solution to this problem. However, injection pumps are expensive, and insufficient dissolved solids in the stock solution can cause damage. For that reason, a pre-filtration to 120 µm is convenient, but these filters are easily clogged when using non-optimal fertilisers. Chapter 4 provides an overview of filtration systems and the issues associated with their use.

8.1.5.4. Sub-issue D: Availability of optimal fertilisers for organic agriculture to be applied by fertigation

Fertilisers applied in organic production are rarely optimal to be applied by fertigation and tend to clog the drippers. This effect is reduced by using adequate drippers and filtration systems and frequently rinsing the irrigation pipes. However, there is a need for good fertilisers for this application.

8.1.6. Brief description of the socio-economic impact of the issue

Application of an unbalanced nutrient solution can have repercussions on the productivity of the crop due to antagonism phenomena, saline effects or even toxicity. The preparation of the nutrient solution is essential especially in closed soilless growing systems to maintain the stability of the composition of the recirculating solution. For that reason, it is necessary to have adequate knowledge about nutrient requirements and to control fertiliser injection.

An unsuitable nutrient solution, together with excess irrigation, can induce the release of nutrients to the environment by leaching, with the following pollution effect.

The use of non-optimal fertilisers in fertigation or inadequate management can provoke clogging problems and higher maintenance requirements, having a negative economic impact on the production cost.

8.1.7. Brief description of the regulations concerning the issue

There are no specific regulations concerning equipment for the preparation of the nutrient solution.

In regions that have been declared Nitrate Vulnerable Zones by the European Nitrates Directive, discussed in Chapter 1, the maximum quantity of nitrogen (N) that can be applied to a crop is limited. Growers have to fill in and retain the N fertilisation sheet, indicating the application of N, as well as the invoices related to the purchase of fertilisers. The N applied is frequently estimated from the irrigation volume and the theoretical concentration in the nutrient solution but not measured because the adequate technology for this purpose is not available on the farm.

Regarding fertilisers, the Regulation (EC) Nº 2003/2003 of the European Parliament and of the Council of 13 October 2003 lays down the mandatory technical characteristics to be met by these products.

8.1.8. Existing technologies to solve the issue/sub-issues

The general approaches of the existing technologies can be organised into the following categories:

- Manually controlled equipment:
    - Simple fertilisation tank (including closed pressurised tank and open fertilisation tank connected to pump aspiration)
    - Venturi injection
    - Injection pump
- Automatic equipment:
    - Automatic injection equipment by Venturi effect based on EC and pH
    - Automatic injection equipment with mixing tank based on EC and pH
    - Automatic injection equipment based on quantitative addition
- Stock solutions:
    - Solubility of fertilisers
    - Preparation of concentrated solutions
    - Liquid versus solid fertilisers

8.1.9. Issues that cannot be solved currently

In general, acceptable technology (although not optimal) is currently available for the preparation of the nutrient solution in fertigation. However, the cost of the best technologies is usually a limiting factor for their application, especially in less profitable crops and small farms. Furthermore, problems related to blocking and failure of injection pumps make simpler and cheaper technologies like Venturi injectors to be frequently considered more reliable and preferred, despite their lower accuracy. The lack of awareness by growers of better technologies can also be a decisive factor in some cases.

There is a need for high-quality fertilisers suitable for fertigation in organic.

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8.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions (TDs)

TD title	Installation cost	Maintenance cost	Strengths	Weaknesses	Limitations
Manually controlled equipment					
Closed pressurised tank	A tank of 60 L: 600 €	Addition of fertilisers before the irrigation	Low cost and simple technology Electricity is not necessary if having enough pressure It can be adequate for small farms	The concentration of fertilisers in the solution is not constant The fertilisers have to be added to the tank before each application	Not suitable for automatic fertigation
Open fertiliser tank with direct aspiration	A tank of 200 L: 350 €	Addition of fertilisers before the irrigation	Low cost and simple technology It can be adequate for small farms	The tank can empty during the irrigation and air can reach the pump	A pump is necessary for the aspiration of the fertiliser solution
Venturi injection	A/B tanks + acid: 1500–2000 €	Labour for flow adjustment	Electricity is not necessary if having enough pressure Cheap and simple technology It can be used in small farms	Injection no proportional to irrigation flow. It must be adjusted if changing Stable pressure needed for acceptable control of injection	Manual Venturi injectors are not very suitable for automatic fertigation Venturi injectors provoke a loss of pressure of 1,5-2 bars
Injection pump	Hydraulic pump (0-350 L/h): 700 € Electric pump (similar characteristics): 1000 €	Periodical recalibration (hydraulic pumps), energy cost (electric pumps), pump maintenance	Use of pressure existing in the network if using hydraulic pumps An accurate injection can be achieved	Electricity is necessary if using electric pumps Hydraulic pumps must regularly be recalibrated to maintain dosage accuracy	Proportional hydraulic injection pumps are limited by irrigation flow (lower than 20 m^3/h) Investment costs if starting from scratch with an irrigation system may limit the adoption of this technology
Automatic equipment					
Automatic injection equipment by Venturi effect based on EC and pH	Equipment with 5 injectors: 5000–8000 €	Flow adjustment, revision/change of pH and EC sensors and solenoid valves, energy cost	If having enough pressure, electricity can be only necessary to activate the controller and the electro-valves This technology permits to adapt Venturi injectors to automatic fertigation with an acceptable cost	Any pressure modification causes a variation of the injection flow. It must be maintained stably Supervision is necessary to ensure that fertiliser injection is correct	Price (although being relatively low) can limit its installation in small farms Fertilisation is few flexible if using A/B stock solutions for better control of fertiliser injection

TD title	Installation cost	Maintenance cost	Strengths	Weaknesses	Limitations
Automatic injection equipment with mixing tank based on EC and pH	Equipment with 5 injectors: 10000–14000 €	Revision/change of pH and EC sensors, magnetic drive injection pumps and solenoid valves, energy cost	Higher accuracy than with automatic equipment using Venturi injectors and individual stock solutions	Electricity required. Possible use of existing pressure for irrigation but not for injection Magnetic pumps burn if working without water More expensive than automated fertigation equipment using Venturi injectors	Its cost is the most limiting factor compared to automatic Venturi injectors
Automatic injection equipment based on quantitative addition	Equipment with 5 injectors: 15000 €	Revision/change of pH sensor, valves, membranes, oil and pleat of the pumps, energy cost	This is the most accurate technology The injection of fertilisers is proportional to the irrigation flow, not being based on EC. This facilitates the injection of fertilisers with a low effect on EC	Electricity is necessary. Pressure existing in the network can be used for irrigation but not for fertiliser injection It is the most expensive technology Maintenance of the injection pumps is essential for an exact injection The injection pumps are negatively affected by not well-dissolved solids	The use of liquid fertilisers is recommended to avoid damage to the injection pumps Solid fertilisers have to be completely dissolved by using effective mixers for the preparation of the stock solutions
Stock solutions					
Solubility of fertilisers			Fertigation can be a very effective way of supplying nutrients	Knowledge is needed for dissolving different fertilisers	Only 100% water soluble fertilisers must be used in fertigation
Preparation of concentrated solutions		Cost of fertilisers, labour for the preparation of the concentrated solutions, energy cost	Cost of fertilisation by using concentrated solutions prepared with soluble solid fertilisers tends to be lower than directly using liquid fertilisers	Electricity is necessary for mixer activation The preparation of the stock solutions takes time	Knowledge about compatibility between fertilisers and their solubility is required Low temperature reduces fertiliser solubility and can provoke sedimentation
Liquid versus solid fertilisers		Cost of fertilisers	Lower labour requirements when using prefabricated liquid concentrated solutions instead of soluble solid fertilisers because stock solutions do not have to be prepared in situ Liquid solutions are completely dissolved and do not have sediments provoking clogging (if crystallisation is avoided)	Prefabricated liquid concentrated solutions tend to be more expensive than soluble solid fertilisers	Liquid solutions tend to be more used in big than in small farms in order to reduce personnel cost. They must be around 20% less concentrated in winter to avoid crystallisation. Solutions with high temperature of crystallisation must not be stored during winter

8.3. Simple fertilisation tank

(Author: Juan José Magán[9])

8.3.1. Used for

Addition of fertilisers to the irrigation water.

8.3.2. Region

All EU regions.

8.3.3. Crops in which it is used

All fertigated crops.

8.3.4. Cropping type

All cropping types.

8.3.5. Description of the technology

8.3.5.1. Purpose/aim of the technology

This technology allows the injection of fertilisers into the irrigation water for the fertigation of soil-grown crops.

8.3.5.2. Working Principle of operation

It is possible to differentiate two types of simple fertilisation tanks:

- Closed pressurised tank: it is a tank of 40-250 L, connected in parallel to the irrigation pipe, able to support the irrigation pressure (Figure 8-1). It has a lid on top which allows compatible fertilisers to be placed inside and to be closed hermetically later. The water inlet is near the bottom, whereas the outlet is at the upper part (Figure 8-2). A valve is installed in the irrigation pipe between the inlet and the outlet to generate a pressure difference between 0,2 and 0,5 kg/cm^2. This provokes a derivation of flow through the tank which sweeps along the fertilisers to the irrigation pipe

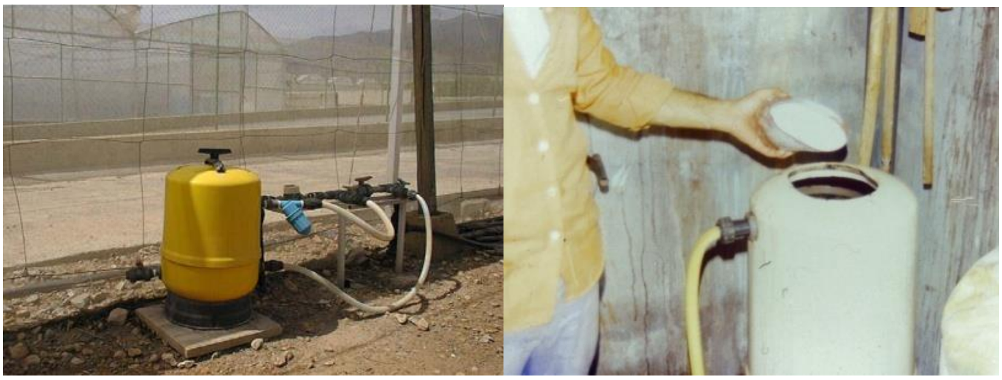

Figure 8-1. Pictures of closed pressurised tanks (Source: Juan Carreño Sánchez)

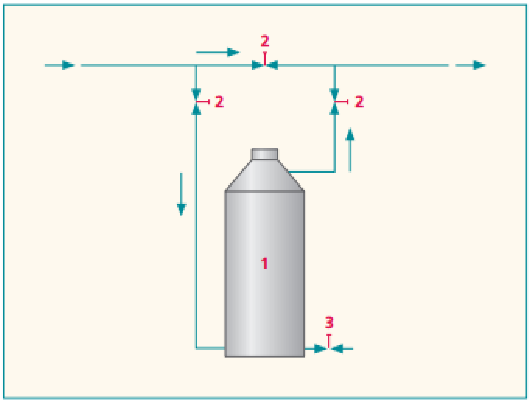

Figure 8-2. Scheme of installation of closed pressurised tank: 1) Fertilisation tank, 2) Valve, 3) Drain valve (Carreño and Magán, 2003)

- Open fertilisation tank connected to the pump aspiration: it is a normal tank, usually of 200-500 L, connected to the aspiration of the pump, which creates a negative pressure able to suck the fertiliser solution (Figure 8-3). The injected flow can be regulated by using a valve placed between the tank and the aspiration (Figure 8-4). It is a simple method if the pump is above the pond. However, if the opposite, it is necessary to provoke a pressure loss in the aspiration by partially closing a valve

Figure 8-3. Picture of open fertilisation tank connected to the pump aspiration (Source: Juan Carreño Sánchez)

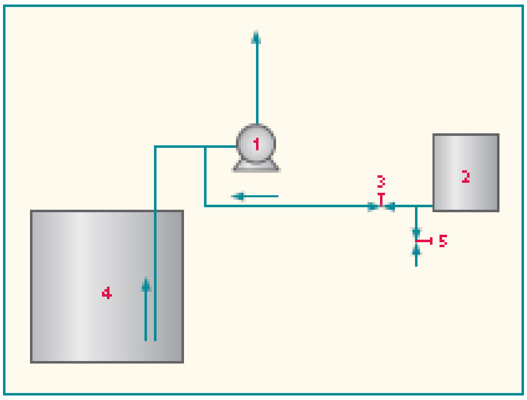

Figure 8-4. Scheme of installation of open fertilisation tank: 1) Pump, 2) Fertiliser tank, 3) Valve, 4) Pond, 5) Drain valve (Carreño and Magán, 2003)

8.3.5.3. Operational conditions

When using closed pressurised tank, a unit of 40-60 L is usually installed for an irrigation sector of 2500 m^2, whereas a tank of 80-120 L is used for 5000 m^2. A tank of 250 L is convenient for an irrigation sector of 1 ha.

If using an open tank connected to pump aspiration, a tank of 200-300 L is usually installed for an irrigation sector of 5000 m^2, whereas a tank of 500 L is typically used for 1 ha.

Fertiliser injection is not constant in a closed tank but decreases exponentially. Water flow through the tank (in L/h) necessary for tank emptying in a given time (t, in hours) can be calculated by using the following equation:

$$q = \frac{-V \ln \frac{A}{A_0}}{t}$$

where:

V is the volume of the tank (L)

A_o is the initial quantity of fertiliser in the tank

A is the quantity of residual fertiliser in the tank after that time (for instance 2% of the initial quantity)

To improve the uniformity of the fertiliser injection, it is possible to use a tank with a big volume or to reduce water flow through the tank. It is also possible to put solid fertiliser inside the tank. In this way, the solution is constantly closed to the solubility limit. However, this practice is not recommendable because solid particles can enter into the irrigation system.

8.3.5.4. Cost data

The cost of a typical closed pressurised tank of 60 L is 600 €, including accessories and installation. For an open fertilisation tank of 200 L connected to the pump aspiration, the price is 350 €.

8.3.5.5. Technological bottlenecks

No control of fertiliser injection during the irrigation when using a closed tank. Furthermore, fertilisation is not based on supplying a balanced nutrient solution to the crop but on providing with absolute quantities of nutrients. Finally, tank refill with fertilisers has to be done before each irrigation and this makes automation of fertigation difficult. Thus, its use is only justified in small farms, where it is not profitable to install a more sophisticated injection system.

Regarding the open tank, it also has to be refilled before each irrigation if only having one unit and different fertilisation programmes have to be established. This can be solved by installing more than one tank of enough capacity and a flow meter for each tank to adjust the injection.

8.3.5.6. Benefit for the grower

Advantages

- Low cost and simple technologies
- Electricity is not necessary if having enough pressure (with closed tank)
- It can be adequate for small farms

Disadvantages

- The concentration of fertilisers in the solution is not constant (with closed tank)
- The fertilisers have to be added to the tank before each application (with closed tank)
- The open fertilisation tank can empty during the irrigation and air can reach the pump. To avoid this a float valve can be installed to maintain a minimum level of water inside the tank or an electro-valve to close the aspiration from the tank if it is empty

8.3.5.7. Supporting systems needed

An irrigation pump is needed if using an open fertilisation tank connected to the pump aspiration.

8.3.5.8. Development phase

Commercialised.

8.3.5.9. Who provides the technology

Companies installing fertigation systems.

8.3.5.10. Patented or not

No.

8.3.6. Which technologies are in competition with this one?

Venturi injection, injection pump.

8.3.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this technology operates independently of climate and crop. However, it is not adequate for soilless culture.

8.3.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks for using this equipment.

8.3.9. Brief description of the socio-economic bottlenecks

None.

8.3.10. Techniques resulting from this technology

Closed pressurised tank connected to the impulsion of the pump or using natural pressure.

Open fertilisation tank connected to the aspiration of the pump. It is possible to install more than one tank for applying incompatible fertilisers at the same time or for establishing different recipes.

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8.4. Venturi injection

(Authors: Alberto Alfaro[13], Carlos Campillo[5], Juan José Magán[9])

8.4.1. Used for

Addition of fertilisers to the irrigation water.

8.4.2. Region

All EU regions.

8.4.3. Crops in which it is used

All fertigated crops.

8.4.4. Cropping type

All cropping types.

8.4.5. Description of the technology

8.4.5.1. Purpose/aim of the technology

The Venturi injector is a device used for the application of liquid or dissolved fertilisers (fertigation) and agricultural chemicals (chemigation) into a pressurised irrigation system.

8.4.5.2. Working Principle of operation

This injector is based on the Venturi effect, by which fluid velocity increases as it passes through a constriction in the pipe according to the principle of mass continuity, while its static pressure decreases according to the principle of conservation of mechanical energy. The constriction in the Venturi injector is enough to promote a pressure decrease below atmospheric pressure, causing the solution to be sucked into the injector from the stock tank and mixed with the mainstream (Figure 8-5). A Venturi injector uses excess pressure in the irrigation system to create this low-pressure zone in the injector throat. Hence fertiliser and chemicals solutions may be efficiently supplied into the pressurised water pipe without using an injection pump.

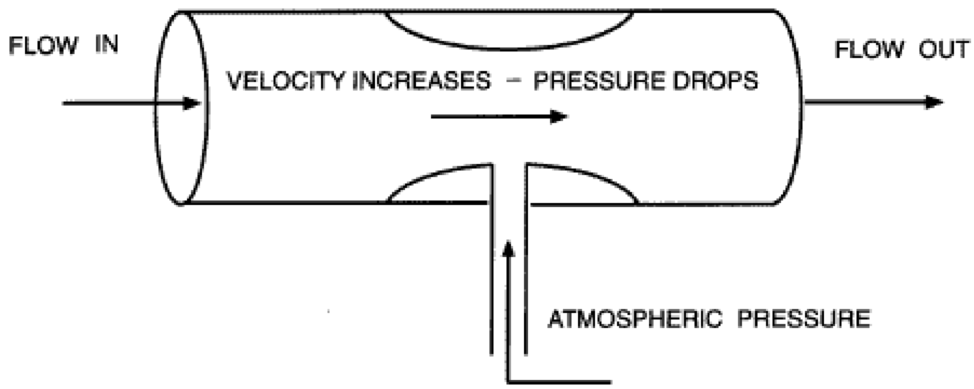

Figure 8-5. Functioning scheme of Venturi injector (https://www.lenntech.com/venturi.htm)

Venturi injectors can be easily connected to the irrigation system in two ways (Figure 8-6):

- In line: installed directly on the main line (typical for very low capacity systems)
- By-pass: installed as a by-pass from the main line. In this configuration, a manual or hydraulic pressure reducing valve is used for flow deviation through the injector

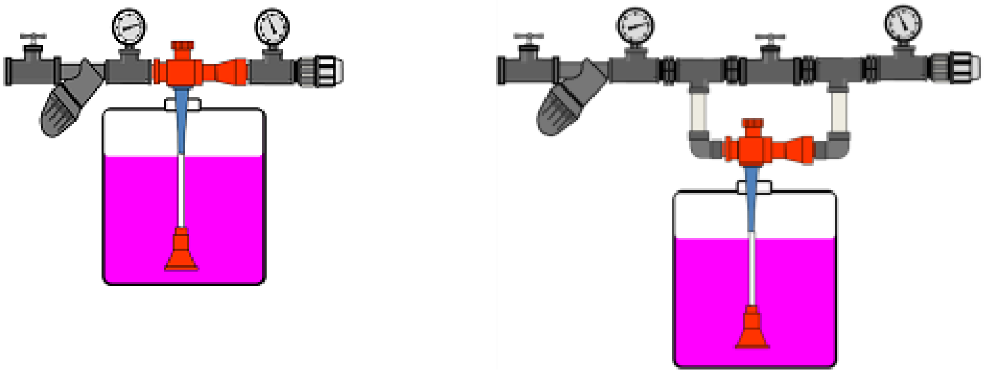

Figure 8-6. Ways of installation of Venturi injectors in an irrigation system: in line (left) and by-pass (right)

8.4.5.3. Operational conditions

The system requires a minimum pressure difference between the inlet and the outlet of 1,5-2 bar. Otherwise, the injection will not be high enough. When using a pump for irrigation, it is possible to connect the outlet of the injector to the suction of the pump. This reduces the absolute pressure required at the inlet of the injector, although a higher flow must be pumped since a part is derived through the injector.

Injection flow is usually regulated by using a valve and measured with a flow meter, which is normally calibrated for water. Since water density is 1 kg/L, a flow of 1 kg/hour is equivalent to 1 L/hour (which is the unit typically shown in flow meters). However, if stock solutions with a significantly different density are injected, it is necessary to take into account that the indicated flow is expressed in kg/hour and it has to be divided by the solution density to express it in L/hour. This can be especially important when liquid fertilisers are injected.

8.4.5.4. Cost data

Installation cost

The cost of a Venturi injector is 30-200 €. A complete manual installation including three injectors with their respective stock tanks, flow meters, valves, accessories and labour costs around 1500-2000 € and can be installed in one day.

Maintenance

The suction filter must be cleaned and injection flow adjusted periodically.

8.4.5.5. Technological bottlenecks

Injection flow is very sensitive to pressure variations and is not proportional to irrigation flow. Hence, it has to be adjusted in non-automated installations whenever these parameters change.

8.4.5.6. Benefit for the grower

Advantages

Injection by Venturi effect is a cost-effective method of supplying fertilisers and chemicals into a pressurised irrigation system, being very popular because of its simplicity, reliability and low cost, and because it does not require a power source if having enough pressure. Thus, it can be an adequate technology for small farms.

Disadvantages

- Fertiliser injection is not proportional to the irrigation network flow and has to be adjusted whenever it changes
- Injection flow depends on pressure; thus, this parameter must be maintained stably for obtaining an acceptable control of injection

8.4.5.7. Supporting systems needed

This technology can be applied to any farm. If there is not a hydraulic network with enough pressure, it will be necessary to install a pump giving adequate pressure and flow. The installation of a pressure regulator before the Venturi injector can be advisable for a more stable pressure and injection flow.

8.4.5.8. Development phase

Commercialised.

8.4.5.9. Who provides the technology

Companies installing fertigation systems.

8.4.5.10. Patented or not

Some injectors are patented.

8.4.6. Which technologies are in competition with this one?

Dosing pumps (electric or hydraulic), direct aspiration.

8.4.7. Is the technology transferable to other crops/climates/cropping systems?

It is transferable to all of them but it is not an adequate technology for soilless culture, for which automatic equipment is preferable.

8.4.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks for the use of Venturi injectors.

8.4.9. Brief description of the socio-economic bottlenecks

None.

8.4.10. Techniques resulting from this technology

Automatic injection equipment based on Venturi effect is commercially available (see 0). They incorporate at least three Venturi injectors, one for acid injection based on pH measurement and the rest for other fertilisers (which are injected based on EC measurement and a proportion established between stock solutions), what allows to separate incompatible fertilisers in different stock tanks and elaborate a complete final nutrient solution. Fertiliser injection through the Venturi injectors is regulated by installing a solenoid valve per injector, which opens at regular intervals based on the target parameters.

8.4.11. References for more information

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[2] Calder, T., & Burt, J., (2007). Selection of fertigation equipment. Farm note 35/2001. Department of Agriculture, Western Australia. Retrieved from http://www.agric.wa.gov.au/objtwr/imported_assets/content/hort/eng/f03501.pdf

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[4] Kranz, W. L., Eisenhauer, D. E. & Parkhurst, A. M. (1996). Calibration accuracy of chemical injection devices. *Applied Engineering in Agriculture*, *12*(2), 189-196

[5] Goyal, M. R. (2015). *Sustainable Micro Irrigation: Principles and Practices*. Apple Academic CRC Press

8.5. Injection pump

(Authors: Claire Goillon[2], Georgina Key[1], Alberto Alfaro[13], Juan José Magán[9], Benjamin Gard)*

8.5.1. Used for

Addition of fertilisers to the irrigation water.

8.5.2. Region

All EU regions.

8.5.3. Crops in which it is used

All fertigated crops.

8.5.4. Cropping type

All cropping types.

8.5.5. Description of the technology

8.5.5.1. Purpose/aim of the technology

Injection or dosing pump is a technology for applying balanced nutrient solutions to the crop. Injection pump ensures a precise and stable injection of fertilisers into water irrigation in order to obtain the right concentration of nutrients into the solution. This technology allows automation and a consistent supply of fertiliser.

8.5.5.2. Working Principle of operation

For proportional dosing, a constant ratio between the volume of irrigation water and the volume of the concentrated solution of fertiliser is maintained throughout the process, resulting in a constant nutrient concentration in the irrigation water. Nutrients are pumped from a fertiliser tank containing the concentrated solution of nutrients. The control of the injection is performed with small valves that partially open at each injector pulse time, keeping a user programmed, constant equilibrium.

Water flow coming from the irrigation network has a constant flow rate. Clearwater enters at the inlet of the pump and fills a chamber while activating the dosing piston (Figure 8-7). The dosing piston takes up the required percentage of the concentrate solution directly from the tank. The piston stroke regulates the solution uptake and it is defined by the operator using the command, and the scale (% adjustment) placed on the dosing pump. Then, clear water and concentrate solution are mixed together in the chamber and the solution with the desired concentration is released through the outlet of the pump by the water pressure (hydraulic pump) or by a mechanical pulse (electric pump).

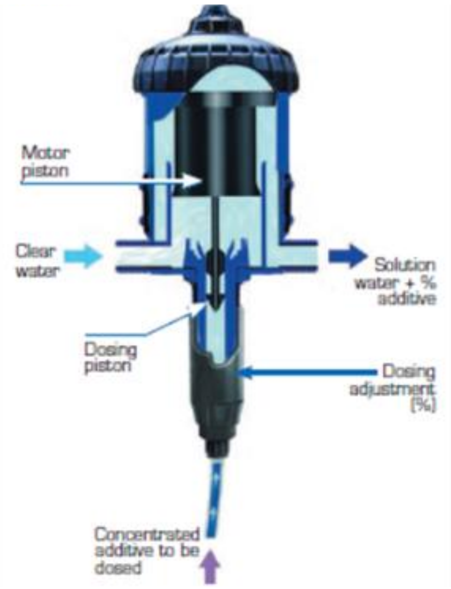

Figure 8-7. Scheme of injection pump (http://www.amg-france.fr/dosage.php)

The calculation of the injection rate is as follows:

$$\text{Injection flow (L/h)} = \frac{\text{weight of nutrient to deliver (kg)}}{\text{total weight of nutrient in stock solution (kg)}} \times \frac{\text{Tank volume (L)} \times 60}{\text{Injection time (min)}}$$

Two different technologies are available on the market:

- Electric injection pump: the mechanism of injection is triggered by an electric motor and the injection flow is set directly on the pump
- Hydraulic injection pump: the injection is triggered by the water under pressure from the irrigation network. To set up the pump, the user calculates an injection rate:

$$\text{Injection rate (\%)} = \frac{\text{Injection flow (L/h)}}{\text{Irrigation network flow (L/h)}}$$

8.5.5.3. Operational conditions

It is necessary to evaluate the time of injection to ensure a good concentration in the diluted nutrient solution. In order to avoid any physiological disorders, the concentration of the nutrient in the diluted solution must be below 2 g/L. Therefore, it is first necessary to calculate the concentration of the diluted nutrient solution (C_d).

$$C_d\ (g/L) = \frac{Weight\ of\ nutrient\ in\ stock\ solution\ (g)\ \times\ 60}{Injection\ time\ (min)\ \times\ irrigation\ network\ flow\ (L/h)}$$

8.5.5.4. Cost data

Installation cost

- Proportional injectors: a typical hydraulic injection pump with a water flow range of 10-2500 L/h and injection rate of 0,2-2% costs 352 €. An electric injection pump with a water flow range of 10-3000 L/h and an injection rate of 1-10% costs 609 € (prices from the UK).

- Non-proportional injectors: the price of a hydraulic pump with an injected flow of 0-350 L/h is 700 € and that of an electric pump with similar characteristics is 1000 € (prices from Spain).

Maintenance

Yearly change of the oil and revision of membranes and valves, periodical recalibration of hydraulic dosing pumps.

8.5.5.5. Technological bottlenecks

None.

8.5.5.6. Benefit for the grower

Advantages

- Electric dosing pump:
  - Large range of flow settings
  - The possibility to inject several tanks of nutrient stock solutions
  - Precise set up of the concentration
  - Consistent concentration and flow
  - The possibility of total automation of the system
- Hydraulic dosing pump:
  - Autonomous technology (no need for external energy)
  - No risk of overpressure
  - No risk of overdose
  - Large range of prices and designs, of flow and settings
  - Possibility to inject several tanks of nutrient stock solutions
  - Precise set up of the concentration
  - Consistent concentration and flow
  - The possibility of total automation of the system

Disadvantages

- Electric dosing pump:
  - The technology needs electricity
  - High investment costs
- Hydraulic dosing pump:
  - Leakage rate or loss of pressure according to the model
  - Needs a minimal pressure to operate
  - For most of the models, injection of only one tank of the nutrient stock solution is possible
  - Pumps need to be recalibrated regularly to maintain dosage accuracy

8.5.5.7. Supporting systems needed

Electricity supply is necessary if using electric dosing pumps.

8.5.5.8. Development phase

Commercialised.

8.5.5.9. Who provides the technology

Companies selling fertigation systems.

8.5.5.10. Patented or not

Some injection pumps are patented by the manufacturing companies.

8.5.6. Which technologies are in competition with this one?

Venturi injector, direct aspiration.

8.5.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

8.5.8. Description of the regulatory bottlenecks

None.

8.5.9. Brief description of the socio-economic bottlenecks

Buying one or two pumps would not be a bottleneck, but investing in several pumps or high investment costs if starting from scratch with an irrigation system, may limit the adoption of this technology.

8.5.10. Techniques resulting from this technology

Fertigation equipment based on injection pumps is currently available on the market, allowing simultaneous automatic control of proportionality, EC and pH.

8.5.11. References for more information

[1] Coullet, A., Izard, D., Boyer, I., Odet, J., Bouvard, F. & Ernout, H. (2007). Conduite de l'irrigation fertilisante. p. 8. ARDEPI. Retrieved from http://www.ardepi.fr/fileadmin/images_ardepi/Fiches_EF/Fiches_en_pdf/07Irrig_Fertil.pdf

[2] Kafkafi, U. & Tarchitzky, J. (2011). Fertigation: A tool for Efficient Water and Nutrient Management. International Fertiliser Industry Association (IFA) and International Potash Institute (IPI), Paris, France. Retrieved from http://www.ipipotash.org/en/publications/detail.php?i=327

[3] Lajournade, M., Aymard, J., Bouvard, F., Charton, P., Izard, D., Leclercq, J. B., Piton, N. & Soing, P. (2002). Les appareils d'injection. p. 8. Retrieved from http://www.ardepi.fr/les-fiches-eau-fertile.html

8.6. Automatic injection equipment by Venturi effect based on EC and pH

(Authors: Rafael Baeza[11], Juan José Magán[9])

8.6.1. Used for

Addition of fertilisers to the irrigation water.

8.6.2. Region

All EU regions.

8.6.3. Crops in which it is used

All fertigated crops.

8.6.4. Cropping type

All cropping types.

8.6.5. Description of the technology

8.6.5.1. Purpose/aim of the technology

This is a technology for applying balanced fertiliser solutions which allows automation and homogeneous supply of fertiliser in each irrigation pulse. It does not require high skills for correct management.

8.6.5.2. Working Principle of operation

This type of equipment may use several fertiliser tanks, from where fertilisers are injected into the main irrigation network through Venturi injectors. The control of the injection is performed with solenoid valves that partially open at each injector pulse time, keeping a constant user-programmed equilibrium, EC and pH. The optimal operation of the system requires the flow injected by all injectors to be identical. If flow deviation occurs, it must be adjusted by a manual valve coupled with a rotameter type flowmeter. There are different installation options: 1) upstream from the pump, by connecting in parallel between the suction and discharge of the pumping equipment (Figure 8-8); 2) downstream from the pump, installing an auxiliary pump to avoid variations in pressure and flow in the pipeline (Figure 8-9).

8.6.5.3. Operational conditions

In facilities upstream from the pump, installation requires only power increase of the drive pump. This increase depends on the size of the equipment but is usually lower than 1,5 kW. In facilities downstream from the pumping, an auxiliary pump is needed.

The injection capacity depends on the installed injector model that should be dimensioned based on the concentration of the stock solution and the targeted fertigation solution.

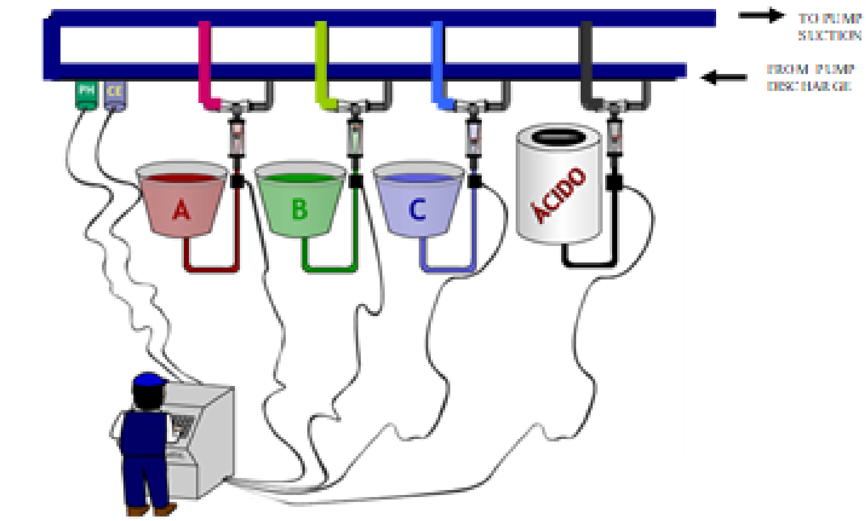

Figure 8-8. Parallel connection with the pump of automatic injection equipment by Venturi effect. Fertigation system is connected in parallel between the suction and discharge of the pump

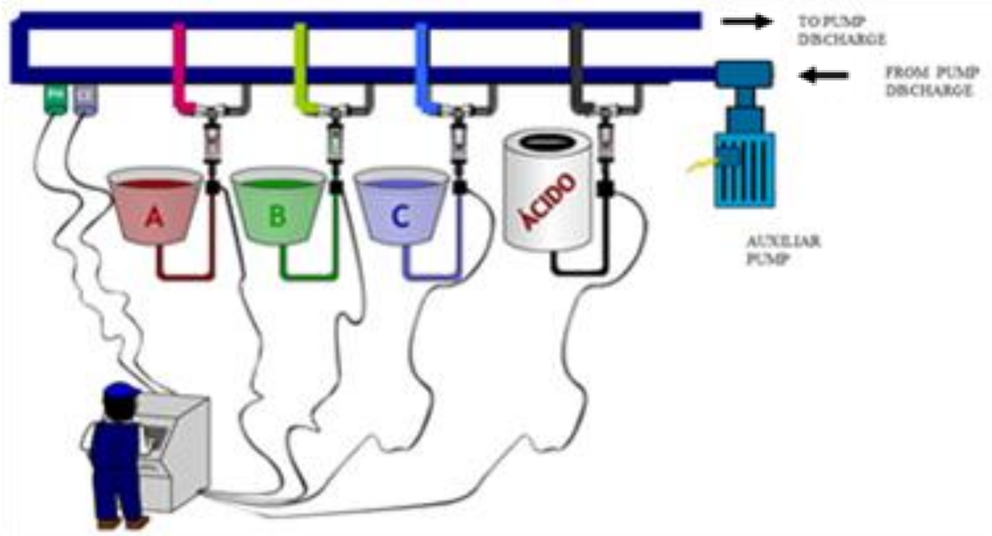

Figure 8-9. Parallel connection with the discharge pipe. An auxiliary pump maintains the flow of the circuit

8.6.5.4. Cost data

Installation cost

Installation time is usually 1-2 weeks. The cost varies depending on the size. For standard facilities of 4-5 tanks, each one of 1000-2000 L and with injectors of 200-300 L/h of capacity, a modular irrigation controller equipped with 10-20 outlets to control solenoid valves and pH and EC sensors, the costs range from 3000-15000 €.

Maintenance

- Daily control of the implementation of irrigation and fertiliser consumption
- Monthly calibration of pH and EC sensors

- Monthly checking the flow injected by Venturi injectors and cleaning and regulation if necessary
- Replacing of solenoid valves every five years
- Usual maintenance (cleaning of filters, tanks, etc.)

8.6.5.5. Technological bottlenecks

Electricity is necessary, at least for the functioning of the controller and the electro-valves. Furthermore, an irrigation pump is frequently installed when using this technology.

Constant pressure is necessary for the correct functioning of the system. As a hydraulic basis, any pressure variation causes a variation in the injection flow and thus, it will affect the fertiliser dose.

8.6.5.6. Benefit for the grower

Advantages

- Acceptable reliability
- Relatively low initial investment
- Low power consumption
- Low maintenance costs
- Low levels of technical knowledge for handling
- Technology widely developed and readily available

Disadvantages

- It requires electricity on the farm
- It cannot take advantage of water supply networks if they have unstable pressure, common in this type of supply

8.6.5.7. Supporting systems needed

Electricity supply is necessary.

8.6.5.8. Development phase

Commercialised.

8.6.5.9. Who provides the technology

Different companies installing fertigation systems.

8.6.5.10. Patented or not

This technology is not patented.

8.6.6. Which technologies are in competition with this one?

- Injection pump (electric or hydraulic)

- Automatic equipment with mixing tank

8.6.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, but the cost can be a limiting factor in small farms.

8.6.8. Description of the regulatory bottlenecks

There are not regulatory bottlenecks.

8.6.9. Brief description of the socio-economic bottlenecks

Despite its relatively low cost, the small size of farms often limits the use of this technology in some horticultural areas.

8.6.10. Techniques resulting from this technology

The most typical installation of Venturi injectors is inserted in a linear collector (Figure 8-10), although it tends to provoke some pressure differences between injectors. An alternative is to place them in a circular configuration, which allows a homogeneous pressure to be obtained (Figure 8-11). Furthermore, it is possible to install a flowmeter per injector for automatic dosage regulation and a more exact injection.

Figure 8-10. Installation of Venturi injectors inserted in a linear collector (Source: J. Antonio Marhuenda)

Figure 8-11. Installation of Venturi injectors in a circular configuration (Source: J. Antonio Marhuenda)

8.6.11. References for more information

[1] Baeza, R., Fernández, M., García, C. & Gavilán, P. (2007). Gestión del agua de riego en cultivos hortícolas bajo abrigo. Análisis del asesoramiento técnico a regantes en la provincia de Almería. XXXVII Seminario de Técnicos y Especialistas en Horticultura. Ministerio de Medio Ambiente y Medio Rural y Marino, Spain

[2] Bracy, R. P., Parish, R. L. & Rosendale, R. M. (2003). Fertigation uniformity affected by injector type. *HortTecnology*, *13*(1), 103-105

[3] García García, M. C., Céspedes López, A. J., Pérez Parra, J. J. & Lorenzo Mínguez, P. (2016). *El sistema de producción hortícola protegido de la provincia de Almería*. Instituto de Investigación y Formación Agraria y Pesquera. Consejería de Agricultura, Pesca y Desarrollo Rural

[4] Huang, X., Li, G., & Wang, M. (2008, October). CFD simulation to the flow field of Venturi Injector. In *International Conference on Computer and Computing Technologies in Agriculture* (pp. 805-815). Springer, Boston, MA

[5] Marhuenda, J. A. (2008). Diseño y principios básicos de los programadores de riego para cultivo en sustrato. Sistemas abiertos y cerrados. In: *Relaciones hídricas y programación de riego en cultivos hortícolas en sustratos*. pp. 79-88. INIA and IFAPA, Spain

8.7. Automatic injection equipment with mixing tank based on EC and pH

(Authors: Juan José Magán[9], Georgina Key[1])

8.7.1. Used for

Addition of fertilisers to the irrigation water.

8.7.2. Region

All EU regions.

8.7.3. Crops in which it is used

All fertigated crops.

8.7.4. Cropping type

All cropping types.

8.7.5. Description of the technology

8.7.5.1. Purpose/aim of the technology

This technology allows growers to automatically prepare a balanced nutritive solution adequate for crop development and to control the irrigation strategy in the farm by controlling electro-valve activation.

8.7.5.2. Working Principle of operation

The mixing tank is an element of a fertigation system which allows the creation of stabilised nutrient solutions. It consists of a non-pressurised tank, which agitates and circulates the irrigation water in order to mix it efficiently with the fertilisers and form a homogeneous nutrient solution. This tank is most commonly installed in a by-pass configuration, where only a part of the irrigation flow is diverted to the mixing tank, being subsequently driven from the tank to the irrigation pipe with a less powerful second pump, able to operate at higher pressure than the main one. In by-pass configuration, a static mixer is installed in the irrigation pipe in order to achieve adequate mixing of the solution coming from the mixing tank with the mainstream water. Water entering the tank is regulated by a hydraulic valve with a buoy in both configurations.

The mixing tank can be installed in equipment using Venturi effect injectors but is more often installed when using injection pumps (Figure 8-12). In that case, magnetic drive injection pumps, which are capable of moving relatively high flow rates with very low energy consumption, are incorporated.

During watering, the magnetic drive pump runs continuously, sucking solution from the stock tank and driving it towards the solenoid valve, which, by default, diverts the solution back to the tank. However, every few seconds, the controller sends an injection signal which opens the solenoid valve, allowing the solution to enter the mixing tank. The frequency with which each solenoid valve opens is determined by the percentage injection of the corresponding stock solution, as well as by the target EC. This excludes acid injection, which is regulated by the target pH. The function of the nozzle is to generate a resistance which increases the uniformity of the flow, driven by the different injection pumps in the equipment. This reduces the influence of water height in the concentrated solution tank on the injected flow. In the most advanced equipment, a flow meter is installed for each injection pump, which allows the amount of concentrated solution injected to be measured and the dosage regulated, thereby improving injection accuracy.

Figure 8-12. Picture of automatic fertigation equipment with mixing tank and magnetic drive injection pumps (Source: J. Antonio Marhuenda)

In some fertigation systems the magnetic pump does not drive the concentrated solution directly to the mixing tank but to a vertical pipe higher than the mixing tank, so that the pipe is continuously overflowing, being the excess solution returned to the stock solution tank (Figure 8-13). A solenoid valve placed at the bottom of the pipe allows the solution to fall into the mixing tank. This system avoids the influence of water height in the stock tank on injection flow to the mixing tank. However, since stock solutions are discharged to the mixing tank with low pressure, their mixture with water is slower, which can make adjustments more difficult when compared to the previous system.

Figure 8-13. Picture of automatic fertigation equipment with mixing tank and vertical pipes (https://pbs.twimg.com/media/DFlXyzUUQAEnlEL.jpg)

It is possible to install membrane pumps instead of magnetic pumps in order to more precisely inject fertilisers (Figure 8-14). These pumps incorporate a piston, responsible for fluid injection, enabling the determination of the volume injected in each pulse. Thus, counting the number of pulses, it is possible to know the total volume of stock solution injected without installing a flow meter. In some membrane pump models, it is possible to regulate the frequency of pulses and vary the flow. However, these pumps are more expensive than magnetic pumps and require more costly maintenance because the membranes and valves tend to get dirty and worn away frequently due to the fertilisers.

Figure 8-14. Picture of automatic fertigation equipment with mixing tank and membrane pumps (Source: J. Antonio Marhuenda)

8.7.5.3. Operational conditions

Small mixing tanks are usually used (100-150 L flow, up to 200 m^3/h) to enable a quicker response rate in the nutrient solution when adjustments are needed.

When the mixing tank is inserted directly into the suction of the irrigation pump, it is necessary to carry out a double pumping in order to fill the tank and pump the nutritive solution if there is not a pressurised water supply network. For that reason, this configuration is only used in small installations (flow usually of 5-10 m^3/h, maximum 30 m^3/h). In commercial farms the mixing tank is usually installed in a by-pass configuration, circulating only 10% of the irrigation flow, which reduces the investment cost and can achieve energy savings of at least 30%. In horticultural crops (where concentrated nutrient solutions are applied) it is not convenient to reduce the bypass flow through the mixing tank further, otherwise, you may get precipitation out of fertilisers. However, in fruit crops (where more diluted nutrient solutions are managed) it can be reduced to 5%.

Injection pumps usually offer a flow rate of 400-600 L/h, although this will depend on the irrigation flow and the concentration of the stock solutions. There are special models of magnetic pumps made from materials which will cope with the most aggressive acids. The inside diameter of the nozzles installed at the entrance of the stock solution to the mixing tank is usually 2-3 mm. Regarding the flow meters, pulses should be high frequency (at least 100 pulses/L) in order to achieve good accuracy. Additionally, it is necessary that the opening time of the solenoid valve is longer than one second.

8.7.5.4. Cost data

Installation cost

- Two days are necessary for installing and connecting the fertigation equipment
- The cost of standard equipment with five magnetic drive injection pumps and a mixing tank is between 8000 € and 12000 €, which is significantly higher than that of equivalent equipment with injectors based on the Venturi effect (5000-8000 €). The price does not include the cost of flow meters (250 € per unit plus 150-200 € for the electronic connection of all of them) and labour (500-1000 €). The cost of a membrane pump with analogical control is around 700 €/unit

Maintenance

- Monthly cleaning and calibration of pH and EC sensors
- Replacement of pH sensors every 1-3 years
- Replacement of magnetic drive injection pumps every 3-4 years
- Replacement of solenoid valves every 5 years

8.7.5.5. Technological bottlenecks

Electricity is necessary.

8.7.5.6. Benefit for the grower

Advantages

- High reliability
- Technology widely developed and readily available

Disadvantages

- It requires electricity on the farm
- Magnetic drive injection pumps instantly burn if they run out of the water, therefore emptying of the stock solution tanks must be avoided under any circumstance
- This technology is more expensive than automated fertigation equipment using Venturi injectors

8.7.5.7. Supporting systems needed

The fertigation system has to be complemented with the tanks for preparing the stock solutions, as well as filters, pipes and accessories.

8.7.5.8. Development phase

Commercialised.

8.7.5.9. Who provides the technology

Some companies installing fertigation systems offer this technology.

8.7.5.10. Patented or not

No.

8.7.6. Which technologies are in competition with this one?

- Injection pumps (electric or hydraulic)
- Automatic fertigation equipment using Venturi injectors

8.7.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

8.7.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

8.7.9. Brief description of the socio-economic bottlenecks

Price is a limiting factor for the use of this technology, especially for small farms. If the grower decides to install automatic fertigation equipment, he frequently prefers to install equipment using Venturi injectors, which is cheaper.

8.7.10. Techniques resulting from this technology

Different modalities have been previously described in the section 8.7.5.2 Working Principle of operation.

8.7.11. References for more information

[1] Marhuenda, J. A. (2008). Diseño y principios básicos de los programadores de riego para cultivo en sustrato. Sistemas abiertos y cerrados. In: *Relaciones hídricas y programación de riego en cultivos hortícolas en sustratos*. pp. 79-88. INIA and IFAPA, Spain

8.8. Automatic injection equipment based on the quantitative addition

(Authors: Juan José Magán[9], Ilse Delcour[19])

8.8.1. Used for

Addition of fertilisers to the irrigation water.

8.8.2. Region

All EU regions.

8.8.3. Crops in which it is used

All fertigated crops suitable.

8.8.4. Cropping type

All cropping types.

8.8.5. Description of the technology

8.8.5.1. Purpose/aim of the technology

This technology allows a nutrient solution to be prepared by proportionally injecting pre-set concentrations of stock solutions to the irrigation flow without considering EC of the final solution.

8.8.5.2. Working Principle of operation

In many fertigation systems, the addition of fertilisers to the water for the preparation of the nutrient solution is based on EC because its measurement is reliable and easy to do. However, this is an indicator of the global salinity of the solution, not knowing the injected quantity of each fertiliser. For this objective, a flow meter can be installed per injector, although the accuracy is limited, with a minimum deviation of 5-10%, because of the intermittent flow of stock solution through the flow meter, which makes the measurement difficult.

Injection pumps allow the volume of injected stock solution to be known without installing flow meters because the volume of the chamber inside the pump (see 8.5.5.2) is known. Automatic fertigation systems based on injection pumps count the number of injections carried out by each pump. Thus, the total injection during the irrigation can be automatically calculated by multiplying the number of injections by the volume pumped per pulse. Fertiliser injection can be related to the water flow by installing a flow meter, electrically connected to the fertigation system, in the irrigation pipe. Knowing the injected flow of fertilisers and the irrigation flow, the ratio between them can be calculated and the injection of fertilisers can be automatically adjusted online to achieve the desired proportion. Figure 8-15 shows a picture of an automatic fertigation system based on injection pumps, able to proportionally inject the stock solutions into the irrigation flow.

Although EC and pH sensors are not required in fertigation with proportional injection into the irrigation flow, they are frequently installed as security measures.

Figure 8-15. Picture of automatic fertigation equipment based on the proportional injection of fertilisers to water flow (http://www.itc.es/es/electric/item/420-acc070-bancada-de-dosificación-y-control.html)

8.8.5.3. Operational conditions

The accuracy of injection can be quite good, with a deviation of only 2-5%. It is possible to reach a sensitivity of proportionality of 0,01%. The injection flow per pump can reach around 3000 L/h (depending on the model). For big irrigation sectors, several pumps can be installed in parallel.

8.8.5.4. Cost data

Installation cost

The cost of the equipment, with five piston injection pumps, with their respective variable frequency drive, including a meter of the irrigation flow and a pressure transmitter, is around 15000 €.

Maintenance

- Monthly cleaning and calibration of pH sensor
- Replacement of pH sensors every 1-3 years
- Yearly revision of suction and discharge valves and of piston injection pumps (in the case of membrane injection pumps the change of the membranes is usually carried out every 3 years)
- Annual change of the oil of the injection pumps
- Quinquennial change of the pleat of the pumps

8.8.5.5. Technological bottlenecks

The injection pumps are negatively affected by not well-dissolved solids, which can block pipes and valves. This can be a limitation when using organic fertilisers.

8.8.5.6. Benefit for the grower

Advantages

- Highly accurate
- The quantity of fertilisers supplied to the crop can be quite accurately measured
- Quantitative injection is applicable when using fertilisers with low effect on EC (as typical in organic production)

Disadvantages

- Too expensive to be used in small farms
- Failure when fertilisers are not well dissolved
- High maintenance needed

8.8.5.7. Supporting systems needed

Liquid fertilisers are preferred when using injection pumps. Solid fertilisers need to be adequately dissolved in order to avoid the pumps to be damaged.

8.8.5.8. Development phase

Commercialised.

8.8.5.9. Who provides the technology

Some companies selling fertigation systems.

8.8.5.10. Patented or not

Some injection pumps are patented by the manufacturing companies.

8.8.6. Which technologies are in competition with this one?

- Automatic injection equipment by Venturi effect based on EC and pH
- Automatic injection equipment with mixing tank based on EC and pH

8.8.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this technology operates independently of climate and cropping system.

8.8.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks for using this equipment.

8.8.9. Brief description of the socio-economic bottlenecks

The cost of the technology may limit the adoption of the technology, especially in small farms and less profitable crops.

8.8.10. Techniques resulting from this technology

In the market, there is automatic fertigation equipment based on injection pumps arranged on a bench which can be easily installed (http://www.itc.es/es/electric/item/420-acc070-bancada-de-dosificaci%C3%B3n-y-control.html)

8.8.11. References for more information

[1] Personal communication from ITC (manufacturer of dosing pumps) (28th of March 2017)

8.9. Solubility of fertilisers

(Authors: Katarina Kresnik[3], Juan José Magán[9], Ilse Delcour[19], Georgina Key[1], Benjamin Gard)*

8.9.1. Used for

Preparation of stock solutions.

8.9.2. Region

All EU regions.

8.9.3. Crop(s) in which it is used

All fertigated crops.

8.9.4. Cropping type

All cropping types.

8.9.5. Description of the technology

8.9.5.1. Purpose/aim of the technology

The solubility of a fertiliser is defined as the maximal amount of the fertiliser that can be completely dissolved in a given amount of distilled water at a given temperature. When producers apply fertilisers through the irrigation water (fertigation), it is essential that they are familiar with some important facts regarding fertiliser solubility.

8.9.5.2. Working Principle of operation

Fertilisers applied in fertigation have to be dissolved in water. Generally, concentrated solutions (stock solutions) are injected in the irrigation water. When preparing a solution, growers must always add fertilisers into the water and not the contrary to prevent caking of the fertilisers. If doing a test to verify the practicality of a solution, the fertilisers should be mixed exactly in the same concentration as in the stock tanks. If some precipitate forms or the solution has a “milky” appearance, the test should be repeated with lower concentrations of fertilisers.

When mixing fertilisers that contain a common element (for example potassium nitrate and potassium sulphate) the solubility of the fertilisers decreases. In such case, we cannot refer to the fertiliser solubility data alone. The same happens when the water used for dissolution is highly rich in minerals, e.g. calcium (Ca), magnesium or sulphate. In such cases, additional chemical reactions come into play and calculations become more complex. Usually, these are not calculated in the field; instead, trial-and-error practices are common.

8.9.5.3. Operational conditions

In fertigation, only 100% water soluble fertilisers containing all nutrients in totally soluble forms may be used. Indeed, any non-soluble part can be the reason for the blockage of the irrigation system. To avoid precipitation and collaging of the irrigation network, growers must take into account compatibility of the fertilisers before mixing them during the preparation of stock solutions (Table 8-1). Incompatible fertilisers have to be added to different stock tanks (see 8.10).

Table 8-1. Compatibility between fertilisers for mixing in the preparation of stock solutions.

	Ammonium nitrate								
Ammonium sulphate	Yes	Ammonium sulphate							
Magnesium nitrate	Yes	Yes	Magnesium nitrate						
Calcium nitrate	Yes	NO	Yes	Calcium nitrate					
Potassium nitrate	Yes	Yes	Yes	Yes	Potassium nitrate				
Potassium sulphate	Yes	Yes	Yes	NO	Yes	Potassium Sulphate			
Magnesium sulphate	Yes	Yes	Yes	NO	Yes	Yes	Magnesium sulphate		
Ammonium phosphate	Yes	Yes	Yes	NO	Yes	Yes	Yes [1]	Ammonium phosphate	
Potassium chloride	NO	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Potassium chloride
Calcium chloride	-	NO	Yes	Yes	Yes	NO	NO	-	Yes

[1]Warning! these fertilisers cannot be mixed either dry or in an alkaline environment

The solubility of the fertilisers is very important information for two reasons: 1) the evaluation of the time needed to dissolve a certain amount of fertiliser, since the dissolution speed of a fertiliser slows down with increasing concentration; 2) the establishment of the volume of stock solutions to be prepared, which is related to fertiliser concentration in both stock and supplied nutrient solutions and the irrigation flow.

Dissolving some fertilisers (such as urea, ammonium sulphate, ammonium, potassium and calcium nitrate and some other) provokes an endothermic reaction, which strongly cools the stock solution, thereby decreasing fertiliser solubility. When preparing the stock solution, these fertilisers must be added at the end.

The main rule for the preparation of the stock solution is to fill the tank with water for 50% (but sufficient water); add the fertilisers gradually into the water and agitate, finally adding the remaining quantity of water and agitating until the fertilisers are completely dissolved.

The solubility of some fertilisers in water at different temperatures is shown in Table 8-2. As observed, this parameter dramatically decreases with temperature, which must be taken into account when preparing stock solutions. It is necessary to clarify that ions are not completely dissociated in a concentrated solution, but form colloids in a stable suspension, which are dissolved when diluting the stock solution into the irrigation water. In practice, producers do not usually prepare very highly concentrated solutions but use concentrations up to 10-20% for macronutrients. Indeed, the preparation of such a concentrated solution is very time-consuming because fertilisers only slowly dissolve.

Table 8-2. Maximum amount of fertiliser dissolving in one litre of water at different temperatures

Fertiliser ($N:P_2O_5:K_2O$)	Solubility (g/L)			
	0ºC	15ºC	20ºC	30ºC
Urea 46% (46:0:0)	680		1060	1330
Calcium nitrate (15,5:0:0)	1020	1130	1200	1526
Ammonium nitrate (34:0:0)	1180	2400		3440
Ammonium sulphate (21:0:0)	706	742	750	780
Mono-ammonium phosphate (12:61:0)	227	333	370	480
Mono-potassium phosphate (0:53:34)	148	197		285
Potassium chloride (0:0:60)	280		340	370
Potassium nitrate (13:0:46)	133	257	316	459
Potassium sulphate (0:0:50)	74	102	110	130
Magnesium sulphate	260	332		409
Magnesium nitrate (10,8:0:0)			423	

Fertilisers used in fertigation should have the following characteristics: complete solubility (<0,2% insoluble in water), high nutrient content in the concentrated solution, fast dissolution in the irrigation water, without chemical interactions between the fertiliser and the irrigation water and absence of undesired ions.

8.9.5.4. Cost data

Installation cost

Not applicable.

Maintenance

Cost of the fertilisers (and the water).

8.9.5.5. Technological bottlenecks

Incompatibility between fertilisers has to be considered. From this point of view, the producer should know which fertilisers can be mixed.

8.9.5.6. Benefit for the grower

Advantages

Fertigation is an effective way of supplying fertilisers.

Disadvantages

- Knowledge is needed for mixing different fertilisers
- Producers have to use water-soluble fertilisers very carefully and consider the amount of water when these fertilisers are applied

8.9.5.7. Supporting systems needed

A reliable injection system is needed to accurately inject the stock solution into the irrigation network in order to get the correct concentration of fertiliser and distribution to the crop.

8.9.5.8. Development phase

Commercialised.

8.9.5.9. Who provides the technology

Fertiliser suppliers.

8.9.5.10. Patented or not

No.

8.9.6. Which technologies are in competition with this one

Direct application to the soil of fertilisers not suitable for fertigation.

8.9.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, to all fertigated crops.

8.9.8. Description of the regulatory bottlenecks

Fertilisers used in fertigation have to be soluble in water and their label has to indicate "soluble for fertigation".

8.9.9. Brief description of the socio-economic bottlenecks

Good quality fertilisers must be used in fertigation despite their higher cost to avoid clogging problems in the irrigation system.

8.9.10. Techniques resulting from this technology

Not applicable.

8.9.11. References for more information

[1] Cadahía, C. (2000). Fertirrigación. Cultivos hortícolas y ornamentales. Mundi-Prensa, Madrid, Spain
[2] Coullet, A., Izard, D., Boyer, I., Odet, J., Bouvard, F. & Ernout, H. (2007). Conduite de l'irrigation fertilisante. Coll. L'eau fertile, ed. B. Laroche
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[4] Pastor, M. (2005). Cultivo del olivo con riego localizado. Mundi-Prensa and Junta de Andalucía
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[6] Rincón, L. (1993). Equipamiento de la fertirrigación. *Hortofruticultura*, 9, 35-42
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8.10. Preparation of concentrated solutions

(Authors: Alain Guillou[4], Esther Lechevallier[4], Georgina Key[1], Juan José Magán[9])

8.10.1. Used for

Preparation of stock solutions.

8.10.2. Region

All EU regions.

8.10.3. Crop(s) in which it is used

All fertigated crops.

8.10.4. Cropping type

All cropping types.

8.10.5. Description of the technology

8.10.5.1. Purpose/aim of the technology

The technique is used for the preparation of concentrated nutrient solutions (macronutrients, micronutrients and iron), which will be mixed and diluted and injected into the irrigation network.

This technique aims to provide a complete nutrient solution to feed the crops with a simple preparation made from soluble fertilisers. Soluble fertilisers are separated in A and B tanks depending on their compatibility with each other.

8.10.5.2. Working principle of operation

The nutrient solution conception should follow these steps:

- Take the mineral composition of the water supply into account (pH, elements (usually expressed in mmol/L))
- Fix the composition objectives of the nutrient solution: the nutrient balance target should take into account the crop stage (adjusting K, Ca, Mg)
- Choose the different fertilisers depending on the nutrient balance desired
- Calculate the conductivity (EC, dS/m)
- Calculate the fertiliser quantities that should be added to achieve the desired nutrient composition

For the preparation of concentrated solutions in an A/B tank system, fertilisers have to be distributed between the different tanks as indicated in Table 8-3. When diluting the fertilisers, two-thirds of the water is first added to the tanks, and then fertilisers are added. The solution should be mixed with a mixer between each fertiliser addition, to ensure fertilisers to dissolve properly, and it is recommended to use slightly warm water to improve the solubility of fertilisers (especially for potassium nitrate and sulphate). Finally, the rest of the water is added.

Table 8-3. Distribution of fertilisers between tanks in an A/B system

Tank A	Tank B	Acid tank **
Water (Nitric acid) Potassium nitrate (2/3) Monopotassium phosphate Magnesium sulphate Micronutrients (Potassium chloride)* Water	Water Calcium nitrate*** Potassium nitrate (1/3) Iron (Calcium chloride)*	Water Nitric acid Pour the acid into the water (not the opposite!)

*It is possible for some crops (e.g. tomato) to limit the N input. In this case, a part of potassium nitrate and calcium nitrate can be replaced by chlorides (potassium or Ca) or sulphates, in order to add enough potassium and calcium to the solution. When drainage is recycled, we should, however, take care not to increase the chloride input too much, to avoid accumulation.

**Depending on the pH of the supply water, it can be necessary to adjust the pH using a base instead of an acid; in this case, potassium carbonate can be added. It is also possible to use a Moerl filter (e.g. for non-buffered rainwater).

*** Calcium nitrate is increasingly used as liquid fertiliser.

A complete analysis of the nutrient solution supplied should be done to verify if the solution composition fits the initial target. Drain water analyses enable growers to correct the solution to achieve their desired balance if necessary.

Nowadays, almost all irrigation systems allow for fertiliser injection depending on the desired conductivity, but in some systems, it is still possible to work with volumetric injection. In this case, it is very important to fit the desired concentration to the concentrated solution.

8.10.5.3. Operational conditions

Some fertilisers cannot be mixed together, therefore separated A and B tanks should be considered.

- Calcium nitrate cannot be mixed with sulphates (including micronutrients based on sulphates) and phosphates, because of precipitation risks
- Iron chelates should be added to the concentrated solution which has a pH between 4 and 6, to avoid degradation. There are different forms of iron chelates (the most common are EDTA, DTPA, HEDTA, EDDHA), which assimilate at different pH ranges. If pH is high, the use of EDDHA is recommended because its suitability range is broader
- If the injection is based on volumetric injection, the concentrations should be perfectly adjusted

8.10.5.4. Cost data

The cost for the preparation of concentrated solutions includes the cost of fertilisers and the labour necessary for dissolving them.

8.10.5.5. Technological bottlenecks

The incompatibility between fertilisers should be considered.

8.10.5.6. Benefit for the grower

Advantages

Cost of fertilisation by preparing concentrated solutions with soluble solid fertilisers is lower than directly using liquid fertilisers.

Disadvantages

- The implementation of the nutrient solution takes time
- Corrections and adjustments are longer possible if the solution does not conform to the desired solution, compared to liquid fertilisers (especially with direct injection)

8.10.5.7. Supporting systems needed

A and B (or multiple) tanks, fertilisation unit, mixer tank, ability to use slightly warmed water.

8.10.5.8. Development phase

Commercialised.

8.10.5.9. Who provides the technology

Several companies (e.g. PRIVA, Hoogendoorn, Hortimax, etc.).

8.10.5.10. Patented or not

Not patented.

8.10.6. Which technologies are in competition with this one

Direct injection of liquid fertilisers.

8.10.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, to cropping systems using complete nutrient solution.

8.10.8. Description of the regulatory bottlenecks

Not applicable.

8.10.9. Brief description of the socio-economic bottlenecks

No socio-economic bottlenecks, except that the grower should be careful with the fertilisers when mixing them (explosion risks, etc.).

8.10.10. Techniques resulting from this technology

As previously indicated, the different fertilisers necessary for supplying a complete nutrient solution to the crop can be distributed in two concentrated solutions A/B in order to separate incompatible fertilisers. These solutions are usually made in such a way that they have to be injected in the same proportion, thereby allowing an easy visual control of injection accuracy.

However, some growers prefer to prepare more than two concentrated solutions in order to dissolve the fertilisers individually. This technique of multiple tanks allows round amount of fertiliser to be added to each tank, thereby facilitating the preparation of the concentrated solutions and allowing the preparation of nutrient solutions with a different composition. Its disadvantage is that the visual control of injection accuracy is more difficult. For that reason, it is recommended to incorporate in the fertigation system devices for the automatic control of injection in this case, such as injection pumps or flow meters.

8.10.11. References for more information

[1] Letard, M., Erard, P. & Jeannequin, B. (1995). Maîtrise de l'irrigation fertilisante. Tomate sous serre et abris en sol et hors sol. CTIFL, Paris, France

[2] Sonneveld, C. & Voogt, W. (2009). Plant Nutrition of Greenhouse Crops. Springer, ISBN 9048125316, New York, USA

8.11. Liquid versus solid fertilisers

(Authors: Valme González[5], Esther Lechevallier[4], Juan José Magán[9])

8.11.1. Used for

Nutrition of crops.

8.11.2. Region

All EU regions.

8.11.3. Crop(s) in which it is used

All fertigated crops.

8.11.4. Cropping type

All cropping types.

8.11.5. Description of the technology

8.11.5.1. Purpose/aim of the technology

A natural or industrial material having at least 5% of one or more of the three primary nutrients (N, phosphorus pentoxide (P_2O_5), potassium oxide (K_2O)) may be called a fertiliser. They are substances that contain nutrients in forms that can be absorbed by plants. Depending on the amount required by plants, nutrients are classified as primary nutrients (N, phosphorus and potassium), secondary nutrients (Ca, magnesium, sodium and sulphur) and micronutrients (boron, chloride, cobalt, copper, iron, manganese, molybdenum and zinc), the last group being essential for plant growth although in small quantities compared to the main and secondary nutrients.

8.11.5.2. Working Principle of operation

Fertilisers allow the content of nutrients in the soil to be maintained or increased, thereby improving the nutritional quality of the substrate, stimulating the vegetative growth of the plant and allowing a greater production and quality of the crop.

Fertilisers may be classified according to their formulation as solids, liquids and gaseous, the two first categories being the most used:

- Liquid fertilisers applied directly or dissolved in water, allow obtaining a fast effectiveness because they are absorbed quickly and can be applied to the crop before or after sowing. Their formulation can be a suspension or solution:
    - Suspensions or mixtures are obtained by dispersing a solid fertiliser in a liquid medium
    - Solutions contain nutrients dissolved homogeneously in water, with a chemical origin, natural or combined. These solutions are normally found without pressure, with one or more nutrients dissolved in the water, but it is

possible to find them with pressure, which needs to be applied by specialised equipment

- Solid fertilisers can have different formulations (powder, granules, macro-granules, in tablets, sticks, etc.):
    - Powders are used in the more traditional culture and also in hydroponics. They are applied directly or diluted in water. The size of the powder usually varies depending on the type of fertiliser used
    - Granules offer a more precise dosage, releasing the nutrients gradually and helping to make the operations performed with them more comfortable. Their application, manual or with appropriate equipment, permits to obtain a more uniform distribution in the field
    - Macro-granules are formed by granules of considerable size, between 2-3 cm, thereby releasing the nutrients progressively. The rods are a kind of spikes of concentrated fertiliser, which are placed into the soil, gradually giving its content to the soil

The fertiliser application can be done in different ways:

- Direct application to the soil or root: the fertiliser is applied directly, with the final purpose to make their effect as soon as possible
- Foliar application: the fertiliser is applied on the leaves of the crop dissolved in water so that nutrients are absorbed immediately. With this technique, the results can be visualised in a short period of time
- Fertigation: in this technique, the fertilisers are dissolved in the water used for irrigation

8.11.5.3. Operational conditions

When programming fertilisation, it is necessary to consider the solubility of the fertilisers and compatibility between them if mixed, the maximum concentration accepted in the nutrient solution and salinity. Furthermore, the following recommendations are very important:

- To do a soil analysis in order to determine its fertility level and physicochemical characteristics that may affect the effectiveness of fertilisers
- To analyse the irrigation water in order to know its nutrient concentration, the level of toxic ions, electrical conductivity, salinity, etc.
- The total concentration of fertilisers in the irrigation water should not be higher than 1‰ (1 kg of total fertilisers per 1000 L of irrigation water).
- It is not advisable to mix fertilisers unless being sure that they are fully compatible with each other and with the irrigation water
- With soluble fertilisers, it is advisable to use an agitator or a mixing system by air bubbling at the bottom of the tank to facilitate the dissolution
- It is not advisable to use fertilisers containing additives which can produce foams

- For soil-bound crops it is advisable to supply water without fertilisers at the beginning and at the end of the irrigation to reduce nutrient leaching (supplying a dose of water without fertilisers equivalent to the required leaching fraction at the beginning of the irrigation) and dripper clogging (washing the irrigation system with the minimal quantity of water at the end of the irrigation)
- Phosphorus fertilisers should not be mixed with fertilisers containing calcium, magnesium or iron; Ca fertilisers with sulphate-based fertilisers; or ammoniac forms with basic reaction fertilisers
- Potassium fertilisers must be dissolved properly before applying
- High care must be taken when using liquid fertilisers at low temperatures because they are too concentrated and can generate precipitates (insoluble compounds)
- If different fertilisers have to be mixed for their simultaneous application, it is necessary to know the compatibility between them

Insoluble solid fertilisers allow a gradual release of the nutrients. When using soluble solid fertilisers, it is interesting to firstly know its solubility, which depends on temperature, and also the type of reaction provoked by the solubilisation process, as many fertilisers when dissolved, increase the temperature of the solution (exothermic reaction), whereas others decrease it (endothermic reaction). Thus, when preparing a concentrated solution mixing different fertilisers, those with exothermic reaction must be first dissolved to facilitate the dissolution of the others. Besides, it is also necessary to know how it affects the pH of the irrigation water and the electrical conductivity of the final solution.

8.11.5.4. Cost data

Installation cost

The use of solid (soluble and insoluble) or liquid fertilisers will depend on the resources of the farm. The economic cost of the fertilisers will depend on their physical form and chemical composition. For the use of insoluble solid fertilisers, it is necessary to have a tractor with dosing equipment, whereas for liquid and soluble solid fertilisers the irrigation system is used for the application but it is necessary to have tanks for its storage or for the preparation of the concentrated solution. The price of fertilisers varies according to their formulation, from 300-350 €/ton for solid fertilisers and from 200-320 €/1000 L for liquid fertilisers.

Maintenance

The annual maintenance relative to the economic cost depends on crop requirements. The type of installation required for the application of fertilisers depends on the type of fertiliser. Liquid and soluble solid fertilisers can be applied by using the drip irrigation system or by foliar application, whereas insoluble solid fertilisers have to be applied directly to the soil with farm equipment.

8.11.5.5. Technological bottlenecks

Fertilisers must be used properly to avoid pollution and superfluous cost.

8.11.5.6. Benefit for the grower

Advantages

- The main advantage for the grower is to increase crop yield. Fertilisers provide nutrients to help plants grow
- Handling of insoluble solid fertilisers can be fully automated, enabling a high performance in the application and a great uniformity in the distribution on the ground
- Liquid fertilisers are easy to handle, what reduces labour. Furthermore, they avoid legality problems in transport because they are transported directly to the tank, and improve the availability by plants because of the supply of solubilised nutrients, optimum pH and the availability of customised solutions adjusted to plant requirements
- Prefabricated liquid stock solutions are completely dissolved and do not have sediments provoking clogging (if crystallisation is avoided)

Disadvantages

- Use of fertilisers has a cost (although it is usually profitable)
- Their inappropriate use can contaminate the environment and cause health problems
- Soluble solid fertilisers have to be dissolved in situ and this takes time
- Prefabricated liquid stock solutions can be more expensive than soluble solid fertilisers

8.11.5.7. Supporting systems needed

Some regions offer a service for the advice on the use of fertilisers, which consists on a software application allowing farmers to have information about fertilisation of their farms, including recommendations of fertilisers and consulting the meteorological conditions of the municipality to optimise the application of fertilisers and rationalise their use. On the other hand, some fertiliser companies can advise about concentrations, form and moment of application.

8.11.5.8. Development phase

- Research: it is important to know the advancement of knowledge in the use of fertilisers. There are conferences, congresses, etc. in which researchers from all over the world present the latest advances in research of fertilisation, whose objective is to study the use of responsible fertilisation, to avoid, as far as possible, environmental, public health problems, increased costs of cultivation, reduction of production, etc., which can be caused by the excessive or insufficient use of fertilisers in crops
- Experimental phase: the experimental phase is evidenced by the realisation of research projects with different doses of fertilisers in the different crops

- Field tests: field experiments are conducted either in experimental fields of research centres or in commercial plots belonging to a company
- Commercialised

8.11.5.9. Who provides the technology

Fertilisers are provided by companies working in the development, formulation and marketing of these products.

8.11.5.10. Patented or not

Numerous companies have patented some fertilisers to increase crop yields.

8.11.6. Which technologies are in competition with this one

Organic farming is in competition with the use of fertilisers of chemical origin. It is defined as a growing system based on the optimal use of natural resources, without using synthetic chemicals or genetically modified organisms, thus obtaining organic food, while preserving the fertility of the land and respecting the environment, all this in a sustainable and balanced way.

The main objectives of organic agriculture are to obtain healthy food, of higher nutritional quality, without the presence of chemical synthesis substances and obtained through sustainable procedures. This type of agriculture is a global production management system that increases and enhances the health of agro-systems, including biological diversity, biological cycles and soil biological activity. This is achieved by applying, whenever possible, agronomic, biological and mechanical methods, as opposed to the use of synthetic materials to perform any specific function of the system. This way of production, besides contemplating the ecological aspect, includes in its philosophy the improvement of the living conditions of its practitioners, in such a way that its objective is attached to achieve the integral sustainability of the system of agricultural production; that is, to become a social, ecological and economically sustainable agro-system.

8.11.7. Is the technology transferable to other crops/climates/cropping systems?

The application of liquid or solid fertilisers can be performed in all crops, climatic conditions and cropping systems and their use depend on the investment that the farmer wants to make.

8.11.8. Description of the regulatory bottlenecks

8.11.8.1. Brief description of the European directive and implications for growers at European level

The Regulation (EC) Nº 2003/2003 of the European Parliament and of the Council of 13 October 2003 on fertilisers establishes the technical characteristics of the products sold as fertilisers.

8.11.8.2. Implementation at the country level

The indicated European Regulation is transposed at the national level. For instance, the Royal Decree 506/2013 on fertilisers, on 28 of June, is in force in Spain.

8.11.8.3. Implementation at the regional level

At the regional level, there is legislation promoting an adequate use of fertilisers. For instance, in the Autonomous Community of Extremadura (Spain) Decree 87/2000, on 14 of April, regulates the integrated production in agricultural products in that region, which establishes the general rules of integrated production, understood as that agricultural system of production, processing and marketing which makes the maximal use of natural resources and mechanisms of production and ensures long-term sustainable agriculture by introducing biological, chemical and other techniques compatible with environmental protection and agricultural productivity. This legislation establishes specific technical standards in Integrated Production for different crops (stone fruit, tomato, etc.), specifying the maximum amounts of fertilisers to be applied.

8.11.9. Brief description of the socio-economic bottlenecks

There is a trend of over-fertilisation, trying to avoid nutrient deficiencies and yield limitation. This leads to pollution problems, especially if an excess of N is applied in vulnerable areas or near areas of special protection. Hence, a mentality change of growers is necessary for an optimal use of fertilisers.

8.11.10. Techniques resulting from this technology

Filtration equipment and variable fertilisation. Adaptation of the machines for fertiliser application and integration with zoning sensors (reflectance sensors).

8.11.11. References for more information

[1] Cadahía, C. (2000). Fertirrigación. Cultivos hortícolas y ornamentales. Mundi-Prensa, Madrid, Spain

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Chapter 9. Fertigation equipment – Soilless systems

Coordinators: Juan José Magán[9], Elisa Suárez-Rey[11], Ilse Delcour[19]

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9.1.1. These techniques concern the issue

- Preparation of the nutrient solution to be supplied to the crop
- More efficient use of water
- More efficient use of fertilisers
- More efficient use of other chemicals applied by the irrigation system
- Minimising the impact on the environment by nutrient discharge

9.1.2. Regions

All EU regions.

9.1.3. Crops in which the problem is relevant

Vegetable crops, ornamentals, soft fruits.

9.1.4. Cropping type

Soilless crops under protected conditions and open air.

9.1.5. General description of the issue

Soilless growing systems are an alternative to soil cropping in which plant roots develop in a media different to the soil, either a substrate or the nutrient solution itself. These growing systems allow better control of soil diseases and to optimise the supply of water and nutrients to the crop, having a higher productive potential. In hydroponic systems (those not using a substrate) the nutrient solution has to be recovered and recirculated necessarily, whereas this is not usually indispensable if using a substrate as a growing media. However, open systems are being transformed into closed-loop systems to avoid contamination by minimising or reducing the discharge of nutrients and pollutants to zero. In this case, the nutrient solution is recovered, and in most cases disinfected, replenished and recycled (Figure 9-1). However, closed systems require more precise and frequent control of the nutrient solution compared to open systems. The returned nutrient solution has to be treated to restore its original nutrient element composition and to remove any foreign substance. Moreover, spreading of root-borne diseases may occur. Therefore disinfection of the recirculated nutrient solution must be provided to reduce the disease risk substantially. The nutrient solution is normally recirculated until specific threshold values are reached. These parameters are: electrical conductivity (EC), the concentration of some potentially toxic ions or other problematic substances or microorganisms (pathogen concentration, root exudates, residues of plant protection products, etc.). Once these threshold values are reached, the solution must be replaced, at least partially; the term “semi-closed” is used for such a system.

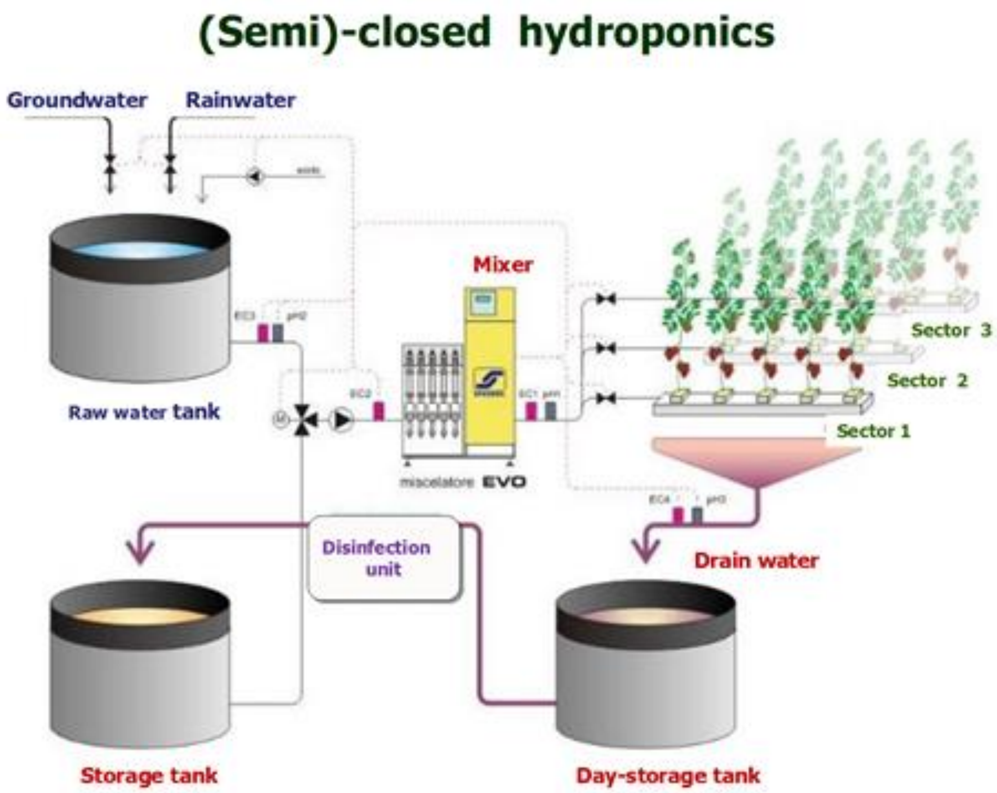

Figure 9-1. Example of the semi-closed soilless system (Pardossi, 2012)

The different issues related to soilless systems are the followings:

9.1.5.1. Sub-Issue A: substrates

Sustainable substrates alternative to peat, commonly used for growing in protected conditions, can reduce husbandry costs, the use of water and nutrients, the impact of soil-borne diseases and soil-fatigue, and improve the uniformity of the crop. Rockwool, perlite and coir are the most common applied substrates, each one having advantages and disadvantages. Rockwool has higher cost and lower buffer capacity than coir but instead, non-buffered coir needs to be first washed to remove excess of Na and K and immersion in a calcium nitrate solution is required to improve Ca availability for the plant. Perlite is a substrate with a complicated hydraulic behaviour.

There has been some testing on substrates combination to improve water management and crop yield. Preventive control of root diseases is a problem that might be solved by using amended growing media with compost. This type of growing media is an economically viable alternative compared to the peat-based substrate.

9.1.5.2. Sub-Issue B: specific water and nutrient management in soilless growing systems

In many European Member States, the use of chemical products to disinfect the soil is under severe pressure and the interest to switch from traditional soil bound crops to cheaper soilless cropping systems is increasing. Furthermore, cultivation in substrates has been characterised by a shift from open- to closed-cycle cultivation systems, involving the reuse of drainage solution. It can substantially reduce the pollution of water resources by nitrate, phosphorus and plant protection products, and contribute to an appreciable reduction in water and fertiliser consumption. However, optimal economic management of most crops in closed-loop systems requires irrigation water of good quality. This factor is limiting switching over to closed growing systems, especially in regions with low-quality water (e.g., coastal regions with high EC water) where recirculation is difficult or even impossible without a pre-treatment to reduce salinity. This is particularly an issue in Mediterranean areas.

When using substrates, their type and composition must be taken into account. Chemical characteristics of the substrate may have an important impact on the concentration of nutrients in the solution. This is a particular concern for organic substrates, like coir and peat with high cationic exchange capacity. On the other hand, physical properties of the substrate have a decisive influence on irrigation management.

In other growing systems roots develop directly in the nutrient solution (NFT-nutrient film technique, DFT-deep flow technique, Ebb-flood), being exposed to water, oxygen, and nutrients. Design and management differ in each system, but they can be used for some vegetable and ornamental plants. They are commercially available and are well adapted to greenhouses with controlled climatic conditions. One of the drawbacks is their high initial investment as automation is usually required, although small-scale NFTs do exist. Other problem can be the management of the voluminous nutrient solution if it gets contaminated. On the other hand, one of the major advantages of using this type of techniques is the lower dependency to soil bound diseases leading to lower use of plant protection products and not being longer confronted with regulations concerning soil disinfection.

9.1.5.3. Sub-Issue C: Adjustment of the recirculating solution in closed soilless growing systems

In closed soilless systems, it is necessary to replace the nutrients absorbed by the crop with the equivalent addition of nutrients supplied by water and fertilisers to ensure the stability of the nutrient solution composition. For this objective, it would be optimal to install affordable (and with low maintenance) and reliable selective ion sensors in the fertigation equipment for nutrient monitoring and automatic adjustment of the ion concentrations in the recirculating solution. However, this system is not currently available and frequent chemical analysis are carried out instead.

9.1.6. Brief description of the socio-economic impact of the issue

The use of (semi-)closed recirculating systems faces some socioeconomic bottlenecks. One of them, mentioned above, is that optimal management of most closed-loop crops requires irrigation water of good quality. Some solutions to this problem are the use of desalination plants, strategies to decrease water drainage and nitrate emissions, providing new life to waste through cleaning of leachates by using constructed wetlands, or modelling salinity build-up in recirculating nutrient solution culture.

The main bottleneck for hydroponic systems (NFT, DFT, and ebb-flood) is the high financial investment to install a professional automated system. Some low-cost versions are available for use by small-case growers. Other limitations may be that these systems are limited for some specific vegetable crops and, in the case of DFT, the system does not allow the grower to take the risk of testing new products, due to management and design limitations. Algae bloom or spread of diseases is also a concern in hydroponics, as well as oxygen management in the nutrient solution.

When using substrates, the choice of the grower often depends on prices, disinfection type used, experience with the substrate, monitoring tools (e.g. moisture sensors), the capacity of the system to establish small, precise frequent irrigations, water source and type of system (open, semi-closed or entirely closed). For growers using substrates, recycling of the substrate is forced by most European countries to avoid waste. Waste management must be considered as an important economic and environmental issue.

9.1.7. Brief description of the regulations concerning the issue

EU regulations do not permit the nutrient solution to be discharged into surface waters if the nitrate (NO_3) content is higher than 50 mg/L. This obligates to search a solution for disposal in semi-closed systems, primarily if a large volume of recirculating solution is managed, like in ebb and flood systems, DFT and NFT system. Some Member States prescribe the how this water should be removed. As an example, the Flemish regulation prescribes that discharged water has to be spread on grassland or purified (removal of nutrients). In case of soilless growing systems in open air specific problems might arise as high volumes of drain water are produced due to heavy precipitation.

There are existing European Directives for waste management, adapted at national and/or regional level.

9.1.8. Existing technologies to solve the issue/sub-issues

The general approaches of the existing technologies can be organised into the following categories:

- Substrates for soilless culture:
    - Rockwool
    - Coir
    - Perlite
    - Disease suppression by organic growing media (compost amended substrate)
- Closed systems: design and water/nutrient management:
    - Automatic mixing systems for reuse of drainage
    - Semi-closed soilless system
    - Nutrient Film Technique
    - Deep Flow Technique
    - Ebb and flow (Flood-and-Drain) system

9.1.9. Issues that cannot be solved currently

Regarding substrates, their optimal recycling is sometimes a problem. For instance, this is the case of rockwool in areas located far from an industry able to process this residue. On the other hand, in some countries legislation exists on labelling of substrates but not for recycling.

Growers managing soilless growing systems like DFT are looking for solutions for the discharge water. This water should be spread on grassland or purified (removal of nutrients) to comply with regulations. However, spreading on grassland is not always feasible because sufficient grassland must be available to process the high volume of this nutrient water stream. On the other hand, there are no technologies at this moment offered to remove nutrients from a large amount of discharge water produced once every 1,5-2 years.

The availability of an affordable automatic system based on selective ion sensors would be very interesting for the optimal management of closed systems. Furthermore, in areas where good quality water is scarce, affordable alternative sources are necessary to make recirculation of the nutrient solution possible.

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9.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions (TDs)

TD title	Cost	Technological requirements	Strengthen	Weakness	Limitations
Substrates for soilless culture					
Rockwool	Installation: 1,75 € (45 kg/m³) – 2,36 € (75 kg/m³)/15 L slab		The inert and well-draining substrate, most of the retained water is readily available	Higher cost than coir needs to be placed on a fully levelled surface, precise irrigation management required because of its low water buffer capacity, susceptible to pH shifts, not biodegradable and must be recycled	Recycling is expensive in production areas far from a rockwool factory
Coir	Installation: 0,25-0,35 €/7-9 L block 1,3-1,85 €/30 L bag		Excellent air porosity and water retention, quick water re-absorption compared to rockwool, fast germination times and quick seedling rotations, sustainable substrate, low degradation rate compared to other organic substrates, free from soil diseases	Adequate initial management is essential to wash Na and avoid Ca and Mg deficiencies, small and frequent irrigations required as a loose substrate	The substrate with fine particles (dust) can produce compaction and root asphyxia
Perlite	Installation: 2 €/37 L bag 6,8 €/100 L bag		Excellent water retention and drainage capabilities, the low degradation rate	Lower readily-available water content than rockwool, higher volume of substrate required, the presence of small open pores giving to the substrate a hydrophobic behaviour if full with air instead of water, potential particle inhalation danger	Presence of dust contributes to excessive water retention and nutrient solution turbidity. It must be removed by flushing with water before use
Compost amended substrate with disease suppression	Installation: 10-15 €/ton		Reduced use of fungicides if sufficiently effective against pathogens, leftover material,	Preventive use only, the limited shelf life of products, time-consuming preparation of substrates	Stability of compost, availability, and quality of composted material, longevity and variability

TD title	Cost	Technological requirements	Strengthen	Weakness	Limitations
activity			can be used at farm level		
Closed systems: design and water/nutrient management					
Automated mixing systems for reuse of drainage	Installation: Basic installation without updating fertigation software: 3500 € Mixing system for recirculation including software: 10500 € Maintenance: Revision/change of EC sensor, valves and pumps, energy cost	Knowledge about crop nutrient uptake Knowledge about crop response to salinity	Reusing drainage allows a significant percentage of water and fertilisers to be saved and a huge reduction of pollution	Electricity is necessary It must be combined with a disinfection technology. Global cost is not always financially compensated by water and fertilisers saving Precise and frequent control of the nutrient solution is required	High-quality water is necessary for a complete recirculation of the nutrient solution
Semi-closed soilless system	Installation: 42500-57500 €/ha (disinfection not included)	Relevant technological knowledge, computer skills	More efficient use of water and fertilisers, reduction of nutrient discharge, positive environment impact	Installation cost, good quality water required for economical optimal management, more precise and frequent control of the nutrient solution needed, use of disinfecting methods required	Accumulation of ballast ions in the recirculating solution
Nutrient Film Technique (NFT)	Installation: 100-230 €/m^2 Maintenance: Replacement of plastic elements, cleaning water and products for re-use of channels, pumps, electronics and possibly chains (in automated systems)	Relevant technological knowledge, computer skills	More efficient use of water, fertilisers and chemicals, permit preparation of irrigation water, reduction of nutrient discharge, allows working ergonomically, great potential for automation, more efficient use of space making artificial light economically feasible	Very high installation cost, possible easily spread of water infections all over the system if the sterilisation protocol fails, highly susceptible to any breakage of the water flow system	Very high initial investment (but low-cost versions of NFT already exist) Temperature and dissolved oxygen can be sometimes limiting, especially in summer

TD title	Cost	Technological requirements	Strengthen	Weakness	Limitations
Deep Flow Technique (DFT)	Installation: 37-60 €/m^2	Relevant technological knowledge	More efficient use of water, fertilisers and chemicals, permit preparation of irrigation water, higher yield, positive environmental impact, fluctuations in nutrients, water temperature, etc. are lower than in NFT	The system is quite labour consuming, rainwater can lead to an unstable nutrient solution in outdoor crops, deficits of some nutrients have to be supervised, lettuce is more sensitive to *Microdochium panattonianum*	A large volume of water is produced when discharging the nutrient solution. At present, there are no technologies offered for removing the nutrients from all this water Testing new technologies or products in this system is a risk as has to be done on a big scale from the start
Ebb and flow (Flood-and-Drain) system	Installation: 80-85 €/m^2	Relevant technological knowledge	More efficient use of water, fertilisers and chemicals, positive environmental impact, not labour intensive, more uniform plants, excellent aeration, plants can be spaced as needed, fewer diseases due to lower humidity	High installation cost, maintenance requirements (pump failure, adjustments of auto-syphons), small cracks can occur in the concrete ebb and flood systems provoking water leaks to the environment requires a larger sump tank, roots can block the pipework, over time some sediment can be collected in the reservoir	Possible nitrite accumulation leading to plant growth problems Big volumes have to be discharged if problems occur with the nutrient solution

9.3. Rockwool

(Authors: Esther Lechevallier[4], Alain Guillou[4], Elisa Suárez-Rey[11])

9.3.1. Used for

More efficient use of water.

9.3.2. Region

All EU regions.

9.3.3. Crop(s) in which it is used

Vegetables (tomato, aubergine, cucumber, sweet pepper) fruit crops (melon, strawberry) and cut flowers.

9.3.4. Cropping type

Soilless crops under protected conditions.

9.3.5. Description of the technology

9.3.5.1. Purpose/aim of the technology

Rockwool, also known as stone wool or mineral wool, is one of the most widely used substrates for the commercial soilless production. It is an inert (mineral) substrate which provides a proper environment for the development of the root system.

9.3.5.2. Working Principle of operation

Rockwool is made from basalt which is re-liquefied and spun, hardened, compressed and cut. The formed products are available in various sizes and shapes which are adaptable to many applications.

Different types of growing slabs, seeding and propagation cubes and plugs are available on the market for diverse uses. They are often wrapped in polyethene foil. Loose rockwool can also be used.

For growing slabs, several lengths are available, depending on the crop and the density wished. The most common size is 120 (or different length) x 20 x 7,5 cm. Recently higher slabs appeared: 120 (or different length) x 15 x 10 cm. These substrates have a better draining capacity, minimising the development of *Agrobacterium*. The structure of the substrate was thus more adapted to the water retention.

Properties of the growing media such as the moisture holding capacity, the aeration (or air-filled porosity) and the moisture gradient from the top to the base of the substrate depending on the way in which the molten rock fibres are stacked (vertical or horizontal) and the density of fibres inside the rockwool substrate. Usually, the volume of air between fibres reaches 95% and bulk density is around 70-80 kg/m³.

By altering rockwool properties, products for different applications have been made available to growers. Products with horizontally orientated fibres drain slower but provide more lateral (sideways) root growth (typically slabs). Those with vertical fibre orientation are quicker to drain and encourage the downward growth of roots (typically cubes, making them an excellent choice for rooting cuttings). The best results are obtained with vertical fibre structures, thus avoiding substrate compaction. Draining characteristics of the substrate depend on the density and structure of the fibres but are always higher than in substrates with coir. With the development of root systems, the substrate increases its water-holding capacity.

Figure 9-2. Examples of rockwool substrates (Source: Cultilène, Grodan)

9.3.5.3. Operational conditions

Irrigation should be managed regarding the draining behaviour of the rockwool substrates. Small and frequent doses are more adapted to rockwool substrates. Standard rockwool products drain freely after irrigation and will then typically contain 80% nutrient solution, 15% air pore space and 5% rockwool fibres, although these ratios differ slightly between rockwool brands and products. Substrate type should be adapted to the specific needs of the crops and the climatology (temperature, lighting, etc.).

One of the most important characteristics of rockwool is that most of the water is retained by the rockwool as readily-available water. That means that plants can easily extract water when the rockwool is saturated from recent irrigation and when the rockwool slab has dried considerably and lost as much as 70-80% of its moisture content, levels which in other growing media would cause severe wilting to the crop.

The slab has a limited lifespan because the structure breaks down with time. The availability of oxygen in the medium decreases as the structure of the medium breaks down.

Checking the EC in the root zone is important with rockwool just as it is with any other substrate. Even though rockwool does not contain any naturally occurring minerals or salts, which may influence EC levels, the EC of the nutrient solution inside the growing substrate will change since plants extract different ratios of water and nutrients from the root zone.

One important aspect of rockwool is the high pH. All rockwool substrates should be soaked in a pH adjusted water or mild nutrient solution prior to planting. Soak for at least 24 hours at a pH of 5,5. The pH will still tend to climb higher than desired for the first couple of weeks but gradually stabilises. The pH in the reservoir can be significantly lower than in the medium. If the pH in the reservoir is maintained around pH 5,5 it should be near pH 6,3 at the roots.

9.3.5.4. Cost data

Installation cost

Cost of a 100 cm x 15 cm x 10 cm slab (6 tomato stems) depends on the type of slab and ranges from 1,75 € (density of 45 kg/m^3) to 2,36 € (density of 75 kg/m^3).

Maintenance

Yearly maintenance or inputs needed: in Spain, rockwool of higher density (75 kg/m^3) is usually reused for 3 years to reduce the cost. However, there is a risk for pathogen development for which a lot of growers renew their substrate each cropping season (thus using a slab of lower density). Growers can disinfect the substrate with vapour between two cropping seasons.

9.3.5.5. Technological bottlenecks

The buffer capacity is lower than in substrates with higher water retention (e.g. coir). It depends on the type of structure of the substrate, for example, rockwool usually has higher water retention capacity than perlite.

The low water holding capacity of the substrate forces the grower to make small irrigations with precision and he needs to adapt the irrigation system to have the capacity to irrigate more frequently the crop.

9.3.5.6. Benefit for the grower

Advantages

- Inert (no effect on pH / EC of the supplied nutrient solution)
- Does not contain organic matter susceptible to react with nutrients or be discharged in the drainage water (clogging of filters and disinfection systems)
- Well-draining
- Can be used with UV disinfection
- 100% recyclable
- Rockwool, being a “sterile” product (only directly after production) does not contain any naturally occurring beneficial microbial populations when first planted out
- Can be reused after disinfection
- Management of this substrate is well-known and widely used

Disadvantages

- Higher cost than coir
- Not biodegradable and must be recycled. The cost of it should be taken into account. Some rockwool providers take this process in charge, or specialised companies can provide this service
- Lower water buffer capacity than coir substrates

- Needs to be placed on a fully levelled surface to allow the moisture gradient inside the substrate to be even and prevent the development of saturated or overly dry patches
- Fibres can irritate the skin and a face mask is recommended if handling granulated rockwool or disposing of old rockwool products
- Rockwool has a high pH which means that the nutrient solution must be adjusted so that the root zone is neutral
- Susceptible to pH shifts meaning more routine maintenance to keep the pH levels correct

9.3.5.7. Supporting systems needed

Rockwool substrate is formed in cubes or slabs in polyethene foil and lay on a suspended gutter or on a levelled surface (ground or foam cubes) (Figure 9-3).

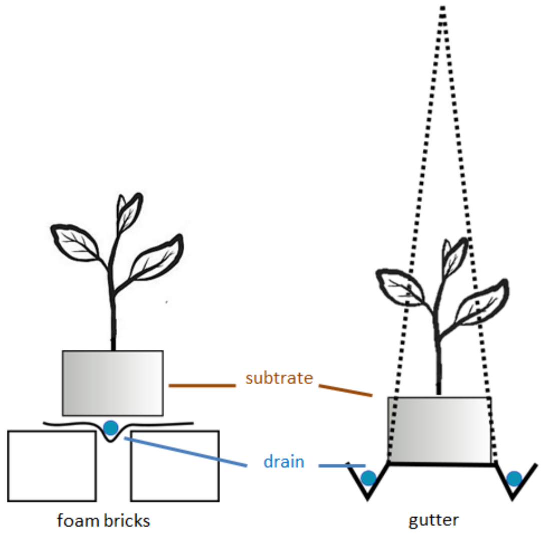

Figure 9-3. Supporting systems needed: substrates can be placed on the ground or on systems to collect the drain (foam cubes or suspended gutter) (Source: CATE)

Some companies have developed adapted moisture meter to monitor irrigation with rockwool slabs: e.g. GroSens (GRODAN), WET Sensors (Delta-T Devices), 30MHz Substrate moisture sensor (30 MHz).

9.3.5.8. Development phase

Commercialised (and widely used in greenhouse production).

9.3.5.9. Who provides the technology

Several rockwool providers occupy the market, such as Grodan, Cultilene, BVB, Rockwool, Delta.

9.3.5.10. Patented or not

Yes, depending on the type and company.

9.3.6. Which technologies are in competition with this one

Coir and perlite substrates are the most competing with rockwool substrates because they are used for the same type of crops (pepper, tomato, cucumber, etc.).

9.3.7. Is the technology transferable to other crops/climates/cropping systems?

Rockwool substrates are meant to be used in soilless systems. Due to the inert property, they can be used with a wide range of crops and climates under protected conditions. Fruits vegetables (tomatoes, pepper, etc.) and cut flowers are well adapted to the use of rockwool substrates.

9.3.8. Description of the regulatory bottlenecks

Recycling of the substrate is mandatory in many European countries. Some suppliers provide solutions to collect and recycle the substrate slabs but the purchase price is higher. In some countries, local companies are dedicated to the recycling of agricultural substrates.

In Spain, legislation exists on labelling of substrates, not for recycling (Real Decreto 868/2010 and 1039/2012).

In France, the recycling of rockwool substrates is mandatory (Arrêté du 12/03/03 relatif à l'industrie du verre et de la fibre minérale).

9.3.9. Brief description of the socio-economic bottlenecks

Rockwool substrates are more expensive than other material but it does not appear to be a major economic bottleneck.

The waste management (mandatory recycling in some countries) must be considered as an important socio-economic issue.

9.3.10. Techniques resulting from this technology

Rockwool is a well-draining substrate. Irrigation scheduling and doses must be adapted to the substrate. It is recommended to give short irrigations when using rockwool.

9.3.11. References for more information

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9.4. Coir

(Authors: Eleftheria Stavridou[15], Esther Lechevallier[4], Alain Guillou[4], Elisa Suárez-Rey[11], Juan Del Castillo[13])

9.4.1. Used for

More efficient use of water.

9.4.2. Region

- Nordic
- North-West Europe
- Mediterranean

9.4.3. Crop(s) in which it is used

Vegetables (tomato, peppers, courgette, aubergine, leafy salads), fruit crops (melon, strawberry, raspberry, blackberry) and cut flowers (roses, orchids).

9.4.4. Cropping type

Soilless crops under protected conditions.

9.4.5. Description of the technology

9.4.5.1. Purpose/aim of the technology

Coir a sustainable organic substrate alternative to peat used to cultivate in protected conditions in order to reduce husbandry costs, the use of water and nutrients, the impact of soil-borne diseases and soil-fatigue and improve the uniformity of the crop.

9.4.5.2. Working Principle of operation

Coir is a by-product of processing coconut husk fibre. The source, the moisture level and the compression pressures often differ among producers, so that coir is not a uniform material resulting in a large variability of end-product. With the addition of water, coir dust expands 5-9 times its compressed volume. It has pH of 5,7-6,5 and a high cation exchange capacity (ranging from 30 and 100 meq/100 g).

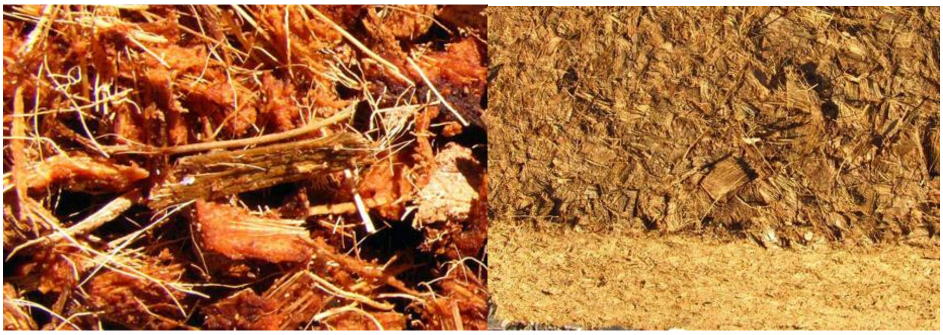

Figure 9-4. Fibre and small chips of coir (left). Block of coir as it is sold (right) (Source: Tucson Cactus and Succulent Society)

9.4.5.3. Operational conditions

Coir can be commercially supplied in bags or in blocks that need wetting prior planting/seeding. Initial wetting is very important to achieve an optimal decompression of the substrate and to increase its calcium content.

9.4.5.4. Cost data

Installation cost

0,25-0,35 € per 7-9 L brick/block or 1,3-1,85 €/30 L bag.

Maintenance

In comparison with other substrates, coir retains its physical integrity longer and repotting is needed with lesser frequency. In addition, coir can be recycled and reused very easily.

9.4.5.5. Technological bottlenecks

Non-buffered coir is naturally rich in Na and K and can bind Ca and Mg, so plants may experience deficiencies of these cations. Therefore, coir is first washed to remove the excess of Na and K and then immersed in a calcium nitrate solution that improves the availability of Ca for the plant. Application of irrigation prior to planting with calcium nitrate at a dose of 9 g /10 L of the substrate is recommended. In addition, fertiliser is indispensable in order to grow plants. Coir also has little capillarity transport because it is very loose. Water retention, in this case, is low and needs more frequent irrigation. The substrate with fine particles (dust) can produce compaction and root asphyxia.

9.4.5.6. Benefit for the grower

Advantages

- Reduces the use of water and nutrients
- Excellent air porosity and water retention
- Quickly reabsorbs water from a dry state compared to rockwool. Thus, plants grown in coir tend to recover better and more quickly from dry conditions.
- Faster germination times and quicker seedling rotations
- Sustainable
- Low degradation rate considering that it is an organic substrate
- Free from soil diseases

Disadvantages

- Cultivation in coir requires irrigation and fertilisation
- Small volumes require higher irrigation frequency
- Protected and extensive cultivation requires high initial investment on structures, covers, training systems, table tops, irrigation and fertilisation equipment

9.4.5.7. Supporting systems needed

Coir needs to be held in a pot or a bag.

9.4.5.8. Development phase

Commercialised.

9.4.5.9. Who provides the technology

In the UK the biggest players are Botanicoir and Cocogreen. In Spain, main providers are Projar, Pelemix, Ispemar.

9.4.5.10. Patented or not

Coir is not patented since it is a by-product of another industry.

9.4.6. Which technologies are in competition with this one

Mainly peat, perlite and rockwool.

9.4.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, it is very versatile.

9.4.8. Description of the regulatory bottlenecks

None observed. Coir has a very easy recycling.

9.4.9. Brief description of the socio-economic bottlenecks

At present, the use of a substrate or another is more linked to its cost or to its adaptation to a crop than to the technology necessary for its use.

Regarding supply shortage, bad weather conditions and unprecedented rainfall (i.e. 2014-2016) can hamper the natural drying of the coconut by-product affecting the entire coir industry in Sri Lanka and India. Coir pith is typically dried by natural sunlight. However, continuous rain meant that the coir was insufficiently dried, causing knock-on effects for UK growers who use coir substrate to plant crops. Unpredictable weather conditions can result in price increases of the raw material in line with demand and increased processing costs.

9.4.10. Techniques resulting from this technology

- Other additives can be added to the coir to increase the efficiency of the nutrient and water use, e.g. Cocogreen H_2CoCo
- Coir supplied in disks or blocks which are placed in pots. Coir is then wetted and expands to occupy the whole volume available

9.4.11. References for more information

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9.5. Perlite

(Authors: Eleftheria Stavridou[15], Esther Lechevallier[4])

9.5.1. Used for

More efficient use of water.

9.5.2. Region

- Nordic
- North-West Europe
- Mediterranean

9.5.3. Crop(s) in which it is used

Vegetables (tomato, cucumber, sweet pepper, eggplant, courgette, lettuce), fruit crops (melon, watermelon, strawberry) and cut flowers (rose, gerbera, gypsophila, carnation aster, etc.).

9.5.4. Cropping type

Soilless crops under protected conditions.

9.5.5. Description of the technology

9.5.5.1. Purpose/aim of the technology

This is a substrate used to cultivate in protected conditions in order to reduce husbandry costs, the use of water and nutrients, the impact of soil-borne diseases and soil-fatigue and to improve the uniformity of the crop.

9.5.5.2. Working Principle of operation

Perlite is a substance made of volcanic rock. It is white, lightweight and often used as a soil additive to increase aeration and draining of the soil. In composition, it is a potassium sodium aluminium silicate. Perlite has a neutral pH, excellent wicking action, and is very porous. It is chemically inert with almost no cation exchange capacity or nutrients, and a neutral pH. Perlite is available in many grades. A size of particles of 0-5 mm (without dust) is the most common for horticulture. Perlite can be used alone or amended into coir, vermiculite, peat moss or soil mixes to improve aeration/drainage.

Figure 9-5. Loose perlite (left) and tomato plants grown in perlite (right) (Source: The Egyptian Co. for Manufacturing Perlite)

9.5.5.3. Operational conditions

It can contain excessive perlite "dust". This must be removed by flushing with water prior to use. Goggles and a dust mask should be worn. Some growers prefer to fill their bags of perlite with water before opening to reduce or even eliminate airborne particulate. The substrate must be adequately saturated before planting because it has a high proportion of small open pores that, if containing air instead of water, make perlite to have a hydrophobic behaviour.

9.5.5.4. Cost data

Installation

2 €/37 L bag. Perlite bags of 100 L for replacing the substrate lost when pulling up the plants cost 6,8 €.

Maintenance

Perlite can be reused, having a long-life cycle. It can be washed and dried to be restored back to its 7,0 pH level. Steam sterilisation of the used perlite before planting a new crop has been recommended to safeguard against pathogen contamination. Alternatively, perlite in grow bags can be agitated and sterilised with hot water treatment by using a heavy-duty water breaker mounted on the steel wand of a hot water pressure washer.

9.5.5.5. Technological bottlenecks

Readily-available water is relatively low because perlite has a significant proportion of small pores retaining water strongly. Furthermore, a proportion of pores are closed and do not contribute to water retention. Hence, a higher volume per bag (30-40 L) is used for growing vegetables in comparison to other mineral substrates.

Perlite can contain excessive perlite "dust". This must be removed by flushing with water prior to use. Dust contributes to excessive water retention and to nutrient solution turbidity which in turn facilitates unwanted bacterial growth. Perlite dust is a problem for pumps and tubing. Debris from loose perlite can lead to clogging of irrigation lines in hydroponic systems.

9.5.5.6. Benefit for the grower

Advantages

- As a porous substance, perlite offers both excellent water retention and drainage capabilities
- It provides proper aeration which is necessary for healthy root growth in plants
- It is free from soil diseases
- It has a neutral pH level but will take on the acidity or alkalinity of the nutrient solution
- Low degradation rate
- Acts as an insulator to protect plants from temperature changes

Disadvantages

- Cultivation in perlite requires irrigation and fertilisation
- Require higher irrigation frequency
- Too lightweight for certain hydroponic systems
- Perlite is obtained from quarries and this involves environmental concerns
- Potential particle inhalation danger
- Tends to float when flooded
- Small open pores give the substrate a hydrophobic behaviour if full with air instead of water, which have an important repercussion on irrigation management

9.5.5.7. Supporting systems needed

Perlite needs to be held in a pot or a bag. Perlite works great in net cups, and even better in fabric pots. Ebb and flow, dutch buckets and drip systems are all excellent methods for growing in perlite.

9.5.5.8. Development phase

Commercialised.

9.5.5.9. Who provides the technology

In Spain, the main providers are Otavi Iberica S.L. and Europerlita Española S.A.

9.5.5.10. Patented or not

Perlite is not patented.

9.5.6. Which technologies are in competition with this one

Mainly coir, rockwool and peat.

9.5.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, it is very versatile.

9.5.8. Description of the regulatory bottlenecks

Perlite has to be recycled at the end of its life. It can be mixed with soil to increase aeration.

9.5.9. Brief description of the socio-economic bottlenecks

Perlite is a non-renewable resource (volcanic rock), though the supply on the planet is quite extensive.

Perlite can affect the human respiratory system. It is listed as a "nuisance dust," which means it can aggravate your eyes, mouth, throat and lungs. Long-term exposure to high levels of this dust can cause a non-cancerous disease called silicosis.

9.5.10. Techniques resulting from this technology

Perlite is usually used in plastic bags although it can be placed in pots as a loose material.

9.5.11. References for more information

[1] Canna (2017). Soilless cultivation - What makes a good medium? Retrieved from http://www.canna-uk.com/what_makes_good_quality_soilless_growing_medium

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9.6. Compost amended substrate with disease suppression activity

(Authors: Federico Tinivella[7], Elisa Suárez-Rey[11])

9.6.1. Used for

Minimising the impact on the environment by reducing pesticide application.

9.6.2. Region

All EU regions.

9.6.3. Crop(s) in which it is used

Mainly vegetables and ornamentals. Limited in the case of extensive crops for economic reasons.

9.6.4. Cropping type

Soil-bound (with limitations) and soilless crops mainly under protected conditions.

9.6.5. Description of the technology

9.6.5.1. Purpose/aim of the technology

Compost amended substrates can provide some level of disease suppression with specific regards to root diseases and therefore reduce the risk of yield losses due to soil-borne diseases.

9.6.5.2. Working Principle of operation

The improvement of growing media with compost can lead to a rapid increase in microbial and fungal activities and microbial population diversity. The suppression phenomenon consists of a complex set of mechanisms:

- Competition for nutrients, space and occupation of infection sites by other micro-organisms (and related increase of siderophore producers) – e.g. by *Pseudomonas*
- Hyperparasitism followed by lysis – e.g. by *Trichoderma harzianum*
- Antibiosis, i.e. the production of antibiotics – e.g. by *Gliocladium virens*
- Futile pathogen germination thanks to the compost's role in mimicking root exudates. Normally a pathogen propagule will not germinate in the absence of a host as signalled by root or seed exudate). In compost-containing media, germination of pathogens may be triggered before the pathogen comes in contact with living plants so that the existing inoculum is spent
- Induced Systemic Resistance – e.g. by many rhizosphere bacterial and fungal isolates

The main pathogens controlled with this technique are *Fusarium, Rhizoctonia, Pythium* and *Phytophthora*.

Moreover, compost can be enriched with selected strains of antagonistic bacteria or fungi in order to improve the suppression phenomenon.

9.6.5.3. Operational conditions

Preferably 20-30% of the total volume of the peat-based substrate should be replaced by compost. Higher rates should be checked with target crops.

The characteristics of the compost intended for the cultivation of potted plants must be:

- pH: 5,5-8
- Moisture content: 35-55%
- Particle size: pass through 1/2 mesh screen or smaller, acceptable particle size is based on pot/container size
- Stability: stable to highly stable, thereby providing nutrients for plant growth and assuring no substantial shrinkage
- Maturity/growth: must pass maturity test or demonstrate its ability to enhance seed germination and plant growth
- EC: 300 µS/cm for media blend

Figure 9-6. Substrate with peat (left) and with peat and compost (right)

9.6.5.4. Cost data

The average price of compost is 10-15 €/ton.

9.6.5.5. Technological bottlenecks

- The stability and quality of the compost and the shelf life, in case of commercialised composts, can be limited. In addition, the availability of raw and composted material is not always certain. There is also a certain variability and unpredictability of compost. Hence, similar compost may give different results
- The degree of decomposition of compost has a strong effect on the rate of disease suppression: both immature and excessively stabilised compost show low rates of disease suppression. It should also be taken into account that the longevity of the suppression capacity is related to the survival of beneficial microorganisms

9.6.5.6. Benefit for the grower

Advantages

- Can prevent pesticide use if sufficiently efficient against pathogens
- Possibility to exploit leftover material at the farm level

Disadvantages

- Preventive use only
- Limited shelf life of products
- Possible limited workability
- Time-consuming preparation of cultivation substrates

9.6.5.7. Supporting systems needed

- Facilities for compost production
- Transportation networks for delivering substrates to producers
- Facilities for compost mixing with cultivation substrates

9.6.5.8. Development phase

Commercialised.

9.6.5.9. Who provides the technology

There are very few specialised companies that provide such products, e.g. AgriNewTech in Italy (www.agrinewtech.com).

9.6.5.10. Patented or not

Antagonistic strains are not patented; the final product can be patented.

9.6.6. Which technologies are in competition with this one

This technology is an alternative in specific cases to the use of pesticides or biocontrol agents for the control of soil-borne pathogens.

9.6.7. Is the technology transferable to other crops/climates/cropping systems?

The use of compost as a substrate is specifically related to the cultivation of certain crops (vegetables and, to a lesser extent, ornamentals) but normally it is not intended for the application of extensive cultivation.

9.6.8. Description of the regulatory bottlenecks

Compost production is regulated by the Italian Legislative Decree n° 75 of 29/04/2010 entitled "Riordino e revisione della disciplina in materia di fertilizzanti, a norma dell'articolo 13 della legge 7 luglio 2009, n° 88", i.e. compost is included into the legislation regarding growing media and fertiliser with regards to the different legislative aspects that apply to it.

In such legislative decree the following issues are mainly described:

- The different typologies of composts according to the raw materials used to produce them
- The methodologies of production
- The physical and chemical characteristics they must comply with
- The content of nutritive elements

9.6.9. Brief description of the socio-economic bottlenecks

No specific socio-economic bottlenecks are encountered.

9.6.10. Techniques resulting from this technology

Not available.

9.6.11. References for more information

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[6] van Loon, L. C., Bakker, P. A. H. M. & Pieterse, C. M. J. (1998). Systemic resistance induced by rizosphere bacteria. *Annual Review of Phytopathology*, *36*, 453-483

9.7. Automatic mixing systems for reuse of drainage

(Authors: Evangelina Medrano[11], Elisa Suárez-Rey[11])

9.7.1. Used for

- Preparation of the nutrient solution to be supplied to the crop
- More efficient use of water and fertilisers
- Minimising the impact on the environment by nutrient discharge

9.7.2. Region

All EU regions.

9.7.3. Crop(s) in which it is used

Vegetable and ornamental crops.

9.7.4. Cropping type

Soilless crops under protected conditions and open air.

9.7.5. Description of the technology

9.7.5.1. Purpose/aim of the technology

This technology allows to automatically mix drainage and fresh water for its reuse. Two strategies are described (Figure 9-7): adding fresh water in the drainage collecting tank and adding fresh water to the recycling solution by the irrigation controller.

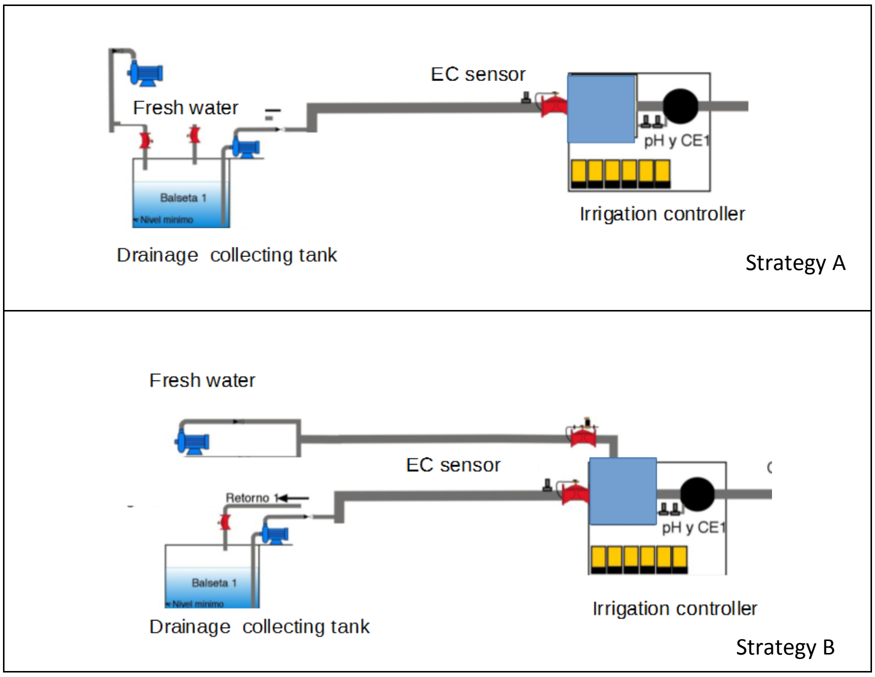


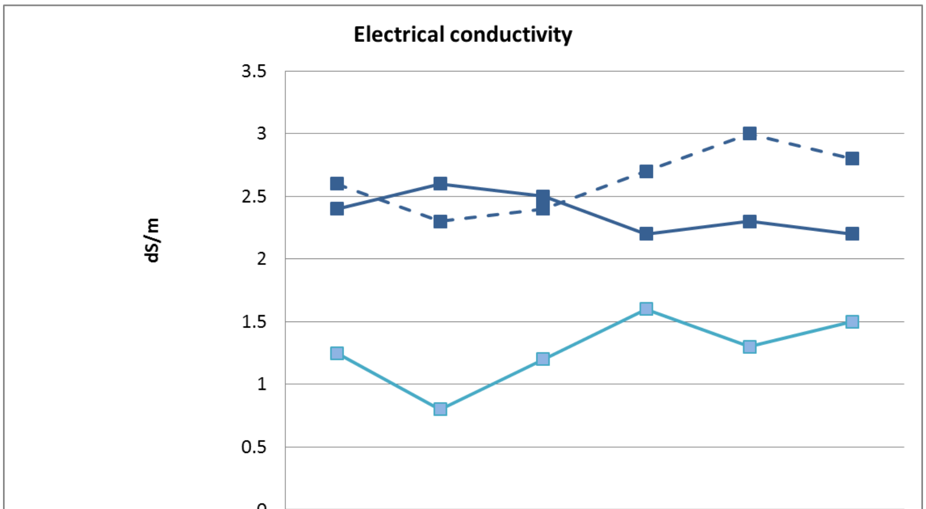
Figure 9-7. Strategy A: addition of fresh water in the drainage collecting tank. Strategy B: addition of fresh water to the recycling solution by the irrigation controller

9.7.5.2. Working Principle of operation

In recent years, cultivation in substrates has been characterised by a shift from open to closed-cycle cultivation system, involving the reuse of the drainage solution. Compared with the open-loop system, closed systems require more precise and frequent control of the nutrient solution. The returned nutrient solution has to be treated to restore its original nutrient element composition, existing different strategies.

Strategy A: Addition of fresh water in the drainage collecting tank

In this strategy, the drainage solution is mixed with fresh water in the collecting tank, which is provided with two sensors (down and up). During irrigation, the water level (mixture drain water and fresh water) goes down. When the sensor indicates that the lower limit is reached, fresh water flows into the tank until the upper sensor is reached. This sensor avoids overflow. By adding fresh water, the drainage solution is diluted, causing a decline in EC value and nutrient concentration when compared to the initial nutrient solution. Figure 9-8 shows the EC values of the drainage solution and the reduction of this EC when the water is mixed with fresh water (collecting tank solution).

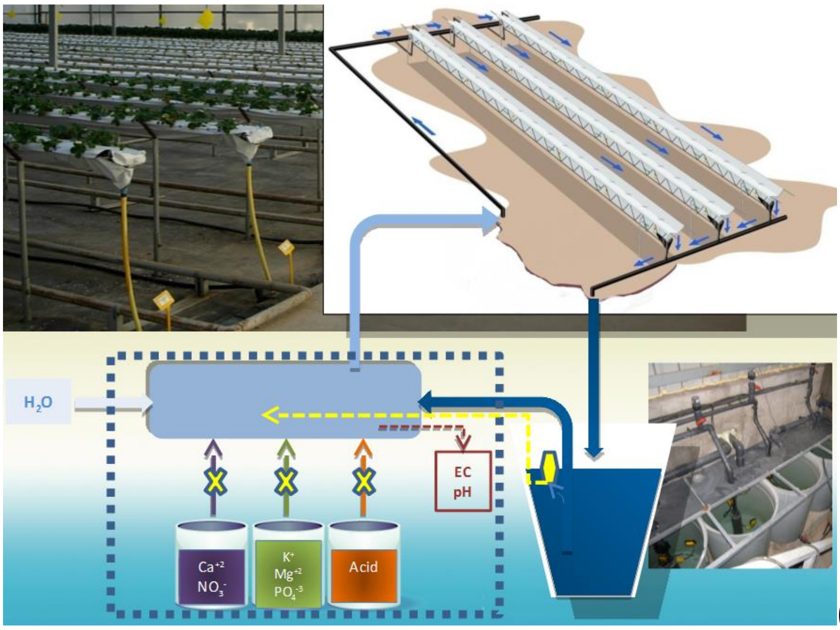


	05-nov.	19-nov.	03-dic.	30-dic.	14-ene.	12-feb.
nutrient solution	2.4	2.6	2.5	2.2	2.3	2.2
drainage solution	2.6	2.3	2.4	2.7	3.0	2.8
collecting tank solution	1.25	0.8	1.2	1.6	1.3	1.5

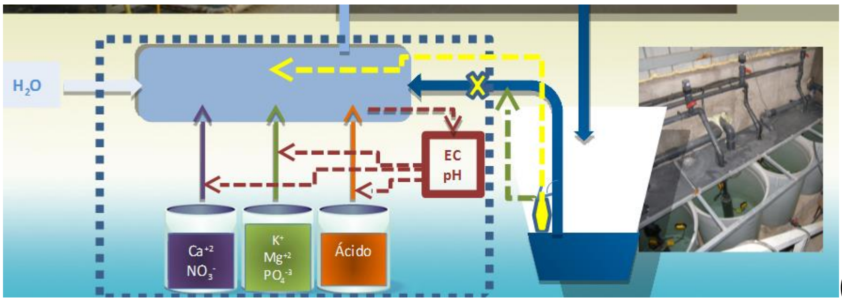
Figure 9-8. Evolution of the drainage, collecting tank solution (mixture of drainage solution and fresh water) and supplied nutrient solution electrical conductivity in a recirculating system using the strategy A (adding fresh water in the recycling tank)

Strategy B: Addition of fresh water to the drainage water by an irrigation controller

The drainage solution is collected in the drainage collecting tank, provided with a sensor (yellow colour in Figure 9-9). During every irrigation event, the irrigation controller automatically adjusts the drainage solution from the storage tank to fit the target EC, by adding fresh water. In case of having to increase EC of the drainage solution, the equipment will inject fertilisers according to the established thresholds. If the storage tank solution is depleted during the irrigation event, watering continues with a new nutrient solution. This system enables better use of the recycled nutrient solution and ensures that the appropriate parameters of pH, EC and balance of nutrients are maintained. A periodical monitoring of the nutrient concentration has to be done to adjust fertiliser addition and maintain the balance.



(a)



(b)

Figure 9-9. Ways to prepare the nutrient solution with freshwater input into the fertigation equipment.

a) When the yellow level sensor detects drainage water in the collection tank, the irrigation controller adds fresh water to obtain a mixture with drainage water

b) When the level sensor detects that there is no drainage solution, the irrigation controller begins to develop a new nutrient solution by adding fertilisers to fresh water

9.7.5.3. Operational conditions

Along with the risk of a possible diffusion of root pathogens, the salinity of irrigation water represents the main difficulty for the management of closed growing systems. When the use of saline water is imposed, there is an accumulation in the recirculating solution of ballast ions, like sodium and chloride, which are dissolved in the water at concentrations higher than the corresponding crop uptake concentration (the ratio between the absorption of an ion and water by the crop). In that case, a partial discharge of the recirculating solution will be necessary to avoid an excessive salt accumulation and as a consequence, yield decrease. The percentage of water which must be eliminated from the recirculated system ("We", the difference between the percentage of drainage and that of the recirculated water), can be calculated by using the following expression (Magán, 1999):

$$We = \frac{Wa * (Cw - Cu)}{Cm - Cw}$$

where:

Wa is the percentage of water absorbed by the crop

Cw is the concentration of the limiting ion in the fresh water

Cu is the uptake concentration of the crop for that ion

Cm is the maximum concentration allowed for that ion in the drainage water

9.7.5.4. Cost data

The specific software, sensors, storage tank, additional valves and pumps cost between 3500 and 10500 €, depending on the complexity of the program for both strategy A and B.

9.7.5.5. Technological bottlenecks

Switching to closed cultivation systems does not seem to restrict crop yield or product quality. However, a factor limiting the broad expansion of closed-cycle cultivation systems in substrate-grown crops is the accumulation of salt ions in the recycled nutrient solution.

9.7.5.6. Benefit for the grower

Advantages

- Reduced water use (20-30%), even when some flushing/bleeding of the system is necessary
- Reduced use of nutrients (40-50%)
- Reduced pollution of ground and surface waters by fertilisers and chemicals

Disadvantages

- Additional financial investment in tanks, pump, pipes, etc.
- Use of disinfecting methods required

9.7.5.7. Supporting systems needed

Compared with the open-loop system, it requires more precise and frequent control of the nutrient solutions and technical know-how. Channels and tanks for drainage collection and pumps for water impulsion are necessary. Installation of disinfection equipment is convenient to avoid phytosanitary problems.

9.7.5.8. Development phase

Commercialised.

9.7.5.9. Who provides the technology

Companies installing fertigation controllers.

9.7.5.10. Patented or not

Not patented.

9.7.6. Which technologies are in competition with this one

Different strategies are used to get the desired nutrient solution. One alternative used in the Netherlands is to mix a refreshment nutrient solution with the drainage solution to get the final EC set point.

9.7.7. Is the technology transferable to other crops/climates/cropping systems?

This technology is applicable to any water culture: deep water culture, float hydroponics, nutrient film technique, deep flow technique or aeroponics and substrate culture (gravel, sand, bag or container culture).

9.7.8. Description of the regulatory bottlenecks

In the Netherlands, the environmental law (since 2002) states that in most cases it is compulsory to capture the drain water above ground and use it again as irrigation water.

In Andalusia (Spain) the Order 15/12/2015 which regulates the specific rules for the integrated production of horticultural protected crops recommends the recirculation of the nutrient solution in soilless culture.

9.7.9. Brief description of the socio-economic bottlenecks

Economical optimal management of most closed-loop crops in a greenhouse requires irrigation water of good quality. A price structure of irrigation that shifts the economic optimum towards poorer irrigation water has the consequence that the irrigation loop cannot be closed. In view of the environmental impact, it would be advisable for irrigation and local authorities in horticultural areas either to provide good water at a reasonable price or to consider subsidising investment costs of on-site desalinisation plants, rather than stimulating the use of poor quality water or attempting to prevent pollution through regulations that may be uneconomical and unenforceable.

9.7.10. Techniques resulting from this technology

The different strategies which can be applied to the recirculation of the nutrient solution have been previously described.

9.7.11. References for more information

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9.8. Semi-closed soilless system

(Authors: Evangelina Medrano[11], Miguel Giménez[11], Elisa Suárez-Rey[11])

9.8.1. Used for

- Preparation of the nutrient solution to be supplied to the crop
- More efficient use of water and fertilisers
- Minimising the impact on the environment by nutrient discharge

9.8.2. Region

All EU regions.

9.8.3. Crop(s) in which it is used

Vegetable and ornamental crops.

9.8.4. Cropping type

Soilless crops under protected conditions and open air.

9.8.5. Description of the technology

9.8.5.1. Purpose/aim of the technology

A semi-closed soilless system is that which re-uses the drainage solution but it is not completely closed. The aim of this system is to substantially reduce pollution of water resources by nitrates and phosphates from fertigation effluents and contribute to an appreciable reduction in water and fertiliser consumption but avoiding yield decrease at the same time.

9.8.5.2. Working Principle of operation

In semi-closed systems, the drained nutrient solution is recovered, disinfected, replenished and recycled (Figure 9-1). The nutrient solution is normally recirculated until EC and/or the concentration of some potentially toxic ions reach a maximum acceptable threshold value, afterwards, it is replaced, at least partially. In the Netherlands, growers are allowed to leach their system whenever a crop-specific sodium concentration limit is reached: for example, 8 mmol/L for tomato or 4 mmol/L for cut roses.

The practical management of the recirculating drain water is generally based on the premix EC, which is the EC value of mixing raw water and recycled drain water. This EC value sets the proportion of drainage water and raw water to mix before the addition of fertilisers. This technique allows preserving an effective conductivity of the fertilisers.

9.8.5.3. Operational conditions

Together with the risk of a possible diffusion of root pathogens through the recirculating solution, the salinity of the irrigation water represents the main difficulty for the management of closed growing systems. When the use of saline water is imposed, there is a more or less rapid accumulation of ballast ions, like sodium and chloride, which are dissolved in the water at concentrations higher than the uptake concentration (the ratio between nutrient and water uptake). The type of substrate must be taken into account. Indeed, chemical characteristics of the substrate may have an important impact on the concentration of nutrients in the nutritive solution. This is a special concern for organic substrates with a high cationic exchange capacity. It is recommended to avoid recirculation during the first weeks of using these substrates.

In closed systems, a disinfection equipment is important to get the crop rid of pathogens. But, disinfection can interfere with nutrients present in the solution, especially oligo-elements. This is the case with oxidative disinfection (UV-C, ozonisation, chlorination) which destroys part of the iron chelates. Hence, it is better to use a formulation of oligo-elements adapted to closed systems.

9.8.5.4. Cost data

Installation cost

The fertigation equipment used in open soilless systems can be also used in semi-closed systems by adding the following specific installations (prices are referred to 1 ha of substrate horticultural crop):

- Channels collecting drainage: 30000 €
- Storage tanks: 5000 €
- Pumping for the drive of drain: 4000-12000 € (depending on the recycling strategy selected)
- Specific software + sensors: 3500-10500 € (depending on the complexity of the program)

Maintenance

It includes the maintenance of pumps, storage tanks and pipe network to transport the nutrient solution. Be aware of the risk of algae proliferation in the storage tanks.

9.8.5.5. Technological bottlenecks

Switching over to closed cultivation systems does not seem to restrict crop yield or product quality. However, a factor limiting the broad expansion of closed-cycle cultivation systems in substrate-grown crops is the accumulation of salt ions in the recycled nutrient solution. The quality of raw water may be restrictive for the implementation of this technology. With low quality of raw water (high salinity) recirculation is difficult, or even impossible without a pre-treatment to reduce salinity, because of the accumulation of ballast ions.

9.8.5.6. Benefit for the grower

Advantages

- Lower use of water (20-30%), even when some flushing/bleeding of the system is necessary
- Reduced use of nutrients (40-50%)

- Reduced polluting effects of fertilisers and chemicals in ground and surface water

Disadvantages

- Financial investment in tanks, pumps, channels, etc.
- A disinfecting method is required

9.8.5.7. Supporting systems needed

Compared with the open-loop system, it requires more precise and frequent control of the nutrient solution and technical know-how is needed. The management of recirculation must be automated and assisted by a computer. Software compatibility (irrigation, fertigation, climate, recirculation, etc.) is compulsory.

9.8.5.8. Development phase

Commercialised.

9.8.5.9. Who provides the technology

Companies selling fertigation controllers.

9.8.5.10. Patented or not

This system is not patented.

9.8.6. Which technologies are in competition with this one

Hydroponic growing systems like Nutrient Film Technique, which are necessarily closed due to the high irrigation frequency applied.

9.8.7. Is the technology transferable to other crops/climates/cropping systems?

This technology can be applied in any water culture (Deep water culture, Float hydroponics, Nutrient film technique, Deep flow technique) or aeroponics and substrate cultures (gravel, sand, bag or container culture).

9.8.8. Description of the regulatory bottlenecks:

Following the implementation of the Nitrate Directive (Council of the European Communities, 91/676/EEC), many areas in Europe affected by NO_3 pollution have been designed as Nitrate Vulnerable Zones (NVZs). In NVZs an action program is laid down with a number of measures for the purpose of tackling NO_3 loss from agriculture and husbandry.

In the region of Andalusia (Spain), the Decree 36/2008 establishes 20 NVZs from agricultural activities, of which seven are located in greenhouse production areas.

9.8.9. Brief description of the socio-economic bottlenecks

See point 9.7.9.

9.8.10. Techniques resulting from this technology

- Strategies to decrease water drainage and nitrate emission from soilless cultures of greenhouse tomato (Massa et al., 2010): by means of EC modulation and/or short-term nutrient starvation, it is possible to prolong the recirculation of nutrient solution in semi-closed soilless cultivations of greenhouse tomato conducted under saline conditions with the aim to reducing the use of water and fertilisers and minimising N emission with no important effects on fruit yield. The implementation of these procedures is quite simple since EC is routinely measured in soilless cultures and NO_3 concentration could be easily measured by means of quick tests
- Modelling salinity build-up in recirculating nutrient solution culture (Carmassi et al., 2005): this work presents a simple model for the changes in ion concentration and EC of the recirculating nutrient solution in a closed-loop soilless culture of tomato (*Lycopersicon esculentum* Mill.). The model was designed on the basis of a balanced equation for plant nutrient uptake: for macro-cations (K, Mg and Ca), a linear dependence of concentration on crop water uptake was assumed, while for non-essential ions, such as sodium (Na), a non-linear function was used. The model was developed for closed-loop hydroponic systems, in which crop water uptake (namely, transpiration) is compensated by refilling the mixing tank with a complete nutrient solution. In these systems, EC gradually increases as a result of the accumulation of macro-elements and, mainly, of non-essential ions, like Na, for which the apparent uptake concentration is lower than their concentration in the irrigation water. For model calibration, data from both the literature and a previous work were used, while validation was performed with data from original experiments conducted with tomato plants in different seasons and using water with different sodium chloride (NaCl) concentrations (10 and 20 meq/L). The results of validation indicate that the model may be a useful tool for the management of closed-loop hydroponics because it simulates rather well the salt accumulation that occurs in the recirculating nutrient solution when it is prepared with irrigation water of poor quality. Furthermore, the model is able to estimate the amount of crop evapotranspiration that leads to a value of EC at which flushing is necessary, thus enabling the prediction of the water and nitrogen runoff of the semi-closed soilless culture

9.8.11. References for more information

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[5] Stanghellini, C., Kempkes, F., Pardossi, A. & Incrocci, L. (2005). Closed water loop in greenhouses: effect of water quality and value of produce. *Acta Horticulturae*, *691*, 233-241

9.9. Nutrient Film Technique

(Authors: Elise Vandewoestijne[17], Els Berckmoes[21], Elisa Suárez-Rey[11])

9.9.1. Used for

- Preparation of irrigation water
- More efficient use of water and fertilisers
- Minimising the impact on the environment by nutrient discharge

9.9.2. Region

All EU regions.

9.9.3. Crop(s) in which it is used

- Leafy vegetables
- Small root vegetables (e.g. beet)
- Herbs
- Strawberries
- Fruiting vegetables (however in a small amount)
- Tomatoes (research phase)

9.9.4. Cropping type

Soilless crops under protected conditions and open air.

9.9.5. Description of the technology

9.9.5.1. Purpose/aim of the technology

Nutrient Film Technique (NFT) is a type of hydroponic system which supplies water, oxygen and nutrients to the plants.

9.9.5.2. Working Principle of operation

A shallow stream of water containing all the dissolved nutrients which are necessary for plant growth is recirculated through the crop roots in a watertight channel. The right channel slope, flow rate and channel length allow for an ideal thickness of the “nutrient film” which in turn results in the root mat being exposed to water, oxygen and nutrients. The three base requirements for healthy plant growth are in this manner met simultaneously and continuously.

Figure 9-10 shows the basic components of an NFT system. The bottom blue-coloured reservoir contains the nutrient solution which has the right amount of nutrients, pH- and EC-value. This solution is then pumped to that side of the NFT channel of the highest altitude. By pressure and gravitational force, the nutrient-rich water flows from the top to the bottom and flows aside from the plant roots of the crops in the channel. Naturally, plants that are put in this channel should have sufficient root development and exposure to allow for nutrient and water uptake.

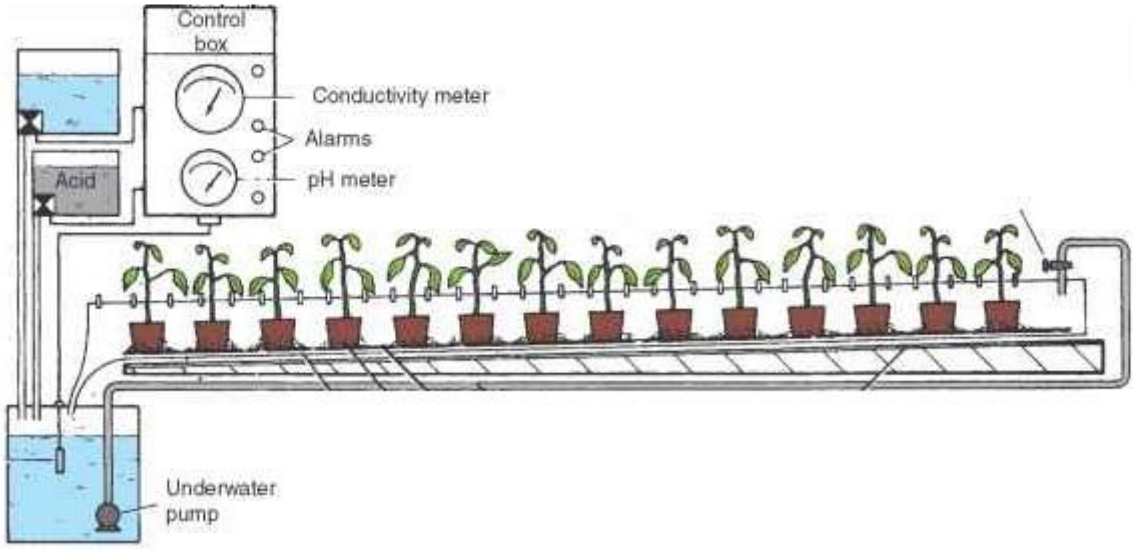

Figure 9-10. Example scheme of a nutrient film technique setup (https://biocyclopedia.com/index/principles_of_horticulture/hydroponics.php)

At the end of the channel, the remaining water, also called “drain”, is collected and sent back to the nutrient solution reservoir. Generally, horticultural businesses send the collected drain first to a screen or sand filter to get rid of floating dirt particles whenever the substrate in which the crops are planted contains soil, e.g. lettuce in peat pots. Depending on the crop type, that drain is sent over another system. In case of lettuce, the drain is generally sent over an activated charcoal filter in order to remove root exudates. In case of tomatoes, a UV-equipment is used to get rid of bacteria, spores or viruses. However, many technologies exist to allow for both the physical and biological filtration of the drain water.

Of course, the collected drain water is depleted in nutrients and therefore does not allow ideal plant growth anymore. Thus, fresh water (usually rain or groundwater) in combination with nutrients is supplied to the drain water once it passed the filtration. These nutrients generally come from a concentrated nutrient solution which is prepared based on a recipe suitable for the crop. The difference in harvestable parts of the commonly grown horticultural crops translates to different crop needs and, as such, different nutrient needs.

In order to finally prepare a nutrient solution which has the ideal composition, EC and pH must be checked and regulated by a control unit during nutrient and water addition to the drain water. From this point onwards, the cycle starts again.

9.9.5.3. Operational conditions

- Limits: flow rate must be ± 1 L/min
- Scale:
    - Channel slope: ideally 1:100
    - Channel length: should not exceed 10-15 m. The length of the gutter is limited for different reasons:

  - A slope of at least 1% must be maintained
  - The nutrient solution must be ideal for all plants in the gutter: the water temperature increases and the oxygen level decreases as the water flows through the gutters (especially in summertime)
  - The nutrient composition must stay optimal for all plants
- Capacity: the overall capacity depends on the crop, regarding planting density, but can be increased by adopting vertical installations

9.9.5.4. Cost data

Installation

It costs around 100 €/m² for a mobile gully system for lettuce and herbs (dating from 2003). It is 230 €/m² for an all-in system including greenhouse, lights and mobile gully system.

Maintenance

- Replacement of plastic connection parts/closing caps
- Cleaning water and products for re-use of channels
- Pumps, electronics and possibly chains (in automatic systems)

9.9.5.5. Technological bottlenecks

- Shutdown of the nutrient pumps
- Disconnecting/plugging of the drip tube/tap is detrimental
- The greenhouses are divided into different bigger water sections. Each section can have its own water regime. In case some gutters need a special water regime, the gutters have to be translocated manually. For example, in case *Phytium* infections occur in the Mobile gully system of lettuce, the gutters have to be moved manually if the grower wants to cut off them from the water supply
- The temperature of the nutrient solution increases when it flows through the gutters. This leads to lower oxygen concentrations. This can be solved by using a new type of gutters, for example, the gutter of Horti Technology

9.9.5.6. Benefit for the grower

Advantages

- Allows working ergonomically
- Great automation potential
- Saves on water, nutrients and crop protection products
- More efficient use of space, making artificial light economically feasible
- Higher profitability

Disadvantages

- Water infections are easily spread all over the system if the sterilisation protocol fails
- Highly susceptible to any breakage of the water flow system

9.9.5.7. Supporting systems needed

The gutters require a physical support that takes care of the slope to allow for a gravitational movement of the nutrient solution past the roots of all the plants in a channel. Depending on the desired degree of automation, frameworks and motorised or robotic handling of the channels are also required.

9.9.5.8. Development phase

Commercialised.

9.9.5.9. Who provides the technology

Horticultural fertigation technology suppliers: HortiPlan, New Growing System (NGS).

9.9.5.10. Patented or not

No, however, there are patented versions of the technique, e.g. the mobile gully system of HortiPlan.

9.9.6. Which technologies are in competition with this one

Other types of semi-closed hydroponic systems: deep flow technique, ebb and flood system and aeroponics.

9.9.7. Is the technology transferable to other crops/climates/cropping systems?

Because of its soilless character and great flexibility, the technology has a realistic potential to be implemented by horticulturists all over the world, in warmer climates possibly outdoors, while in colder climates preferably covered. However, other supporting systems might be necessary in those cases (more organic material in the drain when applying this technique outdoors, faster evaporation in case of direct sunlight, etc.). The value has already been proven, however, the technology might be further transformed into a suitable system for other vegetables and fruits.

9.9.8. Description of the regulatory bottlenecks

As a recirculating system, this technology is in line with the Water Framework Directive (2000) (http://ec.europa.eu/environment/water/water-framework/index_en.html) and the Groundwater Directive (2006) (http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02006L0118-20140711)

9.9.9. Brief description of the socio-economic bottlenecks

The main bottleneck of this technique is the heavy financial investment which is required to install a professional, automatic NFT system. However, low-cost versions of NFT do exist and are already used by small-scale growers across the world.

9.9.10. Techniques resulting from this technology

- Mobile Gully System by HortiPlan: the channels with the plants are moved automatically from the planting site to the harvest site. Each cultivation phase is characterised by an optimal plant density as the space between the gullies increases as the plants become more mature. In the initial phase, plants are transplanted to the gutters at a density of 40 plants/m². As the plants grow, the distance between the gutters increases. In this way, the plant density decreases to 14 plants/m². The mobile gully system allows already a high level of automation. For example, the transplanting from the plants on plastic crates to the gutters can be carried out automatically (Figure 9-11)

Figure 9-11. Automatic transplantation of lettuce from plastic crates to the gutters (Source: Isabel Vandevelde)

Figure 9-12. The nutrient solution flows in the gutters through small tubes (Source: Els Berckmoes)

- FarmFlex Container by Urban Crops: a 12m climate controlled freight container with a leafy green growing rack setup. This system allows for a fully automatic 4-layer growing solution and is as such an example of a vertical NFT system

Figure 9-13. FarmFlex Container (https://urbancropsolutions.com/farm-systems/farm-flex/)

- Horti construct: this system is based on fixed gutters. The innovative part lies in the construction of these gutters as they consist of 3 canals (a nutrient solution canal, a plant canal and a drain canal (Figure 9-14). The fresh nutrient solution is transported through the nutrient solution canal, directly to the plant. The nutrient solution is transported to the plant substrate by use of a sheet. The excess of nutrient solution, referred to as drain water, is collected in the drain canal and transported to the drain tanks. This design makes it possible to provide all plants in the gutters with a nutrient solution with a homogeneous composition and optimal oxygen concentration. Only a minor volume of drain is produced, compared to other systems. In this way, the dimension of the filters and disinfection system can be limited

Figure 9-14. Construction of the gutters of Horti construct (http://horti-technology.com/nl/)

- New growing system (NGS): the NGS system is based on flexible plastic bags. These bags are placed in a structure which is placed on a slope, the so-called "steel latticework" (Figure 9-15). New growing system provides different types of bags in order to make sure the roots receive sufficient water (the roots may cause obstacles for the water, leading to water deficiency in the downstream parts of the bags. Due to the separation of different layers, the roots receive sufficient water as the water flows in a new compartment, once it is blocked in the first compartment.

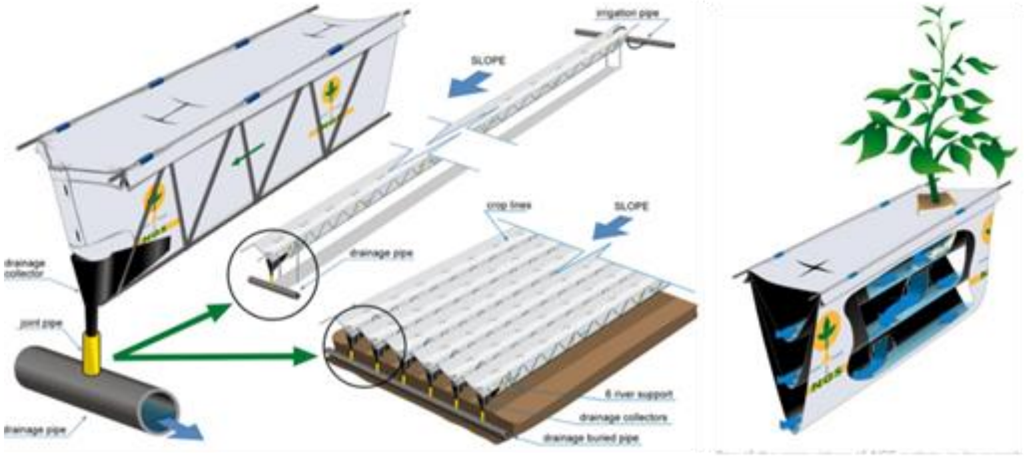

Figure 9-15. New growing system (NGS) (http://ngsystem.com/en/ngs/multibanda)

9.9.11. References for more information

[1] Cooper, A. (2002). *The ABC of NFT, Nutrient Film Technique*. Casper Publications. 171 pages.
[2] http://www.hortiplan.com/nl/mgs/
[3] https://www.urbancrops.be/farm-systems/farm-flex/
[4] http://horti-technology.com/nl/
[5] http://ngsystem.com/en/ngs/multibanda

9.10. Deep Flow Technique

(Authors: Els Berckmoes[21], Elisa Suárez-Rey[11])

9.10.1. Used for

- More efficient use of water and fertilisers
- Minimising the impact on the environment by nutrient discharge

9.10.2. Region

- North-West Europe
- Central-East Europe

9.10.3. Crop(s) in which it is used

Vegetables.

9.10.4. Cropping type

Soilless crops under protected conditions and open air.

9.10.5. Description of the technology

9.10.5.1. Purpose/aim of the technology

The DFT is a modified hydroponic culture method, developed and used in Japan since 1973. It is one of the soilless cropping systems to grow for example lettuce, vegetables, etc. As many soilless growing systems, the DFT system aims to:

- Reduce the environmental impact of growing crops
- Reduce the water and nutrient requirements for production
- Reduce the need for chemical treatments as the soil is no longer a host of pathogens

9.10.5.2. Working Principle of operation

In a DFT system, several young plants are placed on floats, which are placed on a big pond, which contains a continuous water level of 18-30 cm of nutrient solution. The plants are placed in special holes in the floats. The roots of the plants touch the water and retrieve the nutrients directly from the nutrient solution. As the plants grow, the floats are moving from one end of the pond to the other end. The growing process and its related management aspect are explained below.

Figure 9-16. Deep flow installation

Construction

In general, a water level of 18-30 cm is maintained in order to achieve a stable water temperature. Depending on the scale, two DFT systems occur:

- In case of smaller systems, the nutrients are added directly to the water volume in the system
- In case of bigger systems, the nutrient solution is sent to the unit where the nutrient solutions are adjusted to the required composition. From there the nutrient solution is pumped to different water compartments

Generally, a farm has several separated pools. This is done from a preventive point of view in order to minimise the risks whenever a defect occurs (e.g. a human error in preparing the nutrient solutions, an outbreak of a disease, etc.). In order to create a homogeneous nutrient concentration in the water, oxygen is pumped into the water, creating water movement and maintaining oxygen concentration higher than 2,1 ppm.

Floaters for leafy vegetables

At this moment, several types of floaters are available for the DFT systems. The construction of these floaters is of major importance to make crop growing on DFT a success. The floaters differ in the position of the plant or seedling in relation to the water (air chambers, plants per m², etc.). Depending on the type of the floaters, different phases can be distinguished in the DFT-cycle:

- The seedling/nursery phase: some companies, like Botman Hydroponics, offer a floater in order to rear the lettuce seedlings on the DFT system (Figure 9-17). The substrate plug is placed in the specific holder and, in this way, the substrate makes contact with the nutrient solution. Plants are placed at a density of 100 plants/m² (www.teeltdegronduit.nl)

Figure 9-17. Nursery phase of lettuce seedlings on DFT system (www.teeltdegronduit.nl)

- The production phase: when the seedlings have reached the desired size and/or roots are sufficiently developed, they are transplanted to the floats (Figure 9-18), existing two different systems for this second phase: continuous system (1 transplant) and discontinuous system

Figure 9-18. Transplanting the young lettuce plants to the floats (www.teeltdegronduit.nl)

  - Continuous system: in this system, the plants coming from the plant nursery are transplanted to the floats at the end density. For example, in the Viscon system, plants are directly placed at the end density of 20 plants/m². The floats with the young plants are placed at one end of the “water pool”. Each time a new series of floats is transplanted, the previous series moves towards the other end of the “water pool”. By the time the floats arrive at the other end of the pool, the crops are fully grown and the floats are taken out of the water in order to harvest the crop
  - A discontinuous system: an intermediate transplantation occurs. In the first phase, the small plants are placed on the first type of floats. The plant density depends on the substrate dimensions and the provider of the floats (e.g. 48 plants/float or 52 plants/m² for 4 cm peat blocks and 35 plants/float or 42 plants/m² for peat blocks of 5-6 cm. In North-West Europe, the plants are transplanted to new floats with a density of 12 plants per float or 14 plants/m². The floats with the young plants are placed at one end of the “water pool”. Each time a new series of floats is transplanted, the previous

series moves towards the other end of the "water pool". By the time the floats arrive at the other end of the pool the crops are fully grown and the floats are taken out of the water in order to harvest the crop

9.10.5.3. Operational conditions

Not all kinds of crops can be grown on the DFT system. For example, in the case of butterhead lettuce, it is hard to grow crop weights of 450-500 g, which is a Belgian demand. Varieties like Lollo Bionda and Lollo Rossa, which are generally harvested at a weight of 300-500 g/crop, can be grown perfectly on DFT.

Not all varieties that are grown in soil can be grown on DFT. Sometimes very specific varieties have to be selected.

9.10.5.4. Cost data

The installation cost of plates is 12-25 €/m² and that of the DFT pond is 15-20 €/m². The installation cost of the unit, heating, harvesting systems, etc. is 10-15 €/m².

9.10.5.5. Technological bottlenecks

- Need for automation: at this moment the system is still quite labouring consuming (1-2 times transplanting, taking out of the floats, harvesting, etc). Automation is required to make the system economically viable
- Rainwater leads to an unstable nutrient solution: When DFT is applied in outdoor crops, precipitation may lead to serious dilution of the nutrient solution. This can cause serious plant damage (tip burn, interveinal chlorosis, etc.). Botman Hydroponics developed a special float that collects the rainwater falling on the upper part of the float and leads it to the rainwater storage (Figure 9-19)

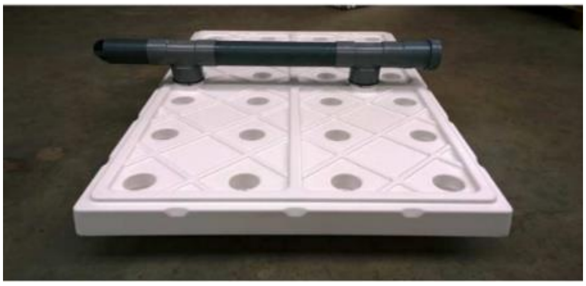
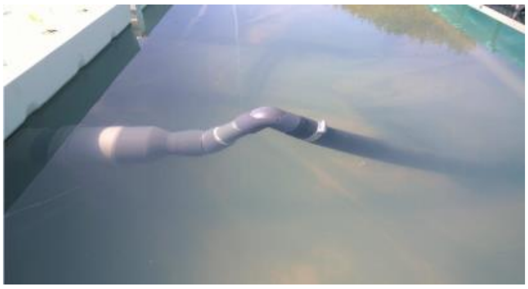

Figure 9-19. Specific float for rainwater collection (left). Connection to the rainwater storage (right) (www.teeltdegronduit.nl)

- Deficits of some nutrient elements, mainly iron and manganese have to be supervised (Blind, 2014)
- Lettuce crops grown on DFT are more sensitive to *Microdochium panattonianum* (Blind, 2014). This disease occurs mainly due to prolonged exposure to raindrops nearby an infection source. The fungus can survive temperatures of -9°C

Figure 9-20. Lettuce crop infested with *Microdochium panattonianum* (Matthijs Blind, 2014)

9.10.5.6. Benefit for the grower

Advantages

- Shorter production cycle compared to soil grown conditions (for lettuce)
- More production cycles per year
- Higher crop density
- Requires less crop protection due to the absence of soil-related pathogens (e.g. *Rhizoctonia* sp.)
- The large water volume acts as a buffer. The fluctuations in nutrients, water temperature, etc. are lower compared to the NFT system
- Water temperature of 14°C is maintained
- Significantly lower investments compared to Mobile Gully System
- Increased yields (see Table 9-1)

Table 9-1. Yield levels of some crops grown on DFT compared to the soil-bound production (De Haan et al., 2013)

	Soil-bound	Deep flow system	Factor	Unit
Leek	65	286	4,4	Tons/ha/year
Head lettuce	163	684	4,2	1000 heads/ha/year
Spinach	52	229	4,4	Tons/ha/year
Cauliflower	21	40	1,9	1000 heads/ha/year

Disadvantages

- Due to the enormous water volumes:
  - One mistake in e.g. the nutrient solution can cause enormous damage.
  - The system does not allow the grower to experiment. Growers often do not take the risk to test new
- Lower crop weights (butterhead lettuce)

- Production significantly decreases after 1,5-2 years and the water should be refreshed. This means that often serious amounts of nutrient-rich water have to be discharged
- Labour intensive (generally 2 times of transplanting, harvesting)
- Algae bloom in the system (when floats are removed)

9.10.5.7. Supporting systems needed

Automatic spray boom, nutrient unit, oxygen dispersion system in the water body, harvesting system, cleaning system for the drivers, etc.

9.10.5.8. Development phase

- Field tests: at this moment different types of crops are screened for their possibilities to be grown on the DFT system (e.g. leek)
- Commercialised: for lettuce crops (e.g. 2,75 ha in Flanders)

9.10.5.9. Who provides the technology

Different companies provide the system.

9.10.5.10. Patented or not

- The floats are patented, not the system
- Planting and harvesting machines are patented

9.10.6. Which technologies are in competition with this one

Mobile gully system.

9.10.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, at this moment the possibilities to grow for example leek on DFT are being investigated. Since in many of the European Member States the use of chemical products to disinfect the soil is under serious pressure, the interest to switch traditionally soil bound crops to cheaper soilless cropping systems is increasing.

Additionally, costumers demand food with fewer residues. Also for this, the interest in these kinds of soilless systems has significantly increased.

9.10.8. Description of the regulatory bottlenecks

Currently, growers are struggling to achieve good status under the current European Water and Nutrient legislation. In countries like the Netherlands, Germany, Belgium, etc. growers of soil-bound crops are forced to reduce their use of fertilisers in order to meet the national or regional criteria for N residues in the soil. As these criteria are sharpened year after year, growers are searching for alternative soilless growing systems.

On the other hand, growers that already made the shift to soilless growing systems like DFT are looking for ways to discharge the nutrient discharge as it is not allowed to discharge nutrient wastewater (NO_3 content above 50 mg/L) in surface waters. This water should be spread on grassland or should be purified (removal of nutrients). Seen the volume of this nutrient water stream, spreading on grassland is not feasible. Growers do not have sufficient grassland available. At this moment there are no technologies offered to remove nutrients from the large amounts of discharge water that are produced once every 1,5-2 years.

9.10.9. Brief description of the socio-economic bottlenecks

Growers are afraid to apply and test new technologies or products as they see it as a risk for their crops. If something goes wrong, it will affect a serious part of their production.

Costumers demand vegetables with no or only very low residues of pesticides. This trend forces growers to search for other growing systems in order to meet the demand of the market. More and more growers are looking at soilless growing systems.

However, even if the growers switch to soilless cropping systems, the market is not always willing to pay the additional cost for this.

9.10.10. Techniques resulting from this technology

- "Cultivation system" provides specific floats for lettuce and vegetable crops that have an air chamber between the substrate and the nutrient solution (Figure 9-21)

Figure 9-21. Cultivation system with specific floats having an air chamber between the substrate and the nutrient solution

- "Viscon" provides a system where plants can be positioned directly at the end density (Figure 9-22)

Figure 9-22. Viscon system where plants can be positioned directly at the end density

9.10.11. References for more information

[1] Blind, M. (2014). Research results for crops grown on DFT. Presentation during symposium Hydroponics 24th of September 2014, Zwaagdijk, the Netherlands

[2] De Haan, J., van Dijk, S., Spruijt, J., Blind, M. & Breukers, A. (2013). Soilless cropping systems for outdoor vegetable production. Presentation at Nutrihort, 17th of September 2013, Ghent, Belgium. Retrieved from http://www.teeltdegronduit.nl/upload_mm/b/4/1/a760dc97-8be7-4ac9-bc9c-b50bfb50b432_25.%20Soilless%20cultivation%20systems%20presentation%20Nutrihort%2017-09-13.pdf

[3] Goto, E. (1996). Effect of dissolved oxygen concentration on lettuce growth in floating hydroponics. *Acta Horticulturae*, *440*, 205-210

[4] Tesi, R., Lenzi, A. & Lombardi, P. (2003). Effect of salinity and oxygen level on lettuce grown in a floating system. *Acta Horticulturae*, *609*, 383-387

[5] Vandevelde, I. (2014). New technologies for growing lettuce. Presentation during symposium Salads in (r)evolution, 18th of September 2014

[6] http://www.teeltdegronduit.nl/upload_mm/3/6/1/ae02317b-d436-4db5-9b63-8ff39a5cbdf2_Presentatie%20Botman%20Hydroponics%20Nederland.pdf)

9.11. Ebb and flow (Flood-and-Drain) system

(Authors: Ilse Delcour[19], Els Berckmoes[21], Elisa Suárez –Rey[11])

9.11.1. Used for

- More efficient use of water and fertilisers
- Minimising the impact on the environment by nutrient discharge

9.11.2. Region

All EU regions.

9.11.3. Crop(s) in which it is used

- Protected potted plants
- Tomatoes, peppers, ornamentals, herbs

9.11.4. Cropping type

Soilless crops under protected conditions.

9.11.5. Description of the technology

9.11.5.1. Purpose/aim of the technology

To maximize the availability of oxygen for the roots and to saturate the medium with nutrients and water. This technique reduces labour and it is suitable for recirculating water and nutrients.

9.11.5.2. Working Principle of operation

Ebb and flow is an irrigation technique that alternately floods the plant-growing area and then allows the water to ebb away. The system consists of a shallow moulded plastic bench top or concrete floor which is flooded up to 5 cm depth, then all the drainage water is returned to a storage tank or reservoir before being cleaned and recirculated. Ebb and flood systems can be built as an integrated part of the floor of the glasshouse, be installed as trays on the floor or as trays on benches.

The irrigation flooding the area contains a nutrient solution. When the area floods, the plant pot is filled with a nutrient solution from the bottom. As the nutrient solution rises in the pot by capillary flow, it forces the air out and saturates the growing media. When the nutrient solution drains from the pot, fresh air is pulled back into the growing media enriching it with oxygen, which is vital for healthy root growth.

Most water is absorbed within the first five minutes of ebb and flood irrigation. Frequent flooding and draining of the pot should occur in order to irrigate sufficiently and to optimise the available oxygen in the root zone. Flooding frequently for five minutes at a time is enough to supply enough water and nutrients.

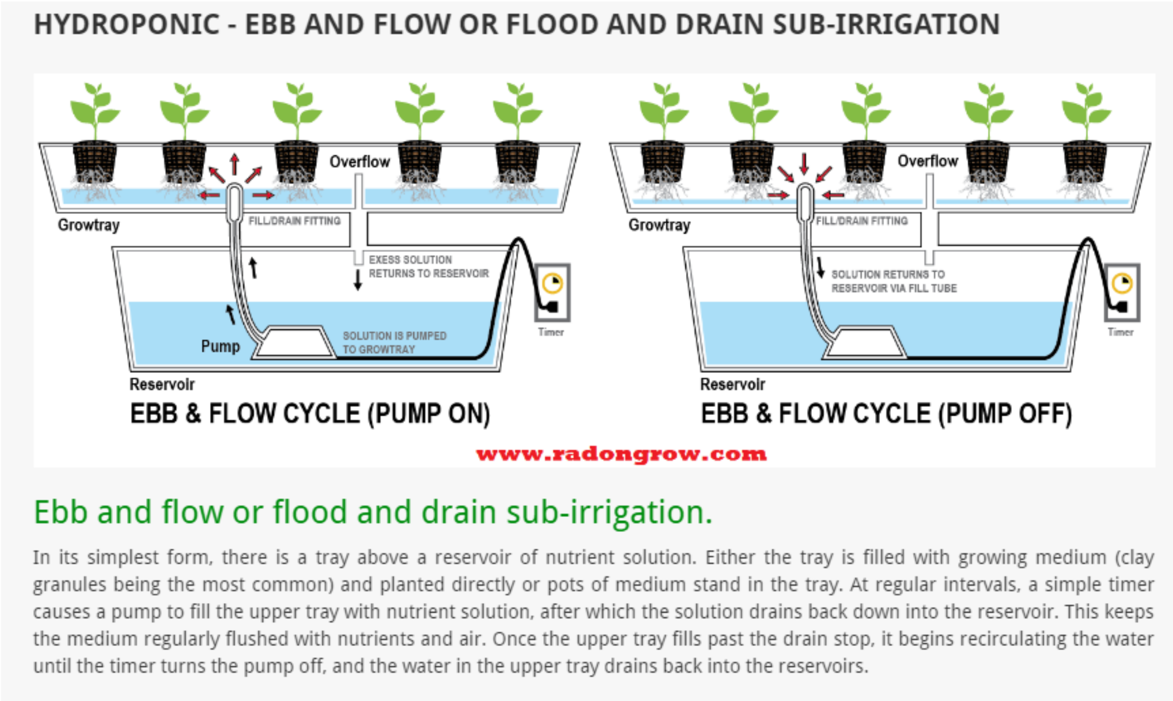

Figure 9-23. Ebb and flow or flood and drain sub-irrigation system (www.radongrow.com)

Figure 9-24. Different commercial Ebb and flow systems (https://www.growell.co.uk/blog/2014/03/optimising-the-iws-flood-and-drain-system; https://www.maximumyield.com/ebb-and-flow-hydroponic-systems/2/1192)

9.11.5.3. Operational conditions

Not all varieties that are grown in soil can be grown on Ebb and flow system. Sometimes very specific varieties have to be selected. Good results can be achieved with many different media and mixes but the key features are the following:

- Low-to-medium water holding capacity
- High air-filled porosity

A growing medium ideal for flood and drain (without the need for anything to be added or mixed in) is lightweight expanded clay aggregates, whose porous structure absorbs and releases nutrient solution over time and can be flooded frequently with a low risk of over-watering, helping to keep the root zone full of oxygen and fresh nutrients.

To get the best possible results from the Flood and Drain system you must endeavour to get the flood cycle right. It is made up of three elements:

- Flood frequency: this is how often you flood the pot, which largely depends on the type of growing medium being used and how well the plants are established
- Flood height: this is how high the water goes up each pot. Generally, we suggest that you always flood to the maximum height
- Flood duration: this is the total time of each flood and will depend on the number of pots your systems has and the choice of growing medium

All elements play an important role in the irrigation strategy, requiring you to be very precise with your decisions for the settings.

It is also possible to install pot filters that screw onto the inside of the outer pot and prevent roots from growing into the pipes.

9.11.5.4. Cost data

Installation

The specific system shown in Figure 9-25 costs about 640 €, depending on the number and size of the pots.

Figure 9-25. MultiPod System (http://www.1-hydroponics.co.uk/hydroponic-systems/flood-and-drain-systems)

A modern flood and flow table, including draining tubes and pump, costs about 80-85 €/m².

9.11.5.5. Technological bottlenecks

In case of concrete ebb and flood systems, small cracks can occur. When the floor is flooded, the nutrient solution flows through these cracks and saturates the soil beneath. In the case of companies with bigger surfaces, this can lead to serious environmental problems.

If problems occur with the nutrient solution, big volumes have to be discharged.

Some plant nurseries complain of nitrite accumulation leading to plant growth problems.

9.11.5.6. Benefit for the grower

Advantages

- Not labour intensive
- More uniform plants, possibly due to a more even and complete moistening of the substrate

- Excellent aeration and supplementary nitrification
- Less fertiliser is required
- No leaching
- No groundwater pollution as all the drainage is recirculated (where no cracks occur. Table systems are more reliable)
- Flexibility as plants can be spaced as needed
- Plants can be put in any growing medium (soil, clay, coir or mapito) and there is flexibility as to whether you grow in pots or in the flood tray over clay pebbles
- Fewer diseases due to lower humidity
- Works well with integrated pest management techniques
- Full control over the number of flood periods benefits your plants by giving them doses of food and water throughout the day

Disadvantages

- Fluctuating water level in fish or sump tank
- Requires a larger sump tank
- Need for adjustments and maintenance of auto-syphons
- Higher likelihood of pump failure due to continuous starting and stopping
- The nutrient strength and irrigation must reflect your grow room environment
- Roots growing out of the pot can block the pipework
- Over time some sediment and/or debris may collect in the reservoir or brain pot
- The pump can get air locked or blocked
- The anti-syphon valve in the reservoir can get submerged or blocked

9.11.5.7. Supporting systems needed

Pump drains, disinfection system.

9.11.5.8. Development phase

Commercialised: a mainstream technique for irrigation of potted plants.

9.11.5.9. Who provides the technology

Different companies that build greenhouses.

9.11.5.10. Patented or not

Yes (US patents).

9.11.6. Which technologies are in competition with this one

Drip irrigation and top irrigation.

9.11.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, as long as they consider soilless cropping systems.

9.11.8. Description of the regulatory bottlenecks

As a recirculating system, this technology is in line with the Water Framework and the Groundwater Directives. However, cracks can provoke a serious nutrient enrichment of the environment. For big companies, it can be difficult to make the system completely closed.

9.11.9. Brief description of the socio-economic bottlenecks

The cost of the system is a relevant issue although it is significantly lower than that of a mobile gully system (see 9.9.5.4).

9.11.10. Techniques resulting from this technology

The new Alien® flood and drain hydroponic system consists of a new heavy-duty steel wall mounted control module. The module is a controlled microprocessor, so that there are no moving parts inside, making this the most reliable flood and drain system on the market today. The intelligent module will pause at the maximum flood height for 20 seconds, ensuring an equal water level in all pots. Even if you forget to top up your tank, the system will drain at the end of the cycle even if there is not enough water in the tank to fill the system completely. Some characteristics of the system are:

- No float switches
- Electronic level sensing
- Faster flood + drain times
- Collapsible tanks
- 32 mm pipe + fittings
- Silent operation

9.11.11. References for more information

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[5] https://ag.umass.edu/greenhouse-floriculture/fact-sheets/subirrigation-for-greenhouse-crops
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Chapter 10. Fertigation management – Irrigation

Coordinators: Carlos Campillo[5], Ilse Delcour[19], Miguel Giménez[11], Rodney Thompson[23]

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10.1. Introduction

10.1.1. These techniques concern the issue

- Estimation of irrigation water amount
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge
- Identification of water needs

10.1.2. Regions

All EU regions

It is essential to adopt efficient irrigation management strategies in all regions; however, for an individual region, or even for a given location within a region, the most effective strategies may differ because the conditions are different.

In the Mediterranean region, the limited rainfall and increasing competition for limited water resources increasingly requires the adoption of strategies, techniques and technologies to optimise the water use efficiency of water applied as irrigation.

In other European regions, water scarcity is generally not yet a consistently limiting factor. However, during summer and during droughts, irrigation can be necessary; and competition for, and the increasingly strict control of water resources, is creating increasing pressure to irrigate more efficiently.

10.1.3. Crops in which the problem is relevant

All crops.

10.1.4. Cropping type

All cropping types.

Because of the limited water holding capacity of many substrates and the small root volume of soilless cropping systems, irrigation management for soilless grown crops differs appreciably from that of soil-grown crops. Also, irrigation management of fruit trees differs from that of vegetable crops because of the much larger soil volume with roots. Within a crop type and growing system, there can be appreciable differences in the irrigation requirements particularly regarding frequency.

10.1.5. General description of the issue

There is considerable and increasing societal pressure to use limited water resources efficiently. There is increasing competition from other sectors such as tourism, industry and for domestic use. Additionally, there is increasing pressure to maintain the recreational value and ecosystems services capacities of water resources. Furthermore, environmental problems, associated with badly managed irrigation, such as aquifer depletion, saltwater intrusion into aquifers, nitrate contamination of aquifers etc. are increasingly considered to be unacceptable and are being increasingly controlled by legislation. Consequently, horticultural growers are under growing pressure to use irrigation water as efficiently as possible. The problems and issues associated with irrigation, in relation with minimising environmental, are described more fully in Chapter 1 (Introduction) and are associated to issues described in Chapters 7 and 8 (Fertigation Equipment), and Chapter 11 (Optimal Nutrient Management).

Optimising irrigation at farm level requires providing the right amount of water at the right time to cover the needs of the crop at that moment. Those needs vary with crop development, weather conditions, soil type, and other site specific factors. Poor irrigation management can result in less yield and quality, either due to an excess of water or a lack of water at critical growth stages of the crop.

Knowledge of the water requirements of crop is an initial requirement. Monitoring technologies of the soil or the crop can provide important information to guide irrigation management regarding the timing and amounts of irrigation. Information of both crop water requirements and the use of monitoring technologies can be used to implement irrigation management strategies based on applying controlled periodic crop water deficits.

Growers face major uncertainties when irrigating. Some of these questions are: What is the correct estimation of crop water requirements? What irrigation strategies can be used? How to best monitor crop and/or soil water status? How should the irrigation strategies be adjusted according to plant and soil water status? This chapter describes the techniques and technologies that can help provide growers with answers to these questions.

10.1.5.1 Sub-issue A: Correct estimation of crop water needs

The adoption of a programmed irrigation schedule helps to ensure that the supply of irrigation considers local climatic conditions and crop development stage. Water balance estimations and the calculation of crop evapotranspiration (ETc) are methods used to estimate crop water requirements. Water balance estimations consider calculated ETc and the relevant inputs and outputs of water to a given crop such as changes in soil water, effective precipitation, run-off, drainage etc.

Climatic and crop development parameters influence calculations made using these methods. Consideration of climate is important to adjust crop water requirements in different locations. Growers and advisors can input climatic data from climate sensors installed in fields and greenhouses, from national or regional climate monitoring services, or from weather forecast services.

Calculated ETc is the product of the potential evapotranspiration (ETo) and the crop coefficient (Kc). Potential evapotranspiration is calculated using empirical equations, of which several are in use; the most suitable equation depends on the cropping system and the availability of climatic data. Potential evapotranspiration is a function of the atmospheric demand in a given cropping situation. Crop coefficient values are specific to crop species, growth stage and cropping season. Standardised values can be obtained from tables; specific values for a given crop or location can be calculated from different crop simulation models, and more recently from remote sensing or image analysis technologies.

10.1.5.2 Sub-issue B: Irrigation strategies adapted to different crops

Once crop water requirements have been determined, it is necessary to consider the effect of the irrigation volume on each of the different phenological stages. These data will influence a wide range of decisions that have to be made regarding the management of water required by the crop, the total volume of which may be limited by a restricted local water supply.

Growers can use irrigation scheduling adapted to meeting crop water requirements, or with some crops can adopt a water saving strategy, such as controlled deficit irrigation, where the volume of water supplied is less than the crop water requirements. During certain development stages of some species, particularly of fruit trees, deficit irrigation does not negatively affect production. When correctly managed, the use of controlled water deficits during insensitive growth stages can save appreciable volumes of irrigation water, without reducing yield. It can, in some cases, result in increased fruit quality or earlier fruit production.

Different deficit irrigation strategies are used in different crops, for example, Sustained Deficit Irrigation; Controlled Deficit Irrigation; and Partial Root Drying.

Information on water requirements and irrigation strategies can be used to develop decision support systems (DSSs) which can be used to advise growers on irrigation scheduling.

10.1.5.3 Sub-issue C: Adjusting irrigation to plant and soil water status

In many cases, theoretical irrigation scheduling and irrigation strategies may induce situations of over-irrigation and/or water stress, and consequently reduce water use efficiency.

New technologies applied to irrigation management can help to have irrigation scheduling that is adapted to the requirements of individual crops. Sensors that monitor crop or soil water status provide information on the adequacy of the water supply available to the crop at a given time, by making measurements on plants or in the soil. Soil sensors use direct and indirect methods to determine soil water content. Plant sensors use measurements of parameters related to plant physiology, such as photosynthesis, transpiration, water potential or biomass variations.

10.1.6. Brief description of the socio-economic impact of the issue

Probably the main issue for growers regarding adoption of technologies for improving irrigation management are the costs. Growers may not see the cost of these technologies as a worthwhile investment considering the financial returns that directly result from their use. The economic benefits for growers will most likely be indirect in terms of reduced purchases of water and of fertilisers where fertigation is used.

Another issue influencing the adoption of these technologies by growers will be their attitude and familiarity with information and communication technologies. Many of the technologies for improving irrigation management involve the use of smart technologies such as computers, internet, smart phones, sensors etc. Older and less educated growers are likely to be more resistant to adopt such technologies. However, considerable effort is being made to make tools, using these technologies, as user-friendly and as intuitive as possible.

Reduced water use by horticulture will benefit the local community by making more water available for other uses. Reduced water use resulting from the adoption of new irrigation management technologies would certainly help the image of a local horticultural industry, suggesting that it was modern, efficient and environmentally responsible.

10.1.7. Brief description of the regulations concerning the issue

There are generally no regulatory limitations concerning tools and technologies for irrigation management, besides those concerning the use of neutron probes because they use radioactive material. Because the regulations on the use and transport of neutron probes are so restrictive, and there are numerous alternatives available, there is now very little use of neutron probes in farming practice.

10.1.8. Existing technologies to solve the issue/sub-issues

There are numerous techniques and technologies that can be used to optimise irrigation of horticultural crops. These can be categorised as being in several broad approaches – estimation of irrigation volumes (crop water requirements), irrigation strategies, information tools for irrigation management, plant/crop measurements for irrigation management, measurements in soil for irrigation management, tools for soilless cropping systems, and the use of weather measurement and forecasting. In this chapter, a total of 26 different techniques and technologies are described. Their distribution within the previously-described classes is as follows:

Estimation of irrigation volumes

- Water balance methods
- Irrigation management with soil moisture sensors

Irrigation strategies

- Partial Root Drying
- Deficit irrigation

Plant/crop measurements for irrigation management

- Plant growth balance analysis system
- Thermal Infrared Sensor
- Dendrometers
- Leaf turgor sensor
- Pressure chamber for plant water potential measurement

Measurements in soil for irrigation management

- Neutron probe
- Combined water, EC and temperature sensor
- Auger method
- Wetting Front Detector
- Tensiometers
- Granular Matrix Sensors
- Time Domain Reflectometry
- Capacitance probe
- Digital penetrating radar

Tools for soilless cropping systems

- Slab balances
- Drain sensor
- Demand tray system

Use of weather measurement

- Weather sensors

10.1.9. Issues/sub-issues that cannot be solved currently: bottlenecks

Among the problems that affect the use of existing techniques and technologies are:

- Non-uniformity of soils within the same field
- Lack of irrigation uniformity
- Damage to sensors or technical equipment (robbery or vandalism)
- The difficulty of introducing complex technologies to growers. Some growers will require technical support to install equipment and to interpret data.

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10.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions (TDs).

	Technology	Cost		Required	Weaknesses	Strengths	Limitations
		Installation	Maintenance				
Estimation of irrigation volumes	Water balance methods	2500 €	Yes	Moderate level of computer skills	Time-consuming when real-time climatic data are used Technical support required for management	Good assistance with decision making	Availability of suitable software, climatic data and technical support
	Irrigation management with soil moisture sensors	500-1500 €	120 €	Technical support for sensor installation, determination of SWC thresholds and data interpretation Computer skills	Difficult management of large data sets (short time intervals)	Identification of problems in irrigation management Data collection	Coarse-textured soils
Irrigation strategies	Partial Rootzone Drying (PRD)	Not applicable	Yes	Management skills required Potential increase in labour and irrigation system costs	Reduction of vegetative growth	Potential savings of water and fertilisers	Requires very good control of soil humidity
	Deficit irrigation	Not applicable	No	Identify plant growth stages	Strong technical support needed for implementation	Improves nitrate use efficiency, minimises leaching of nutrients.	Only in regions with limited water availability
Information tools for irrigation management	DSS water requirements	0-2000 €	200 €	Computer skills and technical training	Limited access for growers	Reliability adjusts very well water demands if well calibrated	Normally used by advisors
	Integrated sensor in DSS for irrigation management	See technologies "DSS water requirements" and "Irrigation management with soil moisture sensors"					
	Weather forecast related tools	Generally no cost	No	In-depth knowledge of data acquisition and processing, calibration and evaluation Computer skills	Limited access to these technologies and complexity	Meteorological data available. ETo forecasting allows anticipating irrigation volumes	Not accessible to all growers

	Technology	Cost		Required	Weaknesses	Strengths	Limitations
		Installation	Maintenance				
	Remote sensing	700 €	No	Good command of GIS Computer skills	High expertise in computer use	Easy to detect problems and crop heterogeneity	Some limits in the operational conditions. High cost if images are processed
Plant/crop measurements for irrigation management	Growth analysis system	25000 €	1490 €	Computer skills	Expensive Difficult data interpretation Technical support required No real-time data	Constant monitoring of the crop	Internet 24/7
	Thermal infrared sensor	500-1000 €	Not applicable	Computer skills and technical knowledge	Difficult data interpretation and management	A non-destructive method to determine crop's water content	Thermal cameras are more expensive (10000 to 20000 €) Processed image and crop water status with a cost of 20-30 €/Ha.
	Dendrometers	34-475 €	Not applicable	Moderate level of computer skills Technical support required	Data can be influenced by climate (fog, rain, overcast weather), crop development stage, fruit load and other factors like insects, birds	They are generally reliable, robust, and relatively inexpensive to buy	Absolute SDV values must be normalised to non- limiting soil water conditions In fast-growing plants repositioning of the sensor is required
	Leaf turgor sensor	4150-6200 €	100 €	Moderate level of computer skills Adapt software to specific requirements	Devices need frequent maintenance, repositioning, and calibration	Non-destructive measurement and easy to handle sensor	Growers require assistance to source the instruments It is necessary to have internet access

	Technology	Cost		Required	Weaknesses	Strengths	Limitations
		Installation	Maintenance				
	Pressure chamber for plant water potential measurement	1000-6000 €	No	Technical training required	The time required to monitor checks, interpret measurements, and take agronomic decisions	Valuable information about the crop water status	Reference values are needed for each crop and irrigation strategy
Measurements in soil for irrigation management	Neutron probe	14000 €	3500 €	License and compliance with all regulations concerning use, transport and storage of radioactive sources	Data not instantaneously available Usually provided by irrigation consultants	Provides volumetric water contents and data are easy to interpret	Need to be licensed to use radioactive equipment
	Combined water, EC, and temperature sensor	2660-3220 €	No	Knowledge of electronics Moderate level of computer skills	Each sensor must be calibrated Careful placement of probes in stony soils	Easy use and data interpretation Calibrations available for many soils and growing media	Effect of soil salinity and texture on measurements
	Auger method	50-250 €	No	Nothing relevant	Manual method	Simplicity	In some type of soils, extraction can be difficult
	Wetting front detector	150 for two detectors	Yes	Frequent readings	Hard installation	Very simple and intuitive system. Suitable for farmers without experience with sensors	It should be installed when the soil is dry to avoid excessive compacting The obtained solution is drainage, not soil solution
	Tensiometers	300-3000 €	Yes	Moderate level of computer skills Technical training	Fragile during installation and cultural practices Maintenance required	User-friendly. It indicates well the thresholds in which it is necessary to irrigate for different crops and soils	Coarse soils, good contact between the soil matrix and the ceramic cup is required

	Technology	Cost		Required	Weaknesses	Strengths	Limitations
		Installation	Maintenance				
	Granular matrix sensors	40-200 €	Not relevant	Moderate level of computer skills	The short lifespan of sensors. Maintenance and support required	User-friendly software	Relatively slow responding to soil moisture changes
	Time domain reflectometry	1200-1900 €	40-200 €	High level of computer skills	Technical assessment during the first periods of use and interpretation help needed in many cases	Accurate	Limited applicability in saline soils Good contact is required between soil and probe
Measurements in the soil for irrigation management	Capacitance probe	2000 €	100 €	Technical advice and data logging	Salinity can influence the measurements	Response time is instantaneous	Effect of temperature on moisture measurements should be considered especially in soilless systems
	Digital penetrating radar	15000-20000 €	None	Interpretation of radar grams needs experience	Large and complex, costly, normally used for soil surface Technical support required	Fast High resolution Measurement of large areas overcomes the limitation of point sampling techniques	Large and complex system
Tools for irrigation management in soilless	Slab balances	3600 €	Not applicable	Computer skills (moderate) Technical knowledge of equipment Training	Cannot shift position after installed at the beginning of the season	Real-time monitoring	Accurate information on crop water needs
	Drain sensor	2345 €	No	Moderate level of computer skills	Expensive compared to manual measurement High maintenance required	Transferable to all soilless systems with drain collection system	Connection with the controller is required

	Technology	Cost		Required	Weaknesses	Strengths	Limitations
		Installation	Maintenance				
	Demand tray system	800 €	130 €	Connection to a fertigation controller for automatic watering activation	Point measurement of water demand	Simplicity	Does not provide information about the water status of the substrate
Weather Measurement	Weather sensor	2500-6000 €	Yes	Moderated -high level of computer skills	Periodic maintenance and calibration is important to assure reliable results	Prediction of disease and pest outbreaks Automatic weather stations save human labour and enable availability of data from remote areas	Cost

10.3. Water balance methods

(Authors: Marisa Gallardo[23], Jadwiga Treder[12])

10.3.1. Used for

- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.3.2. Region

All EU regions.

10.3.3. Crop(s) in which it is used

- All vegetables
- Fruit trees
- Ornamentals

10.3.4. Cropping type

- Soil-bound
- Protected
- Open air

10.3.5. Description of the technology

10.3.5.1 Purpose/aim of the technology

The water balance is a well-established method used for crop irrigation scheduling. Using this method, users can obtain recommendations of the volume and frequency of irrigation for a given crop in given climatic and soil conditions.

10.3.5.2 Working Principle of operation

The water balance method calculates daily variations of soil water content (SWC) in the root zone as the difference between gains and losses of water. The objective is to maintain the SWC above a threshold value below which the plants experience water stress. The water content is generally expressed in terms of water depth (that is mm of water) of depletion in relation to Field Capacity. The amount of permitted depletion (from Field Capacity), is also known as “permissible depletion” or “allowable depletion”. In the water balance calculation, rainfall and irrigation add water to the root zone. Crop evapotranspiration (ETc) removes water from the root zone, thereby increasing depletion. The daily water balance, expressed as the increment in depletion, at the end of day i, is:

$D_i = D_{i-1} + ETc - NI - Re$

Where D_i and D_{i-1} are the water depletion at the end of days i and i-1, respectively, ETc is the crop evapotranspiration of day i, and NI is the net irrigation and Re the effective rainfall during day i. ETc is estimated from climate and crop data. Re is the amount of rainfall that remains in the root zone after subtracting water lost by percolation and runoff; there are simplified procedures to estimate Re from rainfall data. To initiate the water balance, the

initial depletion can be measured with a sensor. Generally, users start the water balance after heavy rain or following the first irrigation, and assume Field Capacity conditions and an initial depletion of zero.
Each irrigation should be applied shortly before the readily available soil water (RAW) is depleted ($D_i \leq$ RAW) (see Figure 10-1). The RAW is the threshold soil water content below which the amount of soil water is insufficient to meet the evapotranspiration demand and the crop commences to experience water stress. The day when the accumulated water depletion becomes close to RAW, an irrigation is scheduled with a volume equal to the RAW so that the soil is restored to Field Capacity, and consequently, the deficit returns to zero i.e. D_i=0 (Figure 10-1). Other options are to apply an irrigation volume smaller than RAW and increase the irrigation frequency or to apply a larger irrigation volume if leaching of salts from the root zone is required. For more information on the calculation of the different components of the water balance equation, see the FAO56 Manual of the United Nations Food and Agriculture Organisation (http://www.fao.org/docrep/X0490E/X0490E00.htm).
When using high-frequency irrigation systems such as drip irrigation, it is possible to simplify the water balance by ignoring the soil component and assume that the soil is constantly maintained close to Field Capacity. Consequently, the applied volume of a single irrigation is equivalent to the cumulative ETc (or the ETc divided by the application efficiency) for the period between subsequent irrigations. This applies to irrigation scheduling, using the water balance method, with crops grown in soil in Mediterranean greenhouses.

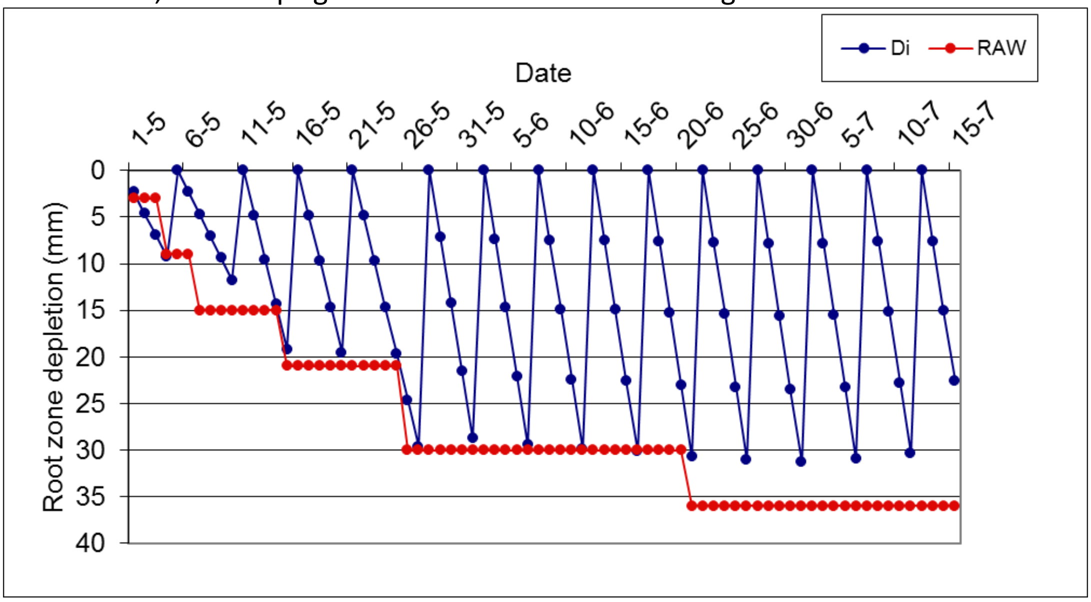

Figure 10-1. Example of the use of the water balance to determine the irrigation schedule of a tomato crop grown in soil. Di is the soil water deficit (in relation to Field Capacity) at day i, and RAW is the amount of Readily Available Water in the root zone of the expected rooting depth. The expected rooting depth increases as the crop grows

10.3.5.3 Operational conditions

The water balance method for irrigation scheduling can be used at a very small scale (e.g. greenhouse), at farm level (several crops in a farm) or for an irrigation district.

10.3.5.4 Cost data

The use of the water balance method requires the use of a personal computer, and internet access to download climatic data. In some cases, such as in greenhouses or when there are no nearby official climate stations, ETc can be calculated from real-time climatic data measured in-situ in the growers' crop or greenhouse; for this, a low-cost meteorological station provided with a logger is required. Generally, the software needed to compute the water balance method is free and provided by local irrigation or extension services. The time required to implement this technique will depend on whether historical (2h/week) or real-time climatic data (4 h/week) are used.

10.3.5.5 Technological bottlenecks

The technical bottlenecks that can influence the adoption of the water balance method are the availability of suitable software to make the calculations of ETc and of the soil water balance, the availability of suitable climatic data for the calculation of ETc, and the availability technical support to assist using the software and implementing the water balance method.

10.3.5.6 Benefit for the grower

Advantages

It provides growers with a tool that assists in making decisions about the volume and timing of irrigation based on the crop demand. It results in reduced water use and reduces the environmental impacts associated with excessive irrigation. Optimal irrigation will also enhance crop performance by avoiding reduced growth associated with deficient and excessive irrigation, and the risks of pathological issues associated with excessive irrigation.

Disadvantages

In case of using real-time climatic data, the time involved in collecting climatic data and inputting them into the irrigation scheduling software; the initial difficulty of learning the system.

10.3.5.7 Supporting systems needed

It is essential that there is a technical support to assist growers to implement the water balance method. It is likely that assistance will initially be required when commencing to use a relevant software package when learning how to download meteorological data from the nearest climatic station or from an on-farm station, and in data interpretation during the cropping season when first using this approach.

10.3.5.8 Development phase

- Research: Research is continually being conducted to developed new DSSs for irrigation scheduling based on the water balance method, adapted to specific crops and systems
- Experimental phase: As with research, applied experimental work is on-going
- Field tests: Field testing is often conducted to adapt the technique to particular crops and cropping systems

- Commercialised: There is software available for irrigation scheduling based on the water balance method at international level and at regional or local level

10.3.5.9 Who provides the technology

At the international scale, the software CROPWAT version 8.0 is provided by FAO (http://www.fao.org/nr/water/infores_databases_cropwat.html). This software has provision to make water balance calculations for many cropping situations.
Commonly, at the local level, the software has been developed to deal with specific cropping situations. For example, in Andalusia (Spain), the regional government offers online advice for irrigation scheduling, using the water balance for olive trees and strawberries.

10.3.5.10 Patented or not

Generally, public authorities freely provide the software and relevant information. While software may be registered, generally, the associated information is publicly available.

10.3.6. Which technologies are in competition with this one

Alternative approaches, to irrigation scheduling with the water balance method, are the use of soil and plant sensors. Soil sensors measure the soil water content or the soil matric potential and can be used to schedule the volume and frequency of irrigation. Alternatively, soil sensors can be used as a complement to the water balance method, to verify the recommendations. Plant sensors that measure the plant water status are still in a research phase and there appears to be little practical application.

10.3.7. Is the technology transferable to other crops/climates/cropping systems?

The use of the water balance method for irrigation scheduling with adaptions can be applicable to all crop types, climates, and cropping regions. The FAO publications of the Irrigation and Drainage Series, No. 56 "Crop Evapotranspiration - Guidelines for computing crop water requirements" contains information about the application of this method for different situations.

10.3.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks at European, country, or regional level.

10.3.9. Brief description of the socio-economic bottlenecks

The socio-economic bottlenecks relate to the time requirement. Time is required to download the climatic data and input them into the software. Additionally, there is the general reticence of growers, particularly older growers to adopt new approaches and to change their habitual ways of doing things.

10.3.10. Techniques resulting from this technology

1) FAO provides the free software CROPWAT 8.0 for irrigation scheduling based on the water balance that can be downloaded at: http://www.fao.org/nr/water/infores_databases_cropwat.html

2) CROPWAT 8.0 for Windows is a computer program for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data and using the water balance method. In addition, the program allows the development of irrigation schedules for different management conditions. CROPWAT 8.0 can also be used to evaluate farmers' irrigation practices and to estimate crop performance under both rain-fed and irrigated conditions. This software can be used in combination with the climatic database CLIMWAT also from FAO which can be downloaded at: http://www.fao.org/nr/water/infores_databases_climwat.html. CLIMWAT 2.0 offers agro climatic data from 5000 meteorological stations worldwide
3) FAO also provided the tool ETo calculator that allows the calculations of reference evapotranspiration using the Penman-Monteith equation.
4) The crop model AQUACROP by FAO (http://www.fao.org/nr/water/aquacrop.html) also has applications for irrigation scheduling using the water balance approach
5) In California, the CropManage is a web application for managing irrigation and nitrogen in lettuce (http://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=8501)
6) In Italy, IRRINET in a web service freely available developed by the CER (a consortium of canal irrigation) that provides irrigation advice for several crops using the water balance.
7) In Spain, the ISS-ITAP (Albacete) is an irrigation scheduling service that was created in 1988 and provides recommendations on 33500 ha, about 30% of the irrigable area
8) In Australia, the IrriSAT is a weather-based irrigation management technology that use remote sensing to provide site-specific crop water management recommendations across large spatial areas

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10.4. Irrigation management with soil moisture sensors

(Authors: María Dolores Fernández[9], Rodney Thompson[23])

10.4.1. Used for

More efficient use of water.

10.4.2. Region

All EU regions.

10.4.3. Crop(s) in which it is used

Irrigated crops.

10.4.4. Cropping type

- Soil-bound
- Protected
- Open air

10.4.5. Description of the technology

10.4.5.1 Purpose/aim of the technology

The use of sensors to monitor soil water status offers the potential to irrigate in accordance with the characteristics of individual crops. Additionally, these sensors offer the potential for a fine degree of crop management such as applying controlled stresses for product quality considerations and accurate control of drainage for salinity management.

10.4.5.2 Working Principle of operation

The most widespread irrigation scheduling method is based on the determination of the soil-water balance, which implies the estimation of a crop's evapotranspiration (ETc). The other approach to irrigation scheduling entails the use of sensors to obtain soil moisture status and to replenish the water in a growing medium to a pre-set level. The use of soil water sensors for irrigation management requires maintaining soil water content within upper and lower limits (Figure 10-2).

The maximum permitted amount of soil moisture is referred to as the Full Point or Upper Limit and is defined as the moisture content at which water movement beyond the root zone drops to an acceptably low rate. The minimum permitted the amount of soil moisture is referred to as the Refill Point or Lower Limit and is defined as the moisture content at which mild drought stress first becomes apparent. The Refill Point identifies when to commence irrigation, and Full Point identifies when to stop; the distance between the two limits indicates the maximum amount that can be applied. Maintaining soil water within this range ensures that the crop maintains an adequate water status and appreciable drainage is avoided.

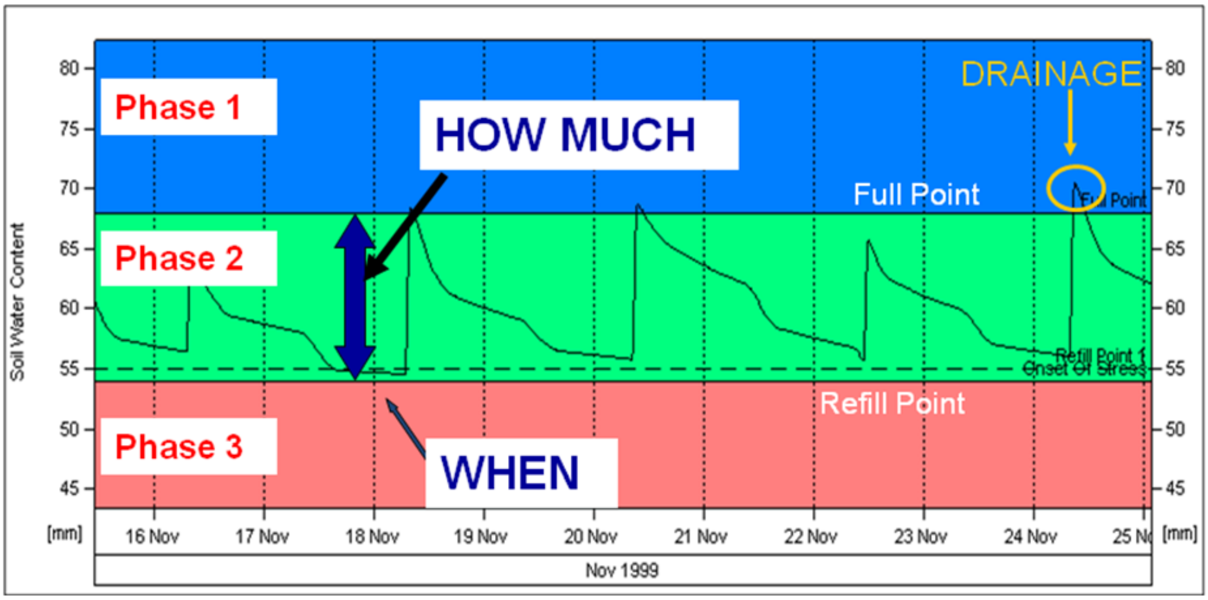

Figure 10-2: The three important phases of soil water for Irrigation scheduling

For practical purposes, the SWC in drying soil can be separated into three distinct phases (Figure 10-2), based on the rate at which the soil water content changes.

In phase 1, the change in volumetric soil water content is relatively fast due to the processes of drainage and evapotranspiration. In phase 2, the rate of change is predominantly due to evapotranspiration and the drainage component has ceased, SWC reduces in a step-like manner with sharp reductions during daylight periods because of crop water uptake and relatively constant SWC during overnight periods when little or no drainage occurs. In this phase, the soil moisture is readily available to the crop. In phase 3, the declining slope of the continuous soil water dynamics changes (Figure 10-3). As soil progressively dries, day-time reductions in SWC get progressively smaller. The daily reduction in SWC is less and is also has a steeper slope because ETc is progressively reduced because there is insufficient readily available soil water to meet crop requirements. Such data indicate to the irrigation manager that there is insufficient readily available water in the soil.

10.4.5.3 Operational conditions

The location of soil sensors and the Full and Refill values for each crop are important when using sensors for irrigation scheduling. The sensor must be located spatially and depth-wise within the maximum concentration of active roots. The depth of the sensor will depend on the rooting depth of the species and soil characteristics. Another sensor can be located at a depth at the bottom of the root zone. This deeper sensor enables the depth of wetting to be controlled ensuring that the full depth of the root zone is adequately wetted and also that drainage is controlled.

The setting of the limits may be done through: 1) using recommended numerical threshold values (Fixed values) or 2) visual interpretation of data. Fixed values are generally suitable for soil matric potential sensors, but they should be used with care with volumetric soil water content sensors. Fixed values or threshold values may not be available and laboratory-determined values may not reflect field conditions. An alternative is the in-situ determination of upper and lower limits based on the interpretation of soil water dynamics.

A suggested approach for defining lower limit SWC values is first to identify the SWC at which ‘‘commencement of stress’’ occurs, and then to select a slightly higher value. The transition from adequate to insufficient soil water supply for crop growth occurs during the progressive reduction in the rate of daily water loss. A decline in SWC in drying soil occurs in two phases: 1) a relatively rapid phase and 2) a subsequent slower phase when soil water is strongly limiting crop water uptake. The transition between the two phases is the “breaking point” and can be used to identify the beginning of crop water stress (Figure 10-3).

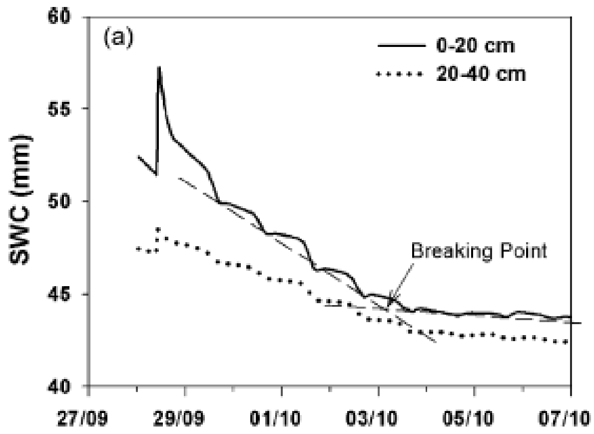

Figure 10-3. Example of estimating the Refill Point. The straight broken lines represent periods of relatively fast and slower soil drying; the intersection between the two is the ‘‘breaking point’’ (Thompson et al., 2007b)

In-situ determination of the upper limit of SWC can be made using the cessation of drainage from the root zone after irrigation or precipitation event; data of drainage beneath the root zone can assist in these assessments.

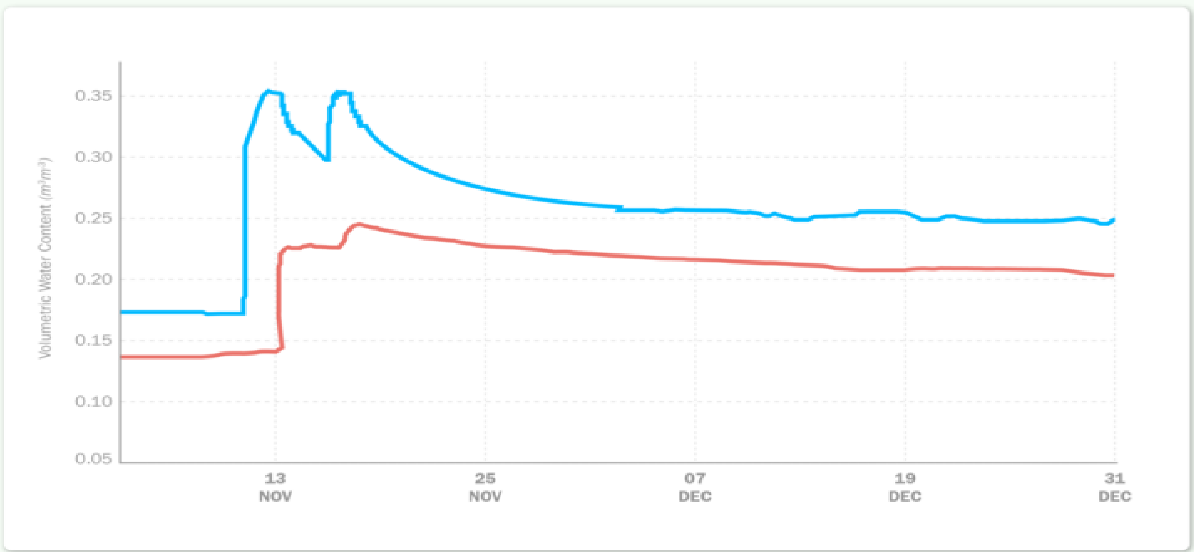

Figure 10-4. Example of Upper Limit or Full Point estimation using soil moisture data (www.decagon.com)

In the example shown in Figure 10-4, Decagon 5TE water content sensors were installed in silt loam at 0,5 m and 1 m in a vineyard. On November 13th and 17th, two significant precipitation events increased the water content at both depths. After the second event on November 17th, it is possible to see the soil water decrease, which is mainly determined by drainage as evapotranspiration is minimal in this period of the year. From the beginning of December, the water content levels stop changing, suggesting that drainage had ceased and that SWC at that time corresponded to the upper limit.

10.4.5.4 Cost data

The cost of the sensors is variable (≈ 100-1000 €). The more sophisticated sensors include a data logger for capturing and transmission of data, and it is also necessary to additionally buy software which handles multiple sensors (400-500 €).

Access to the data logger via mobile requires contracting a mobile phone line and costs approximately 10 €/month. The grower has to view the data daily for decision-making (approx. 0,5 hours/day).

10.4.5.5 Technological bottlenecks

For all sensors, it is essential that the recommended procedures for preparation, installation and maintenance be followed. The user will require technical support and assistance for sensor installation, determination of SWC thresholds (Full and Refill Points) and data interpretation. In addition, he/she must learn how to manage software, download data and communicate with the logger.

Full and Refill values can vary for each point of installation, particularly for volumetric soil water content sensors. In-situ determination of Full and Refill values is often necessary with volumetric soil water content sensors. Where the soil is not very homogeneous, it may be necessary to determine these in-situ for all locations.

The measurements of some capacitance sensors are affected by salinity and changes in salinity. Some sensors have a useful life of less than 4 years.

Sensors and wires can interfere with or be damaged by farm operations.

10.4.5.6 Benefit for the grower

Advantages

- Automated readings
- Changes during short duration events can be observed
- Continuously recorded data from sensors provide a detailed history
- Helps to identify problems in irrigation water management (excessive intervals between irrigations, inadequate wetting, too frequent irrigations, and differences in soil moisture extraction patterns, broken pipes)
- Improved water use efficiency

Disadvantages

- Restricted extrapolation of SWC limits when using volumetric SWC sensors
- Close contact with the soil matrix required
- Large volumes of data are generated
- Difficult data management

10.4.5.7 Supporting systems needed

The use of sensors for irrigation scheduling requires at least, apart from the sensors, a data logger, a computer, and software for information display. It is recommended that climate data such as solar radiation, temperature, wind speed, also be obtained to assist with data interpretation.

10.4.5.8 Development phase

Commercially available: Sensor providers usually supply software for displaying information collected from sensors. Storage and display systems of sensor data in the Cloud are available for users. These systems may allow the incorporation of alarms, limits, comfort zones, predictions, and the possibility of adding indices and models, and information display for different electronic devices.

10.4.5.9 Who provides the technology

There are different companies supplying soil water sensors, such as Sentek (www.sentek.com.au), Delta-T (www.delta-t.co.uk), Decagon Devices (https://www.decagon.com), etc. These companies usually supply the software for information display.

10.4.5.10 Patented or not

Sensors and software are usually patented.

10.4.6. Which technologies are in competition with this one

Irrigation scheduling based on the estimation of crop evapotranspiration. However, both methods can be used together.

10.4.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.4.8. Description of the regulatory bottlenecks

Not applicable.

10.4.9. Brief description of the socio-economic bottlenecks

In general, many growers are interested in this technology; however, they consider that many of the currently available sensors are too expensive. This perception is a barrier to their adoption.

The main obstacles to the adoption of soil moisture technology at farm level appear to be the overall costs of the technology and the lack of effective dissemination and technology transfer activity including grower training. On-going progress in the field of electronics and information technology suggests there will be on-going reductions in prices and a more incorporation of these technologies into intensive horticulture.

For on-farm use, there are several general practical issues to be considered by potential users:

- Training in the use, installation, and maintenance of the sensor system

- Continued support for data interpretation, and use and maintenance of equipment
- Software must be user-friendly and easy to use
- Clear guidelines provided for interpretation of data

10.4.10. Techniques resulting from this technology

Different types of SWC sensors can be used for irrigation management such as time domain reflectometry (TDR) or capacitance sensors. The approaches described for the determination of the soil moisture limits for irrigation management be applied independently of the sensor used.

10.4.11. References for more information

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10.5. Partial Root Drying

(Authors: Eleftheria Stavridou[15], Carlos Campillo[5])

10.5.1. Used for

- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.5.2. Region

All EU regions.

10.5.3. Crop(s) in which it is used

All crops.

10.5.4. Cropping type

All cropping types.

10.5.5. Description of the technology

10.5.5.1 Purpose/aim of the technology

Partial root drying (PRD) is an irrigation technique that aims to:

- Reduce the use of irrigation water
- Control vegetative growth
- Increase the contents of antioxidants in the plant

10.5.5.2 Working Principle of operation

PRD is an irrigation technique by which two different parts of a plant root system are alternated from wet to dry state, so shoots and leaves are simultaneously supplied with water and water stress signalling compounds. PRD is also described in the scientific literature as controlled alternate partial root-zone irrigation and alternate partial root-zone irrigation.

PRD requires that dual dripper lines serve every row of trees or grapevines and that each dripper line can be used independently of the other. To achieve such independence, there must be a duplication of sub-mains and the valves regulating water flow to the sub-mains. Direct measurement of root zone soil water content is required so as to control the duration of irrigation events and the timing of the switch from drying to re-wetting. Soil profiles need to be well monitored to ensure that the alternating wet/dry sides are re-wetted to the full depth (i.e. root depth).

The frequency of wetting will vary with seasonal conditions, but irrigation volumes generally are fixed. The frequency of re-wetting is adjusted according to variation in crop evapotranspiration (ETc) as the cropping season progresses. Reference has already been made to “duty cycles” of drying and re-wetting that range to 10-14 days under mild conditions to 3-5 days under hot conditions.

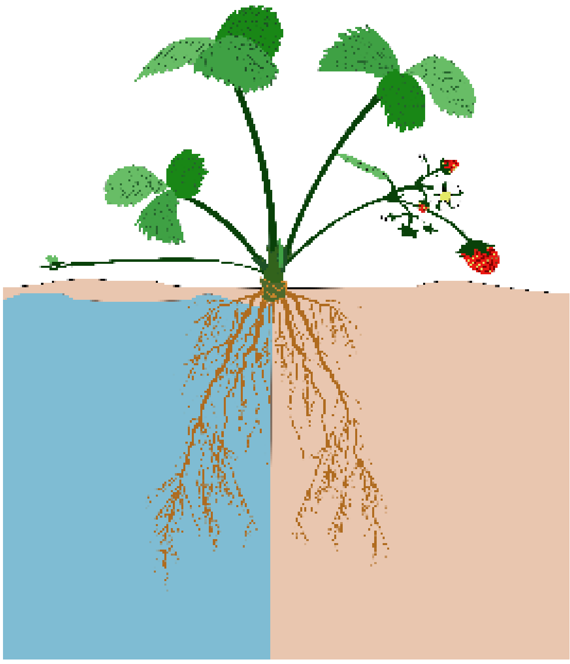

Figure 10-5. Only half of the root system is irrigated (Wet zone). The other half produces signalling compounds (Dry zone) that will be "pushed" towards the shoots when the irrigation is switched to the dry zone (Credit to Mark E. Else)

10.5.5.3 Operational conditions

In strawberry, when supplying 80% of ETc with PRD management, ascorbic and ellagic acid contents, and the total antioxidant capacity increased, whereas yields were maintained. However, when irrigation was 60% of that needed to maintain the soil at full capacity, yields decreased compared fully irrigated plants.

Deep porous sandy loam soils offer best prospects for successful partial root zone drying. Orchards and vineyards that have been established with a drip irrigation system will most likely already have restricted root zones, and are thus more immediately suited to a partial rootzone drying irrigation regime.

10.5.5.4 Cost data

It depends on the irrigation system in use. In the case of drip irrigation, doubling the number of driplines etc., will double the cost of the drip irrigation system.

Managing this technique requires an increased labour input.

10.5.5.5 Technological bottlenecks

Determining the time at which to switch irrigation between dry and wet zones is difficult. The decision on the farm may be based on experience or on soil moisture readings, if available.

10.5.5.6 Benefit for the grower

Advantages

- Increased fruit quality and shelf-life
- Reduction of vegetative growth

- Potential savings in water and possibly fertilisers

Disadvantages

- Potential increase in labour and irrigation system costs
- Challenging management, high management skills required

10.5.5.7 Supporting systems needed

The irrigation system may need to be adapted to facilitate the application of this technology.

10.5.5.8 Development phase

Commercialised: in viticulture and fruit production in Australia, New Zealand, Spain, Israel, the United States, and South Africa. To date, most installations use a second drip line either above or below ground. Several irrigation-equipment manufacturers are working to eliminate the need to install two separate drip lines.

PRD is now an active area of research in various vegetable crops including strawberry, raspberry, basil, coriander, or processing tomato.

10.5.5.9 Who provides the technology

PRD is a management strategy, that is applied by growers, often with the assistance of advisors or consultants.

10.5.5.10 Patented or not

Not patented.

10.5.6. Which technologies are in competition with this one

Other water saving techniques such as regulated deficit irrigation (see relevant technology description in this chapter) or transient deficit irrigation which triggers similar effects on the plant but requires different management.

10.5.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.5.8. Description of the regulatory bottlenecks

There are no relevant directives or regulatory bottlenecks at European, country or regional level.

10.5.9. Brief description of the socio-economic bottlenecks

- Potential increase in labour costs
- Challenging management, high management skills required

10.5.10. Techniques resulting from this technology

Fixed partial root-zone drying is a variation of PRD by which the wet and dry zones are not alternated PRD treatments and can be applied at different levels of stress.

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10.6. Deficit irrigation

(Authors: Jadwiga Treder[12], Carlos Campillo[5])

10.6.1. Used for

More efficient use of water.

10.6.2. Region

Mediterranean.

10.6.3. Crop(s) in which it is used

- Fruit trees and vines
- Vegetables

10.6.4. Cropping type

- Soil-bound
- Protected
- Open air

10.6.5. Description of the technology

10.6.5.1 Purpose/aim of the technology

This is an irrigation strategy that imposes water stress on crops at key stages of vegetative and fruit development to limit water consumption without impacting yield.

10.6.5.2 Working Principle of operation

Deficit Irrigation (DI) is the application of less water than full crop water requirements based on full crop evapotranspiration (ETc). DI is a watering strategy that can be applied to different types of irrigation application methods. The correct application of DI requires a thorough understanding of the yield response to water (crop sensitivity to drought stress) and of the economic impact of reductions in harvest. In DI, the entire root-zone is irrigated (different with partial root irrigation, see Technology 10.4). It's necessary to determine ETc for each crop (generally known for herbaceous crops, but is more complicated for tree crops and vines). For deficit irrigation, there may be two situations. Either the reduction of volume irrigation is compensated by water stored in the soil reservoir or the soil water supply is insufficient, and ETc is reduced because of a limited supply of available soil water.

Two main techniques are based on the knowledge of crops response to water stress: Regulated deficit irrigation (RDI) and partial deficit irrigation also called partial root-zone drying (PRD) where only half of the root system is watered. The mechanism is that roots detect drought and generate abscisic acid, an anti-stress root chemical signal that is transported in the xylem to the shoots. In the shoots, increasing abscisic acid reduces the stomatal opening and transpiration.

In the scientific literature, there is substantial variation in the definition of "water deficit" for agricultural crops. To facilitate analysis and the summary of published research findings, we define water deficit at the following five levels:

1) Severe water deficit: Soil water is less than 50% of the field capacity
2) Moderate water deficit: Soil water is maintained at 50-60% of the field capacity
3) Mild water deficit: Soil water is maintained at 60-70% of the field capacity
4) No deficit or full irrigation: Soil water is generally greater than 70% of the field capacity during the key plant growth period
5) Over-irrigation: The amount of water irrigated may be greater than what plants would require for optimal growth

Stage-based deficit irrigation is defined as RDI applied at different stages of plant development, with water applied to meet full plant evapotranspiration (ET) at the critical growth stages, and with less water applied at non-critical growth stages. The principle behind this approach is that the response of plants to RDI-induced water stress varies with growth stages and that less irrigation applied to plants at non-critical stages does not cause a significant negative impact on crop yield even though it may reduce crop growth. To apply this approach effectively, one must predetermine the critical growth stages for a specific crop species and cultivar and evaluate the relative sensitivity of crop plants to water deficit at various stages in their life cycle.

The application of RDI improves yield per unit of irrigation (yield per unit of irrigation is commonly known as water use efficiency). An increase from 4,9 to 8,0 t/ha has been observed under RDI in peach that yielded 48 t/ha (Figure 10-6). The increase in water use efficiency is largely due to a reduction in transpiration, which can be as much as 50%.

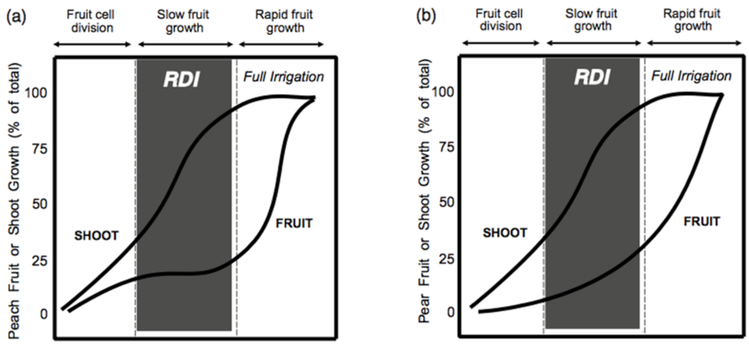

Figure 10-6. Typical shoot and fruit growth pattern for (a) peach and (b) European pear ([Deficit irrigation practices (FAO.org)](#))

10.6.5.3 Operational conditions

Deficit irrigation strategies have been developed for high-density orchards (apple, pear, peach) and to balance vegetative and reproductive growth. Plant tolerance to drought is different at different growth stages. Therefore, deficit irrigation is based on plant growth stages, and full irrigation is applied during establishment and flowering to avoid negative impact on yield potential. To predict the re-irrigation timing, predictive models can be used. Models are based on abscisic acid root production and the simulation of soil-plant-atmosphere water dynamics. However, these models (e.g. DAISY) need to be improved to be used in commercial practice. It is also possible to use Soil Vegetation Atmosphere Transfer models, such as AquaCrop.

DI has been investigated mainly with perennial crops, but some annual crops may also benefit. RDI has been tested in many tree crops and with grape vines with generally good results, particularly with respect to product quality. RDI has been found to control vegetative growth, increase fruiting, advance fruit maturity, and to increase precocity and soluble solids in fruits. The key to successful RDI is good control of all water (irrigation or rain) to limit soil water volumes, which in turn limits vegetative growth. However sufficient water must be available for the entire growing season. Soil water volume control is made possible by two factors, the practical ability to achieve high-frequency irrigation regimes and the capacity to carefully restrict soil water by controlling the amount applied and the size of the wetted volume of soil. In practice, it can be difficult to implement these strategies in many areas because commonly the water savings are mostly early in the season when water is usually most abundant.

10.6.5.4 Cost data

This can be more expensive for PRD because of the cost of doubling the watering installation (see Technology Description of Partial Root Drying).

10.6.5.5 Technological bottlenecks

In a hot and dry environment such as the coastal Mediterranean region, it is not rare to have extremely high temperatures. For vegetables, plants under deficit irrigation are significantly stressed during the short periods of heat waves. In this case, it is necessary to suspend temporary the deficit irrigation and replace by full irrigation. In practice, set up regulated deficit irrigation is difficult because it requires maintaining a plant water status within narrow limits.

10.6.5.6 Benefit for the grower

Advantages

- Save water during irrigation (evapotranspiration losses from the soil and the culture and water losses from the distribution to the land)
- Improve nitrate use efficiency
- Minimise leaching of nutrients
- Improve the fruit quality (increasing the fruit dry weight, total soluble solids, colour intensity, sugar content, total acidity, and total antioxidant contents)

Disadvantages

- Risk of a decrease of the yield of fruits (an increase of non-marketable fruits and small-sized fruits)
- Risk of flower abortion and difficulty with fruit setting
- Risk of an increase in soil salinity
- Cost of double installation for PRD

10.6.5.7 Supporting systems needed

Models are needed to better determine the re-irrigation period. Calibration has been done only for a few soils. Strong technical support is needed to setup the technic.

10.6.5.8 Development phase

- Field tests

- Commercialised

10.6.5.9 Who provides the technology

Not applicable.

10.6.5.10 Patented or not

Not patented, these technics were developed in research centres.

10.6.6. Which technologies are in competition with this one

None.

10.6.7. Is the technology transferable to other crops/climates/cropping systems?

To transfer deficit irrigation, it is recommended to do more studies on different kind of crops in different environmental conditions.

10.6.8. Description of the regulatory bottlenecks

Not applicable.

10.6.9. Brief description of the socio-economic bottlenecks

High risk of potential yield loss. Adapted only for areas suffering from water availability. There is still a lack of data and procedures on determining the optimum timing for irrigation in deficit irrigation.

10.6.10. Techniques resulting from this technology

Partial rootzone irrigation (EU SAFIR Project http://www.safir4eu.org/).

10.6.11. References for more information

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10.7. Decision Support Systems to estimate crop requirements

(Authors: José Miguel de Paz[14], Carlos Campillo[5])

10.7.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.7.2. Region

All EU regions.

10.7.3. Crop(s) in which it is used

- Woody crops
- Annual crops: high economic value crops as vegetables and flowers

10.7.4. Cropping type

All cropping types.

10.7.5. Description of the technology

10.7.5.1 Purpose/aim of the technology

Provide recommendations for irrigation, and in some cases also for nutrient management.

10.7.5.2 Working Principle of operation

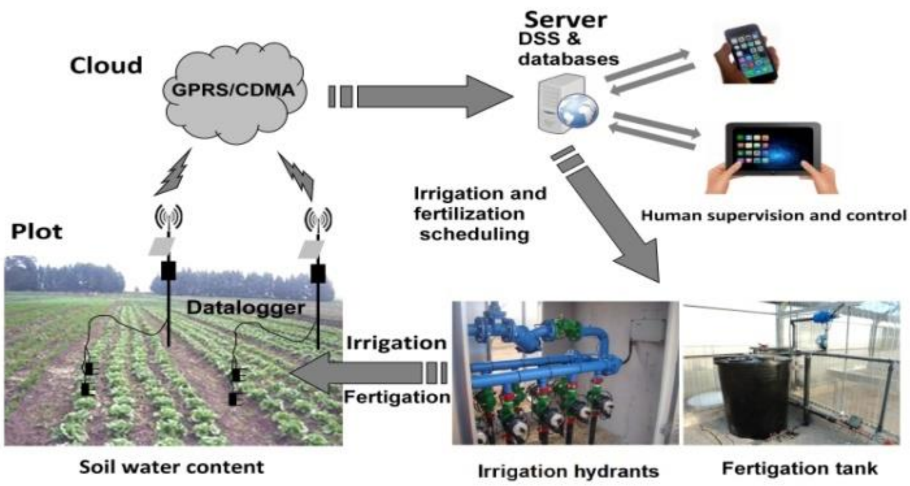

Figure 10-7. Decision Support System scheme (Visconti & de Paz, 2016)

10.7.5.3 Operational conditions

This technology is suitable for irrigation and fertilisation recommendations. Decision Support Systems generally contain simulation models of varying complexity. To obtain more accurate recommendations, these models parameters should be calibrated for local conditions. Sometimes these systems are used by a farmer, and a period of training is required to understand and manage the system. To make them easier to use, many of these systems now work from platforms such as web-systems, smartphones, tablets etc. DSSs are often developed for specific crops in particular conditions, although some generic DSSs have been developed. Those developed for specific conditions should be calibrated and adapted when used in new conditions.

10.7.5.4 Cost data

Most of the DSSs are freely available on the Internet. It just needs a computer or other suitable platform to operate them.

10.7.5.5 Technological bottlenecks

- High costs (money, time) to develop them
- Often not sufficiently user-friendly
- Robustness of software
- Calibration of model parameters
- Often are too complex for farm users
- Training and on-going support required

10.7.5.6 Benefit for the grower

Advantages

- Water savings
- Increase irrigation efficiency
- Reduce nitrate pollution problems
- Help to develop plans for the crop

Disadvantages

- Many require that users are computer literate
- Can be excessively time-consuming
- Requires support in many cases
- Need to be maintained

10.7.5.7 Supporting systems needed

Technical assistance is needed, particularly during the first period of use.

10.7.5.8 Development phase

Commercialised: poor.

Generally, they are developed by research intuitions for local use.

Generic DSSs have been developed by FAO.

10.7.5.9 Who provides the technology

Public institutions and some private initiatives.

10.7.5.10 Patented or not

Unknown.

10.7.6. Which technologies are in competition with this one

Recommendations made by commercials, cooperatives and advisors.

10.7.7. Is the technology transferable to other crops/climates/cropping systems?

Yes. Generally, this technology is welcome in all growing areas, in which the DSS could be adapted to local crops, conditions, soil, climate, crop management etc.

10.7.8. Description of the regulatory bottlenecks

None

10.7.9. Brief description of the socio-economic bottlenecks

A major bottleneck id the user-friendliness of the DSS.

Other bottlenecks are the amount of information to be entered to operate these systems. Complex DSS with high data requirements tend to have few growers using them.

10.7.10. Techniques resulting from this technology

1) VegSyst: Is a DSS for water and N requirements of vegetable crops. More details at: http://www.ual.es/GruposInv/nitrogeno/VegSyst-DSS.shtml
2) SigAgroasesor: Is a Geographic Information System (GIS) platform to optimise crop management specific for each field included in the GIS-PAC. More details at: http://agroasesor.es/en/
3) EU-ROTATE_N. This DSS was developed by several European research groups to provide nitrogen recommendations for vegetable crops. It can also estimate crop irrigation requirements. More details at: http://www2.warwick.ac.uk/fac/sci/lifesci/wcc/research/nutrition/eurotaten/
4) FIGARO: “Flexible and Precision Irrigation Platform to Improve Farm Scale Water Productivity”, is a precision agriculture DSS based on remote sensing and soil sensors measurements to provide significant water and energy savings while leading to increased production and yield. More details at: http://www.figaro-irrigation.net/outputs/the-figaro-platform/en/
5) WATER-BEE: “Smart Irrigation and Water Management system”. This system recommends irrigation management based on soil water content measurements by sensors and crop modelling. http://waterbee.iris.cat/
6) FAO-AQUACROP: AquaCrop is the FAO crop-model to simulate yield response to water of several herbaceous crops. More details and download at: http://www.fao.org/nr/water/aquacrop.html
7) DSS-SALTIRSOIL. This DSS recommend irrigation management depending on the soil salinity and crop tolerance. More details at: www.agrosal.ivia.es or in the article:

8) DSSAT: Decision Support System for Agrotechnology Transfer is a software application program that comprises crop simulation models for over 42 crops. More details at: http://dssat.net/downloads/dssat-v46

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10.8. Integrated sensor in decision support system for irrigation water management

(Authors: Carlos Campillo[5], Dolors Roca[3])

10.8.1. Used for

More efficient use of water.

10.8.2. Region

- Central-East Europe
- Mediterranean

10.8.3. Crop(s) in which it is used

All crops.

10.8.4. Cropping type

All cropping types.

10.8.5. Description of the technology

10.8.5.1 Purpose/aim of the technology

This technology aims to support growers and irrigation manager make decisions about when and how much to irrigate in specific farm conditions, based on estimates of crop growth and water availability measurements of from measurements of soil water and environmental conditions.

10.8.5.2 Working Principle of operation

A DSS is a computer-based information system that supports organisational decision-making activities, typically resulting in ranking, sorting, or choosing from among alternatives. A properly designed DSS is an interactive software-based system intended to help decision makers compile useful information from a combination of raw data, documents, and personal knowledge to identify and solve problems and make decisions.

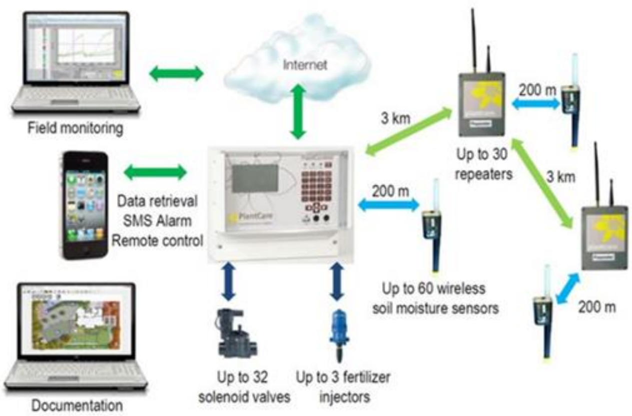

Figure 10-8. Diagram of the inputs and outputs in an integrated support irrigation system

Generally, the DSS incorporated a simulation model. The models are based on the measurement of different sensor types (soil moisture measurement and plant water sensors) that allow real-time corrections to the initial estimation obtained by the model. The system works first with the development and implementation of a crop needs model, calculating the water needs of the crop based on agrometeorological historical data or taken from a nearby agrometeorological station and adjusted with a crop coefficient of each crop, estimated of crop development curves, or measured in the field with digital images.

There are some models that allow the determination of these parameters in a very precise form, allowing the incorporation of water strategies at certain moments of the crop cycle. These systems automatically or manually incorporate values obtained in the field that allow modifications of the irrigation schedules, generated by the water needs model. The model is connected to a series of sensors installed in the field that send the information through a logger to a central computer that analyses the data obtained by eliminating the erroneous or out of range values and providing the model with a certain value. This value is used by the model from a series of algorithms to modify the initial conditions of irrigation and to modify these to adjust the irrigation doses.

10.8.5.3 Operational conditions

It depends on the manufacturer but ranges from one to 60 inputs and 1-35 outputs with or without remote control and access. The system is scalable by adding loggers in numbers dependent on a) the area to cover and b) the maximum distance to the inputs and outputs.

Most of the models that incorporate sensors for decision support can simply provide growers with advice on irrigation, when and how much. More recent models command the head irrigation system and trigger the automatic opening and closing of electrovalves. Threshold set points are assigned to the inputs values (water needs, water contents, etc.). Sensor readings produce a signal that could be opening or closing of the valve. The systems can also incorporate systems for automatically closing the electrovalves from the amount of water that has passed through the flow meter when this is higher than calculated by the system.

10.8.5.4 Cost data

- For installation: 2000 € for the basic equipment plus labour
- Yearly maintenance or inputs needed: 200 €

10.8.5.5 Technological bottlenecks

- Internet access is required
- The instruments need a power source
- Installation and use requires a certain degree of expertise

10.8.5.6 Benefit for the grower

Advantages

- Automated
- Precise water management
- Reduction of irrigation management errors
- Improvement of harvesting in cases of irrigation support
- Reduction of dedication time to schedule and supervise irrigation
- Reliable
- Easy and fast detection of problems
- Better control feels (repeatability, reliability, etc.)

Disadvantages

- Challenging to adapt to certain growing conditions
- Can vary substantially in extensive crops
- Settings must be adapted to varying soil conditions
- Effective water delivery is also dependent on the reliability of the irrigation system: pipes, drippers, sprinkles etc. all must work within manufacturer specification

10.8.5.7 Supporting systems needed

- Internet connection although some systems can work independently
- Some source of electricity: solar panels or batteries that need to be regularly replaced

10.8.5.8 Development phase

Commercialised.

10.8.5.9 Who provides the technology

- Smartfield
- Waterbee system (MAC Ltd. company) http://www.mac.ie/

10.8.5.10 Patented or not

Yes.

10.8.6. Which technologies are in competition with this one

None.

10.8.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, but require specific installation settings and input thresholds.

10.8.8. Description of the regulatory bottlenecks

There are no relevant regulatory bottlenecks for the use of sensors in DSS.

10.8.9. Brief description of the socio-economic bottlenecks

The high cost of the system can hold back growers from using it. It also requires some training to use the software and instruments, which is not very attempting.

10.8.10. Techniques resulting from this technology

Most irrigation strategies can be complemented and controlled by using these devices, such as Controlled Deficit Irrigation, Partial Root Drying, precision irrigation.

Some examples of irrigation modelling and scheduling systems:

The WaterBee system (http://waterbee-da.iris.cat) incorporates a Soil-Moisture Model for optimal water use, continuously self-adapting to each user's situation and business objectives, using machine learning approaches. This system incorporates granular water sensors to determinate when it is necessary to irrigate (Figure 10-9).

Figure 10-9. Waterbee system web (http://waterbee-da.iris.cat)

Another similar case is the DSS Figaro (http://www.figaro-irrigation.net), which allows the integration of sensors with the information provided by the system. FarmConnect software (http://www.rubiconwater.com/catalogue/farmconnect-software-usa) is web-based, connected devices such as soil moisture sensors, weather stations and rain gauges can be remotely monitored.

Most systems use soil moisture sensors to adjust irrigation needs. There are some systems that use plant sensors to establish the water needs of the crop, so the Smartfield™ System (http://www.smartfield.com) has been used in many different environments across the U.S. and many countries around the world. Smartfield™ provides users with many crop monitoring tools and analytical services that allow the user to make better informed and timely management decisions. The Smartfield ™ Base Station is a product that seamlessly collects data from multiple products and bundles the data into one package that is then sent via a cellular network to CropInsight™ for further analysis. The Smartfield™ Base Station also measures ambient temperature, relative humidity, and rainfall. This product is the backbone of the SmartCrop® system which is used to measure infrared canopy temperature in order to determine the stress of a crop (Figure 10-10). These stress calculations have the ability to manage the crop for maximum return on investment.

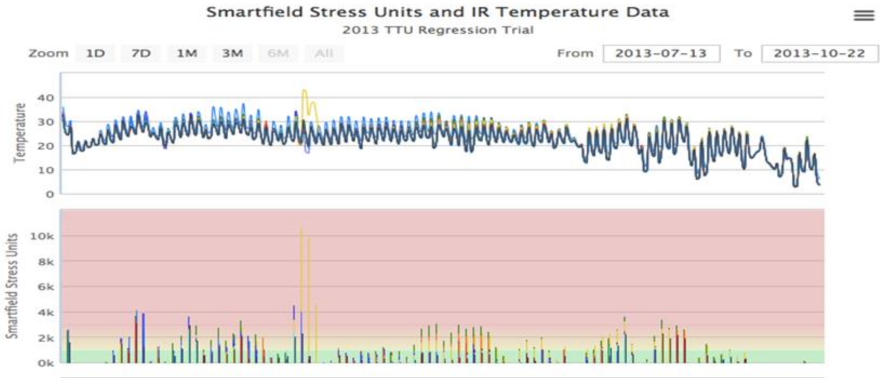

Figure 10-10. SmartCrop system web (http://www.smartfield.com)

Other systems can be developed for specific crops that can integrate different plant measure obtained in the field, for example, the irrigation DSS for processing tomato developed by Campillo and colleagues in 2016, measures the percentage of ground cover (Figure 10-11a) and leaf water potential (Figure 10-11b) are used for crop coefficient adjustment. All information allows the user to do an adjustment to the FAO56 recommendation and water balance (Figure 10-11b).

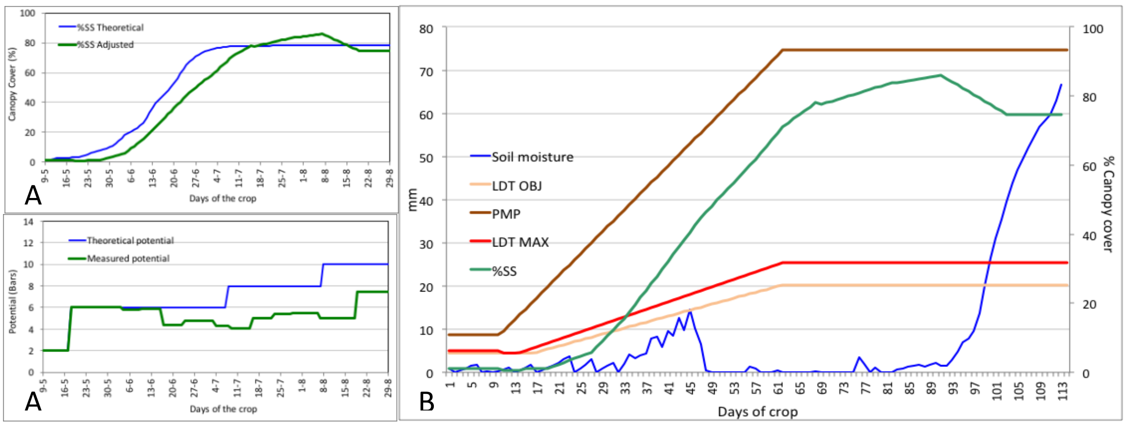

Figure 10-11.Processing tomato water needs a system. Crops parameters measure and estimate (a) and water balance (b)

EFFIDRIP (http://effidrip.eu) is an ICT-based tool for supporting the management and supervision of irrigation and fertigation. It has been conceived for localised irrigation systems in tree crops, although its use could be extended to other scenarios (Figure 10-12). Its overall objective is to offer a cost-effective tool that provides the end-users (farmers or technicians) effortless irrigation and fertilisation help, as well as easy and reliable supervision of the state of the irrigation system. The EFFIDRIP system complements the functionalities of current irrigation and fertigation control equipment by making them part of a higher-level system based on Information and communications technology (ICT).

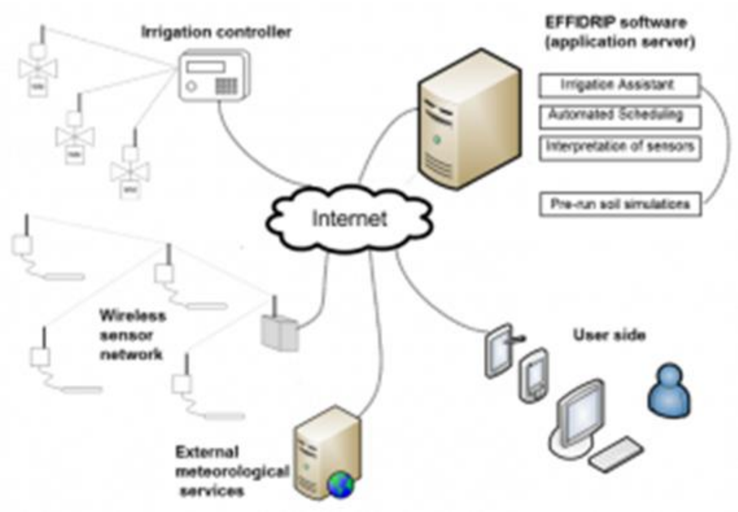

Figure 10-12. EFFIDRIP system (http://effidrip.eu)

The role of that high-level system is the integration of data and information from multiple sources for their usage in automated scheduling decisions and supervision. It can also facilitate user interaction with the system and communication between people involved in the process. The irrigation controller remains as a key component for the execution of irrigation and fertigation schedules with some autonomy. What really makes the difference is that those schedules will be updated remotely once a day for each irrigation sector. For each subsequent application, the precise crop water and fertiliser needs will be estimated as a function of weather conditions, the soil and crop water status assessed by sensors, as well as the productive and environmental goals by the farmer. For this purpose, weather data and sensor measurements are combined in a base of state-of-the-art agronomic knowledge.

The IRRIX system (Figure 10-13) works from collected data through sensors installed in the field that cross with reference meteorological data and available water resources in the plot. With this information, the platform plans the irrigation campaign efficiently and adjusted to each case, without requiring practical dedication by operators. Each day, the system automatically adjusts itself according to the indications of the sensors, within the margins that allow the planning established at the beginning of the campaign. Each day data is collected through sensors and the system adjusts irrigation needs autonomously. The IRRIX web platform for automated irrigation monitoring and control developed by the Institute of Agrifood Research and Technology in Catalonia, Spain (IRTA) will be applied in several areas of Lleida, Badajoz and Almería, in Spain, within a project “Integrating soil water sensors on a seasonal strategy for automated re-scheduling of drip irrigation” funded by the National Institute of Agricultural and Food Research and Technology (INIA) RTA2013-00045-C04.

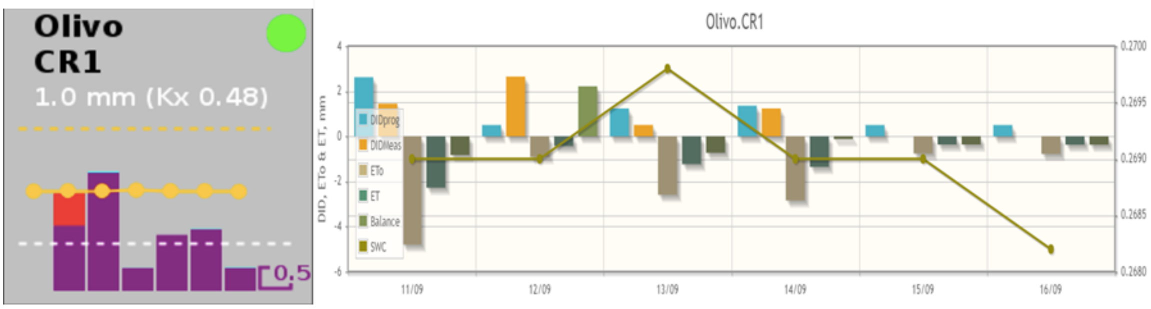

Figure 10-13. IRRIX system irrigation scheduling

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10.9. Weather forecast related tools

(Authors: María Dolores Fernández[9], Carlos Campillo[5])

10.9.1. Used for

More efficient use of water.

10.9.2. Region

All EU regions.

10.9.3. Crop(s) in which it is used

Irrigated crops.

10.9.4. Cropping type

- Soil-bound
- Protected
- Open air

10.9.5. Description of the technology

10.9.5.1 Purpose/aim of the technology

Crop water requirements depend on climatic conditions and crop characteristics (type, development stage, planting distance, etc.) and can be estimated by multiplying the reference evapotranspiration (ETo) by the crop coefficient (Kc) value. ETo forecasting is valuable in planning irrigation or in areas with limited or deficient weather data.

10.9.5.2 Working Principle of operation

ETo varies with weather and is usually estimated using observed weather data from the nearest weather station.

The most widely used method to estimate ETo is the FAO Penman-Monteith equation, which has shown good performance in different climatic zones. This method requires data of solar radiation, temperature, relative humidity, and wind. Networks of agrometeorological stations have been installed in many irrigated areas throughout the world, allowing the measurement of the climatic variables needed for ETo calculation. However, the high cost of these stations and data downloading has limited its expansion; consequently, there are areas where no data is available or where the data do not have the necessary quality to estimate ETo with precision. In these cases, the alternative is the use of expected ETo values.

ETo forecasting procedures can be categorised into direct and indirect methods, depending on the methodology used and the input data. In the direct methods, current and historical data are used to forecast ETo, using time series methods or using artificial or computational neuronal networks, allowing ETo predictions in the medium and long-term. The oldest and simplest way to predict the daily ETo is from average values of a historical series of ETo data. The use of historical values enables irrigation planning for the whole growing season (up to one year) and is an easy tool. However, periods of crop water stress leading to yield reductions may be occasionally induced in a number of years (3 out of 15) when the current climatic conditions determine a crop water demand higher than the corresponding to the mean microclimatic year. For that reason, time series models and artificial or computational neuronal networks have been subsequently developed, enabling better weekly and monthly ETo predictions than the historical average data.

In the indirect method, weather variables needed to calculate ETo are forecasted by numerical weather prediction (NWP). Several public and private institutions provide online daily weather forecast that usually includes numerical daily maximum and minimum air temperatures, wind speed and relative humidity estimations and daily non-numerical forecasts of sky cover. In Europe, the two main consortiums providing daily weather forecast data are HIRLAM and ALADIN. In 2006, both European consortiums collaborated in the development of high-resolution systems (HARMONIE).

10.9.5.3 Operational conditions

Farmers and technical advisors in different parts of the world can obtain free online data of real-time or historical ETo from public advisory services, as well as climatic data measured in agrometeorological stations installed in irrigable areas. The most known public advisory services is the California irrigation management information system, which has served as a model for other services. In Spain, for example, the Agroclimatic Information System for Irrigation (SIAR) is responsible for capturing, recording and reporting the agro-climatic data of 468 stations distributed throughout the country.

Predicted ETo values from NWP are being supplied in the recent years. National Weather Service's, Weather Forecast Offices of USA are providing ETo predictions for that country from 2014 (Figure 10-14).

ETo can be also calculated from NWP provided by National Weather Services. Usually, NWP forecasts numerical daily air temperature, relative humidity and wind speed and daily non-numerical sky cover. However, these variables have to be processed before being used for ETo estimation. Thus, in meteorology wind speed values refer to a standard height of 10 m, so that the wind values provided have to be converted into 2 m (u2; reference for agro-meteorological studies) using the procedure described by Allen et al. (1998):

$$u_2 = u_z \frac{4{,}87}{\ln(67{,}8\ z - 5{,}42)}$$

where u_z is wind speed (m/s) at height z (m) above the ground.

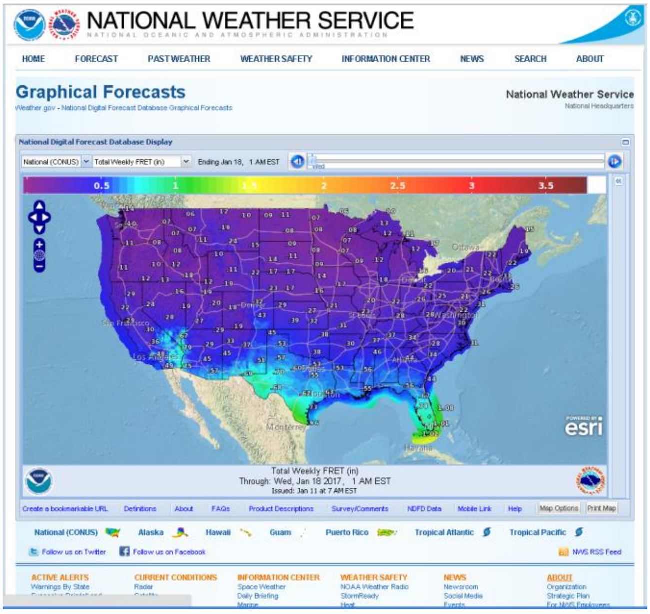


Figure 10-14: ETo forecast provided by National Weather Service in the USA (from http://www.weather.gov/cae/fretinfo.html)

10.9.5.4 Cost data

Growers can download the weather forecast with different electronic devices (PC, Smartphone, tablet, etc.) by consulting internet services of National Weather Agencies.

Access to internet and time are necessary to download weather forecast from services of National Weather Agency. Some companies are providing weather forecast via e-mail or App.

10.9.5.5 Technological bottlenecks

Institutions presently providing ETo forecast are very scarce. However, in many parts of the world, it is possible to obtain estimated climatic data provided by public and private institutions. These data can be used to estimate ETo, but pre-processing of data and calculation of ETo with FAO Penman-Monteith model is complex. Other simpler methods for ETo estimation showing good results in different climatic conditions, such as Hargreaves model, have been proposed.

Forecast performance for weather data and ETo gradually declines with increasing lead time.

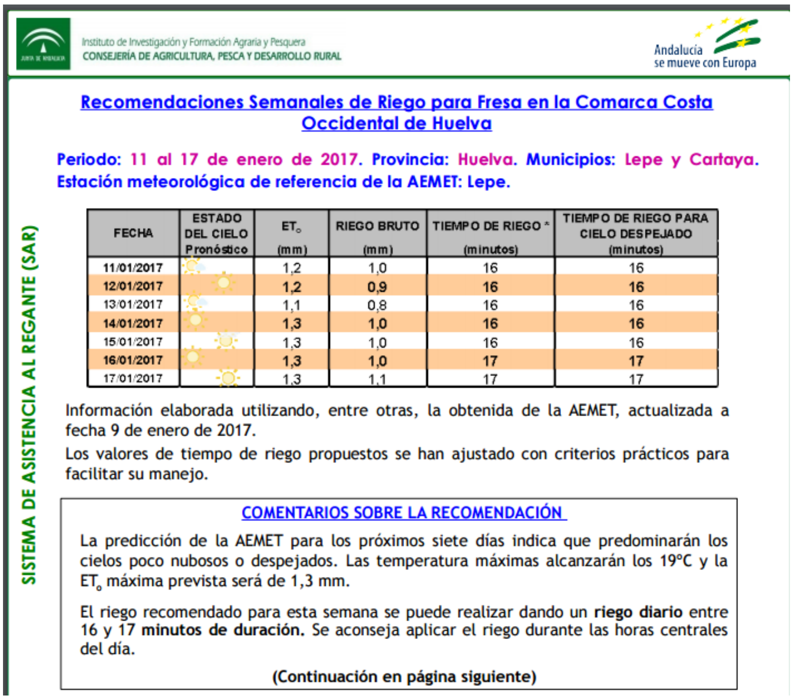
10.9.5.6 Benefit for the grower

Advantages

- Public institutions provide online, mostly free, weather forecasts
- The use of ETo forecast allows anticipating irrigation to water requirements, thus making an efficient use of water and energy
- It is possible to have meteorological data in areas where measured data are not available

Disadvantages

- Not all growers have access to these methodologies
- Requires in-depth knowledge of data acquisition and processing, calibration and evaluation
- NWP provides weather forecasts with a short lead time (1-7 days)
- Forecast performance varies depending on NWP model, lead time, location and climate
- Quantification of ETo forecast using outputs from NWP models has been limited to a small number of studies in certain geographical areas such as United States, Europe, China, Australia and Chile and to relatively short lead times



Instituto de Investigación y Formación Agraria y Pesquera
CONSEJERÍA DE AGRICULTURA, PESCA Y DESARROLLO RURAL

Andalucía se mueve con Europa

SISTEMA DE ASISTENCIA AL REGANTE (SAR)

Recomendaciones Semanales de Riego para Fresa en la Comarca Costa Occidental de Huelva

Periodo: 11 al 17 de enero de 2017. Provincia: Huelva. Municipios: Lepe y Cartaya. Estación meteorológica de referencia de la AEMET: Lepe.

FECHA	ESTADO DEL CIELO Pronóstico	ET_o (mm)	RIEGO BRUTO (mm)	TIEMPO DE RIEGO * (minutos)	TIEMPO DE RIEGO PARA CIELO DESPEJADO (minutos)
11/01/2017		1,2	1,0	16	16
12/01/2017		1,2	0,9	16	16
13/01/2017		1,1	0,8	16	16
14/01/2017		1,3	1,0	16	16
15/01/2017		1,3	1,0	16	16
16/01/2017		1,3	1,0	17	17
17/01/2017		1,3	1,1	17	17

Información elaborada utilizando, entre otras, la obtenida de la AEMET, actualizada a fecha 9 de enero de 2017.
Los valores de tiempo de riego propuestos se han ajustado con criterios prácticos para facilitar su manejo.

COMENTARIOS SOBRE LA RECOMENDACIÓN

La predicción de la AEMET para los próximos siete días indica que predominarán los cielos poco nubosos o despejados. Las temperatura máximas alcanzarán los 19ºC y la ET_o máxima prevista será de 1,3 mm.

El riego recomendado para esta semana se puede realizar dando un **riego diario** entre 16 y 17 **minutos de duración.** Se aconseja aplicar el riego durante las horas centrales del día.

(Continuación en página siguiente)

Figure 10-15: Watering recommendations for strawberry based on weather forecast provided by IFAPA in Andalusia (Spain) (from http://www.juntadeandalucia.es/agriculturaypesca/ifapa/servifapa)

10.9.5.7 Supporting systems needed

Internet access and an electronic device for data capture.

10.9.5.8 Development phase

Applied in some commercial farms but new developments are in progress.

10.9.5.9 Who provides the technology

Public and private institutions supply weather forecasts.

10.9.5.10 Patented or not

No.

10.9.6. Which technologies are in competition with this one

Data of ETo estimated from historical or real-time climatic data.

10.9.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.9.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

10.9.9. Brief description of the socio-economic bottlenecks

The user must have the knowledge, spend time and be persevering to consult or download weather forecasts, perform calculations and vary the irrigation scheduling on a daily basis.

The use of ETo forecast is useful when the irrigation scheduling is carried out in a very short-term (1-3 days). For programming in the medium term, up to 7 days, it must be considered that ETo forecast is less precise than real-time ETo.

10.9.10. Techniques resulting from this technology

There are public institutions giving free available recommendations for irrigation based on weather forecast (California irrigation management information system in the USA (http://www.weather.gov/cae/fretinfo.html), IFAPA in Andalusia (Spain) (http://www.juntadeandalucia.es/agriculturaypesca/ifapa/servifapa))

Irristrat is commercial software (http://www.hidrosoph.com/ES/irristrat.html) able to give such recommendations for different crops.

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10.10. Remote sensing

(Authors: Juan del Castillo[13], Carlos Campillo[5])

10.10.1. Used for

More efficient use of water.

10.10.2. Region

All EU regions.

10.10.3. Crop(s) in which it is used

- All vegetables
- Fruit

10.10.4. Cropping type

- Soil-bound
- Open air

10.10.5. Description of the technology

10.10.5.1 Purpose/aim of the technology

Remote sensing provides information capable of improving the use of water balance, integrated into a DSS to estimate evapotranspiration based on meteorological stations and monitoring and characterisation of actions in plots.

10.10.5.2 Working Principle of operation

Remote sensing uses multispectral vegetation indexes to assist the estimation of plant transpiration through the computation of the basal crop coefficient, both sensitive to plant ground cover fraction. The multispectral vegetation indexes are obtained from remote sensing collected by different platforms: satellite, aircraft or unmanned aerial vehicle (UAV). The main multispectral indexes used in this technology are the Soil Adjusted Vegetation Index (SAVI) and the Normalised Difference Vegetation Index (NDVI).

The advances in the spectral, spatial, and temporal resolution of the remote sensing allow detecting properties of crops related to the growth. The Copernicus program developed by ESA agency provides accurate, timely and easily accessible information about earth observing. The satellite Sentinel-2, with its 13 bands covering the visible to the shortwave infrared spectrum will allow an efficient mapping of vegetation at 10-20 m resolution, suitable for instance for pan-European high-resolution products.

The FAO-56 methodology calculates reference evapotranspiration (ETo) representing the evaporative energy of the atmosphere and a crop coefficient that is related to the state of development of the vegetation. Irrigation management systems in DSS, use dual Kc by separating soil evaporation and plant transpiration, using the evaporation coefficient (Ke) and the basal crop (Kcb), respectively.

DSS use theoretical Kcb curves, depending on the crop and the phenological state. This technology estimates the Kcb of each crop plot from multispectral vegetation index (VI), such as SAVI or NDVI. These data should be compared with the theoretical curve, to provide the farmer with accurate information for correction.

Satellites provide multispectral images due to the reflectance of each crop in incident sunlight (Table 10-1). These images collect information of different wavelengths of the visible and infrared spectrum and are used to calculate vegetative indexes by means of mathematical equations. These indexes correlate well with the relative photosynthetic size of the crop cover and show how vegetative canopy absorbs photosynthetically active solar radiation.

The relationship between vegetation index (SAVI or NDVI) and coverage fraction 1) is used to estimate the Kcb plot level. In each pixel of the plot, a value of fc derived from the image will be calculated and entered the formula of Kcb 2) where the value of the VI will come from a satellite image and the rest of the parameters will be tabulated for each crop.

Table 10-1. Different satellite platforms

Platform	Multispectral resolution (m/pixel)	Frequency images (days)	Minimum image size order	Cost (€/km²)*
Geoeye 1	2,00	3	25 km^2	15,25
*WorldView 3**	1,24	1	25 km^2 2,5 ha	27,87 (0,2788 €/ha 697 €/image)
Pléiades	2,80	1	25 km^2	11,33
Quickbird	2,40	3	25 km^2	15,25
Kompsat 3A	2,20	4	25 km^2	6,97
Sentinel 2A	10,00	3 when Sentinel 2B is available		Free
LANDSAT 7 and 8	20-30	15		Free
UAV	<0,5	According to demand	According to demand	400 €/10-20 ha depending on company and service

10.10.5.3 Operational conditions

Limits:

- Spatial resolution according to the size of the operative irrigation unit
- Uncontrolled conditions in the agricultural plot, or a combination of factors (nutrient deficiency, failures in irrigation equipment, diseases, pests, etc.)
- Factors like clouds, pixel errors, etc. that affect the quantitative values derived from the image
- Temporary resolution not sufficient for decision-making

10.10.5.4 Cost data

It is necessary to differentiate the raw cost of the images from the cost of the final product after manipulated by specialised service companies. These will finally be used by growers.

10.10.5.5 Technological bottlenecks

Use of technology since it is necessary to have a deep knowledge of Geographic Information Systems (GIS).

10.10.5.6 Benefit for the grower

Advantages

- Easy crop tracking display
- Detection of problems or heterogeneity in crops
- Provides information to compare strategies

Disadvantages

High experience in computer needed.

10.10.5.7 Supporting systems needed

DSS (Decision Support System) uses remote sensing indexes to provide irrigation recommendations.

10.10.5.8 Development phase

Commercialised.

10.10.5.9 Who provides the technology

In relation to image services, both public and private companies.

10.10.5.10 Patented or not

Satellite technology is not patented, but image access platforms or analysis software are.

10.10.6. Which technologies are in competition with this one

Companies that base irrigation recommendations on proximal crop and soil sensing.

10.10.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.10.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

10.10.8.1 Brief description of the European directive and implications for growers at European level

- Regulation (EU) No 911/2010 of European Parliament and of the Council of 22 September 2010 on the European Earth Monitoring Programme (GMES) and its initial operations (2011-2013)
- Regulation (EU) No 377/2014 of the European Parliament and of the Council of 3 April 2014 establishing the Copernicus Programme and repealing Regulation (EU) No 911/2010

- Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an infrastructure for spatial information in the European Community (INSPIRE)

10.10.8.2 Implementation at the country level

All the European legislation is implemented at country level.

10.10.9. Brief description of the socio-economic bottlenecks

- Need of good knowledge of geographic information systems. The need to incorporate crop tracking data when using remote sensing data for irrigation conditions growers' involvement through ICT technologies. Therefore, services should be adapted to the level of growers in terms of usability. However, the impact of ICT in this sector is slow, being limited to support the operation of machinery
- Some satellites, as Sentinel (free use), do not work with all wavelengths required for certain tasks, for example, thermal wavelength
- The platforms that are used for irrigation and fertilisation are not adapted for all crops, local adaptations must be conducted for each crop
- The reflectance values given by the satellite do not say much, they must be related to plant parameters

10.10.10. Techniques resulting from this technology

Find below some companies that provide irrigation recommendations based on canopy reflectance measurements from combined platforms (satellite, plane, drone):

- sigAGROasesor (http://agroasesor.es/es/plataforma-sigagroasesor/integracion-de-conocimiento-suelos-clima-riesgos.html)
- Farmstar: http://www.farmstar-conseil.fr/web/fr/7-la-technologie.php
- http://maps.spiderwebgis.org/login/?custom=
- Agrisat : http://www.agrisat.es/
- http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Land_services

10.10.11. References for more information

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10.11. Plant growth balance analysis system

(Author: Eleftheria Stavridou[15])

10.11.1. Used for

More efficient use of water.

10.11.2. Region

North-West Europe.

10.11.3. Crop(s) in which it is used

Tomato.

10.11.4. Cropping type

- Soilless
- Protected

10.11.5. Description of the technology

10.11.5.1 Purpose/aim of the technology

Enables the monitoring and analysis of the daily weight accumulation processes.

10.11.5.2 Working Principle of operation

The system weighs individual plants in the greenhouse using a weighing unit. Data are transferred every 20 minutes by radio to a computer and then to the server to process data, using software that was developed especially for this purpose. Processed data are transferred to the grower via the Internet website on the following day. Climate and irrigation data are collected from the grower's climate and irrigation control system. They enable the grower to:

- Monitor the daily growth of plants in the greenhouse
- Observe growth patterns
- Analyse the correlation between growth patterns with the climate and irrigation data
- Compare performances of:
  - Various varieties
  - Different compartments
  - New techniques or technologies used
  - Different crop management strategies (rootstocks, fertilisers, irrigation, etc.)

The system is not only able to compare compartments (different areas of a crop), but also differences between "Weighing Units". With this information, crops can be tracked at a detailed level.

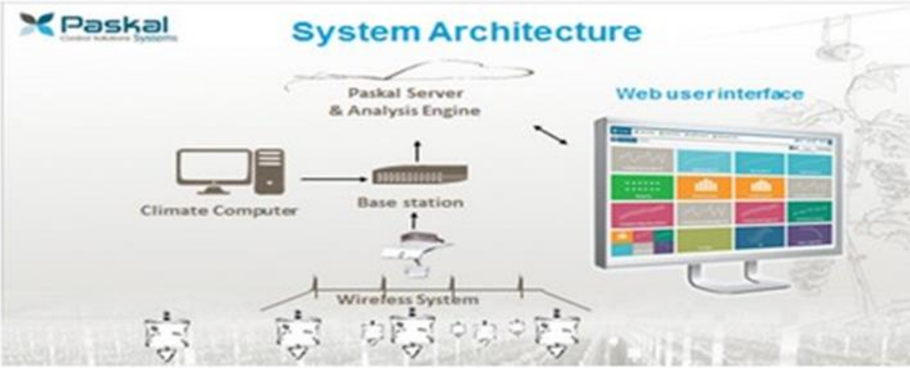

Figure 10-16. System Components Scheme (http://www.hortidaily.com/article/11380/Special-series-of-articles-on-Hortidaily-featuring-Paskals-Plant-Growth-Analysis)

10.11.5.3 Operational conditions

The number and distribution of the weighing units are decided according to the conditions at the site: size and structure of the greenhouse, uniformity factors, sensor location etc.

Using the Paskal system, as an example, a typical unit consists of 100 Weighing Units for 8 ha with 1 type of crop. For smaller areas, the number can be less. The minimum is 32 units for 1 system and at least 16 units per compartment.

10.11.5.4 Cost data

For installation: the minimum units per system costs 25000 €.

Yearly maintenance or inputs needed: subscription to the service and the software for the data analysis 1490 €/year.

10.11.5.5 Technological bottlenecks

There no real-time data. The data need time to be processed and the grower has access to the data 24h later.

10.11.5.6 Benefit for the grower

Advantages

- Automated
- The computer processes the data
- Constant monitoring

Disadvantages

- Expensive
- No real-time data access
- Interpretation of the data is difficult if no other monitoring systems (EC, pH, slab weight) are used

10.11.5.7 Supporting systems needed

To be able to interpret the growth analysis data they need to be combined with other data such as radiation, water, EC, and pH values etc.

The computer that receives the data from the greenhouse must be continuously connected to a stable internet network.

10.11.5.8 Development phase

Commercialised.

10.11.5.9 Who provides the technology

Paskal-tech.

10.11.5.10 Patented or not

This technology is patented.

10.11.6. Which technologies are in competition with this one

Turtina Hydro by Gremon systems.

10.11.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, it can possibly also be used in soilless, covered crops other than tomato. However, an adaption of the software might be needed for that.

10.11.8. Description of the regulatory bottlenecks

There are no relevant regulatory bottlenecks at European, country, or regional level.

10.11.9. Brief description of the socio-economic bottlenecks

The high costs associated with buying the equipment and the yearly license of the software will hold back a lot of growers.

10.11.10. Techniques resulting from this technology

None.

10.11.11. References for more information

[1] http://www.hortidaily.com/article/11380/Special-series-of-articles-on-Hortidaily-featuring-Paskals-Plant-Growth-Analysis.

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10.12. Thermal Infrared Sensor

(Authors: Carlos Campillo[5], Elisa Suárez-Rey[11])

10.12.1. Used for

- More efficient use of water
- Determining water needs

10.12.2. Region

- Central-East Europe
- Mediterranean

10.12.3. Crop(s) in which it is used

- Woody crops
- Annual crops

10.12.4. Cropping type

All cropping types.

10.12.5. Description of the technology

10.12.5.1 Purpose/aim of the technology

Thermal infrared sensors can provide information on plant water status and the amount of water to apply to an orchard during a certain period, the distribution of irrigation water, evaluation of moisture parameters and analysis of plant stress.

10.12.5.2 Working Principle of operation

Thermal images or thermograms are visual displays of the amount of infrared energy emitted, transmitted, and reflected by an object. Because there are multiple sources of the infrared energy, it is difficult to get an accurate temperature of an object using this method. A thermal imaging camera can perform algorithms to interpret that data and build an image. Although the image shows the viewer an approximation of the temperature of an object, the camera uses multiple sources of data based on the areas surrounding the object to determine that value rather than detecting the actual temperature. Thermographic cameras usually detect radiation in the long-infrared range of the electromagnetic spectrum (roughly 9-14 µm) and produce images of that radiation. This technology can be used in agriculture to determinate plant water status.

The instrument's optics pick up the sample of infrared radiation from the warm object to be measured, focusing it on the small infrared radiation sensor that converts it into a proportional electrical signal analogous to incoming infrared radiation (hence the temperature of the object). This signal is amplified and linearised by changing the radiation ratio into a perfectly linear voltage-temperature relationship. The temperature appears in the display.

In plants, the canopy temperature increases when solar radiation is absorbed but is cooled when that energy is used for evaporating water (latent energy or transpiration) rather than heating plant surfaces (Figure 10-17). Canopy temperature commonly follows a diurnal curve, with day-time temperatures rising due to increases in solar radiation and temperature. A water-stressed plant will reduce transpiration and will typically have a higher temperature than the non-stressed crop. This effect has also been explored as a response to nutrient stress and disease stress. Canopy temperature-based algorithms are strongly correlated to important quantifiable crop outputs such as yield, water use efficiency, seasonal ET, midday leaf water potential, irrigation rates, and herbicide damage. Variability of canopy temperature has been used to indicate water stress. Canopy temperature depends on the aerial temperature. The more water is transpired, the more the canopy temperature is below the temperature of the surrounding air.

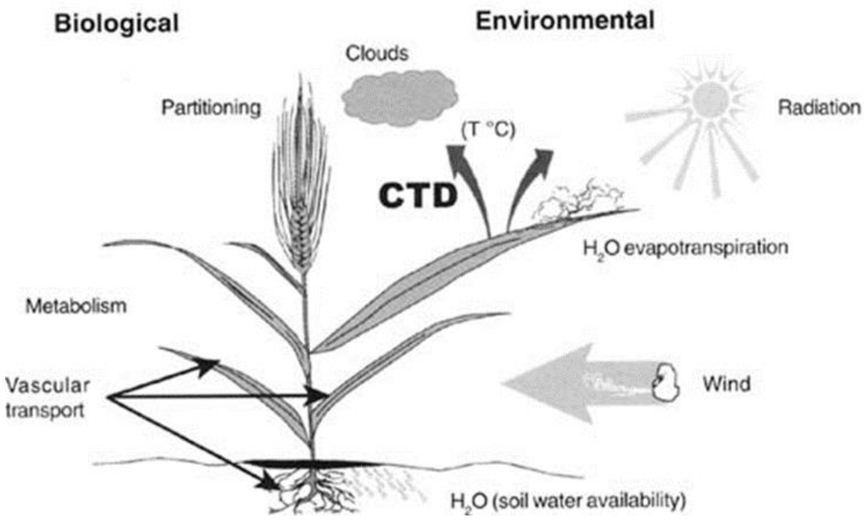


Figure 10-17. Factors affecting Canopy Temperature Depression (CTD) in plants (Reynolds et al., 2001)

The Crop Water Stress Index (CWSI), developed by the U.S. Water Conservation Laboratory in Arizona depends on this. The main criterion of the CWSI, therefore, is the temperature difference between the canopy leaves and the air. If a crop has water stress and therefore cannot transpire, there is hardly any difference between leaf and air temperature. The red upper baseline in Figure 10-18 stands for this situation. For the not water stressed crop, the transpiration depends on the relative humidity of the air. The lower the relative humidity is, the more the crop transpires. And the more the crop transpires, the lower the temperatures of the leaves. The green lower baseline (Figure 10-18) represents the case of the fully transpiring, non-water stressed crop. The vertical distances between the upper and lower baseline define the differences of the temperature span between leaves and air that occur when non-transpiring crops on the one hand with fully transpiring plants, on the other hand, are compared.

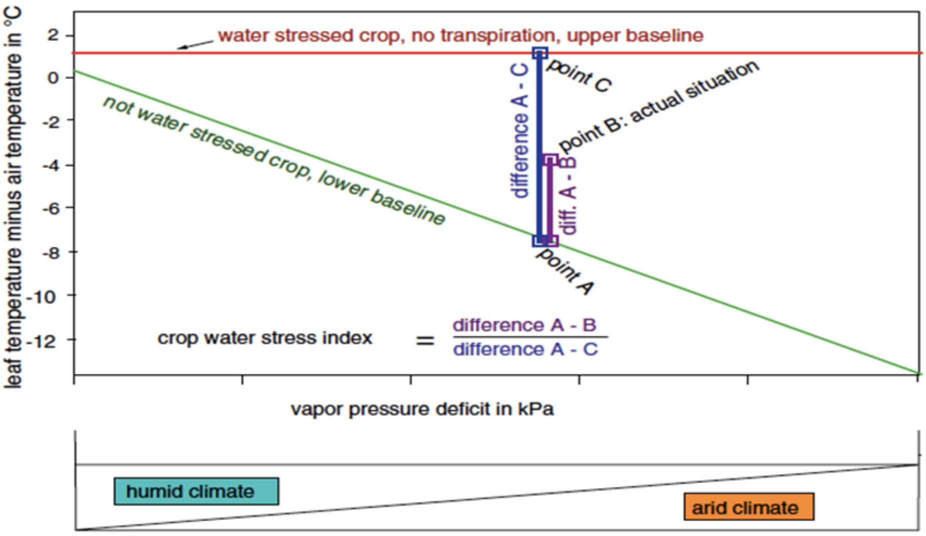


Figure 10-18. Graphical interpretation of the crop water stress index (Heege and Thiessen, 2013)

The crop temperature is measured using an infra-red thermometer or thermal camera, while the air temperature and vapour pressure deficit are measured using dry and wet bulb thermometers, or using formulae to convert relative humidity measurements.

The CWSI value is a measurement of the reduction in transpiration, expressed as a decimal in CWSI units. The CWSI has values ranging from 0 (no stress) up to 1 (maximum stress). A CWSI value of 0,25-0,35 would occur when the irrigation is due. The baselines are different for various phenological stages in certain crops. For winter wheat, different baselines should be developed for pre- and post- head stages. Baselines are strongly location dependent and perhaps species and variety dependent. To determine a non-water stressed baseline, it is a matter of measuring a non-stressed crop canopy temperature over a range of vapour pressure deficits (VPDs). This can be done by monitoring it as it changes over one day or by taking measurements on different days when the VPD is different around solar noon.

10.12.5.3 Operational conditions

Infrared thermometers are sufficiently reliable for continuous use over the period of a growing season and require only minimal in-field maintenance. The placement of the Infrared thermometers (IRTs) is an important consideration in the implementation of the protocol. A typical installation for a drip irrigation system utilises two IRTs viewing the canopy in a nadir view that produces a viewing area with a diameter of 10 cm. The IRTs are in the field in a manner that provides canopy temperatures that are representative of the field. When used with a centre pivot or linear drive irrigation system, IRTs have been mounted on the system in a forward-looking orientation. In this installation, the IRTs view the driest portion of the field. The IRTs are periodically checked for height adjustment and the lenses are cleaned. Temperature is typically monitored every six seconds and 15 minutes averages are used for irrigation decisions.

A thermal camera is installed in UAV before the flight. Images and flight data (position) are recorded in a memory card. The images are saved as mosaics by specialised software. Temperature value of each pixel is calibrated with a field local measurement during the flight. Yearly maintenance or inputs are needed.

Infrared thermometers are accurate and have a wide range of action (from -30 °C to 100 °C). There are different distance / size relationships of the measurement object (e.g. 50: 1, 60: 1, 12: 1). Measurements at long distances will measure larger area. This is something that sometimes is not desired, hence a higher distance/size ratio is preferred. In some catalogues, this characteristic is expressed as field of view and it is measured with the angle of the cone whose apex coincides with the sensor. The field of view angles vary between 0,1° and 50° for the different models. For measurements in plants, thermometers with field of view angles between 4° and 15° are used. There are models with selective and fixed emissivities (0,95).

10.12.5.4 Cost data

Infrared thermometers cost 500-1000 € depending on the accuracy or the commercial company. A logger is necessary to save the data. Thermal cameras are more expensive (10000-20000 €). Different companies do technical works with UAV and thermal images of the farm. Processing images and crop water status on the farm costs 20-30 €/ha.

10.12.5.5 Technological bottlenecks

Variability, correct installation, interpretation of information, easy-to-use friendly software, the threshold for different crops and different crop phase. It's also necessary to know the air temperature.

10.12.5.6 Benefit for the grower

Advantages

- Water savings
- A non-destructive method to determine crop's water content
- Continuous monitoring
- Allows for irrigation scheduling
- Relatively cheaper wireless technology
- Automation possible
- Provides a picture of a whole field or farm
- Using cameras or remote sensors, many fields can be measured with a single instrument

Disadvantages

- Help needed for installation
- Difficult data interpretation and management
- Cost
- In aerial images, image-processing is necessary: Mosaic, Orthorectification, Elimination of soil (reduce errors in the calculation of the temperature of the plant)
- In aerial images, images must be calibrated with data taken from the plot

- The temperature value does not indicate directly whether there are stresses or not, the values obtained must be compared with measurements in the field made with other sensors. Vapour pressure deficit, water potential, soil moisture, etc.
- Variations in temperature depending on the part of canopy and angle of measurement
- Thermographs are expensive

10.12.5.7 Supporting systems needed

A technical assessment during the first periods of use is required.

10.12.5.8 Development phase

Commercialised.

10.12.5.9 Who provides the technology

Infrared Sensor

Apogee: http://www.apogeeinstruments.co.uk/infraredradiometer/

Smartfield http://www.smartfield.com/smartfield-products/equipment/smartcrop-system/

Thermal Camera (used with drone or manual)

FLIR: TAU Thermal camera

Sensefly: thermoMAP

10.12.5.10 Patented or not

Yes, this technology is patented.

10.12.6. Which technologies are in competition with this one

Plant Sensors and Remote sensing.

10.12.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.12.8. Description of the regulatory bottlenecks

For aerial images UAV legislation:

The legislation on the use of drones is different in each country of the European Union, the commission is working on a common legislation. In some countries, there are fewer legal restrictions on how people can use drones, type of drones, flight height, where they can fly, no-fly zones, what types of jobs can be done, what flight permits they need, national database, etc.

In Spain to fly a drone you need a special license and an official course of drones handling, the company must have a permit from the air agency, drones cannot be used in public places or with people, the works must be for professional use, there are areas of special air protection that cannot be flown in any way (http://www.icarusrpa.info/mapa.php?opt=all), in addition the drone must always be visible by the pilot.

10.12.9. Brief description of the socio-economic bottlenecks

- In many places in Spain, water saving is still not an objective of farmers
- Orchards are often too small to afford the costs of sensors and remote sensing technologies

10.12.10. Techniques resulting from this technology

Most irrigation strategies such as Controlled Deficit Irrigation, Partial Root Drying, etc., can be complemented and controlled using these devices.

There are different sensors based on this principle that permit to measure the canopy temperature:

Infrared thermometer: This sensor measures the canopy temperature with a point measurement over the canopy. The ratio of measure (target area) depends on the distance between sensor and crop and the measurement angle. The temperature will be average of the measured area, with a unique value. This sensor can be connected to a logger and take a continuous measurement (with a defined time interval). The GPS technology permits the use of sensors and loggers to carry measurements of all farm holding parts if the sensor is placed on a tractor.

a) 

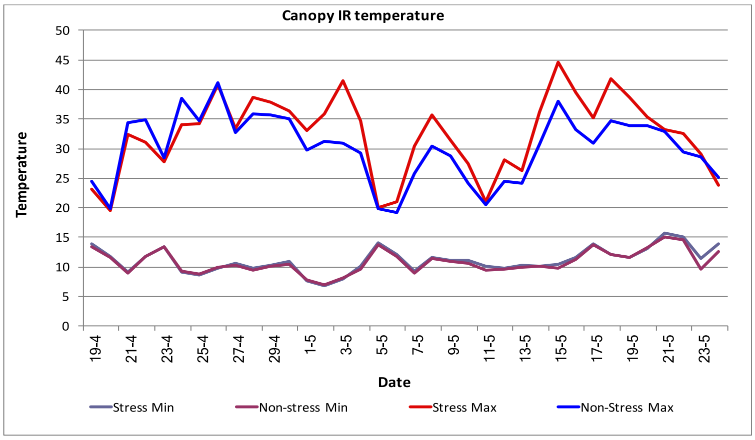
b) 

Figure 10-19. IR thermometer (a) and Canopy temperature evolution (b) during the crop cycle (maximum (Max) and Minimum (Min) temperature in Stress and non-Stress zone)

Thermal camera: This camera permits to take images with pixels expressing the temperature of the crop area. This allows knowing the temperature of a specific area of the crop canopy. This sensor can be used with local images of a specific point of the farm or be installed in a UAV to take measurements of a large zone or even all plots in the farm holding. The UAV system allows to obtain different images and with the mosaic techniques a continuous image of the farm with information on the temperature in each pixel of the image.

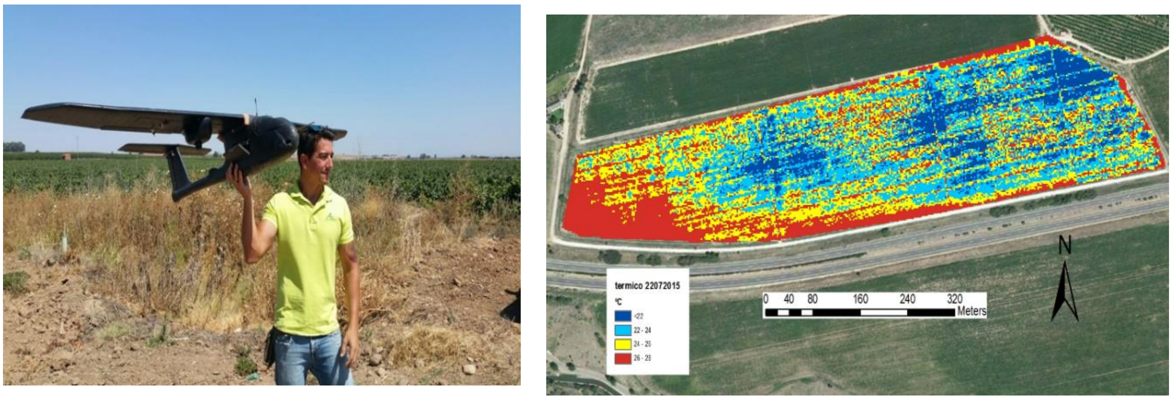


Figure 10-20 Thermal image of processing tomato crop capture from UAV

The aerial inspection of a crop with an UAV is another example of its application and the result could determine areas with possible leakage of irrigation, as well as zones with lack of water and/or with poor fertility to help to change water scheduling in specific parts of the farm holding.

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10.13. Dendrometers

(Authors: Marisa Gallardo[23], Benjamin Gard[*])

10.13.1. Used for

More efficient use of water.

10.13.2. Region

All EU regions.

10.13.3. Crop(s) in which it is used

- All vegetables
- Fruit trees
- Ornamentals

10.13.4. Cropping type

All cropping types.

10.13.5. Description of the technology

10.13.5.1 Purpose/aim of the technology

Dendrometers, which are also known as linear variable displacement transducers, measure Stem (or trunk) Diameter Variations (SDVs) with a very high resolution and are a very sensitive indicator of plant water status.

Using suitable protocols, dendrometers can be used for determining the timing of irrigation. They appear to be most suited for use with grapevines and fruit trees.

10.13.5.2 Working Principle of operation

The stems or trunks of plants experience shrinkage and swelling within 24-hour periods because of a dis-phase between transpiration and plant water uptake. As the evaporative demand increases in the morning, plants begin to transpire using water stored in tissues including stems/trunks; this results in the contraction of the stem and within daily 24-hour periods, stem diameters have minimum values around midday (Figure 10-21). In the afternoon and evening, root water uptake has progressively more influence on stem diameter than transpiration and complete re-hydration of all tissues progressively occurs reaching a maximum value just before sunrise (Figure 10-21). A water-stressed plant has a larger contraction during the day and a lower recovery at night than a well-watered plant. These differences between water-stressed and well-watered plants form the basis of the use of dendrometers. Dendrometers continuously measure stem diameter and consequently stem diameter variations. The dendrometers are connected to data-loggers to enable automatic data collection.

Among the SDV-derived parameters that are used in irrigation scheduling in trees with slow trunk growth, the most sensitive parameter is often the maximum daily shrinkage, i.e. the difference between the maximum stem diameter value before sunrise and the minimum value at approximately midday. For young trees, stem growth rate, the difference of the maximum trunk diameter over two consecutive days (Figure 10-21), is the most sensitive parameter because decreases in trunk growth occur rapidly in response to water stress.

Irrigation protocols have been developed for some mature fruit trees that involve: 1) selecting the derived parameter most suitable for an individual species, particular growth stage and crop load, and 2) relating the derived parameters to reference values of well-watered crops and normalising them for climatic conditions such as VPD, which is a measure of the humidity of air in relation to saturation. In the case of maximum daily shrinkage, equations to predict reference values from meteorological data are available for several woody crops.

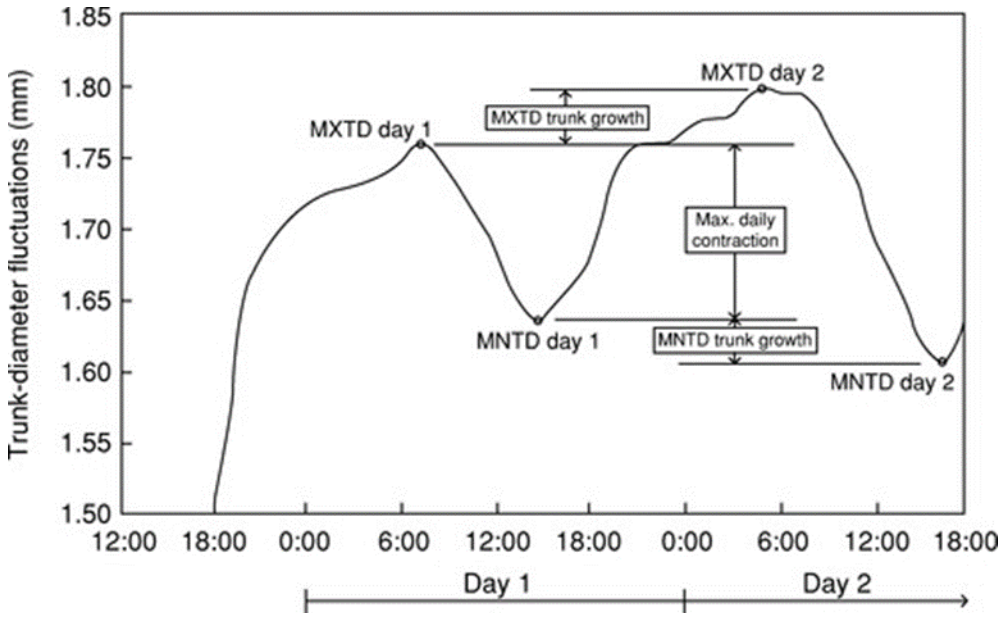

Figure 10-21. Parameters that can be derived from trunk-diameter measurements, including maximum daily trunk contraction, and trunk growth expressed as daily differences in maximum and minimum daily trunk diameters (MXTD and MNTD, respectively) (Adapted from Goldhamer and Fereres, 2001)

10.13.5.3 Operational conditions

Absolute stem diameter variation (SDV) values, without consideration of evaporative demand, can be difficult to interpret. For that reason, SDV values are generally normalised with respect to those in non-limiting soil water conditions with the same evaporative demand, which is they are divided by values from well-watered plants. Other considerations when using this method are the number of replicate measurements required to account for a high between-plant variability and other biological stresses (e.g. diseases, nutritional issues) and abiotic stresses (e.g. high and low temperature) can affect SDV measurements. Normally, the scale of operation is implemented at field level within an orchard. In large orchards with high variability in crop water status, SDV measurements can be combined with aerial or satellite imaging.

10.13.5.4 Cost data

Online, a dendrometer can be bought for 475 €. But, lower cost alternatives are possible, for example, the BEI 9605 sensor is relatively inexpensive (21 €), in which case the total cost for an automatic dendrometer (point and band) will be below 34 € (see reference 9).

The additional costs of data loggers to collect and store data, climate stations and software to analyse data add to the cost.

New users require training and on-going assistance when commencing with this technology. Generally, it is recommended that growers contract the services of consultancy companies that offer sensor installation and data interpretation; data interpretation with dendrometers is challenging for inexperienced users. Some considerations regarding the use of dendrometers are care during installation and good protection of the sensor with insulating reflecting material to minimise heating and the effects of rain both of which can cause unacceptable noise. Unintended contact of the sensor by farm workers can also cause data errors. It is strongly recommended that experienced technicians conduct or assist with sensor installation and data interpretation for new users. The cost of these services adds to the overall cost.

10.13.5.5 Technological bottlenecks

Absolute SDV values must be normalised with respect to those in non-limiting soil water conditions at the same evaporative demand.

SDV data are influenced by climate, crop development stage, fruit load and other factors that must be considered when using them for irrigation scheduling (IS). This can limit their potential for automatic irrigation because of the requirement to consider other data and growers' impressions of these factors when making irrigation scheduling decisions.

SDV data can be difficult to interpret when there are foggy, rainy, and overcast weather conditions and when there has been physical contact with the sensors or cables from farming activities, birds, insect etc. These effects can be reduced with the use of adequate sheltering of the sensors

SDV derived indices such as maximum daily shrinkage and stem growth rate are affected not only by plant water status but by other factors such as crop nutritional stress, salinity etc. Care must be taken to ensure that no factors, other than crop water status, are influencing the dendrometer data.

In fast-growing plants such as vegetables or young trees, dendrometers may have to be repositioned several times during the growing season.

A limitation is a high variability between plants in the derived indices. Consequently, many replicated sensors are required.

10.13.5.6 Benefit for the grower

Advantages

- Reliable and robust
- Provides an integration of the crop's response to both the soil water supply water and the atmospheric evaporative demand
- Automatic measuring
- Very early detection of crop water stress, even when the stress is mild
- Very suitable for trees

Disadvantages

- Difficult data interpretation and decision making
- Several other factors affect data apart from plant water status
- Normalisation of data required
- Correct installation is fundamental
- Need for calibration before use
- High variability between plants/trees

10.13.5.7 Supporting systems needed

Dendrometers require supplementary equipment for data collection, storage, and transmission, which are suitable for field operation. It is also recommended to have climatic data from the same crop as where the sensors are located; these climatic data help with data interpretation and implementation of irrigation protocols.

For untrained people with little knowledge of the technology, it is essential to contract the services of a specialised consulting service to instruct the user with installation, data management and particularly with data interpretation for irrigation scheduling.

10.13.5.8 Development phase

- Research: A large amount of research has been conducted in the last 15 years regarding the development of new sensors, data transmission systems and determination of the sensitivity of various SDV derived-indices to water stress for a range of species. Also, there has been appreciable research conducted during this period to develop Irrigation scheduling protocols based on SDV measurements
- Commercialised: There are several companies that produce different types of dendrometers. There are other companies that provide services in which dendrometers are used for Irrigation scheduling

10.13.5.9 Who provides the technology

Several companies provide services in which dendrometers are used for Irrigation scheduling. These include the French company Agro-Technologie (http://www.agro-technologies.com/) that markets the Pepista system, the Spanish company Verdtech (http://www.verdtech.es/), the Israeli Phytech company (http://www.phytech.com/), and the Belgium company Phyto-sense (http://www.phytosense.net/forgrowers.html) which has developed automatic monitoring systems with several plant, soil, and climatic sensors, including dendrometers. These companies provide complete systems that provide continuous records of soil, plant and weather variables which are provided in a user-friendly format for early detection of water stress and more rational irrigation scheduling. These companies offer services and consultancy for the sale of sensors, sensor installation, calibration, and data interpretation. Some publicly-funded researchers are also involved in the development of companies (spin-off companies) such as the Spanish CEBAS research centre (of CSIC, the Spanish National Research Council) and the Laboratory of Plant Ecology of Ghent University, Belgium.

10.13.5.10 Patented or not

Presumably, some of the technology is patented and the software used for data analysis is registered.

10.13.6. Which technologies are in competition with this one

This technology could be used instead of or in combination with other irrigation scheduling procedures such as the use of the water balance method, the use of soil moisture sensors (tensiometers, Watermark, capacitance sensors) or other plant monitoring approaches such as the use of infrared sensors.

10.13.7. Is the technology transferable to other crops/climates/cropping systems?

The technology is commercially in orchards of grapevines and fruit trees. In some cases, in Israel and Belgium dendrometers in combination with other sensors are being used in commercial applications for irrigation scheduling and climate control of greenhouse-grown crops.

10.13.8. Description of the regulatory bottlenecks

No regulatory bottlenecks at this level.

10.13.9. Brief description of the socio-economic bottlenecks

The main socio-economic bottlenecks are the costs of purchasing or renting sensors and associated equipment and of contracting the services of a consulting company to help with sensor installation, calibration, and data interpretation. Additionally, these sensors will be perceived as a high technology approach. The costs and perception of advanced technology will restrict their use to growers with an interest in high technology and with high-value crops for which sensitive information is required on crop water status.

10.13.10. Techniques resulting from this technology

1) Agro-Technologie (www.agro-technologie.com) manufactures Pepista 4000 that measures and evaluates automatically the demand for water in tree trunks, through a sensor fixed in the plant. The company has certification from INRA
2) The Spanish Verdtech (http://www.verdtech.es/) offers an automatic monitoring system with several plant, soil and climatic sensors including dendrometers for optimal irrigation scheduling
3) The Israeli Phytech (http://www.phytech.com/) offer an automatic monitoring system with several plant, soil and climatic sensors including dendrometers for optimal irrigation scheduling
4) The Belgium Phyto-sense (http://www.phytosense.net/forgrowers.html) offers automatic monitoring systems with several plant, soil and climatic sensors including dendrometers for optimal irrigation scheduling. Data interpretation is based on the use of crop models

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10.14. Leaf turgor sensor

(Authors: Sandra Millán[5], Carlos Campillo[5], Dolors Roca[14])

10.14.1. Used for

More efficient use of water.

10.14.2. Region

All regions, the most likely use is in the Mediterranean region

10.14.3. Crop(s) in which it is used

Fruit trees and olives, it could be used with vegetable crops

10.14.4. Cropping type

- Soil-bound
- Open air

10.14.5. Description of the technology

10.14.5.1 Purpose/aim of the technology

A leaf turgor sensor is used to assess the water status of the plant. In some cases, the readings can indicate when to irrigate.

10.14.5.2 Working Principle of operation

The leaf sensor technology indicates water deficit stress by measuring the turgor pressure of a leaf, which decreases dramatically at the onset of leaf dehydration. Early detection of impending water deficit stress in plants can be used as an input parameter for precision irrigation control. For example, a base system utilising the wirelessly transmitted information of several sensors appropriately distributed over various sectors of a round field irrigated by a centre-pivot irrigation system could tell the irrigation operator exactly when and which sector of the field needs to be irrigated.

The sensor measures the relative changes in the leaf's turgor pressure. Turgor pressure is the pressure caused by fluid pushing against the cell wall of plant cells. It is needed to keep the plant's rigid in order to stand straight and continue normal cellular functions. Turgor is related to the hydration status as cell and bulk leaf turgor pressure decline when leaves dehydrate during transpiration and in response to drought. As the stress level in the tree increases, the turgor potential of its leaves decreases.

10.14.5.3 Operational conditions

The probes show the relative changes in leaf hydration. If the more detailed information is needed, such as predicting absolute turgor pressure values, calibration would be needed. The volumetric elasticity of leaves is temperature dependent, but it is also dependent on the hydration of cell walls and cell turgor pressure.

10.14.5.4 Cost data

The prices of the components are:

Yara Water-Sensor = 290 €.

Transmitter (for connection of up to three 3 Yara Water-Sensors or microclimate sensors) = 535 €.

Base Station (including antennas and Installation Device; excl. SIM-card) = 2750 €.

User data centre (1 year) = 100 €.

The total cost will depend on how many probes are used on a farm. In a field of 20-30 ha, at least six are needed, which would involve a total cost of almost 6200 €.

10.14.5.5 Technological bottlenecks

The devices need frequent maintenance, relocation, and calibration (wind, leaf necrosis, quality of signal) and even then, a high variability of the measurements is possible. Additionally, thresholds are not always available.

Internet access is required for remote access to the data.

Under severe water stress conditions, the information given turgor sensor can be limited by an increase of air in the spongy mesophyll tissue of the leaf, which attenuates the pressure transfer through the leaf tissue.

10.14.5.6 Benefit for the grower

Advantages

- Sensitive sensor
- Versatile
- Non-destructive measurements
- Easy to handle sensor
- Results are immediately available
- Savings in energy and water consumption up to 20%
- Reductions in tree maintenance
- Boosts yield up to 15%

Disadvantages

- Close contact of the probe with the leaf surface is required for reliable measurements
- Unsuitable for plants showing isohydric behaviour
- User requires certain degree of expertise
- Advice required in the first phases, on the interpretation of the information

10.14.5.7 Supporting systems needed

Internet connection.

10.14.5.8 Development phase

Commercialised.

10.14.5.9 Who provides the technology

Yara.

10.14.5.10 Patented or not

Yes.

10.14.6. Which technologies are in competition with this one

10.14.7. Is the technology transferable to other crops/climates/cropping systems?

Many methods have been used previously to measure plant water use or water balance. One of the most standard techniques is the determination of leaf water potential using a pressure chamber. However, this method is destructive. Stomatal conductance and transpiration are commonly measured using porometry and gas exchange equipment and although these measurements can be carried out on intact leaves, they are disruptive and suffer from the same temporal and spatial resolution problems as leaf water potential measurements.

Thermal imaging using infrared technology to measure leaf and canopy temperatures, as a surrogate for stomatal conductance. While thermal imaging has obvious advantages in scaling from leaves to whole fields, turgor can provide the extra information needed to understand the effect of stomatal behaviour on plant adaptation and growth rate.

10.14.8. Description of the regulatory bottlenecks

Not applicable.

10.14.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks known at this time.

10.14.10. Techniques resulting from this technology

Magnetic patch-clamp pressure sensors serve to monitor the leaf hydration. These sensors enable application of water on demand which assists to optimise water use while maintaining production quality and quantity.

Figure 10-22. Yara water sensor

The technology of the leaf turgor sensors is that miniature pressure sensors are clamped to leaves via magnets. The magnets apply a constant clamp pressure to the leaf so that the pressure sensors detect relative changes in leaf turgidity.

Installation: An intact leaf is positioned between the two pads of the probe (diameter 10 mm), each of which is connected with magnets. The probe measures the pressure transfer exerted by the two magnets through the leaf patch. The leaf patch is assumed to be in hydraulic contact with the surrounding unclamped leaf tissue. The output pressure signal (i.e. the so-called patch pressure Pp) is sensed by a pressure sensor that is integrated into one of the pads. The clamp pressure (P_{clamp}) that is exerted by the two magnets onto the leaf patch can be adjusted to the rigidity of the leaf by varying the distance between the two magnets and is constant during the measurements. Essentially, leaf turgor opposes the clamp pressure and the pressure sensor detects changes in turgor by monitoring the change in pressure opposing the magnetic force (i.e. turgor). Therefore, Pp is inversely correlated with leaf turgor pressure, such that when the leaf dehydrates during stomatal opening and in response to water deficit Pp increases and conversely, decreases again when the leaf rehydrates.

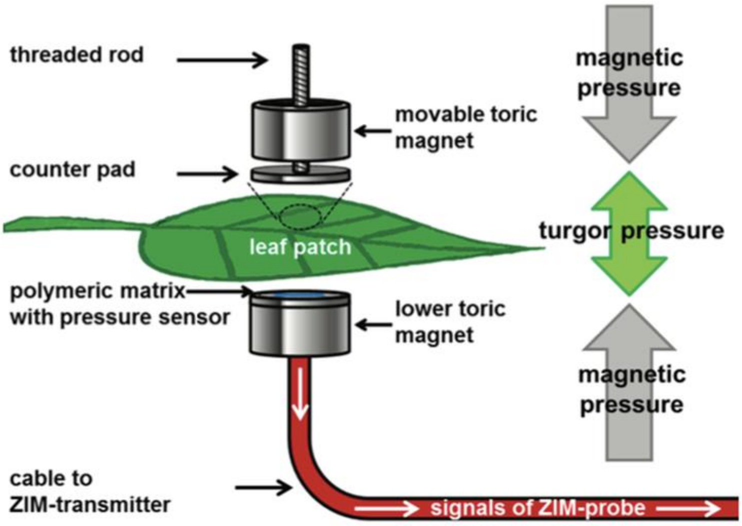

Figure 10-23. The water sensor measures changes in the leaf turgor pressure in real time (Zimmermann et al. 2013)

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10.15. Pressure chamber for plant water potential measurement

(Authors: Henar Prieto[5], Benjamin Gard)*

10.15.1. Used for

More efficient use of water.

10.15.2. Region

All EU regions.

10.15.3. Crop(s) in which it is used

All crops.

10.15.4. Cropping type

All cropping types.

10.15.5. Description of the technology

10.15.5.1 Purpose/aim of the technology

Pressure chambers are used to assess plant water status. The numeric value provided informs not only on the existence of a stress situation but also makes it possible to quantify the intensity of the stress.

10.15.5.2 Working Principle of operation

The principle behind the pressure chamber is simple. If you cut a cross-section of a twig or petiole, it reveals a central core of xylem transport vessels, through which nutrient-laden water goes up from the roots. Surrounding the xylem are the phloem transport vessels, through which sugars and carbohydrates travel down to the roots.

Water within the plant mainly moves through very small inter-connected cells, collectively called xylem, which is essentially a network of pipes carrying water from the roots to the leaves. The water in the xylem is under tension, pulled with a suction force as water evaporates from the leaves. As the soil dries or humidity, wind or heat load increases, it becomes increasingly difficult for the roots to keep pace with evaporation from the leaves. This causes the tension to increase. This tension can be measured; negative values are typically reported. An easy way to remember this is to think of water stress as a “deficit”. The larger the stress, the more the plant is experiencing a deficit of water. The scientific name given to this deficit is the “water potential” of the plant.

The pressure chamber is just a device for applying air pressure to a leaf (or small shoot or any other plant portion), where most of the leaf is inside the chamber but a small part of the leaf stem (the petiole) is exposed to the outside of the chamber through a seal. The amount of pressure that it takes to cause water to appear at the cut surface of the petiole tells you how much tension the leaf is experiencing on its water: a high value of pressure means a high value of tension and a high degree of water stress. The unit of pressure most commonly used is Bar. (1 Bar = 14,5 PSI= 0,1 MPa)). The actual physics of how the water moves from the leaf is more complex than just "squeezing" water out of a leaf, or just bringing water back to where it was when the leaf was cut. However, in practice, the only important factor is for the operator to recognise when water just begins to appear at the cut end of the petiole.

The basic elements of the equipment are, a closed chamber able to withstanding pressure, with a movable head where to place the sample (support by the petiole); an air source to generate pressure inside the chamber and a manometer where carry out the readings. A small twig is snipped, trimmed neatly, and then inserted into the lid of the pressure cylinder, which is filled with compressed air or nitrogen gas under pressure. A gauge registers the pressure under which water begins to flow up the xylem, revealing whether the plant needs water.

There are different models available, differing in the source of air for the pressure, that can be a tank with compressed nitrogen or a simple pumping system that makes the equipment lighter and portable (Figure 10-24). Others differences are related to the design of the instrument as a console or a briefcase or the characteristics of the different components.

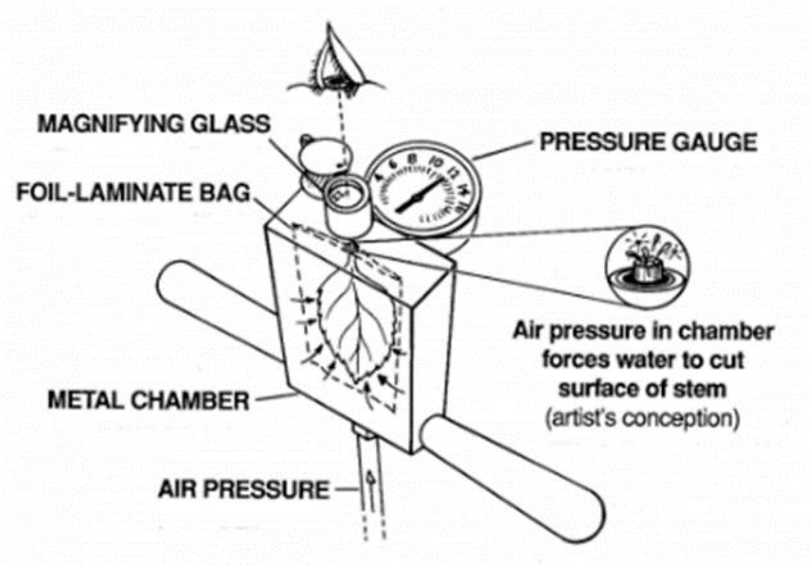

Figure 10-24. Pump-up pressure chamber (https://www.pmsinstrument.com/)

10.15.5.3 Operational conditions

The precision of the measurements depends on the selected model, the most precise being the console type or briefcase. In the "pump-up" (pumping) type (Figure 10-25a), each stroke of the pump increases the pressure in the chamber by 0,5 bar, which is the limit of the precision of this instrument. Moreover, this instrument is limited to 20 bar. Therefore, in order to carry out measurements under conditions of very severe stress that require high precision, another instrument model (Figure 10-25b) is necessary. The use of pressure tanks increases the cost of the measurements and/or makes necessary an investment in infrastructure in addition to the risks to the operators associated with the manipulation of a source with high pressure. The second aspect in relation with the precision is the skill of the worker. Because the measurement depends on visual perception, there is an element of subjectivity. Therefore, trained operators improve the accuracy of the measurements.

Figure 10-25 Measure water potential with pump-up system in processing tomato crop (a) and console chamber system with tank (b) (Source: CICYTEX)

10.15.5.4 Cost data

It is a portable system, so only a fixed installation is required to fill the pressure tanks (if this is the chosen option). The time of measurement depends on the number of leaves/plants measured and the size of the field/greenhouse being assessed. Each measurement takes about one minute; however, the time required to select the most appropriate plants and leaves also has to be considered. In large fields and when there is large variability between plants, the time required to obtain a representative measurement may become an issue.

The cost could be between 1500-6000 € depending on the model and the supplier.

Yearly maintenance or inputs needed to depend on the use, but are low. There is no fixed maintenance or input needed on a yearly basis.

10.15.5.5 Technological bottlenecks

In order to obtain useful information for decision support, it is necessary to have established the sampling procedure and have trained personnel, since the choice of the plant and the leaf (or other part of the plant) are important, as well as the time of day and the meteorological conditions at the moment of measurement. Otherwise, the data must be contrasted with appropriate reference values for the particular crop and sometimes also variety and phenological status. When relative humidity varies during the growing season, it may be necessary to make corrections taking into account the vapour pressure deficit.

10.15.5.6 Benefit for the grower

Advantages

- Enhances efficient use of water
- Valuable information about the crop water status
- Simple technique
- Portable meter

Disadvantages

- Time-consuming to set-up the sampling and measuring procedure
- Dedication of qualified staff time to carry out monitoring checks, interpret measures and take agronomic decisions

- Need of reference values for the particular crop

10.15.5.7 Supporting systems needed

None.

10.15.5.8 Development phase

Commercialised.

10.15.5.9 Who provides the technology

Several manufacturing companies sell different models of pressure chambers.

10.15.5.10 Patented or not

Each company has developed its models, the technology is probably not patented, although some designs are likely to.

10.15.6. Which technologies are in competition with this one

There are several technologies that also pursue the same objective: to quantify the water status of the plant. Some of them measure indirectly the water potential in some parts of the plant but important differences exist between them. Canopy or plant temperature, stomatal conductance, trunk or fruit shrinkage, non-invasive leaf turgor sensor, sap flow, among others, are an example of such technologies.

10.15.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.15.8. Description of the regulatory bottlenecks

There are no relevant directives or regulatory bottlenecks at European, country or regional level.

10.15.9. Brief description of the socio-economic bottlenecks

The socio-economic bottlenecks refer to the training, set-up and time needed to start the instrument and the cost of the equipment. There is no information available on the specific economic improvements that can be derived from the use of this technology, making it difficult to assess the return on investment.

10.15.10. Techniques resulting from this technology

Deficit Irrigation Strategies for water saving, to increase water use efficiency and/or to improve crop quality (This technique allows to control the duration and intensity of the hydric stress supported by the plants).

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10.16. Neutron probe

(Authors: Eleftheria Stavridou[15], Mike Davies[15], Carlos Campillo[5])

10.16.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.16.2. Region

All EU regions.

10.16.3. Crop(s) in which it is used

- Fruit
- Vegetables

10.16.4. Cropping type

- Soil-bound
- Protected
- Open air

10.16.5. Description of the technology

10.16.5.1 Purpose/aim of the technology

A neutron probe is used to determine the volumetric moisture content and the water content in a soil profile. It aids the grower to make irrigation decisions for the crop.

10.16.5.2 Working Principle of operation

The neutron probe consists of a radioactive source (pellet of americium and beryllium), producing fast neutrons, a slow neutron detector and a pulse counter. The neutron probe works by emitting fast neutrons into the surrounding soil, which collide with hydrogen atoms in the soil water, resulting in these neutrons to lose energy and slow down, the slow neutrons are detected by a slow neutron detector which is converted to a count rate. The greater the count rate, the greater the number of neutrons that have been slowed down and therefore the higher the soil moisture.

To measure soil moisture content, aluminium access tubes are inserted vertically into the soil via pre-augured holes, which have a slightly smaller diameter than the access tubes to avoid air gaps. The depth that the access tubes are inserted will depend on the depth of the soil and/or the rooting zone, but access tubes of 1,2 m depth are commonly installed but deeper or shallower tubes can be used. Each access tube needs a plug at the base to stop entry of water and a cap to place on the top to stop rainwater entering the tube.

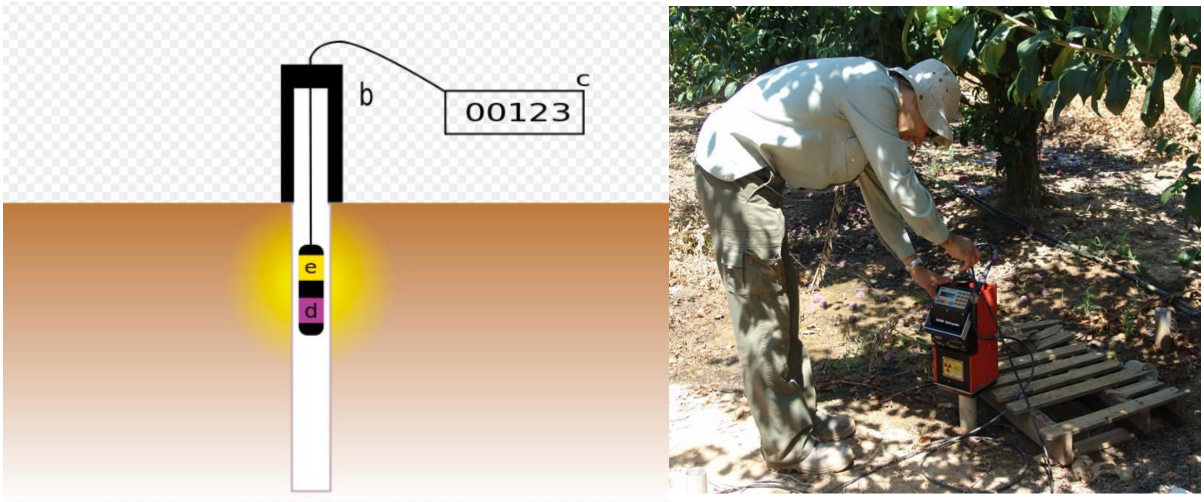

Figure 10-26. Neutron probe (e=neutron emitter -- d=detector -- b=shielding -- c=counter)
(https://en.wikipedia.org/wiki/Neutron_probe)

Once the access tubes are installed in a crop, readings are taken in the same location throughout the life of the crop. To measure the soil moisture content, the neutron probe is positioned over the access tube and the probe is lowered to the first required depth, the count detector is activated and the neutron "count" is displayed. The time for each measurement can be set by the user, commonly 16 seconds is used to give reasonably accurate results, although for greater accuracy a larger time interval can be used. These readings need to be calibrated against samples of soils with known moisture contents to enable the count rate to be converted to soil moisture content. To convert readings to volumetric water content a calibration curve for each soil type is applied. The probe is then lowered further into the access tube for readings at subsequent depths. The depths that measures are taken are determined by the user but commonly readings are taken every 10 - 20 cm. The measurements at each depth are used to determine the total water content of the soil over the measured depth and to determine from which depths of soil the crops are extracting water and ultimately the water deficit from field capacity can be calculated.

Crop daily water use can be estimated. The water deficit (in mm) from soil field capacity can be determined and the amount of irrigation needed to be applied to bring the soil back to field capacity or a specific deficit can be calculated.

A measurement is required when the soil is at field capacity (e.g. in the UK, towards the end of the winter, is a good time provided there has been adequate rainfall) to enable a deficit to be calculated.

10.16.5.3 Operational conditions

Requires the use of a radioactive source.

Only licensed operators, who comply with the rules and regulations for use, transport and storage of the radioactive source can use the equipment.

Neutron meters require little maintenance beyond checking to ensure proper operation. Access tubes should be checked for water or foreign materials in them. The most common failure is a broken or worn cable, which connects the source tube to the electronic readout device. A repaired instrument may also require recalibration. Operator recertification is required every two years.

10.16.5.4 Cost data

Device 10755 €, training and documentation development 2440 €, signs 200 €, radiation monitors 400 € or more per bunker, according to the construction company.

Yearly maintenance; national taxes 2500 €, 900 € medical examinations to check radiation levels.

Installation of the access tubes.

Measurements carried out and data interpreted on at least a weekly basis through the growing season, usually by specialist irrigation advisors.

10.16.5.5 Technological bottlenecks

Probes cannot be left in-situ to measure continuously, therefore data cannot be logged.

Cannot be used in an automatic irrigation system.

Accurate readings in the top 10-15 cm of soil are more challenging to obtain as some neutrons leave the soil at the soil/air interface. Soil-specific calibration at 10 cm may improve the accuracy.

Only licensed operators can use this device, usually, it is provided by irrigation consultants who provide the neutron probe technology.

10.16.5.6 Benefit for the grower

Advantages

- Increases water and nutrient use efficiency
- Easy data interpretation
- Total soil water content can be calculated along with the water deficit
- Daily/weekly crop water use can be calculated
- Volumetric moisture content and the changes over time at different depths can be determined
- Accurate readings, soil surface measured is relatively large. The greatest in relation to others soil moisture sensor

Disadvantages

- Expensive
- Limited use
- Need of a license for use of radioactive substances
- Data from a couple of neutron probe readings per week are not sufficient to optimise water use efficiency
- Data are not instantaneously available.
- Accuracy in top 10-15 cm of the soil profile is difficult
- The neutron probe cannot measure reliably irrigation and rainfall input, with or without a field-specific calibration on temperate climates, which has major implication on irrigation scheduling

10.16.5.7 Supporting systems needed

None.

10.16.5.8 Development phase

Commercialised.

10.16.5.9 Who provides the technology

Neutron probe devices provided by e.g. CPN (a Instro Tek company) providing rh 503 Elite Hydroprobe; Troxler who provide the Troxler moisture monitoring gauges.

Irrigation consultants are often the ones to provide a service to growers (e.g. in UK 0 Agri-tech services the UK provide a Neutron probe service).

10.16.5.10 Patented or not

Not known.

10.16.6. Which technologies are in competition with this one

Various soil water sensors, profile probes, matric potential sensors.

10.16.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.16.8. Description of the regulatory bottlenecks

Various legislation governing the use, transport, and storage of radioactive substances e.g. The Ionising Radiation Regulations 1999 (abbreviated IRR99), European Agreement Concerning the Carriage of Dangerous Goods by Road 2009 (ADR).

10.16.9. Brief description of the socio-economic bottlenecks

Expensive technique and the need to be licensed for use of radioactive substances with, transporting and storage of radioactive material to use make it economically less interesting for growers. Risk of exposure to the radioactive source, requires film badge monitoring to detect any exposure to the operator are social bottlenecks.

10.16.10. Techniques resulting from this technology

None

10.16.11. References for more information

[1] Bell, J. P. (1987). *Neutron probe practice*

[2] Else, M., & Atkinson, C. (2010). Climate change impacts on UK top and soft fruit production. *Outlook on Agriculture*, *39*(4), 257-262

10.17. Combined water, EC and temperature sensor

(Authors: Eleftheria Stavridou[15], Mike Davies[15], Carlos Campillo[5])

10.17.1. Used for

More efficient use of water.

10.17.2. Region

- Nordic
- North-West Europe
- Mediterranean

10.17.3. Crop(s) in which it is used

- Soft fruit
- Vegetables

10.17.4. Cropping type

All cropping types.

10.17.5. Description of the technology

10.17.5.1 Purpose/aim of the technology

The combined sensor is used to measure three of the most important indications of root zone health:

- Water content (%)
- Pore water conductivity (ECp), which is the EC of the water available to plant roots
- Temperature (^{o}C)

This sensor is particularly useful in horticulture for monitoring and correcting variation when applying fertigation, control released fertilisers or organic treatments.

10.17.5.2 Working Principle of operation

The WET sensor of Delta-T Devices uses three pins to maintain an electromagnetic field at a frequency of 20 MHz. Like other capacitance sensors, the combined sensor measures changes in the electromagnetic field, which are related to the dielectric constant. The raw measurements taken are soil permittivity, conductivity, and temperature, and these are converted to soil water content and bulk EC using calibration tables. The sensor pins are 7 cm long and, with a measurement radius of 2 cm, this gives a measurement volume of about 220 cm^3.

Generalised calibrations are provided for most common soil types and specialised calibrations are available as separate cost options for several artificial substrates.

The pore water conductivity calculation is based on a unique formula that minimises the effects of probe contact and soil moisture on the readings. Temperature is measured using a miniature sensor built into the central rod.

The combined sensor is designed to be used with the HH2 Moisture Meter, but can also be interfaced to control systems for fertigation control.

Figure 10-27. WET sensor used to take measurements on rockwool and soil in open air (https://www.delta-t.co.uk)

10.17.5.3 Operational conditions

The combined sensor was originally designed to be used in soil, where normally the EC is lower than 2 dS/m. In horticultural growing media, however, the EC may be as high as 10 dS/m. Delta-T Devices Ltd. supplies extended calibration curves up to 5 dS/m. In high-saline soils, the accuracy of the standard WET is not warranted.

10.17.5.4 Cost data

The combined sensor probe costs about 1200 € and handheld meter 620 €. The sensor can be connected to a logger for continuous measurement such GP1 or GP2 data loggers which cost 840 -1400 €

You need approximately 30 seconds to take each measurement; there is no financial cost apart from that of the time and sensor doesn't need any maintenance.

10.17.5.5 Technological bottlenecks

- The relatively low oscillation frequency in the combined sensor (20 MHz) makes the measurements much too dependent on soil salinity and therefore, impairs the estimations of θ, and thus ECp
- Only one sensor can be practically handled per handheld reader
- Each sensor must be calibrated
- Calibration tables do not exist for mixtures of media and measurements are not accurate in such situations
- Careful application of probe in stony soils
- Underestimating of permittivity in media with low permittivity (ε > 40, clay and organic soils)
- Inaccurate values in saturated media

10.17.5.6 Benefit for the grower

Advantages

- Water and fertiliser savings
- Rapid measurements (~5 seconds) of all 3 parameters
- Easy use and data interpretation
- Calibrations available for many soils and growing media (peat, coir, mineral wool)
- Lightweight ergonomic design, rugged
- *Disadvantages*
- High cost
- Automatic logging of the sensor needs a high level of electronic knowledge

10.17.5.7 Supporting systems needed

HH2 meter for handheld measurements or GP2 data loggers for continuous recording.

10.17.5.8 Development phase

Commercialised.

10.17.5.9 Who provides the technology

Several companies sell these sensors, among others WET sensors (see 10.20.6).

10.17.5.10 Patented or not

This technology is patented.

10.17.6. Which technologies are in competition with this one

Alternative approaches to combined sensors are various soil/substrate water monitoring sensors. These are TDR, neutron probe, water potential sensor etc. (see relevant TDs).

10.17.7. Is the technology transferable to other crops/climates/cropping systems?

The combined sensor can be used in various crops, climates, different cropping systems, such as crops in soil or substrate and crops in the open field or in greenhouses. However, for each application, it is necessary to calibrate the sensor for the substrate that is being used.

10.17.8. Description of the regulatory bottlenecks

There are no relevant European directives or regulatory bottlenecks at European, country or regional level.

10.17.9. Brief description of the socio-economic bottlenecks

- When using a manual device, the time required to take the samples should be accounted for
- The costs associated with buying the equipment

10.17.10. Techniques resulting from this technology

- Grodan B.V. has modified the original design of the WET sensor and calibrates their WCM up to 10 dS m^{-1} for use on stone wool production systems. The WCM control (a handheld meter) the WCM Continu (connected to a climate control computer) and the GroSens were developed especially for measuring the water content, the conductivity and the temperature in stone wool substrates used in greenhouse production
- 5TE (Decagon Devices Inc.)
- Hydraprobe (Stevens Inc.)

10.17.11. References for more information

[1] Charlesworth, P. (2005). Soil Water Monitoring, An Information Package. *Irrigation Insight No 1*

[2] Pardossi, A., Incrocci, L., Incrocci, G., Malorgio, F., Battista, P., Bacci, L., ... & Balendonck, J. (2009). Root zone sensors for irrigation management in intensive agriculture. *Sensors*, *9*(4), 2809-2835

[3] Delta-T2005, WET Sensor User Manual v1.3 (2005),Hydraprobe (Stevens Water) http://www.stevenswater.com/resources/datasheets/hydraprobe_brochure_web.pdf

10.18. Auger method

(Authors: Claire Goillon[2], Carlos Campillo[5], Rodney Thompson[23], Benjamin Gard)*

10.18.1. Used for

More efficient use of water.

10.18.2. Region

All EU regions.

10.18.3. Crop(s) in which it is used

All vegetable and fruit crops.

10.18.4. Cropping type

- Soil-bound
- Protected
- Open air

10.18.5. Description of the technology

10.18.5.1 Purpose/aim of the technology

Sampling with an auger enables the soil to be sampled at different locations and different depths to assess soil type and to estimate soil moisture. With this method, it is possible to estimate water retention properties of the soil and soil available water capacity (AWC). The estimation is empirically based on the appearance and feel of the soil.

10.18.5.2 Working Principle of operation

Figure 10-28. Parts of the metallic auger.

Soil samples are taken with a metallic auger at several depths and locations of the field. Depth depends on the crop's root zone but, generally, samples are taken between 10 and 40 cm. At least 15-20 soil samples for 1 ha are needed to have an accurate view of the soil moisture. It is important to select plots representative of the field. Choose a homogeneous area and avoid the areas adjacent to the field, areas compacted by passages of tractor and agricultural machinery, low points and mounds.

The soil sample taken with the auger is then analysed according to the feel and appearance. With practice, this method can provide a good indication of the moisture content that can assist in irrigation management decisions.

Table 10-2. Guidelines for estimating soil texture and approximate percentage of the available water capacity of soil samples, by the feel of the sample during manual manipulation.

Soil appearance				
Coarse	**Moderately Coarse**	**Medium**	**Moderately Fine and Fine**	**% of Available Water Capacity (AWC)**
Free water appears when the soil is bounced in hand	Free water is released by kneading	Free water can be squeezed out	Puddles and free water forms on the surface	Exceeds field capacity – runoff & deep percolation
Upon squeezing, no free water appears on soil, but wet outline of ball is left on hand				100% – At field capacity
Tends to stick together, forms a weak crumbly ball under pressure	Forms a weak ball that breaks easily; does not stick	Forms a ball and is very pliable; sticks readily if relatively high in clay	Ribbons out between thumb and finger; has a slick feeling	70-80% of AWC
Appears to be dry; does not form a ball under pressure	Appears to be dry; does not form a ball under pressure	Somewhat crumbly but holds together under pressure	Somewhat pliable; balls up under pressure	25-50% of AWC
Dry, loose, single-grained flow through fingers	Dry, loose, flows through fingers	Powdery dry, sometimes slightly crusted but easily breaks down into powder	Hard, baked, cracked; sometimes has loose crumbs on the surface	0-25% of AWC

10.18.5.3 Operational conditions

In some soil types, the extraction of soil can be difficult, for instance when the soil contains a lot of stones or when the soil is packed.

10.18.5.4 Cost data

- For installation: Augers are inexpensive tools; the price ranges at 50-100 €, for a manual auger. Besides, it can be easily handmade for a price below 30 €. The part of the auger used for soil sampling must be round to penetrate easily in the soil. For soils with a high percentage of stones, it is possible to use mechanical augers, but prices rise from 150-250 €
- Yearly maintenance or inputs needed: None, the auger is a very resistant tool

10.18.5.5 Technological bottlenecks

There is no technological bottleneck. The auger method does not need any complex device. The grower just has to think to take its auger when he goes to the field. It is often forgotten.

10.18.5.6 Benefit for the grower

Advantages

Easy, cheap.

Disadvantages

Not automatic, it takes time and you need to be familiar with soil appearance and feeling method.

10.18.5.7 Supporting systems needed

None.

10.18.5.8 Development phase

Commercialised.

10.18.5.9 Who provides the technology

Retailers or handmade.

10.18.5.10 Patented or not

Not patented.

10.18.6. Which technologies are in competition with this one

All the method for measuring soil moisture (tensiometer, capacitance probe, etc.).

10.18.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, except soilless crops.

10.18.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

10.18.9. Brief description of the socio-economic bottlenecks

None.

10.18.10. Techniques resulting from this technology

None.

10.18.11. References for more information

[1] Morris, M., & Energy, N. C. A. T. (2006). Soil moisture monitoring: low-cost tools and methods. *National Center for Appropriate Technology* (NCAT), 1-12

[2] Delaunois, A., Boucher, G., & Plence, A. (2014). Le sondage des sols à la tarière. Caractérisation de la réserve en eau des sols à partir des sondages pédologiques à la tarière. Chambre d'Agriculture du Tarn. Retrieved from http://www.tarn.chambagri.fr/fileadmin/documents_ca81/DocInternet/filieres/agronomie_environnement/2014-methode_sondage_tariere-v2.pdf

10.19. *Wetting Front Detector*

(Authors: Juan José Magán[9], Benjamin Gard)*

10.19.1. Used for

More efficient use of water.

10.19.2. Region

Mediterranean.

10.19.3. Crop(s) in which it is used

Vegetables.

10.19.4. Cropping type

- Soil-bound
- Protected
- Open air

10.19.5. Description of the technology

10.19.5.1 Purpose/aim of the technology

The Wetting Front Detector is a type of equipment that can help growers with irrigation scheduling in soil crops by detecting if watering is insufficient or excessive, as well as the presence of waterlogging. Furthermore, it can be used for assisting in the management of fertilisers and salts.

10.19.5.2 Working Principle of operation

Knowing the position of the wetting front is useful information to improve irrigation management. This equipment is a buried funnel-shaped container (Figure 10-29) able to detect the position of the wetting front in the soil. When the wetting front reaches the device, the unsaturated flow lines converge towards the base of the funnel, where soil water content reaches saturation and free water appears. This water flows through filtered sand and accumulates in a small reservoir, activating a float which raises a visual indicator placed at the top of the tube emerging from the soil when the wetting front has reached a certain depth of soil. The indicator float rises when 20 mL of water has been collected. If the float is up, then a wetting front passed the buried funnel but if the float is down, then not enough water was applied to produce a wetting front which the equipment could detect. When the soil around it is drier than the soil inside the funnel, the first will act as a "wick" to draw the water out of the funnel after irrigation end. An indicator allows the grower to detect the activation of the device at any moment, so it is not compulsory to visit it just after irrigation. However, if the indicator has popped up, it needs to be reset before the next irrigation. If the indicator immediately pops up again it means that the soil around the device is still very wet (http://www.fullstop.com.au/).

It is possible to extract the water accumulated with a syringe via a 4 mm flexible pipe which connects the reservoir to the soil surface. This water can be analysed to determine salt or nutrient concentration. The solution obtained contains the ions which are moving from one soil horizon to another.

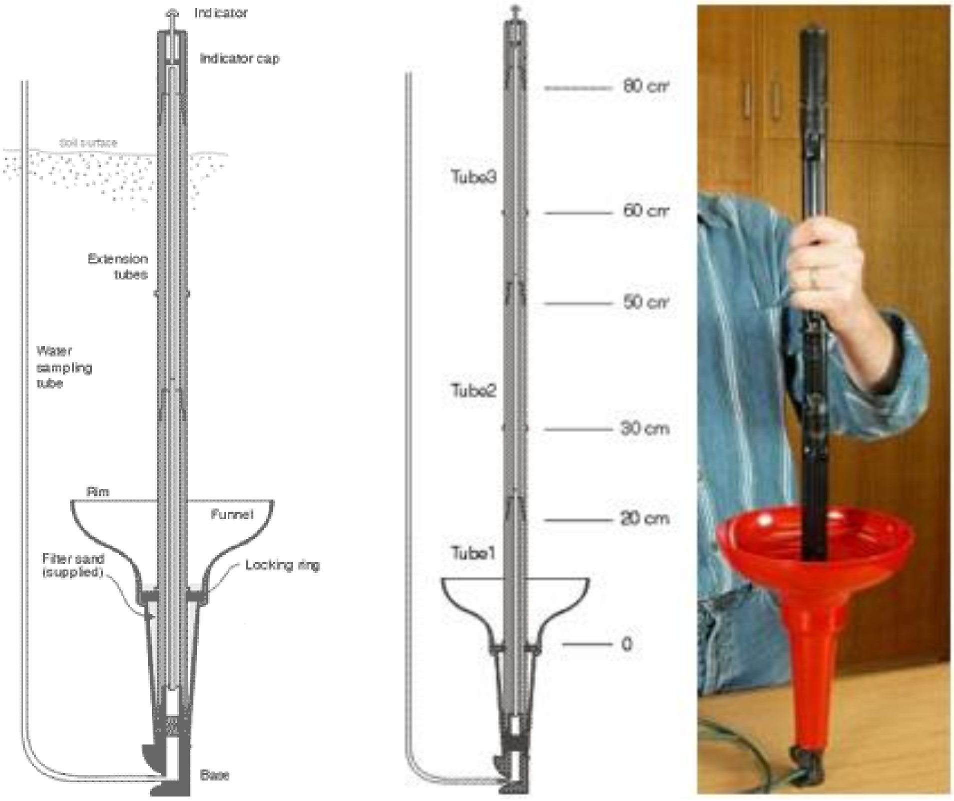

Figure 10-29. Schemes (indicating components and dimensions) and picture of a FullStop before being installed (from http://www.fullstop.com.au/)

10.19.5.3 Operational conditions

The manufacturer recommends installing the wetting front detectors in pairs so that one of them is buried about one-third of the way down the active root-zone and the other about two thirds.

The optimum depth of placement depends on the irrigation method and the frequency of irrigation, as well as the type of crop and soil. A guide given by the manufacturer is shown in Table 10-3 but these recommendations must be adjusted for local conditions and management styles. Placement depths are measured from the soil surface to the locking ring (0 cm level in Figure 10-29).

The different situations of activation of the wetting front detectors are shown in Figure 10-30. If neither indicator is triggered (left), then watering is generally too shallow. If the higher indicator is triggered and the lower is down (centre), then water has moved past the shallow detector to the lower part of the root zone; this is usually the best situation. Finally, if both indicators are triggered (right), then the wetting front is at the low part or under the root-zone. However, if this happens frequently, irrigation can be excessive. Some additional details about this are shown in Table 10-4.

Table 10-3. FullStop installation depths recommended by the manufacturer based on the irrigation system used (http://www.fullstop.com.au/)

Type of irrigation	Notes	Shallow detector (cm)	Deep detector (cm)
Drip	Amount applied per dripper usually less than 6 litres at one time (e.g. row crops, pulsing)	30	45
Drip	Amount applied per dripper usually more than 6 litres at one time (perennial crops)	30	50
Sprinkler	Irrigation is usually less than 20 mm at one time (e.g. centre pivot, micro-jets)	15	30
Sprinkler	Irrigation is usually more than 20 mm at one time (e.g. sprinklers and draglines)	20	30
Flood	Deeper placements than shown needed for infrequent irrigations or very long furrow	20	40

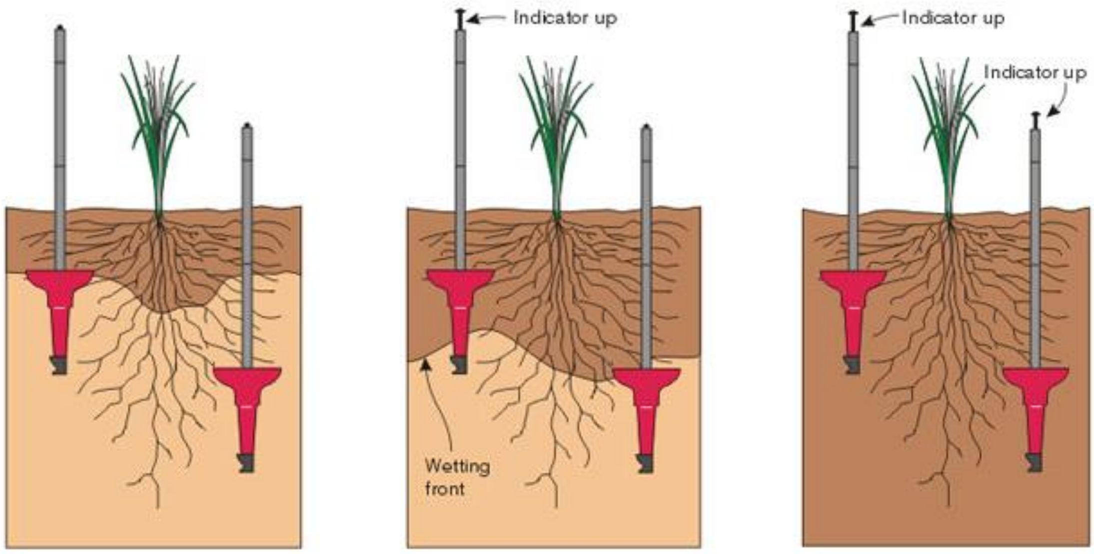

Figure 10-30. Different situations of activation of the wetting front detectors after watering (from http://www.fullstop.com.au/)

On the other hand, the system can detect waterlogging. Since the vertical distance from the base of the funnel to the rim is greater than 20 cm, a suction greater than 20 cm (> 2 kPa) will be needed to wick the water out. When the soil dries beyond 2 kPa suction, the soil outside can start withdrawing water from the funnel. The time it takes to empty the funnel depends on the soil type and amount of water in the funnel. If the indicator cannot be reset for several days, the soil is waterlogged.

The solution obtained can be analysed in order to assist in nutrient management but it is necessary to take into account that this device collects freely draining soil solution whereas a suction cup can sample soil solution from soil pores with longer residence times, especially under unsaturated flow conditions, and might represent better the available element concentrations for plant nutrition studies. In a study carried out in Almería (Spain), Cabrera et al. (2016) found the same average relationship between the electric conductivity (EC) obtained from 0,25 m depth funnels and that measured from suction cups (81%) in two different tomato growing cycles. Furthermore, the relationship corresponding to sodium and chloride concentration was around 85% in both crops and that corresponding to calcium and magnesium was around 73 and 77% respectively. However, the relationship between nitrate and potassium was more variable, what makes this system non recommendable for nutrient monitoring.

Table 10-4. Recommendations for different situations of device activation (http://www.fullstop.com.au/)

Shallow detector	Deep detector	What it means	What you should do
		Not enough water for established crops	Satisfactory for young crops or after fertigation when it is important to eliminate leaching Apply more water to established crops at each irrigation or shorten the interval between two irrigations
		The wetting front has penetrated into the lower part of the root zone	Mostly, this is the desired result. However, during hot weather or when the crop is at a sensitive growth stage irrigation should be increased The deep detector should respond from time to time, showing that the entire root zone is wet
		The wetting front has moved toward the bottom or below the root zone	Both detectors should respond when irrigating to satisfy the high demand for water. However, if this happens on a regular basis, particularly in the case of sprinkler irrigation, over-watering is likely Reduce irrigation amounts or increase the time interval between irrigations
		Soil or irrigation is not uniform or the soil surface is uneven	Ensure the soil level is over the detectors and water is not running towards or away from the installation site Check uniformity of irrigation or location of drippers

10.19.5.4 Cost data

Installation time is around 1-2 hours/unit. The cost of a couple of detectors is 150 €.

It is convenient to check the activation of the system after each irrigation for a better adjustment of watering.

The device has to be removed at the end of the growing season if the soil is going to be ploughed but it can be maintained in the soil between crops in the opposite case.

Nevertheless, it is convenient to remove the tube emerging from the soil for avoiding its deterioration by sun radiation or an accidental breakage and to cap the hole of coupling for avoiding soil entrance to the device.

10.19.5.5 Technological bottlenecks

The installation of the device is critical for a good functioning. It is better to do it when the soil is dry by avoiding excessive compacting, which can impede water to enter into the funnel. In drip irrigation, the dripper must be placed above the rim of the funnel.

10.19.5.6 Benefit for the grower

Advantages

- Very simple and intuitive system. It can be suitable for farmers without experience with sensors
- Low initial investment
- Low maintenance costs
- Technology readily available

Disadvantages

- It does not give numerical information about the water status of the soil
- It is necessary to spend time for device checking after irrigation
- The installation of the device can be a quite hard work
- The soil inside the device is more humid than the rest
- There are sometimes problems to recover water
- The solution recovered is not soil solution but drainage, which are not the same

10.19.5.7 Supporting systems needed

None.

10.19.5.8 Development phase

Commercialised.

10.19.5.9 Who provides the technology

FullStop is a technology developed and owned by the company CSIRO Land and Water.

10.19.5.10 Patented or not

Yes.

10.19.6. Which technologies are in competition with this one

- Sensors measuring water status of the soil (tensiometers, capacitance sensors)
- Lysimeters
- Suction cups

10.19.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this technology may be used in any crop grown in soil.

10.19.8. Description of the regulatory bottlenecks

None.

10.19.9. Brief description of the socio-economic bottlenecks

A problem with this technology is that the grower can feel tired of checking the activation of the device.

10.19.10. Techniques resulting from this technology (add as many needed)

In Almería (Spain) some growers have eliminated the magnets of the device in order to estimate how much water is accumulated in the deposit, based on the height reached by the visual indicator. Moreover, in this way, the grower does not have to take down the indicator after water re-absorption. On the other hand, in Almería greenhouses, the installation depth is generally lower than usual for drip irrigation because the sand mulching typically used ("enarenado") induces the development of a more superficial root system. Furthermore, there is frequently a layer of supplied soil (cultivable layer) of only 30 cm on the original soil (usually too rocky).

10.19.11. References for more information

[1] Cabrera, F.J., Bonachela, S., Fernández-Fernández, M.D., Granados, M.R., & López-Hernández, J.C. (2016). Lysimetry methods for monitoring soil solution electrical conductivity and nutrient concentration in greenhouse tomato crops. *Agricultural Water Management*, *128*, 171-179

[2] Stirzaker, R.J. (2003). When to turn the water off: scheduling micro-irrigation with a wetting front detector. *Irrigation Science*, *22*, 177-185

[3] Stirzaker R.J., & Hutchinson, P.A. (2005). Irrigation controlled by a wetting front detector: field evaluation under sprinkler irrigation. *Australian Journal of Soil Research*, *43*(8), 935-943

10.20. Tensiometer

(Authors: Claire Goillon[2], Carlos Campillo[5], María Dolores Fernández[9], Benjamin Gard)*

10.20.1. Used for

More efficient use of water.

10.20.2. Region

All EU regions.

10.20.3. Crop(s) in which it is used

Tensiometers are used in a large variety of fruit and vegetable crops.

10.20.4. Cropping type

- Soil-bound
- Protected
- Open air

10.20.5. Description of the technology

10.20.5.1 Purpose/aim of the technology

The purpose of a tensiometer is to directly measure the soil water matric potential, the force that root systems must develop to extract water from the soil. This is a reliable measure of the water availability for the plants.

10.20.5.2 Working Principle of operation

A tensiometer is a sealed water-filled tube with a porous ceramic cup in contact with soil in one extremity (Figure 10-31). Water in the tube is equilibrated with the soil solution. When plants and environment remove water from the soil, water is drawn from the ceramic cup, creating a depression in the tube. This depression can be measured with a manometer or a pressure gauge linked to a data logger. It is directly linked to the soil water matric potential (SMP) and expressed in centibar (cbar) or kPa.

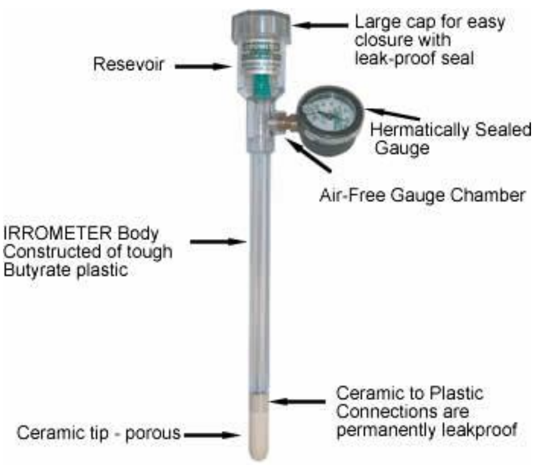

Figure 10-31. Description of the parts of a tensiometer
(https://wiki.metropolia.fi/display/sensor/Soil+moisture+sensors)

10.20.5.3 Operational conditions

Soil tensiometers provide a measure of the soil water matrix tension from 0 to 85 cbar. Tensiometers measure the water tension at one point of the agricultural parcel (few centimetres around the porous probe). Several tensiometers must be located, at different soil depth (e.g. 20, 40 and 60 cm) and repeated in different locations, to have a good measure of water availability in the soil. For managing irrigation, the location of the tensiometers must consider the soil heterogeneity. Generally, SMP provides a useful measure of the availability of soil water to plants. Irrigation management with tensiometers is based on irrigating when the soil water matric tension reaches a lower limit (drier value) or threshold value. Thresholds are available for vegetable crops in open field and greenhouse (Table 10-5). These limits vary with crop species, crop developmental stage, soil texture and the evaporative conditions.

Table 10-5. Thresholds values of soil water matric potential (in cbar) for vegetable crops in open field and greenhouse (Thompson et al., 2007)

Crop	Open field	Greenhouse[1]
Pepper	40-50	58
Melon	30-40	35
Tomato	40-60	60 (under low evaporative conditions: ETo ≈ 0,8 mm/day) 40 (under higher evaporative conditions: ETo ≈ 2-3 mm/day)

10.20.5.4 Cost data

For installation: for 6 tensiometers with

- manual data collection 300-400 €
- automated data collection 600-1000€
- automated data collection and remote data transmission 1400-3000 €

yearly maintenance or inputs needed: weekly or daily maintenance is needed to check the water level in the tube, to check good contact between soil and the porous cup and to maintain water within the water column free of dissolved air.

10.20.5.5 Technological bottlenecks

Tensiometers are sustainable tools and need to be removed after use. When the ceramic tip is immersed in water, it could indicate 0 cbar (saturation) but after several installations, a derive is notified and tensiometers have to be changed. The electric connections often break or the data logger becomes deficient and a new investment is necessary. There is a risk of water discharge in not high frequently irrigated crops when the evaporative demand is high. Consequently, it is not a useful tool to manage irrigation if crop water requirements are not covered (e.g. application of deficit irrigation to favour crop rooting or the reproductive development of the crop, to increase the fruit sugar content, etc.).

10.20.5.6 Benefit for the grower

Advantages

- Good price-quality
- Continuous measurements
- Remote data transmission available
- Thresholds for irrigation triggering for numerous crops and types of soil
- Easy to install

Disadvantages

- Require preparation in order to work effectively
- Maintenance required
- Can break during installation and crop cultural practices

10.20.5.7 Supporting systems needed

Advice from suppliers or extension services may help growers to better use the technology, and to know the threshold values for crops. Data logging and remote transmission can facilitate the use of the tensiometer, if compatible with computer systems.

10.20.5.8 Development phase

Commercialised.

10.20.5.9 Who provides the technology

Several suppliers.

10.20.5.10 Patented or not

Not patented.

10.20.6. Which technologies are in competition with this one

Granular matrix sensors, capacitance probe, Gypsum blocks.

10.20.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, the technology is easily transferable.

10.20.8. Description of the regulatory bottlenecks

None.

10.20.9. Brief description of the socio-economic bottlenecks

Knowledge of the technology and costs and lack of advice for a good use may be the main socio-economic bottlenecks. Further, the constraint of measuring in the case of systems without a data logger can be a bottleneck.

10.20.10. Techniques resulting from this technology

Irrigation scheduling.

10.20.11. References for more information

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10.21. Granular Matrix Sensors

(Authors: Rafael Granell[14], Luis Bonet[14], Mike Davies[15], Eleftheria Stavridou[15])

10.21.1. Used for

- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.21.2. Region

Mediterranean.

10.21.3. Crop(s) in which it is used

- Woody crops
- Annual crops

10.21.4. Cropping type

All cropping types.

10.21.5. Description of the technology

10.21.5.1 Purpose/aim of the technology

A granular matrix sensor (GMS) provides information on the amount of water to apply to an orchard during a certain period.

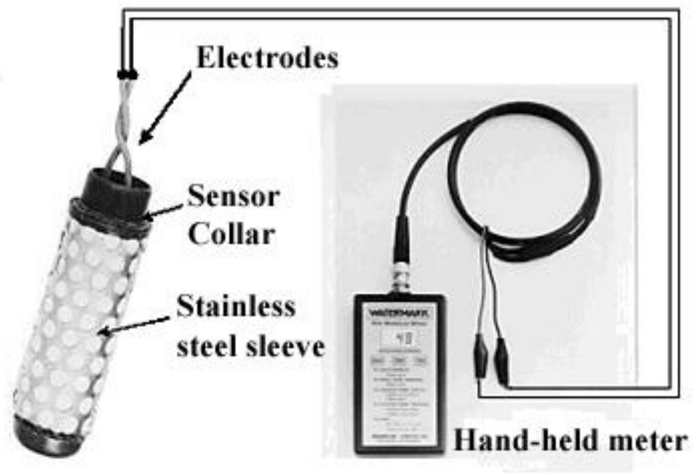

Figure 10-32. Watermark sensor (http://cropwatch.unl.edu/measuring-soil-water-status-using-watermark-sensors)

10.21.5.2 Working Principle of operation

Granular matrix sensor technology reduces the problems inherent in gypsum blocks (i.e. loss of contact with the soil by dissolving, and inconsistent pore size distribution) by use of a granular matrix confined in a metal case. Granular matrix sensors operate on the same electrical resistance principle as gypsum blocks and contain a wafer of gypsum embedded in the granular matrix. The electrodes inside the GMS are embedded in the granular fill material above the gypsum wafer. The gypsum wafer slowly dissolves, to buffer the effect of salinity of the soil solution on electrical resistance between the electrodes.

GMS is similar to tensiometers as they are made of a porous material that reaches equilibrium with the soil moisture. The electrical resistance between electrodes embedded in a porous medium is proportional to its water content, which is related to the soil water matric potential of the surrounding soil. Electrical resistance increases as the soil and the block lose water.

10.21.5.3 Operational conditions

Proper preparation and installation of the GMS are vital to their operation. Sensors should be soaked overnight and installed wet. If time permits, condition the sensor with multiple wet/dry cycles: soak the sensor in irrigation water overnight, allow it to air dry for a day or two, then re-soak overnight. To install the sensor, an access hole should be made to the desired depth using a length of ½ or ¾" PVC pipe. Fill the access hole with water, then seat the sensor firmly in the bottom of the access hole using the PVC pipe. Fill the hole with soil again and tamp firmly, but avoid compacting the soil.

Suitable for dry soil conditions or clay soils, where usually soil matric potential is high. The GMS is convenient for sensing soil water potential to automatically start an irrigation because they do not require periodic maintenance during the growing season The GMS have limitations in reading soil water potential in soils wetter than -10 cbar and in responding in coarse-textured soils.

Regarding the thresholds and reference values for irrigation, it depends on the type of crop, the type of soil (textures and structure) and even irrigation system, so that the following values could be taken as a general reference guideline:

- 0-10 cbar = Saturated soil (field capacity)
- 10-20 cbar = Soil is adequately wet (except coarse sands, which are beginning to lose water)
- 30-60 cbar = Usual range for irrigation (except heavy clay soils)
- 60-100 cbar = Usual range for irrigation in heavy clay soils
- 100-200 cbar = Soil is becoming dangerously dry for maximum production.

In commercial applications of these sensors, the simplest procedure is based on determining the relative values of field capacity from a saturation episode, like a heavy rain. With these values and taking into account the trends in soil moisture content during the previous 4-5 days, appropriate irrigation schedules are established.

10.21.5.4 Cost data

Granular matrix sensors have advantages of low unit cost and simple installation procedures, similar to those used for tensiometers. Annual costs are 40-200 €, depending on the company and the uploading frequency.

10.21.5.5 Technological bottlenecks

Variability, correct installation, interpretation of information, easy-to-use software, the relatively short life of sensors.

10.21.5.6 Benefit for the grower

Advantages

- Water/Fertiliser savings
- Low cost of equipment
- Very little preparation required
- Easy maintenance
- Intuitive information provided

Disadvantages

- Installation and interpretation help needed in many cases
- The short life of sensors
- Relative slowness in their response to soil moisture changes

10.21.5.7 Supporting systems needed

Technical assessment during the first periods of use.

10.21.5.8 Development phase

Commercialised.

10.21.5.9 Who provides the technology

Irrometer.

10.21.5.10 Patented or not

A Granular matrix sensor for electronically measuring soil water has been patented (Larson, 1985: Hawkins, 1993) and is marketed as the Watermark soil moisture sensor (Irrometer Co., Riverside, CA).

10.21.6. Which technologies are in competition with this one

Plant Sensors, Remote sensing, Soil moisture sensors.

10.21.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.21.8. Description of the regulatory bottlenecks

None.

10.21.9. Brief description of the socio-economic bottlenecks

Saving water is still not an encouragement for farmers in many places of Spain.

Orchards are economically too small to cover the costs of the sensors.

10.21.10. Techniques resulting from this technology

Most irrigation strategies can be complemented and controlled by using these devices, such as Controlled Deficit Irrigation, Partial Root Drying, etc.

10.21.11. References for more information

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10.22. *Time Domain Reflectometry*

(Authors: Luis Bonet[14], Dolors Roca[8], María Dolores Fernández[9])

10.22.1. Used for

- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.22.2. Region

Mediterranean.

10.22.3. Crop(s) in which it is used

- Woody crops
- Annual crops

10.22.4. Cropping type

All soil-bound cropping types.

10.22.5. Description of the technology

10.22.5.1 Purpose/aim of the technology

To provide information about soil water content, which can then be used for determining the amount of water to be applied to an irrigated crop during a certain period.

10.22.5.2 Working Principle of operation

Time domain reflectometry technique is based on the measurement of the displacement time of an electromagnetic wave through a transmission line. The velocity of the wave depends on the dielectric permittivity (ε_a) of the material in contact and surrounding the line, that parameter being proportional to the square of the transit time out and back along the transmission line. The soil is composed of air, minerals, organic matter, and water. ε_a of these materials widely varies from 1 for air to 80 for water, with values of 2 to 3 for the mineral particles. Due to the large difference between water ε_a and that of the rest of the soil components, electromagnetic wave velocity will depend mainly on soil water content, which may be determined by knowing ε_a. Toppet et al. (1980) established an empirical relationship between ε_a and volumetric soil moisture (VWC) for a range of frequencies between 1 MHz and 1 GHz:

$$VWC = -5{,}5 * 10^{-2} + 2{,}92 * 10^{-2}\varepsilon_a - 5{,}5 * 10^{-4}\varepsilon_a^{2} + 4{,}3 * 10^{-6}\varepsilon_a^{3}$$

The pulse from the oscilloscope moves towards the stainless-steel rod of the probe to its ends and is reflected (Figure 10-33). The TDR could be made with different lengths of rod, from 4-50 cm. The number of rods used to be 2, but there are other designs with 3 or even more.

The rods have to be inserted into the soil, vertically or horizontally, taking into account that the measure is obtained as the average along the rod.

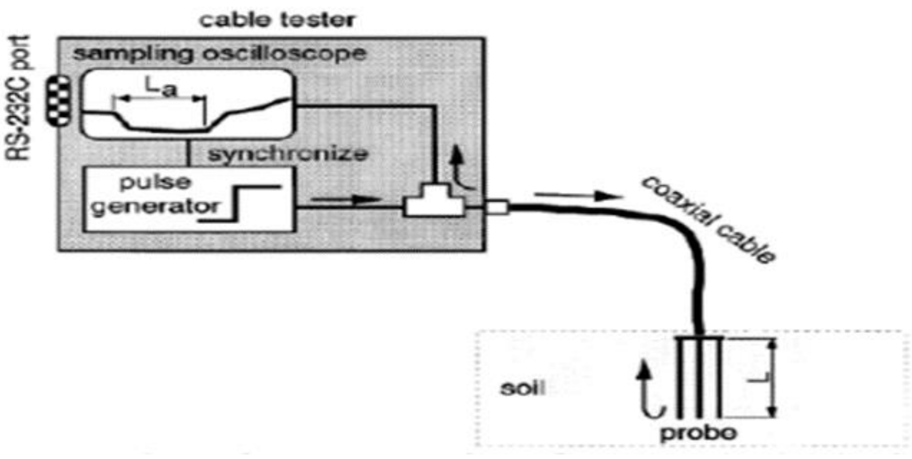

Figure 10-33. Schematic representation of TDR probe (Noborio, 2001)

10.22.5.3 Operational conditions

This technique gives accurate results within an error limit of ±1% and allows continuous measurements over the full soil moisture range, along with measurements of the electrical conductivity of the soil. These sensors are especially suitable for short root crops. TDR, for non-permanent installations or shallow samples, is a non-destructive and relatively less labour-intensive technique, in relation with other soil moisture techniques as can be gravimetric soil moisture or other soil moisture sensors that it need permanent installation; the instrument used could be portable, probes are easy to install and safe to operate. This technique allows reliable measurements of volumetric water content to be made within a short time. No soil-specific calibrations are required.

10.22.5.4 Cost data

A single probe costs around 400 € plus the portable display that costs 500 €. In case of a permanent logger, the prices could vary from 300 € with a manual discharge to 1000 € with GPRS transmission and multiple channels.

Annual transmission data costs 40-200 €, depending on the company and the uploading frequency.

10.22.5.5 Technological bottlenecks

High price, the variability of the measure for small sensing volumes, correct installation is essential, interpretation of information help is needed in many cases, not easy-to-use software, cable length limitations. TDR probes are environmentally sensitive and the probe length influences the accuracy of the moisture. Consequently, the measurements could be erroneous due to gaps between the soil and probe. Further, it has limited applicability in highly saline soils.

10.22.5.6 Benefit for the grower

Advantages

Water/Fertiliser savings.

Disadvantages

- Expensive
- Installation (especially in stony soils) and interpretation help needed in many cases

10.22.5.7 Supporting systems needed

Technical assessment during the first periods of use.

10.22.5.8 Development phase

Commercialised.

10.22.5.9 Who provides the technology

- HydroSense by Campbell Scientific (https://s.campbellsci.com/documents/us/category-brochures/b_soil_water.pdf)
- Trime by Imko (https://imko.de/en/about-trime-tdr)
- FieldScout TDR 300 Soil Moisture Meter (http://www.specmeters.com/soil-and-water/soil-moisture/fieldscout-tdr-meters/)
- Specialised Companies that provide on crop management

10.22.5.10 Patented or not

Unknown.

10.22.6. Which technologies are in competition with this one

Plant sensors, remote sensing, other soil moisture sensors (capacitance sensors).

10.22.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.22.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

10.22.9. Brief description of the socio-economic bottlenecks

In countries such as Spain, the optimisation of irrigation is not a high priority for many growers.

TDR systems are relatively expensive as far as soil moisture sensors are concerned. Capacitance sensors are being presently used for irrigation management rather than TDR sensors because of their lower cost.

10.22.10. Techniques resulting from this technology

Deficit irrigation strategies, such as Controlled Deficit Irrigation, Partial Root Drying, etc., can be complemented and controlled by using these devices.

10.22.11. References for more information

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10.23. Capacitance probe

(Authors: Jadwiga Treder[12], Benjamin Gard)*

10.23.1. Used for

More efficient use of water.

10.23.2. Region

All EU regions.

10.23.3. Crop(s) in which it is used

- Annual vegetable crops
- Fruit crops (orchards and berry plantations)
- Ornamental plants

10.23.4. Cropping type

All cropping types.

10.23.5. Description of the technology

10.23.5.1 Purpose/aim of the technology

The purpose of capacitance probe is to measure the volumetric soil water content in order to indicate when and how much to irrigate.

10.23.5.2 Working Principle of operation

This probe measures the dielectric permittivity of soil/growing medium, which is highly dependent on water content (moisture). The dielectric constant in a dry material consisting of soil particles is relatively small (2-5) whereas the dielectric water constant is ~80 (room temperature). Dielectric permittivity is determined by measuring the capacitance between two electrodes implanted in the soil. The probe is subjected to excitation at a frequency (10-100MHz) to permit measurement of the dielectric constant (Figure 10-34).

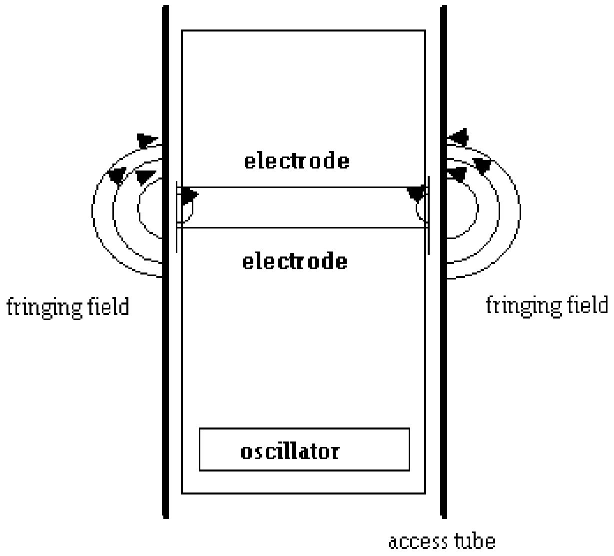

Figure 10-34. Schematic diagram of a capacitance probe in an access tube (White & Zegelin, 1994)

10.23.5.3 Operational conditions

Measurements are influenced by several factors: soil structure, soil texture, temperature, specific salinity and the contact between the soil and the sensor. The probe requires calibration and can provide the absolute value of the soil moisture at any depth as well as the moisture profile with several sensors, distributed on the probe. The choice of a proper sensor is determined by many factors such as the type of soil/growing medium, the required accuracy, cost and ease of use. The way of installing a probe depends on its design and cropping system. Small size sensors can be inserted directly into the soil at a different depth (e.g. 20, 40, 60 cm) and connected to a logger unit. This method can be used for trees and shallow rooting plants (e.g. berry crops, vegetables). A probe that measures the moisture automatically at the desired levels (e.g. every 10 cm) can also be used. An access tube is installed in the soil and readings are taken through the wall of the tube. There are different probe lengths available.

It is recommended to place probes/access tubes close to the active root area, within the irrigated area (if applied), however not directly under a drip emitter (if used).

In containerised plants, a sensor is installed directly in soil/growing medium a few centimetres from the container walls due to the sensor's zone of influence.

Results can be presented in percent (volumetric), m^3/m^3, mm (per depth range – soil profile sensors) or imperial units (depends on the type of sensor).

10.23.5.4 Cost data

Sensors are expensive and long-term sustainability is questionable because of the calibration requirement. For instance, a capacitance probe with 4 sensors, 60 cm long, costs 1000 €. With data logging and remote transmission 2000 €. In Central-East Europe (Poland) the cost of a single (simple) capacitance sensor is about 150 €, multiparameter sensors (moisture, temperature, EC) – 340 €, handheld sensor read-out units – 700 €, a data logger – 700 € (standard) - 1400 € (with GPRS modem).

The purchase costs of sensors can vary appreciably between different manufacturers.

Yearly maintenance or inputs needed: calibration according to the soil characteristics, ensuring a good contact between probe and soil. Costs of data transfer (if wireless transmission is used) – 100 €/year/logger (5 channels).

10.23.5.5 Technological bottlenecks

The effect of temperature on the quality of moisture measurements conducted with the capacitance method should be considered, especially in soilless cultivation systems due to the limited volume of substrate (temperature fluctuations over time) and altered microclimate (if cultivated under protected conditions). Changes in soil salinity can influence the readings of some sensors.

10.23.5.6 Benefit for the grower

Advantages

- Response time is instantaneous
- High level of precision
- Can be read continuously by remote methods
- Sufficiently accurate for irrigation scheduling
- Applicable in soilless cultivation under protected conditions
- Calibration supplied by a manufacturer is often sufficient for monitoring changes in mineral soil water status
- Multi-parameter probes are available (they measure water content, temperature and, for some sensors, EC)
- Applicable for direct control of irrigation valves (under development)
- More reliable than tensiometer
- Responds over a much larger range of soil moisture contents (15-180 cbar) than a tensiometer

Disadvantages

- Expensive
- Less precise than TDR probe
- Calibration is recommended
- Influence of salinity (in modern sensors less pronounced) and temperature (important especially in container production systems)
- Careful site selection is critical to get good representative information (because of the costs, often only one probe is used to monitor a field)
- Specific (for a given medium) calibration may be necessary

10.23.5.7 Supporting systems needed

Advice from suppliers or extension services may help growers to better use the technology and to determine threshold values for crops. Data logging and remote transmission can facilitate the use of capacitance probes.

10.23.5.8 Development phase

- Research: see below
- Experimental phase: see below
- Field test: system controllers, control algorithms which use capacitance probes for direct controlling irrigation valves are being examined and developed
- Commercialised: a variety of capacitance sensors/loggers are available on the market

10.23.5.9 Who provides the technology

Several retailers (Sentek, John Deere, Aquacheck, Buddy, Gopher, Decagon Devices, Spectrum Technologies, etc.).

10.23.5.10 Patented or not

Generic technology. Suppliers build own constructions. Some construction solutions may be patented.

10.23.6. Which technologies are in competition with this

All technologies to measure soil water status: tensiometers (measures soil water potential), electrical resistance sensors, digital ground-penetrating radars, TDR probes, neutron scattering (currently rarely used), gravimetric analysis (sample destructive, laboratory method used for calibration of other methods).

10.23.7. Is the technology transferable to other crops/climates/cropping systems?

Capacitance probes are being used with a wide range of crops, climate and cropping systems

10.23.8. Description of the regulatory bottlenecks

There are no relevant European directives or regulatory bottlenecks at European, country and regional level.

10.23.9. Brief description of the socio-economic bottlenecks

The main socio-economic bottlenecks are the high costs, knowledge of the technology, proper interpretation of the obtained results, basic knowledge about plant-soil-water relations, need for calibration in some situations, probes are often hardly available in the market (in Poland, in most cases irrigation companies do not have this type of equipment in basic offer) and lack of advice for the good use.

These sensors are commonly used by commercial growers in countries such as Australia and the USA. There are often local suppliers who also provide on-going technical support.

Generally, most growers learn how to use this technology so that they can work independently with it.

10.23.10. Techniques resulting from this technology

Irrigation scheduling with capacitance probe.

10.23.11. References for more information

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10.24. Digital penetrating radar

(Authors: Claire Goillon[2], Carlos Campillo[5], Benjamin Gard)*

10.24.1. Used for

More efficient use of water.

10.24.2. Region

All EU regions.

10.24.3. Crop(s) in which it is used

All soil bound vegetable and fruit crops.

10.24.4. Cropping type

- Soil-bound
- Protected
- Open air

10.24.5. Description of the technology

10.24.5.1 Purpose/aim of the technology

Measuring of the soil moisture through the measurement of electromagnetic energy.

10.24.5.2 Working Principle of operation

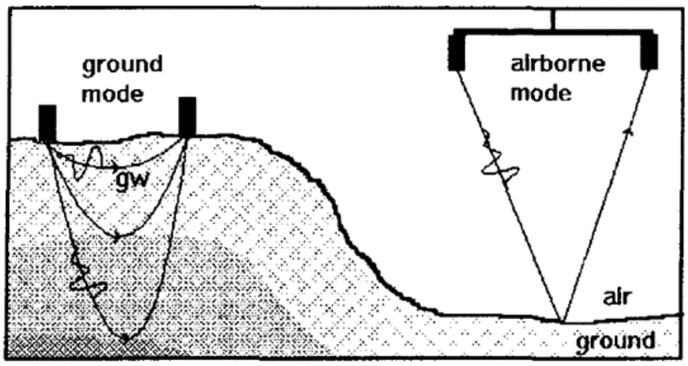

Fig. 1. The operating modes of the ground-penetrating radar. Transmitter and receiver are shown as black boxes.

Figure 10-35. The operating modes of the ground-penetrating radar

Measurements are based on the transmission and reflection of an electromagnetic wave in the soil. The transmitter antenna of the radar system generates radio-waves propagating in a broad beam. The receiver detects variations in the electrical properties of the sub-surface by detecting the part of the transmitted signal that is reflected. The electrical properties are mainly due to the water content in natural soils, thus the difference between the transmission and the reflection of the electromagnetic wave matches to the soil moisture. The less the difference, the more water is present in the soil. There are two systems of measurements: the first has the antenna on the soil surface (ground mode) and the second has the antenna in the air (airborne mode). The system must be calibrated on a large surface of which the measured reflections are known.

10.24.5.3 Operational conditions

This is a method well suited for acquisition of soil moisture across large areas. But the use of this technology is limited because many soil types are radar opaque and dissipate radar energy (they have a high electrical conductivity - EC). It is necessary that there isn't a shallow water table or a stratigraphic transition because the electromagnetic wave would be reflected. On a crop with a large canopy, the measurements are erroneous because trees behave as reflectors. For the ground mode, the equipment needs to be moved for the radar to examine the specified area by looking for differences in material composition.

10.24.5.4 Cost data

Complete systems: transmitter antenna, receiver antenna, control unit, a display unit, power unit and software and GPS, depends on the manufacturer cost varies between 15000 and 20000 €.

10.24.5.5 Technological bottlenecks

The choice of the good wave (Hz). Low frequencies (a few MHz) give good depth penetration but low resolution, we will move between 200 MHz and 1 GHz, depending on the type of soil and its moisture.

10.24.5.6 Benefit for the grower

Advantages

- Fast
- Non-destructive technique
- High resolution
- Remote measurements
- Measurement on a large area which overcomes the limitation of point sampling techniques

Disadvantages

- Large and complex system
- Expensive
- Usually used for soil surface
- Interpretation of data needs experience
- Strong expertise is needed to design, conduct, and interpret ground penetrating radar (GPR) surveys
- Not possible an automatic measurement in soil with high clay and salinity

10.24.5.7 Supporting systems needed

It's necessary to have the equipment to measure electromagnetic waves (transmitter antenna and receptor antenna and a control unit, for example, Pulse EKKO IV GPR). Interpretation of the results can be done solely by someone trained in GPR analysis.

10.24.5.8 Development phase

Commercialised.

10.24.5.9 Who provides the technology

Companies like Mala, Leica, Radio detection provide this technology.

Several companies specialised in GPR analysis offer services for soil analysis and hydrologic investigations.

10.24.5.10 Patented or not

The technology is not patented but the different devices are patented.

10.24.6. Which technologies are in competition with this one

Time domain reflectometry, capacitance probe.

10.24.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.24.8. Description of the regulatory bottlenecks

None.

10.24.8.1 Brief description of the European directive and implications for growers at European level

Directive 2014/53/EU of the European Parliament and of the Council of 16 April 2014 on the harmonisation of the laws of the Member States of the making available in the market of radio equipment and repealing Directive 1999/5/EC Text with EEA relevance. Applicable as of 13 June 2016.

The European Commission (EC) decided to include GPR/WPR within the scope of the Radio and Telecommunications Terminal Equipment (R&TTE) Directive 1999/5/EC.

Protection of the health and safety of the user and any other person, including the objectives, set out in with respect to the safety requirement in the low voltage directive 73/23/EEC, but with no voltage limit applying.

The protection requirement with respect to electromagnetic compatibility (EMC) contained in the Directive 89/336/EEC.

10.24.9. Brief description of the socio-economic bottlenecks

This technology is expensive. A strong experience is needed to conduct such GPR analysis. GPR analysis may be interesting for a hydrologic investigation on soil, to have a clear image of soil water content or soil layers but it is not suitable for irrigation management. This technology seems currently to be more suitable for research studies and experiments rather than for on-farm irrigation management.

10.24.10. Techniques resulting from this technology

Soil Cartography at the farm scale.

10.24.11. References for more information

[1] Chanzy, A., Tarussov, A., Bonn, F., & Judge, A. (1996). Soil water content determination using a digital ground-penetrating radar. *Soil Science Society of America Journal*, *60*(5), 1318-1326

[2] Zazueta, F. S., & Xin, J. (1994). Soil moisture sensors. *Soil Science*, *73*, 391-401

[3] Dobriyal, P., Qureshi, A., Badola, R., & Hussain, S. A. (2012). A review of the methods available for estimating soil moisture and its implications for water resource management. *Journal of Hydrology*, *458*, 110-117

10.25. Slab balances

(Authors: Alain Guillou[4], Esther Lechevallier[4], Jadwiga Treder[12])

10.25.1. Used for

More efficient use of water.

10.25.2. Region

All EU regions.

10.25.3. Crop(s) in which it is used

Tomato, cucumber, leafy vegetable, strawberry.

10.25.4. Cropping type

- Protected
- Soilless

10.25.5. Description of the technology

10.25.5.1 Purpose/aim of the technology

Automatic balance systems can be used to continuously measure the weight of substrate slabs or containers with plants. Real-time monitoring of changes in the weight of slabs or containers with plants is used to trigger irrigation when threshold weight values are reached. The decrease in weight over time is an indication of the amount of water lost through transpiration, evaporation, and leaching (if applicable). This decrease in weight can then be used to determine how much water needs to be applied to replenish the soil/substrate, thus providing a simple and direct method for irrigation control. Balances can be used to quantify the daily water loss and after calibration can be used to estimate the soil moisture of the growing media. The balance helps to determine the number of irrigation events and the amounts applied during the day.

10.25.5.2 Working Principle of operation

The basic concept behind this technique is simple: the substrate and crops are considered as having a relatively constant weight. The variation in measured weight is the variation in available water in the substrate. A slab or container is heaviest when it has just been irrigated but loses weight over time as water is lost by evaporation and transpiration. When the container weight reaches a predetermined weight (threshold value), it is time to irrigate.

The simplest balance consists of a load cell mounted, on a base, with a weighing platform or a platform hanging from the load cell (Figure 10-36 and Figure 10-37). Standing platforms are used for tomato, cucumber, pepper in soilless systems and in container nurseries. Hanging platforms are used in the cultivation of strawberries and ornamental plants.

A balance generally holds two substrate slabs (8-12 crops for a tomato crop). Direct and continuous in-situ measurements (~ every 5 minutes) are recorded by software and can be displayed on the control computer.

The balance can be equipped with a device that enables measurement of the drainage volume from the substrate. In doing so, the measurement of volumes supplied and drained, and the continuous weighing of the substrate helps to optimise irrigation through specialised software.

The software determines when to irrigate according to a transpiration calculation in combination with measurement of the substrate weight and drainage volume. The balance can also be used as a simple control and adjustment tool without acting directly on irrigation programming.

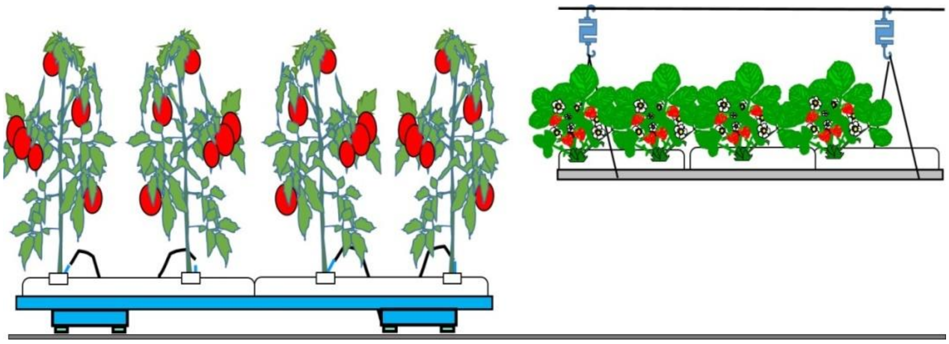

Figure 10-36. Balance that accurately monitors the weight of substrate and/or plants (Source: INHORT)

Figure 10-37. Substrate weighing under a tomato crop (Source: CATE)

10.25.5.3 Operational conditions

It is the plants themselves that determine the amount and timing of irrigation with high accuracy based on calculations that consider the amount of water absorbed by the plant, the water content in the substrate and the drainage volume. These weight and drainage measurement are continuously performed. This enables optimal irrigation which ensures optimal crop water status, good aeration of roots, and avoids unnecessary costs through the excessive application of water and nutrients.

It is used in soilless greenhouses, with vegetable crops, with aromatic and ornamental species.

The size of the slab balances depends on the manufacturer, for example, PRIVA slab balance: drain measurement with capacity 10 L/h and drain gutter lengths of 2 m and 2,8 m and maximum load up to 100-200 kg.

10.25.5.4 Cost data

Installation: 1 balance, with the software program: 3600 €.

10.25.5.5 Technological bottlenecks

Site selection is important. It is necessary to avoid locating the balance in unrepresentative parts of the greenhouse. Once the balance is placed, it is not possible to move it to another place. If plants on the balance die, that can be a problem.

10.25.5.6 Benefit for the grower

Advantages

- Accurate information about plant water needs, irrigation fine-tuning is possible
- Direct on-time monitoring
- Automatic irrigation control based on transpiration rate

Disadvantages

- The device cannot be moved once it is installed at the beginning of the season
- High costs
- Basic technical knowledge is necessary to interpret the results
- Requires regular monitoring of the accuracy of operation

10.25.5.7 Supporting systems needed

A data collection and support system related to the control computer is required. It requires initial training and support. The balance can be coupled to a device measuring the drainage volume.

10.25.5.8 Development phase

Commercialised.

10.25.5.9 Who provides the technology

PRIVA (Groscale), HORTIMAX (Prodrain, Newton), Hoogendoorn (HGM Balance/ Aquabalance).

10.25.5.10 Patented or not

Patented.

10.25.6. Which technologies are in competition with this one

Irrigation controllers equipped with moisture sensors. Irrigation controllers calculating the dose and frequency of irrigation based on evapotranspiration.

10.25.7. Is the technology transferable to other crops/climates/cropping systems?

Yes. Transferable to soilless systems using substrate slabs/pots.

10.25.8. Description of the regulatory bottlenecks

None.

10.25.9. Brief description of the socio-economic bottlenecks

The equipment and supporting software are costly. The grower should be trained to use it.

10.25.10. Techniques resulting from this technology

Crop monitoring: The balance helps determine the number and the doses of irrigation events to bring the substrate to its pre-defined maximum weight in the morning. The balance helps the grower to determine the start and end times of these irrigation events depending on the weight loss wanted during the night (e.g. for a tomato crop on coir substrates, a 10-15% loss of substrate weight from the last irrigation on day D to the first irrigation on day D+1) (Figure 10-38). The balance helps to verify that the irrigations maintain the substrate moisture within the optimal range. The balance also helps the grower to observe the behaviour of the substrate regarding water retention and to plan either fewer irrigation events with bigger doses or more irrigation events with less water provided.

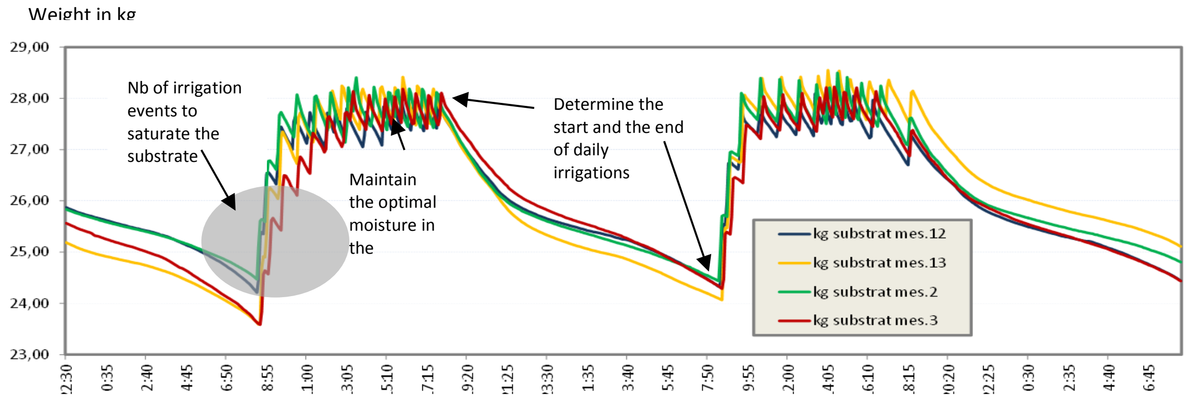

Figure 10-38 Evolution of the substrates' weight in 4 glasshouses in a soilless tomato crop (Source: CATE)

10.25.11. References for more information

[1] Baille, M., Laury J.C., & Baille. A. (1992). Some comparative results on evapotranspiration of greenhouse ornamental crops, using lysimeter, greenhouse H_2O balance and LVDT sensors. *Acta Horticulturae*, *304*,199-208

[2] Beeson, R.C. Jr. (2011). Weighing lysimeter systems for quantifying water use and studies of controlled water stress for crops grown in low bulk density substrates. *Agricultural Water Management*, *98*, 967–976

[3] Boukchina, R., Lagacé R. & Thériault R. (1993). Automation de l'irrigation d'un module de culture à deux niveaux. *Canadian Agricultural Engineering*, *35*(4), 237-244

[4] Van Meurs, W. & Stanghellini C. (1992). Use of an off-the shelf electronic balance for monitoring crop evapotranspiration in greenhouses. *Acta Horticulturae*, *304*, 219-225

10.26. Drain sensor

(Authors: Alain Guillou[4], Esther Lechevalier[4])

10.26.1. Used for

More efficient use of water.

10.26.2. Region

All EU regions.

10.26.3. Crop(s) in which it is used

All crops.

10.26.4. Cropping type

All cropping types.

10.26.5. Description of the technology

10.26.5.1 Purpose/aim of the technology

The aim of the technology is to measure the quantity of drainage under one or several substrate slabs, or of the total greenhouse area.

10.26.5.2 Working Principle of operation

The quantitative measurement of drainage volume is done using a device which collects the drainage on a collection tray, usually containing one or two substrate slabs (2-3 m) or the whole gutter. The tray is installed with a slight slope so that the drain water flows to a drain trough and the volume is then measured by a measurement unit (Figure 10-39). The measuring unit consists of a mechanical volume sensor: a previously calibrated tipping ladle measures the drain water quantity so that each tip of the ladle represents a specific volume. The data are then sent to a computer and are continuously updated. Using appropriate software, the computer calculates the percentage of applied water that has drained, based on the volume of water supplied to the sector and the drainage measured from the same sector. Every morning before irrigation commences, the device is reset to zero. Usually, this device also measures the water temperature and electric conductivity, in order to have more information for the control of irrigation and nutrient solution composition.

The drainage volume collected from the whole cropping area can be measured by a water meter at the entrance of the storage container for drain water.

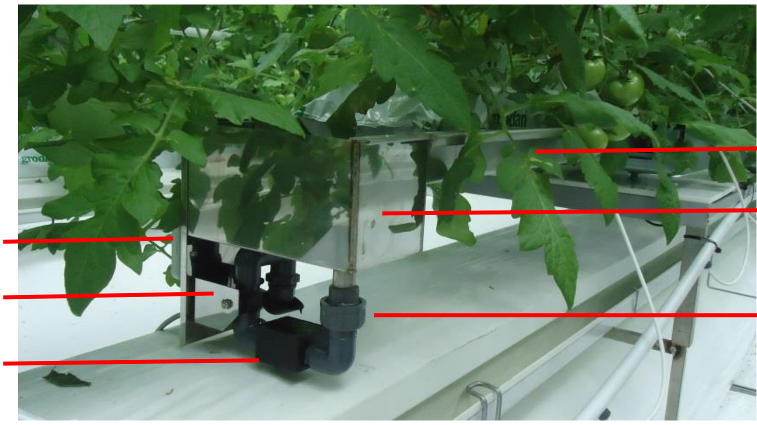

Figure 10-39. A substrate slab balance equipped with a drainage quantity measurement system (PRIVA drain water sensor) (Source: CATE)

10.26.5.3 Operational conditions

The device should be connected to the process computer to centralise the measure and compare it to the water supplied to the crop. Usually, it is coupled to a slab balance so that the grower is able to link the weight variations with the drainage quantity measurement. The device usually has a maximum measuring capacity. Beyond this capacity (in L/h), the tipping ladle is continuously loaded, and some drainage may not be measured.

10.26.5.4 Cost data

For installation: 2345 € (DSS from PRIVA, France).

Yearly maintenance or inputs needed: usual maintenance, no input needed.

10.26.5.5 Technological bottlenecks

No bottlenecks are known (at least in France).

10.26.5.6 Benefit for the grower

Advantages

- Allows a comparison between provided water and drained water, to see if the crop is stressed, over-irrigated, etc.
- Allows prevision of the quantity of drain water that needs to be managed (disinfection, treatment, discharge)

Disadvantages

- The devices (tipping ladle) are often placed on only one or a few sites in the greenhouse so the data might not be representative for the whole greenhouse and the monitoring objectives can be biased (same problem with the slab balances)
- The drainage gauge can be blocked by coir or leaf material which can results in inaccurate measurements. This can result in excessive irrigation and fertiliser application.

10.26.5.7 Supporting systems needed

Computer and software.

10.26.5.8 Development phase

Commercialised.

10.26.5.9 Who provides the technology

PRIVA, Hoogendoorn Aquabalance, Hortimax.

10.26.5.10 Patented or not

The technology is not patented but the specific sensors might be.

10.26.6. Which technologies are in competition with this one

- Integrated solutions that take into consideration both drainage volume and plant growth (e.g. Hortimax, Prodrain, Priva Root Optimizer)
- Manually drainage measurement: Some growers collect daily the drainage for individual slabs and measure the drainage with a measuring jug, but this method is less precise and not continuous

10.26.7. Is the technology transferable to other crops/climates/cropping systems?

Transferable to all soilless systems with drain collection system.

10.26.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

10.26.9. Brief description of the socio-economic bottlenecks

The device is costly compared to a manual measurement.

10.26.10. Techniques resulting from this technology

Monitoring the irrigations depending on the drainage target: The grower sets up a drainage objective depending on the crop type, growth stage, the weather, etc. The instant measure of the drainage will help him to adjust the irrigation dose desired for the next irrigation events.

10.26.11. References for more information

[1] *Drain sensor system* DSS Manual, PRIVA, 2015

[2] Fabre, R., & Jeannequin, B. (1993). Management of water supply in soilless tomato crop influence of drip flow rate on substrates humidity run-off. *Acta Horticulturae*, *408*, 91-100

10.27. Demand tray system

(Authors: Juan José Magán[9], Rodney Thompson[23])

10.27.1. Used for

More efficient use of water.

10.27.2. Region

Mediterranean.

10.27.3. Crop(s) in which it is used

Vegetables.

10.27.4. Cropping type

- Soilless
- Protected

10.27.5. Description of the technology

10.27.5.1 Purpose/aim of the technology

The demand tray is a simple method for automatic activation of the irrigation in soilless cultures.

10.27.5.2 Working Principle of operation

This technology consists of a tray made from fibreglass or from metal that contains one or usually two crop units (substrate bags). The drainage from the substrate accumulates in a channel inside the tray, where there are two vertically-installed adjustable screws at different heights that serve as electrodes for the activation of irrigation (Figure 10-40). This water reservoir is hydraulically connected to the substrate by an absorbent blanket (Figure 10-41), so that water consumption within the substrate causes a water potential difference with respect to the reservoir, thereby promoting water movement towards the substrate and a reduction of the water level in the channel. When water is not in contact with the upper screw, the electrical circuit is open and the resultant electrical signal is detected by the irrigation controller that automatically activates a new irrigation for a fixed time period. The height of the upper screw is regulated to optimise the frequency of irrigation; the irrigation frequency will be excessive if the upper screw is too high, and insufficient if it is too low. To empirically obtain information to assist with the regulation of the screw height, another tray is used, where the drainage volume is measured, and also the electrical conductivity and pH of the drainage are determined.

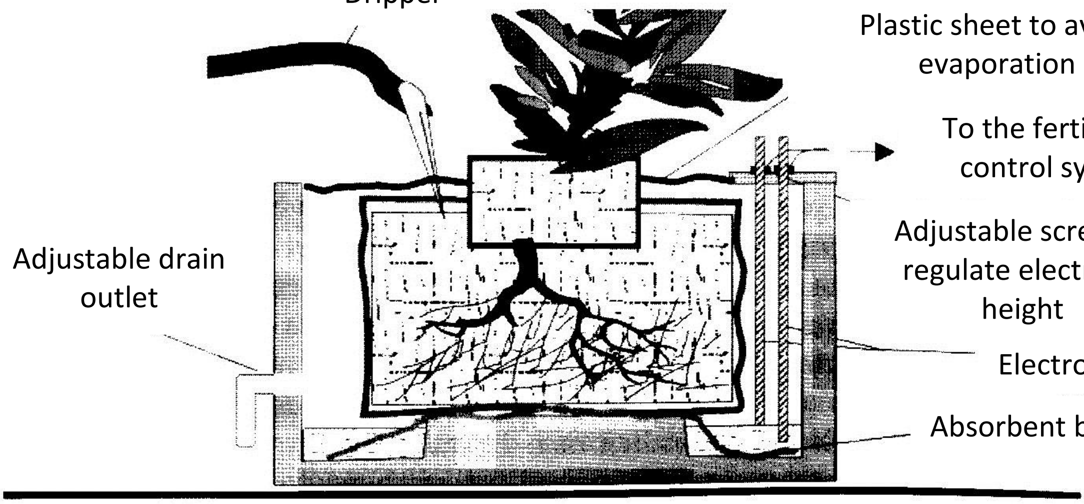

Figure 10-40. Scheme of demand tray system (Urrestarazu, 2004)

Figure 10-41. Picture of demand tray

10.27.5.3 Operational conditions

One tray is required per irrigation sector. It is not recommended to connect more than four demand trays to the same fertigation controller because having too many sectors may make it difficult to irrigate the individual sectors with sufficient frequency during high water demand periods.

This system requires that the plants located in the tray are representative of the entire crop, or at least the sector, and have a uniform development.

10.27.5.4 Cost data

The cost varies depending on the material used to make the tray and the distance to the fertigation controller. The cost ranges at 500-800 €, including tray, screws, wire, accessories, and labour.

- Installation of a new absorbent blanket at the beginning of the crop: 5 €

- Periodical adjustment of the screw height during the crop, especially during the vegetative phase, when there is a progressive increase of leaf area and hence of crop transpiration
- Replacement of the screw if necessary (some models can be affected by an excessively high voltage which can occur during electrical storms): ≈ 125 €
- Cleaning of the screw if necessary to ensure a good electric contact (yearly)

10.27.5.5 Technological bottlenecks

When automating irrigation with this system, the matric potential of the substrate at the start of the irrigation event is not always the same, this value can increase with high water demand (Figure 10-42). (Editor's note: Please note that matric potential is actually negative but commonly is referred to, as here, as being positive. In this case, the real measurements are in units of negative hPa, and when there is high evaporative demand, matric potential values at the start of the may be lower). This effect could be related to the response speed of the system, which is conditioned by the hydraulic conductivity of the absorbent blanket. If water consumption is high, the water flow through the blanket may be too slow to rapidly equilibrate substrate and reservoir water potentials causing a delay in the response of the demand tray and, hence, in activating irrigation. On the other hand, the plants in the demand tray have an additional reservoir of water compared to the rest of the crop; this can also influence the water supply in the substrate bags on the demand tray.

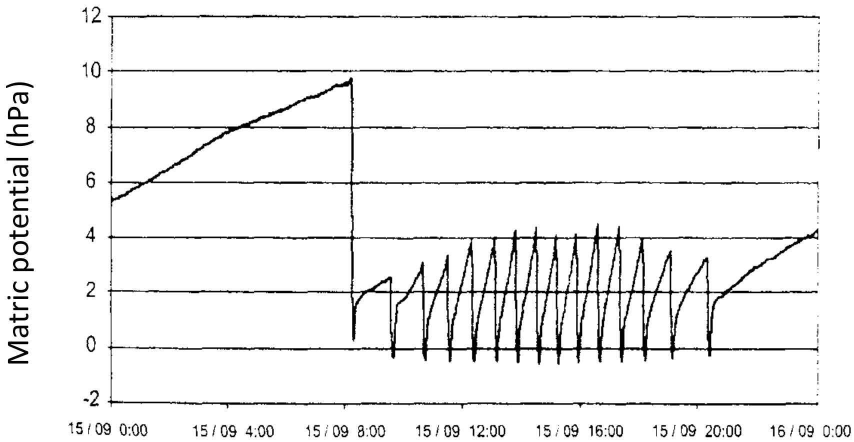

Figure 10-42. Evolution of the substrate matrix potential in rockwool-grown tomato on a sunny day. Watering activation was automated by a demand tray and matrix potential was measured by a tensiometer (Terés et al., 2000)

10.27.5.6 Benefit for the grower

Advantages

- Very simple
- High reliability
- Low initial investment
- Low maintenance costs
- Technology widely developed and readily available

Disadvantages

- It cannot be used soon after transplanting because there is not sufficient root development
- It does not give information about the water status of the substrate
- There is a problem if plants growing in the tray die during the cropping cycle. It is not possible to change the substrate units if plants are too big.

10.27.5.7 Supporting systems needed

The demand tray has to be connected to a fertigation controller for automatic activation of irrigation.

10.27.5.8 Development phase

Commercialised.

10.27.5.9 Who provides the technology

Different companies installing irrigation and fertigation systems.

10.27.5.10 Patented or not

This technology is not patented.

10.27.6. Which technologies are in competition with this one

Sensors measuring water status of the substrate (tensiometers, capacitance sensors)

- Irrigation control system based on radiation measurement (usually combined with automatic measurement of drain volume)
- Crop evapotranspiration models
- Weighing scales

10.27.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

10.27.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

10.27.9. Brief description of the socio-economic bottlenecks

There are no socio-economic bottlenecks.

10.27.10. Techniques resulting from this technology

Irrigation control by programmed irrigations during the beginning of the crop, followed by use of the demand tray once there is good root development. The demand period is usually from 1-2 hours after sun rises to 1-3 hours before sunset. The demand tray can be associated with programmed irrigations during the night in high water demand periods.

10.27.11. References for more information

[1] Lorenzo, P., Medrano, E., & García, M. (1996). Estudio comparativo de la eficiencia hídrica de dos sistemas de control de riego en sustrato. *XIV Congreso Nacional de Riegos, D.G.I.A. Congresos y Jornadas*, *37*, 668-672

[2] Medrano, E., & Alonso, F.J. (2008). Programación del riego en cultivos en sustrato. In: *Relaciones hídricas y programación de riego en cultivos hortícolas en sustratos*. Edited by INIA and IFAPA, pp. 37-48

[3] Terés, V., Artetxe, A., Beunza, A., Pereda, J., & Majada, J. (2000). Utilización del laptómetro para el control de riego en sustratos de cultivo. *Actas de Horticultura*, *32*, 69-84

[4] Urrestarazu, M. (2004). Bases y sistemas de los cultivos sin suelo. En: *Tratado de cultivo sin suelo* (M. Urrestarazu), Ediciones Mundi-Prensa, pp. 3-47

[5] Gallardo, M., Thompson, R.B., & Fernández, M.D. (2013). Water requirements and irrigation management in Mediterranean greenhouses: the case of the southeast coast of Spain. In: *Good Agricultural Practices for Greenhouse vegetable crops. Principle for Mediterranean climate areas*. FAO, Rome, pp. 109-136

10.28. Weather sensors

(Authors: Jadwiga Treder[12], Carlos Campillo[5])

10.28.1. Used for

- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

10.28.2. Region

All EU regions.

10.28.3. Crop(s) in which it is used

It may be used in many crop types: fruit crops, vegetables, ornamentals, agricultural crops.

10.28.4. Cropping type

All cropping types.

10.28.5. Description of the technology

10.28.5.1 Purpose/aim of the technology

Weather sensors are used for measurement of basic climatic parameters (temperature, humidity, atmospheric pressure, precipitation, solar radiation, wind speed and wind direction). Access to the weather data is crucial for estimating water needs for open air and greenhouse crops. The weather data are used to calculate reference evapotranspiration (ETo). This is an important weather parameter to calculate crop water needs and to determinate different water needs between different irrigation zones in the same crop. The correct estimation of the ETo will permit a more efficient water use. Knowledge of local rainfall helps to reduce irrigation.

Parameters such as VPD (relation between temperature and relative humidity) can affect threshold values of different sensors. For example, threshold values of plant water potential can vary with VPD for the same plant water status.

Different crop water relation parameters such as crop water stress index need air temperature and VPD to establish if the crop is in a water stress situation.

Data obtained from weather sensors are used for simulation models that predict the risk of disease and insect pest outbreaks, and the risk of physiological disorders during storage. Temperature monitoring plays a key role in preventing spring frost damage. Sensors are also used in greenhouse climate control systems. Light, temperature, air humidity need to be effectively adjusted to optimise conditions for crop growth in greenhouses. Moreover, monitoring the influence of the external conditions (wind, precipitation) on the internal greenhouse climate is crucial for optimal greenhouse climate management.

10.28.5.2 Working Principle of operation

Evapotranspiration refers to the combined loss of water from soil (evaporation) and plant (transpiration) surfaces. It can be estimated from weather data. This “reference” ETo can be used to determine the irrigation required to replace the water used by a crop. To calculate crop evapotranspiration (ETc) (crop water requirements), it is necessary to multiply ETo by a "crop coefficient" value. These coefficient values are provided for various crops, and change during the growing season to reflect changes in the size of the crop canopy. A wide range of equations has been developed for the estimation of ETo. Simple equations require only measurements of one meteorological parameter (air temperature) as an input (e.g. Hargreaves equation) or two parameters (air temperature, humidity) as inputs (e.g. Grabarczyk equation). The Penman-Monteith equation is considered to be most consistent over a wide range of climatic conditions. It is used as the international standard equation for calculating ETo. The Penman-Monteith equation requires a significant amount of meteorological data input, including radiation, air temperature, air humidity and wind speed data, which creates complexity in data collection and computation. This equation is most often implemented in weather station software calculating ETo.

Figure 10-43 shows a type of station used to obtain data to enable calculation of ETo, with the different equations previously described for open-air crops. These data of the local conditions will be used by computer-based DSS to calculate crop ETc or crop water needs, as a product between ETo and the crop coefficient (Kc).

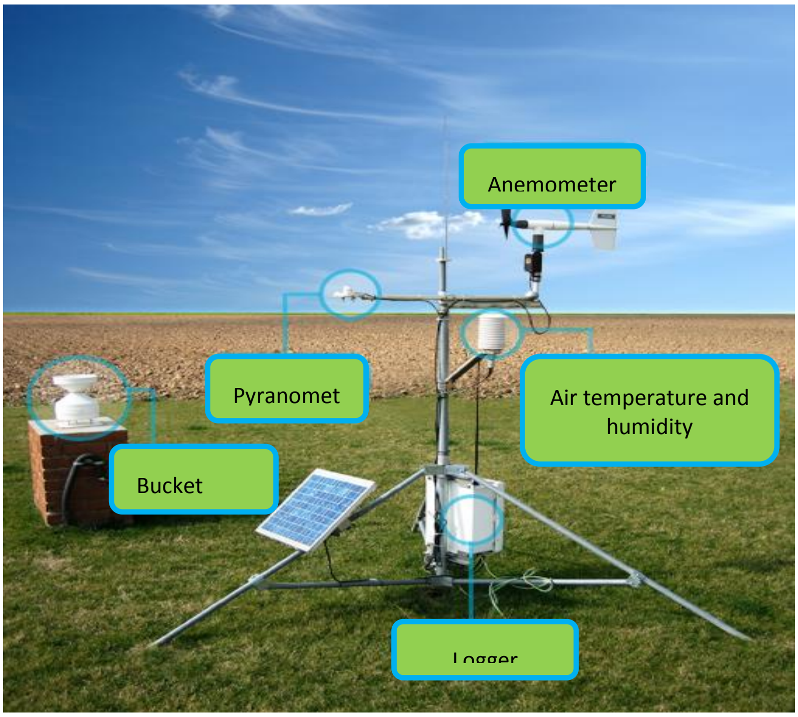

Figure 10-43. Agrometeorological station with all sensor to calculate ETo Penman-Monteith model in open air. (Image from Red SiAR http://www.mapama.gob.es/es/desarrollo-rural/temas/gestion-sostenible-regadios/sistema-informacion-agroclimatica-regadio/presentacion.aspx)

In the case of greenhouses, the calculation of ETo require solar radiation data that is obtained from a solarimeter or pyranometer that is often placed outside, and transmissivity values (percentage of solar radiation transmitted by the cover material) are used to estimate solar radiation inside the greenhouse. Accumulated solar radiation can be used to trigger irrigation. When the accumulated solar radiation reaches a certain value, chosen by the user, a control order is transmitted to an irrigation controller. The chosen value is the “trigger point”, expressed in J/cm².

10.28.5.3 Operational conditions

There are many types of commercially available sensors. Depending on their construction they might have the different methods of operation, durability, operating range and sensitivity (e.g. spectral sensitivity for solar radiation sensors).

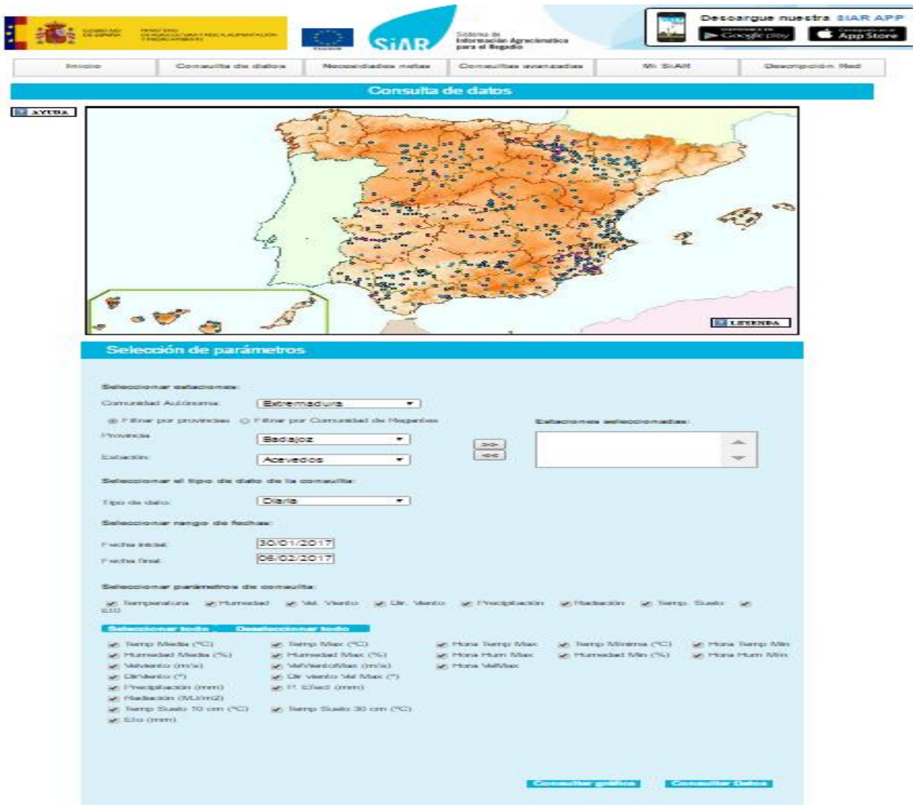

Figure 10-44. SiAR NET (http://eportal.magrama.gob.es/websiar)

In some countries, agrometeorological data can be downloaded from the Internet. e.g. the SiAR network of agricultural weather stations (http://www.magrama.gob.es/siar/), created in 1998 by the Spanish Ministry of Agriculture in cooperation with regional governments. A web page publishes daily-updated agrometeorological information for each agricultural weather station of the SiAR network (Figure 10-44). Published information includes standardised reference evapotranspiration values estimated by the FAO Penman-Monteith method (Allen et al., 1998).

10.28.5.4 Cost data

Installation

Cost of the weather station depends on the manufacturer: 2500 € – simple data logger with basic sensors, 6000 €– automatic station with weather sensors and GPRS data transmission to the computer. Decagon weather station costs 3500-5000 € and Imetos® station (Fieldscan) € 4500-5000 €.

Yearly maintenance or inputs needed

Costs of data transmission (GPRS card) and maintenance (calibration of the sensors) should be considered. The pyranometer should be cleaned from time to time to ensure reliability of the date. Annual calibration is advised.

10.28.5.5 Technological bottlenecks

Sensors available on the market have a different operating range, sensitivity, response time and accuracy. Proper sensor exposure, levelling and orientation are key to obtain accurate weather data.

Sensor performance should be regularly verified. Appropriate calibrations and adjustments should be performed to eliminate errors of sensors. Incorrect data inputs result in erroneous ETo calculations.

10.28.5.6 Benefit for the grower

Advantages

- Improving water use efficiency in crop production systems, predicting disease and pest outbreaks, monitoring and controlling greenhouse climate
- Automatic weather stations (with an autonomous power source) save human labour and enable measurements from remote areas (wireless communication) assuring quick access to the weather data

Disadvantages

- Substantial start-up expenses (costs of sensors, station siting)
- Periodic maintenance and calibration is important to assure reliable results and to maximise the lifespan of the sensors

10.28.5.7 Supporting systems needed

Access to the Internet if wireless transmission of data (GSM/GPRS network) is considered (in most cases the data are available on the supplier's website).

Access to reference instruments and methods (calibration service is often offered by the sensors supplier or independent laboratories).

10.28.5.8 Development phase

- Research: comparisons, validations and improvements of different evapotranspiration models in different climatic regions (to increase their accuracy)
- Experimental phase: climate monitoring and management systems are developed and tested
- Field tests: climate monitoring and management systems are developed and tested.
- Commercialised: many types of sensors are available for use in agricultural and horticultural production systems

10.28.5.9 Who provides the technology

Many suppliers.

10.28.5.10 Patented or not

Not patented.

10.28.6. Which technologies are in competition with this one

The irrigation requirements can be also estimated by monitoring soil water status (water content/potential). Sensors measuring water content and potential are commercially available. The best solution is to combine these two approaches – use weather data for calculating plant water needs (evapotranspiration) and control effectiveness of the irrigation with soil moisture sensors.

Evapotranspiration (plant water requirements) can also be estimated with lysimeters.

10.28.7. Is the technology transferable to other crops/climates/cropping systems?

Yes. The technology is broadly applicable to many climates/cropping systems.

10.28.8. Description of the regulatory bottlenecks

There are no specific regulatory bottlenecks related to the technology use. It is safe and produces no wastes.

10.28.9. Brief description of the socio-economic bottlenecks

There are no specific socio-economic bottlenecks. In many countries, the problem of meteorological data availability exists. Due to this data limitation, simpler (less accurate) models are used for ETo calculation.

10.28.10. Techniques resulting from this technology

There are many suppliers offering weather sensors of different construction and operation principles.

In the open air: Different decision support systems use an ETo calculation to manage irrigation scheduling. These systems normally use an ETo calculation of Penman-Monteith equations and Kc to calculate the water needs for application in the determinate day and determinate irrigation zone. In Spain, there are DDS models available in all regions to calculate an ETc of the most important crops, through SiAR. In Figure 10-45, the irrigation scheduling recommended in the web of Extremadura Advisory network to the irrigator (REDAREX) from SiAR are showed.

PROGRAMACIÓN DE RIEGO

Fecha	D. ciclo	h	Zr	Fw	CRDC	Eto	Kc	ETc	P	P. eff	NN	NB	DASP	DR	DR_min	DotR_min
15-05-2014	31	2.5	0.5	100	100	7.09	0.18	1.28	0	0	1.28	1.6	30	30.48	263	0
16-05-2014	32	2.5	0.5	100	100	6.56	0.21	1.38	0	0	1.38	1.73	30	32.21	278	0
17-05-2014	33	2.5	0.5	100	100	6.04	0.24	1.45	0	0	1.45	1.81	30	34.02	294	0
18-05-2014	34	2.5	0.5	100	100	5.98	0.27	1.62	0	0	1.62	2.03	30	36.05	311	0
19-05-2014	35	2.5	0.5	100	100	5.03	0.3	1.51	0	0	1.51	1.89	30	37.94	328	0
20-05-2014	36	2.5	0.5	100	100	3.64	0.33	1.2	1.2	0	1.2	1.5	30	39.44	341	0
21-05-2014	37	2.5	0.5	100	100	3.57	0.35	1.25	6.3	2.9	-1.63	-2.04	30	37.4	323	0
22-05-2014	38	2.5	0.5	100	100	4.8	0.38	1.82	0	0	1.82	2.28	30	39.68	343	0
23-05-2014	39	2.5	0.5	100	100	4.65	0.41	1.9	0	0	1.9	2.38	30	42.06	363	0
24-05-2014	40	2.5	0.5	100	100	5.1	0.44	2.24	0	0	2.24	2.8	30	44.86	388	0

Figure 10-45. Processing tomato Irrigation scheduling recommended by Extremadura Advisory network to the irrigator web (http://redarexplus.gobex.es)

In greenhouses: Decision support systems to manage irrigation scheduling based on solar radiation accumulation have been developed. Irrigation scheduling is often triggered by solar radiation accumulation after mid to late morning, while earlier irrigations are often triggered on a timer, to fill up the substrate with water. The irrigation scheduling programs integrate parameters like crop type, growing stage, substrate type, target drainage rate, to adjust irrigation dose and trigger value to trigger the irrigation.

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Chapter 11. Fertigation management – Nutrient management and salinity

Coordinators: Rodney Thompson[23], Ilse Delcour[19]

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Minimising the impact to the environment by nutrient discharge.

11.1.2. Regions

All EU regions.

11.1.3. Crops in which the problem is relevant

All vegetable, fruit, vine and ornamental crops.

11.1.4. Cropping type

All cropping systems.

11.1.5. General description of the issue

11.1.5.1. Sub-Issue A: contamination of subterranean water by nitrate

In modern intensive agricultural systems, large amounts of nitrogen (N) are applied, as mineral fertiliser or in organic materials, to generate high crop yields. With conventional management approaches, an appreciable portion of the applied N is not recovered by crops and is lost from soil (or substrate) to the environment. Nitrogen lost to the environment is associated with several serious environmental problems. It can be lost to the atmosphere as 1) ammonia (NH_3) by NH_3 volatilisation causing elevated N deposition and 2) as nitrous oxide (NO_2) by denitrification and through nitrification, thereby contributing to increased atmospheric greenhouse gas conent and global warming. Nitrogen can be lost to surface waters, by surface run-off, contributing to eutrophication, this is discussed subsequently. Nitrate (NO_3) leached from the root zone of crops can contaminate subterranean water (aquifers).

Nitrate contamination of aquifers is a commonly associated with intensive horticultural systems. The presence of NO_3 in water used as drinking water is considered a risk for human health. The major concern with elevated concentrations of NO_3 in drinking water is of metahemoglobinemia, also known as blue baby syndrome. Metahemoglobinemia affects infant children and unborn babies. It occurs following consumption of water, with elevated concentrations of nitrite (NO_2), by infants/babies or lactating mothers. There is concern that when appreciable NO_3 is present in water that it can be converted to NO_2 within the water, or within the human body either in a child's body or that of a lactating mother. Nitrite absorbed through the digestive system of susceptible children enters the blood stream where it blocks the capacity of haemoglobin to transport oxygen. The condition is serious and can be fatal. In older children and adults, NO_2 does not block the transport of oxygen. Because of concern of this issue, there are limits on the allowable NO_3 concentration in subterranean and superficial water bodies. In the European Union, this limit is 50 mg NO_3/L. Most NO_3 that enters subterranean water originates from agriculture.

To reduce NO_3 contamination of subterranean water from agricultural sources, the EU Nitrates Directive was legislated in 1991. This Directive is explained in detail in section 7.1 of this chapter. Agricultural areas that are considered to be associated with NO_3 contamination of subterranean water are declared Nitrate Vulnerable Zones (NVZ) and are required to implement improved management practices to reduce the contamination. Approximately 40% of the EU surface has been declared to be NVZs. Improved management practices relate to both N and irrigation management and must reduce the likelihood of NO_3 accumulating in soil and of it being leached to subterranean water.

In several countries or regions in the north or North-west Europe, the Nitrates Directive is being strictly applied following pressure from the EU on national and regional governments. With time, it is likely that increasing pressure will be applied to countries in southern and eastern Europe.

11.1.5.2. Sub-issue B: eutrophication of superficial water bodies

The second issue of concern regarding nutrient use in intensive horticultural systems and other agricultural systems is eutrophication of inland and coastal superficial water bodies. Eutrophication involves the rapid growth of large algal blooms. The death and decomposition of the algae result in reduced dissolved oxygen concentration in water that can adversely affect the quantity and diversity of aquatic life. Additionally, the algae can produce toxins that can adversely affect animal and fish species.

Algal growth is caused by additions of N and/or phosphorus (P) that originate from agricultural activity. N can enter surface water either as NO_3 that enters from NO_3 contaminated aquifers or as ammonium (NH_4) transported in run-off from the surface of agricultural soils. Phosphorus also enters through being transported in the run-off. Both NH_4 and P are transported in run-off in fine soil particles.

Eutrophication is associated with excess nutrient addition and also with the inadequate timing of nutrient application such as before large rainfall or irrigation event.

11.1.5.3. Sub-issue C: Possibility to reduce fertiliser costs

Excessive fertiliser applications entail an unnecessary cost for horticultural producers.

11.1.6. Brief description of the socio-economic impact of the issue

The main socio-economic impacts are associated with the consequences of impaired water quality. Nitrate contaminated subterranean water cannot be directly used for human consumption; either alternative sources must be found or NO_3 removal processes must be used to ensure that the water meets the required standards for human consumption. These effects influence the cost of water supplied to human populations.

Eutrophied surface water bodies are unpleasant which affects their amenity value for human activities. In addition to being unpleasant, this can negatively affect activities such as tourism. The loss of aquatic life can appreciably economic activities such as fishing.

Additionally, as consumers, particularly those in North-east European countries, become more environmentally conscious they are likely to require that the products that they purchase are produced with minimal negative environmental impact.

Reducing fertiliser applications will reduce grower's variable costs and contribute to the profitability of their enterprise.

11.1.7. Brief description of the regulations concerning the issue

11.1.7.1. European level

The relevant EU legislation is the Nitrate Directive (Council Directive 91/676/EEC) and the Water Framework Directive (Directive 2000/60/EC). The Nitrate Directive requires member states to identify areas that have or are at risk of having groundwater with NO_3 concentrations in excess of 50 mg NO_3/L or eutrophication of surface water. Such areas are declared to be "Nitrate Vulnerable Zones" and there is subsequently an obligation to implement an "Action Plan" of improved crop management practices to reduce NO_3 contamination. Additionally, monitoring is conducted every four years to follow the evolution of the NO_3 concentration in the affected groundwater.

The Water Framework Directive is a broadly-focused directive that deals with various aspects of water quality. It aims to ensure the good ecological quality of surface and subterranean water. It is implemented on the basis of water basins.

11.1.7.2. Country level

Each member country of the EU passes national legislation on how the Nitrate and Water Framework Directives will be applied in that country. Commonly, the legislation related to the Nitrate Directive is applied at the regional level, and that of the Water Framework Directive is applied at national level. There have been differences in the degree to which the Nitrate Directive has been applied in different countries. In some North-west EU countries or regions (e.g. Flanders, The Netherlands, Germany), this legislation is being strictly implemented, whereas as in more southern and eastern countries, the implementation is more relaxed.

11.1.7.3. Regional level

The Nitrate Directive is commonly applied at the regional level.

11.1.8. Existing technologies to solve the issue/sub-issues

The general approaches of the existing technologies can be organised into the following categories.

Fertiliser recommendations

- N Fertiliser recommendation schemes for horticultural crops
- P Fertiliser recommendation schemes for horticultural crops

Soil and substrate monitoring

- Soil analysis
- Dutch 1:2 soil: water extraction method
- Soil solution analysis
- EC measurement in soil using sensors
- EC measurement of substrate drainage
- Measurement of soil EC by conventional methods
- Nutrient analysis of root zone solution and drainage soilless systems

Crop and plant monitoring

- Plant tissue analysis
- Sap analysis
- Chlorophyll meters
- Canopy reflectance
- Fluorescence sensors

On-farm nutrient analysis

- Rapid, on-farm analysis of nutrients

Computer technologies

- Decision Support Systems (DSSs) for soil grown crops
- Models for nutrient uptake
- Models for nitrate leaching

Types of fertiliser

- Use of slow and controlled release fertilisers
- Organic fertiliser

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11.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions (TDs).

Sub-groups in TD group	Technology description	Use	Cost	External services and extra information required	Technical knowledge required
Fertiliser recommendations	N Fertiliser recommendation schemes for horticultural crops	Determine quantity and timing of N fertiliser application	approx. 20 € for associated soil sampling	Public or private laboratory for soil analysis and possible data interpretation. Recommendation schemes generally provided by regional advisory service	Basic agronomic knowledge Some schemes require basic computer skills
	P Fertiliser recommendation schemes for horticultural crops	Determine the quantity of P fertiliser application	approx. 20 € for associated soil sampling	Public or private laboratory for soil analysis and possible data interpretation. Recommendation schemes generally provided by regional advisory service. If not available, general recommendations can be used that consider test method, soil type and crop.	Basic agronomic knowledge Some schemes require basic computer skills
Soil and substrate monitoring	Soil analysis	Determine if fertiliser required for various nutrients. With suitable recommendation schemes indicate quantity	approx. 50 €	Public or private laboratory for soil analysis and for possible data interpretation. Where linked to fertiliser recommendation schemes, these are generally provided by regional advisory service	Basic agronomic knowledge
	Dutch 1:2 soil: water extraction method	Determine if fertiliser required and indicates quantities- all nutrients. For fertigated crops	110-140 €/ha	Laboratory for extraction and analysis. Interpretation guidelines provided by local advisory service. Available for Netherlands and Italy	Basic agronomic knowledge
	Soil solution analysis	Provides information on nutrient supply in root zone, mostly used for N	30-75 € for each sampler; 91-120 € for the pump; plus costs of analyses	Laboratory, if rapid analysis systems not used. Generic reference values available; Local reference values are preferred; Tendencies can be used	Basic agronomic knowledge
	EC measurement in soil using sensors	Root zone salinity management	400-1000 € per sensor	Generally, some reference information will be required. Suppliers should provide this information	Basic agronomic knowledge Familiarity with use of sensors Some training in sensor use

Sub-groups in TD group	Technology description	Use	Cost	External services and extra information required	Technical knowledge required
	EC measurement of substrate drainage	Root zone salinity management	200-500 € for a meter for measurement	Generally, the relevant information is publicly available. Specialist knowledge would be helpful	Specialist knowledge of substrate management an advantage
	Measurement of soil EC by conventional methods	Root zone salinity management	See soil solution analysis for suction samplers	For some methods, a specialist laboratory is required. Information for interpretation is publicly available	Basic agronomic knowledge
Crop and plant monitoring	Nutrient analysis of substrate root zone solutions or drainage water in soilless growing systems	On-going nutrient management in substrate-growing systems	40-50 € for complete nutrient analysis	Generally, the relevant information is publicly available.	Specialist knowledge of substrate management an advantage
	Chlorophyll meters	Assessment of crop N status	AtLEAF: 300 €; SPAD/Yara N-tester: 3000 €	Locally. Derived or verified reference values required for data interpretation. These provided by researchers, technicians, suppliers	Some training in sensor use
	Canopy reflectance for N management	Assessment of crop N status	Generally 3000-6000 €; but simpler and cheaper sensors now available for 400 €	Locally. Derived or verified reference values required for data interpretation. These provided by researchers, technicians, suppliers. Also, need for support	Specialist knowledge of sensor operation; Good computer skills often required
	Fluorescence sensors	Assessment of crop N status	>3000 €	See above, but still in research phase	Specialist knowledge of sensor operation; Good computer skills often required
	Sap analysis	Assessment of crop nutrient status, mostly N and K	Cost lab analysis 50-60 €; also see Rapid analysis systems	Locally. Derived or verified reference values required for data interpretation. These provided by researchers, technicians, suppliers. Generic values should be used with caution	Basic agronomic knowledge
	Plant tissue analysis	Assessment of crop nutrient status	Approx. 40-50 € for a range of nutrients	Locally. Derived or verified values recommended for data interpretation. These provided by researchers, technicians, suppliers. Published values from other	Basic agronomic knowledge

Sub-groups in TD group	Technology description	Use	Cost	External services and extra information required	Technical knowledge required
				systems available, should be used with some caution	
On-farm nutrient analysis	Rapid, on-farm analysis of nutrients	Avoids time delay associated with sending samples to an analytical laboratory.	For individual nutrient: 500 € For multiple nutrients: 2000 €	Suppliers of calibration solutions and replacement parts; on-going support	Good agronomic knowledge; basic chemistry skills
Decision Support Systems and models for nutrient management	Decision Support Systems (DSSs) for supporting nutrient management	Calculation of quantity and timing of fertiliser applications, mostly N	Generally no cost, except for when supplied by private company	Must be adapted/adaptable to local conditions. Technical and computer support often required	Good agronomic knowledge; Good computer skills required
	Models for nutrient uptake	Components of DSSs; research	Generally no cost	Generally, incorporated into DSSs. Otherwise, research tools	V. Good agronomic knowledge; Advanced computer skills required
	Models for nutrient leaching	Components of DSSs; resource management, research	Generally no cost	Generally, research tools or used for resource management applications	V. Good agronomic knowledge; Advanced computer skills required
Types of fertiliser	Use of slow and controlled release fertilisers	Less frequent fertiliser application	More expensive than conventional fertilisers	Objective advice on suitability	Good agronomic knowledge
	Organic fertiliser	Enables access to the particular market sector	Variable	Objective advice on suitability and viability	Good agronomic knowledge

11.3. N Fertiliser recommendation schemes for horticultural crops

(Authors: José Miguel de Paz[14], Rodney Thompson[23], Eleftheria Stavridou[15])

11.3.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.3.2. Region

For all EU regions.

11.3.3. Crops in which it is used

For all vegetable, fruit and ornamental crops.

11.3.4. Cropping type

Soil-bound.

11.3.5. Description of the technology

11.3.5.1. Purpose/aim of the technology

The aim of this technology is to determine the optimal rate of N fertiliser application to obtain high yields and optimal crop quality with low environmental impact. In some cases, a schedule for mineral N fertiliser application is provided with the timing and quantity of individual N applications. Subsequent corrections may be based on monitoring methods such as foliar and sap analysis, soil solution analysis and proximal optical sensors.

11.3.5.2. Working Principle of operation

Nitrogen is a basic element in agricultural production, so to achieve optimal crop yields, it is necessary that N be well managed. In order to establish a good fertilisation scheme, crop requirements and the complex soil-water-crop nitrogen dynamics should be known. Within the N dynamics, the N soil organic forms can be transformed to mineral N forms available for plants, by mineralisation process which is conditioned by soil characteristics, temperature and water content. Therefore, uncertainties arise in the knowledge of crop N requirements, which depends on soil and climatic conditions and crop management, and also in the transformations and losses of N from the soil which are difficult to assess.

In order to provide useful tools for N fertilisation recommendation schemes to farmers, it is essential to reduce these uncertainties considering the crop N demand, expected N supply by the soil, N supplied in irrigation water, soil mineral N at planting date etc.

Several approaches can be followed for N fertilisation recommendation schemes. Depending on the technological level and the availability of local information, farmers can use different systems of N fertilisation recommendation schemes:

Fixed rates: A fixed rate of N application is recommended based on N fertiliser field experiments. Ideally, these fixed rates should be used for similar growing conditions (crop, soil, climate or management) to where the experiment was conducted. Since this type of experiment is very costly, information obtained from a specific experiment is commonly extrapolated to other cropping conditions. This information is usually published in a technical fact sheet provided by public institutions, or by commercial or cooperative advisors.

Based on soil information: This type of system is based on soil analysis, generally of soil mineral nitrogen. The N recommendation is based on the amount of root zone soil N mineral and the crop N demand. Therefore, soil sampling and subsequent laboratory analysis are required to derive a recommendation for the amount of N fertiliser to apply. Various systems have been developed in several different countries: mineral N (N_{min}) in Germany, Pre-side dress soil nitrate test in the US, "Kulturbegleitende N_{min} Sollwerte" (KNS) in Germany, and the RB209 guidelines for Fertiliser Recommendations for Agricultural and Horticultural Crops which is used in the United Kingdom. A more detailed description of some of these systems follows:

1) N min system. This system is based on the determination of mineral nitrogen content of the soil in the root zone at the beginning of the growing season of the crop. The recommended optimal fertiliser amount (N_{rec}) proposed is the difference between the total nitrogen required by the plant ("target value") and the amount of mineral nitrogen found in the soil in the rooting area (Figure 11-1). The total nitrogen required by the plant ("target value") and the rooting depth for the crops are obtained by fertilisation tests, although can be consulted in bibliography (Table 11-1)

$N_{rec} = N_{target} – N_{min}$

where Ntarget is the target value (Table 11-1), N_{min} is the amount of mineral nitrogen in the soil to a certain depth (depending on the crop) before the beginning of the crop. As an example of N_{min} system application for cauliflower crop with a target value of 300 kg N/ha (Table 11-1), and soil N_{min} at planting date of 80 kg N/ha in 60 cm soil depth (Figure 11-1), the N recommended is:

N_{rec} (kg N/ha) = 300 – 80 = 220 kg N/h

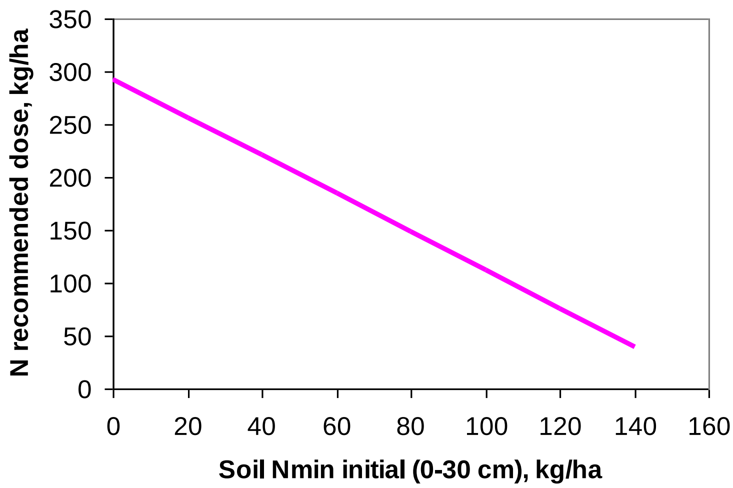

Figure 11-1. N recommendation dose as a function of soil N_{min} at planting date for cauliflower crop

Table 11-1. Target values (A) for several horticultural crops in different European countries

Crop	Target value (A) (kg N/ha)			Soil sampling depth (cm)
	Netherlands	Germany	Spain	
Onion	180	118	170-190	60
Leek	270	142-225	150-190	60
Cauliflower	300	297	260-300	60
Carrot	80	100	170-210	60
Cabbage	350	272-339	230-250	60
Spinach	290	166-182	140-160	30

The N_{rec} assessment does not explicitly consider soil organic matter N mineralisation, neither gas losses by volatilisation or denitrification, nor N leaching, although the field experiments conducted for N_{target} determination are considered implicitly. The N_{target} should be experimentally-determined from fertiliser trials conducted at representative fields within the region

2) KNS. This system is an evolution of the N_{min} system in which the N target is flexible and change depending on crop development. In this case, the determination of soil mineral nitrogen can be at planting date and also later (in two or three times more depending on the length of crop growth). Therefore, the uncertainty about mineralisation, leaching, and N uptake is lower in comparison with the N_{min} system. Since the N_{target} is calculated at planting date and also at any time during the growing season, this permits to the farmer to adopt the fertilisation plans more accuracy to N required by the crop, applying N fertiliser several times. For KNS system two or three soil N_{min} analysis are required that sometimes farmers are unwilling to perform. This system has been implemented as a computer program called the N-Expert decision support system (more information later). KNS is widely used in parts of North-west and Central Europe, and the most common in Flanders (Belgium). In Germany, it is obligatory to use N-Expert to prepare N fertiliser plans for horticultural crops
3) Fertiliser Recommendations for Agricultural and Horticultural Crops (RB209): This is the fertiliser recommendation scheme for the United Kingdom (Figure 11-2). The nitrogen recommendations in this manual are based on seven soil nitrogen supply (SNS) Indices, and each Index is related to a quantity of SNS in kg N/ha. This SNS is calculated as the sum of the soil N_{min} + estimate of nitrogen already in the crop + estimate of soil mineralisable nitrogen. In most situations, the SNS Index will be identified using the field assessment method, which is based on field-specific information for previous cropping, previous manure use, and soil type and winter rainfall. The SNS Index is possible to assess following two approaches, firstly by reading directly from tables and secondly based on soil sampling and N_{min} analysis

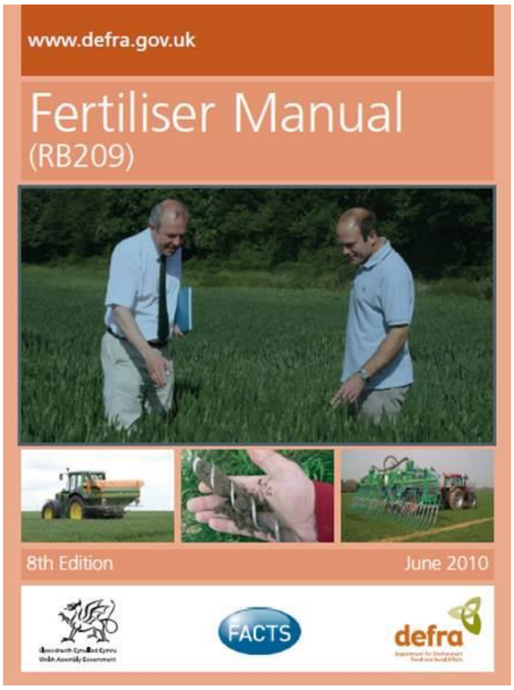

Figure 11-2. Fertiliser recommendations for England and Wales

Based on computer-based decision support systems (DSS) that use simulation models. DSS are systems that calculate the N fertiliser requirement after considering the crop species, cropping season, management practices, and growing conditions. A number of different DSS have been developed; these include N-index, N-Expert, WELL_N, Cropsyst, EU_ROTATE-N, Azofert, and VegSyst-DSS among others. The most-commonly used DSS and simulation models for N recommendation of vegetable crops are the following:

1) N-Expert: Developed by the Institute of Vegetable and Ornamental Crops, Großbeeren, and Germany. Calculates the N requirements for horticultural crops and provide N fertiliser recommendation based on KNS system. The calculations are based on simple plant growth models and soil models that require few input data
2) N-index**:** This DSS developed by the Soil Survey Service of Belgium. This is expert system is an empirical model that uses knowledge from experimental fields to provide N fertiliser recommendations. This recommendation system is based on the N_{min} approach
3) WELL-N**:** This model was developed by the Horticulture Research International, Wellesbourne, UK, and calculates nitrogen fertiliser requirements for most horticultural crops in this country. Using meteorological data, in addition to soil and crop data, this model calculates, for different types of fertilisers, the amount of mineral N in the soil and the amount of nitrate that susceptible to leaching
4) Azofert**:** This DSS has been produced by INRA, the National Institute for Agronomic Research (Laon-Reims-Mons Agronomy Unit) and LDAR, the French Departmental Analysis and Research Laboratory (Aisne Agronomic Station). It is a decision making software programme for nitrogen fertilisation of crops. It uses the complete soil mineral (inorganic) nitrogen balance sheet method. Based on measuring residual inorganic nitrogen, it calculates the optimum amount of fertiliser to be applied to a field plot

Based on fixed rates in combination with plant analysis (leaf or sap): In fruit trees, N fertilisation schemes have to supply nutrients consumed throughout the year by the crop, which are intended to be sufficient for correct plant development and fruit production. Its determination includes the needs of both new developing organs (reproductive and vegetative) and old permanent organs. Regarding these special conditions for fruit production, the N recommendation schemes for fruit trees are usually based on a program that considers N demand (which depends on species, crop age and growing conditions) and then use monitoring of nutritional status to make adjustments to ensure the correct N rate. This N program follows a fixed rates scheme based on information from experimental fields but is corrected depending on the N nutritional status performed by foliar analysis (leaf, sap etc.). Farmers usually take a foliar sample and send it to a laboratory for processing and analysis. Nutrient foliar analysis interpretation relies on specific values established for each species and crop type. Several methods or indices have been developed: the critical value, the sufficiency range approach and more complex methods as the Diagnosis and Recommendation Integrated System (DRIS) which integrate several nutrients. Farmers use these indexes to monitor the N nutritional status of the crop and to correcting detected deficiencies or nutritional imbalances.

- Critical value: This index was defined as the nutrient status at which a 5-10% yield reduction occurs. Since the symptoms are generally evident when nutrient concentrations decrease below the critical value, this index is better suited to diagnose severe deficiencies than to identify moderate deficiencies. Critical values play an important role in establishing lower limits of sufficiency ranges
- Sufficiency range approach: offers significant advantages over the use of critical values. First, un-symptomatic deficiencies can be identified since the beginning of the sufficiency range is clearly above the critical value. Sufficiency ranges also have upper limit, which provide some indication of nutrient excess
- Diagnosis and recommendation integrated system (DRIS): This technique developed by Walworth and Sumner (1987), places emphasis on the relationship among essential nutrients rather than absolute nutrient concentrations in plant tissue. In short, DRIS ranks the essential nutrients in their order of limitedness. Theoretically, if the most limiting nutrient is applied then the second most limiting nutrient becomes the most limiting. DRIS evaluation compares ratios of essential nutrients in the sample being analysed to known ratios of these nutrients in high yielding crops. Nutrients are listed in a descending order of limiting growth and development even when the most limiting most limiting is not a significant problem. Reference ratios of high yielding crops are available for a number of economically important crops.

11.3.5.3. Operational conditions

The availability of information and the accessibility of technology to farmers strongly influence the N recommendation scheme that is adopted. For example, farms with more information and higher technology are likely to use more complex N recommendation schemes, whereas farmers with a lower technological level are more likely to use simpler N recommendation schemes as fixed rates. The N recommendation schemes require several inputs:

The crop requirement. Although there is a great deal of information on the N requirements of the crops, they are not usually adapted to specific soil and climate conditions, and local crop management systems. Therefore, N recommendations schemes are generally based on information from experiments conducted with crops under different conditions (soil, cultivars, climate, management etc.). Consequently, some uncertainties are introduced in the recommendation; to reduce them is important to carry out tests in local plots. This point is already well studied and there are many recommendations depending on crop type. However, the lack of information at the local level is one of the main sources of uncertainty and one of the main practical limitations to apply the N recommendation schemes. Additionally, N requirements are generally assessed for average crop production, and N recommendations should be adapted to expected yield variations

The availability of information on N sources to the soil-water-plant system is essential to select the N scheme approach. The main N sources are: N in irrigation water, N mineralised from soil organic matter and crop residues, symbiotic fixation and N contributions in the form of mineral and organic fertilisation. The more information is available, the better the recommendation will be.

11.3.5.4. Cost data

Most N fertiliser recommendation schemes require a soil analysis for mineral N at or just before planting. The KNS system requires at least two determinations of soil mineral N. Generally, the laboratory performing the soil analysis will also interpret the results and provide the recommendation which is paid by the grower or cooperative. An example of the costs is in Flanders (Belgium) where the determination of soil mineral N is obligatory and where it is commonly used with the KNS system. In Belgium, the costs of soil sampling and N_{min} analysis are 42 € for 0-30 cm soil depth, 55 € for 0-60 cm, and 69 € for 0 - 90 cm, but for just N_{min} analysis the costs is 16 € + VAT.

In the United Kingdom, some laboratories of soil and plant analysis, provide the service of N_{min} analysis for £ 16 + VAT (18 € + VAT) per soil sample. Similar prices are given in Spain within a range 17-23 € + VAT) for N_{min} analysis per sample depending on the number of samples.

In the case of a farmer association or cooperative, the soil sampling and the analysis could be performed by themselves using a quick method of N_{min} analysis. For this purpose, some basic equipment is required:

Soil sampling: One auger to take soil samples at a rooting depth. The cost of auger equipment could be 200-500 €

A simple laboratory (graduated tube, mixer, filter paper) together with quick test equipment to measure the concentration of nitrate in the extracted solution. The Horiba LaquaTwin nitrate meter can be used; it costs about 500 €. Another system is the Merck RQFlex Reflectoquant which costs about 800 €, additional laboratory material would be about 80 €, and test strips for each nitrate determination cost 1 € each. For the LaquaTwin nitrate meter and Merck RQFlex Reflectoquant, the total analysis time per sample about one minute. Some additional time is required to prepare the equipment and prepare dilutions if required for the Merck RQFlex Reflectoquant. There is more information in the technology description (TD) of Rapid on-farm analysis systems, also in this chapter.

Where fixed rates of fertiliser are used, the information is freely provided in fact sheets or public guidelines.

Foliar analysis for macro and micronutrient concentrations costs around 40 € in Spain and many laboratories are capable of doing these analyses with a diagnosis for different fruit species (citrus, peach, kaki, olive, etc.).

11.3.5.5. Technological bottlenecks

The technological bottlenecks depend on the system used.

- If fixed rates are used as scheme, there are less technological bottlenecks. But if a system is based on model and/or laboratory measurements (soil N_{min}, foliar or sap N) the bottlenecks can be important
- A system based on soil analysis. This system requires an auger to sample soil and a space for mixing the soil sampled at different points to prepare a composite soil sample. The grower needs to have material for sending the sample to a laboratory. The time required to take samples and processing in the laboratory can be an important consideration for a grower
- For systems based on simulation models, there are several limitations: 1) model should be adapted to local conditions (calibration-validation), 2) the interface should be user-friendly, and sometimes a training period is required, and 3) some input data may be required that may be difficult or time-consuming for growers to obtain

11.3.5.6. Benefit for the grower

Advantages

The recommendation scheme of N fertilisation is based on technical knowledge, instead of the traditional method of growers' experience, who usually applies excessively large amounts. An additional important benefit for the grower is that the cost of fertiliser is reduced, with a lower environmental impact.

Disadvantages

The use of N schemes requires a certain technical knowledge on the part of the grower. Also, a certain amount of time is required to take the soil or foliar samples and for lab processing that usually are part of N fertiliser recommendation scheme.

11.3.5.7. Supporting systems needed

Some of N recommendation schemes are based on simulation models and use Decision Support System (DSS) software make calculations e.g. N Expert, Azofert. This may be used by the technical advisors of the laboratories that perform the analyses, or by growers.

11.3.5.8. Development phase

- Research: Research into different vegetable species is on-going to determine the N crop demand, and also to adapt different recommendation systems to different conditions
- Experimental phase: New model calibration-validation for new conditions, crops etc. are also being conducted
- Commercialised: Specialised companies are producing apps or computer programs

11.3.5.9. Who provides the technology

This technology can be provided by research institutes, agriculture associations, fertiliser or consulting companies, universities. For example, fixed N-rates are provided by research institutes, fertiliser companies, and agricultural associations. Simulation models or DSS usually are provided by universities, research institutes etc. For example:

- N-Expert 4 software can be downloaded at http://www.igzev.de/n-expert/?lang=en
- Vegsyst: http://www.ual.es/GruposInv/nitrogeno/VegSyst-DSS.shtml
- PLANET: Planning Land Applications of Nutrients for Efficiency and the environment. http://www.planet4farmers.co.uk/Content.aspx?name=PLANET
- PLANET is a computerised version of the RB209 Fertiliser Recommendations for Agricultural and Horticultural Crops used in the United Kingdom.
- Azofert: http://www.npc.inra.fr/Le-centre-Les-recherches/Impacts-environnementaux/Azofert-une-aide-pour-raisonner-la-fertilisation-des-cultures

11.3.5.10. Patented or not

Fixed rates are not patented. Simulation models and the DSS associated are usually registered. The reference tables used for the soil N_{min} and KNS systems and similar are publicly distributed and are not patented.

11.3.6. Which technologies are in competition with this one?

This technology does not compete directly with other technologies.

It is intended to replace the approach traditionally used by growers based on their own experience and/or that of other farmers, or from advisors from co-operatives or private companies.

11.3.7. Is the technology transferable to other crops/climates/cropping systems?

For optimal use of this technology in conditions other than where they were developed, they should be adapted to the new conditions of climate, soil, cropping systems etc. This will often require field studies to test the adapted recommendation scheme to new conditions where it is being used.

11.3.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks. In fact, in accordance with the European directive of nitrates 91/676 growers are encouraged to use these schemes.

11.3.9. Brief description of the socio-economic bottlenecks

Complex systems such as those based on models with high data requirements generally have limited numbers of farmers that are able to use them. In contrast, simpler schemes as the fixed rates which require less knowledge and/or data can be used more widely, although the N fertiliser recommendations may not be as accurate.

Although farmers wish to avoid reductions in yield and quality and tend to use conservative traditional practices to determine N fertiliser rates, systems based on soil testing are increasingly being used in several European countries (Germany, Holland, UK, and Belgium).

In some European counties and regions (Flanders, Germany), the use of these schemes is mandatory.

11.3.10. Techniques resulting from this technology

The main systems in use are:

1) The KNS system
2) The N_{min} system
3) The N-Expert decision support system which is based on the KNS system
4) Fertiliser Recommendations for Agricultural and Horticultural Crops (RB209). The PLANET software can be used to develop the same recommendations as the RB209 booklet on a personal computer

In most of the codes of good management practices applied in the nitrogen vulnerable zones of European Union countries includes information about the use of the N schemes for nitrogen fertilisation.

11.3.11. References for more information

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11.4. P recommendation schemes for horticultural crops

(Authors: Els Berckmoes[21], Georgina Key[1])

11.4.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.4.2. Region

All EU regions.

11.4.3. Crops in which it is used

All vegetables, fruit and ornamental crops.

11.4.4. Cropping type

Soil-bound.

11.4.5. Description of the technology

11.4.5.1. Purpose/aim of the technology

Phosphorus (P) recommendations schemes are used to make recommendations for P-fertilisation in soil grown crops in order to:

- Ensure the P supply meets the P requirement of the crop
- Minimise P enrichment of deeper soil and soil water

11.4.5.2. Working Principle of operation

In order to formulate phosphorus recommendations, a procedure consisting of 3 steps, has to be followed:

Step 1: Measurement of soil-P availability

It is essential to determine the available phosphorus in the soil as crops withdraw 80-90 % of the phosphorus consumed directly from the soil.

Following assessment of the available soil P, recommendations for additional P-fertilisation can then be provided to growers. Various approaches are used:

Chemical extraction methods

Available soil P is generally assessed by the use of chemical extraction methods. For these methods, a certain mass of a soil sample is thoroughly mixed with an extraction agent. Depending on the extraction agent, P-fractions will dissolve or desorb into the solution. In a next step, the dissolved P-fraction is measured and categorised as “available P”. Throughout Europe, more than 10 different P-extraction methods are being used. The types of extraction agents can be divided into 3 main categories:

- Acid solutions (acetic, citric, hydrochloric, lactic, nitric, sulphuric): the extraction agent dissolves calcium phosphate and attacks to varying degrees P that is bound to aluminium and iron oxides resulting in the release of P that was adsorbed on the oxide surface

- Anion exchange (acetic, bicarbonate, citric, lactic or sulphuric): anions in the extraction agent are exchanged for desorbed phosphate
- Cation Complexation: P-forms, such as aluminium- and calcium phosphate, can be complexed by a strong reactive anion (fluoride, citrate or lactate). This means that this anion takes the place of the phosphate and forms a bond with the aluminium- or calcium cation while the phosphate ion (hydrogen phosphate, dihydrogen phosphate) is released
- The phosphate which is present in the aluminium- or calcium phosphate can also be released by a precipitation with sodium bicarbonate. The general mechanism of this process is that the HCO_3, carbonate ions replace the phosphate ions. Calcium or aluminium carbonate is formed and precipitates, because these compounds are insoluble in water, while the phosphate is released

Each extraction agent requires a specific pH, which is maintained by a buffer solution. At higher pH values, additional desorption of P can occur, at lower pH values precipitation can occur.

Sink-method

Sink methods are an alternative for chemical extraction methods. These methods more closely mimic rhizosphere conditions and often provide comparable or better correlations with crop response than chemical extractants.

- Anion-exchange resins: It is the most common P-sink method for assessing available soil P. The procedure typically involves the use of a chloride saturated resin at a 1:1 resin to soil ratio in 10-100 mL of water or a weak electrolyte for 16-24 h
- Iron-oxide impregnated paper: Another P sink that has received attention is Fe-oxide impregnated filter paper (Fe-O strip)

Step 2: Calibration of the soil-P fertility level

The values of available soil P obtained from the extraction procedure should be calibrated; plant responses are correlated against available soil P. In general, institutions providing P-recommendations are reluctant to provide information on this calibration step.

Besides available soil P, many P-recommendation schemes also take into account various other soil-related parameters such as soil texture, organic matter content, pH, carbonate content or soil type. Additionally, P-recommendation schemes can be differentiated by crop type. Again there is a strong regional differentiation in this.

Generally, calibration is presented in a classification of the soil-P fertility level, ranging from (very) low to (very) high (Table 11-2). Often, the medium classification is for adequate soil P status.

Step 3: Estimation of the recommended P-dose.

In Europe, there is a general strategy to maintain a target value for the soil-P fertility level which assures that crops are not P limited. In order to maintain this target value, a balance is made between P exported through crop removal and that is supplied through fertiliser addition (Figure 11-3). Generally, once the level of available soil P is obtained that ensures that P is not limiting, then the general procedure is to supply amounts of P that replace what is exported in crop uptake. How this estimation is made, differs between countries and regions. In some countries, an advice is provided for both the soil (amount to reach the target value) and the crop (amount to compensate for the export of P through crop uptake). Ireland and The Netherlands, both types of advice are provided. Other countries combine both types of advice into one general form of advice.

Table 11-2. Estimation of the recommended P-rate (Jordan-Meille et al., 2012)

Soil-P fertility level	Advise
E: very high	No P fertilisation
D: High	Dose < P-export by the crop
C: target zone	Dose = P-export by the crop
B: Low	Dose > P-export by the crop
A: Very low	Dose >> P-export by the crop

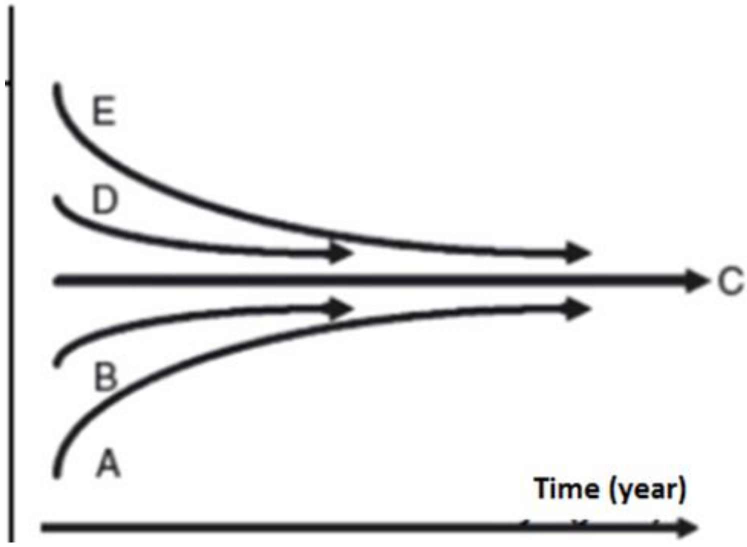

Figure 11-3. Schematic overview of the different soil P fertility levels. C refers to the target level (Jordan-Meille et al., 2012)

11.4.5.3. Operational conditions

Most P-recommendation schemes can only be applied at a local scale as these schemes take into account various other soil-related parameters such as soil texture, organic matter content, pH, carbonate content or soil type. These factors should be known in order to be able to apply the schemes.

11.4.5.4. Cost data

In general, P-recommendation is part of a complete soil analysis. In Belgium, nutrient recommendations, including the P-recommendation, costs around 60 €, VAT excluded. The recommendation is for the upper soil layer (0-28 cm). The samples should be taken before planting/sowing of each new crop.

11.4.5.5. Technological bottlenecks

Measurement of soil-P availability

Chemical extraction methods**:**

Chemical extraction methods operate completely differently compared to plant roots. This sometimes results in poor correlations between the measured soil-P availability and P-uptake by the crop. Still, these chemical extraction methods are generally used, as they are fast and relatively cheap.

When applying a chemical extraction, the soil pores are filled with the extraction agent. By applying this method, the role of the soil moisture content is not taken into account. In reality, however, the soil moisture content can influence soil-P-availability to the crop.

Resins:

Where resins are used, to prevent the diffusion of P from the soil to the resin from being the rate-limiting step, resins should be completely mixed with the soil, which can create difficulties when separating the resin from the soil for subsequent P analysis.

Calibration of the soil-P fertility level

In general, institutions providing P-recommendations are reluctant to provide information on the calibration procedure. As a result, P-recommendations can often be seen as a kind of "black box" with insufficient information being provided to growers, this can negatively influence the evaluation and interpretation of the results.

The optimal soil-P fertility level differs strongly from region to region. Even when the same extraction method is used, the soil-P availability value can be assigned to different classes (e.g. Figure 11-4).

Estimation of the recommended P-dose

Again there are clear regional differences in how the recommended P rate is calculated. Recommendations are sometimes made for the soil (rate to ensure optimal P supply) as well for the crop (rate to compensate the P export due to the removal by the crop). In other countries, both doses are combined together.

Additionally, there can be appreciable differences between the regions in the "insurance application" that is applied as a minimum amount.

Preparation of the soil samples can influence the outcomes of the P-analysis

For example:

- drying of soil samples will increase available soil P
- sieving of the sample
- storage of the soil sample
- the depth of the soil sample

The information on which the recommendation schemes are based may be dated (for example for ornamentals in the UK).

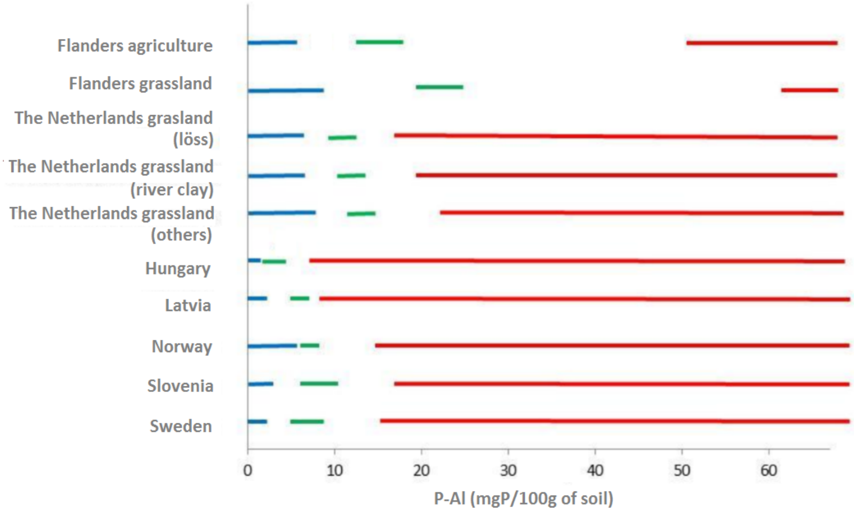

Figure 11-4. P-availability classes of different European countries, using the P-AL method to measure soil-P-availability. (Blue = low availability, green = target zone, red = high availability) (Amery and Vandecasteele, 2015)

11.4.5.6. Benefit for the grower

Advantages

- Growers receive information about available soil P
- Reduces the amounts of crop available nutrients in the environment; these can also be transported to water bodies

Disadvantages

- Large variation in P-recommendation schemes
- Large variation in available methods to measure available soil P
- Large variation in the recommended amounts of available soil P to avoid P limitation of crop growth

11.4.5.7. Supporting systems needed

Certified/qualified soil sampling services should be available, together with certified labs with the capacity to work with soils and to provide the correct interpretation of the analyses.

11.4.5.8. Development phase

Commercialised.

11.4.5.9. Who provides the technology

Bodemkundige Dienst België (Soil service of Belgium), (Belgium, Flanders).

Requasud (Belgium, Wallonia).

Teagasc (Ireland).

11.4.5.10. Patented or not

This technique is not patented.

11.4.6. Which technologies are in competition with this one?

None.

11.4.7. Is the technology transferable to other crops/climates/cropping systems?

The P-recommendation schemes can be transferred to all crops grown in soil.

11.4.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks for the use of P recommendation schemes.

11.4.9. Brief description of the socio-economic bottlenecks

Sink methods more closely mimic rhizosphere conditions and often provide comparable or better correlations with crop response than chemical extractants. Sink methods, however, are more time-consuming and therefore they are very expensive. This is the reason why mostly, chemical extractants are used.

11.4.10. Techniques resulting from this technology

1) Flanders (Belgium): Bemex-expertsystem:

Provided by Bodemkundige Dienst België (Soil Service of Belgium)

In the Bemex-system, the measurement of soil-P availability is based on a chemical extraction using ammonium lactate in acetic acid at pH 3,75 (P-Alℓ). Samples have to be collected from 0-23 cm (arable land) and 0-6 cm (grassland). Additionally, growers have to complete a question list referring to the fertilisation history of the soil, the previous crop and the variety of the current crop. The result of the extraction is categorised in one of the seven P-soil fertility classes.

Disadvantages of the method:

- The soil type is not implemented in this classification
- No representative estimation of the immediate P availability
- The optimal P-threshold value lies above the threshold value in the other European countries which results in higher P-recommendations compared to other European countries

Table 11-3. P-fertility classes based on P-Aℓ as applied by the Soil Service of Belgium for arable land and grassland (Maes et al., 2012)

P-soil fertility class	Arable land P-Aℓ	Grassland
Very low	< 5	<8
Low	5-8	8-13
Fairly low	9-11	14-18
Target zone	12-18	19-25
Fairly high	19-30	26-40
High	31-50	41-60
Very high	>50	>60

2) Wallonia (Belgium):

P analysis method based on ammonium acetate + EDTA at pH 4,65. Advice is provided by laboratories when requested by the grower.

3) The Netherlands:

Provided by the Commission for fertilisation for arable crops and vegetable crops and the Commission for grassland and crops for livestock feed. These commissions consist of researchers, advisors and representatives of the industry. Their advices are freely available.

P-recommendation scheme for vegetable crops: The Dutch P-recommendation scheme consists of both a soil and a crop oriented advice system. Most of the time, these two advice systems provide different results. The soil oriented advice aims to achieve and maintain a good P-status of the soil. The P-status of the soil is based on a water extraction (Pw-number). The current P-recommendations are based on the outcomes of the numerous field and pot trials that were carried out in the fifties and sixties in numerous fields in order to determine the correlation between Pw-number and crop yields. In the case of crops with a higher P requirement, the target value is 25 to 30 mg P_2O_5 per litre, depending on the soil type. For crops with lower P requirement, this target values is 20 mg P_2O_5 per litre. The actual P advice depends on the P fertility level of the soil. If the level is higher than the target value, the commission advises adding more than the P exported plus the unavoidable losses which vary between 5 to 20 kg P_2O_5 per year per hectare.

The crop oriented advice is based on:

- Pw extraction: Crops are divided into 5 groups, depending on their P requirement. A table provides the advice depending on the crop category and the P value
- Calcium chloride-extractable P and ammonium lactate–extractable P

4) Austria:
- P analysis is based on calcium lactate and calcium lactate + acetic acid
- P-recommendation scheme is provided by the government, soil information is included

5) Denmark:
- P analysis is based on Olsen (sodium acetate pH 8,5)
- P recommendation performed by research centres, based on soil analyses and expected uptake by the crops

6) Ireland:
- P analysis is based on Morgan's extract (sodium acetate pH 4,8)
- P recommendation performed by government (Teagasc)

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11.5. Technology: Soil analysis

(Authors: Claire Goillon[2], Benjamin Gard, Rodney Thompson[23])*

11.5.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.5.2. Region

All EU regions.

11.5.3. Crops in which it is used

All fruit, vegetables and ornamentals are grown in soil.

11.5.4. Cropping type

Soild-bound.

11.5.5. Description of the technology

11.5.5.1. Purpose/aim of the technology

Soil analyses are used to determine the physical and chemical characteristics and the agronomic potential of the soil before growing the crop, and to determine initial fertiliser requirements.

11.5.5.2. Working Principle of operation

For agricultural soil, the main factors assessed using soil analysis are N, P and K, pH, structure, particle size (texture), water-retention capacity, Cation Exchange Capacity, and the content of organic matter. These soil physical and chemical parameters can be complemented by biological parameters such as microbial biomass, enzymatic activity, carbon and nitrogen mineralisation, and earthworm species richness and abundance etc.; however, these analyses are much less common.

The frequency of soil analysis depends on the crops and the type of soil. The recommended frequency of soil analysis is generally once every two to four years. To interpret the results of soil analyses, local reference values are required for each crop. Generally, laboratories specialising in soil analyses have local reference values and provide interpretation of the results of the soil analyses.

11.5.5.3. Operational conditions

The main difficulty is sampling correctly to ensure that the sample is representative of the field or section of a field being examined. Soil spatial variability can be a major issue. Therefore, it is important to carefully select the sampling locations in the field and to gather sufficient replicates in order to obtain a good representation of the soil at the field scale. The following general advice on soil sampling procedures (Figure 11-5) may help to reduce the effect of spatial variability: choose the most representative area of the field, and avoid areas adjacent to the field or areas compacted by tractors and agricultural machinery. Also, avoid hollows and mounds. Historical knowledge about the area of land such as where abnormal growth has occurred is very useful when choosing the sampling area. A large "W" or zigzag pattern should be followed when sampling soil. The representative area must not exceed 1 ha in open field, for protected crops the sampling area is the greenhouse or a set of plastic tunnels in the same field.

Figure 11-5. Taking a soil sample with an Auger and collecting the sample (http://cri.crinet.com/news2536/PlanNowForSpringSoilSampling)

Sampling protocol (Figure 11-5) is as follows for each representative area: take at least 25 soil samples, to 25 cm depth with a soil auger or similar tool. Mix all the samples and make a composite subsample of 1 kg of soil to send to the laboratory. For fruit tree production, it is recommended that two composite samples are sent for analysis, one from 0-20 cm depth and a second from 20-40 cm depth.

It is important to perform soil sampling at the right moment to have the best results; in general, soon before planting. To compare results from past soil analyses, it is recommended that samples be taken in the same period (same month). Avoid sampling soil after the application of compost or manure or following lime application to reduce the risk of misleading results.

Figure 11-6. Analysis of soil samples in a laboratory (http://www.skrc.in/)

Analyses of soil sample are conducted by accredited or certified laboratories (Figure 11-6). All analyses are conducted according to national or international standards in order to have reliable and replicable results between laboratories. These laboratories also provide interpretation of the results.

11.5.5.4. Cost data

Analysis ranging to 50-300 €, depending on the parameters analysed. Price of analyses may vary appreciably depending on the country, the region, and the laboratory.

11.5.5.5. Technological bottlenecks

The only bottleneck consists in finding a laboratory in the grower's area. Sometimes during peak periods when many local growers require analyses, there may be delays because the local analytical capacity may struggle to meet the demand.

11.5.5.6. Benefit for the grower

Advantages

- Provides information on soil fertility and soil characteristics prior to planting a crop
- Assists in managing fertiliser applications
- Assists in adjusting the nutrient supply to meet crop requirements
- Reduced risk of nutrient deficiencies that can cause reduced crop production
- Reduce risk of nutrient loss to the environment e.g. nitrate leaching
- It is easy for the grower to take soil samples
- Most laboratories conducting soil analysis provide interpretation of the results

Disadvantages

- Expensive when several fields need to be analysed in the same year
- Uncertainty about the interpretation with crops that are not commonly grown in the region
- Time needed to take soil samples, process them and send them to a laboratory

11.5.5.7. Supporting systems needed

Interpretation of the results of the analyses must be done by someone with training in soil science who understands the values for each parameter that was analysed and who can correctly advise the grower of the most appropriate fertiliser program.

11.5.5.8. Development phase

Commercialised.

11.5.5.9. Who provides the technology

Laboratories performing soil analyses.

11.5.5.10. Patented or not

The technology is not patented but laboratories must use certified or standardised methods of analysis (e.g. COFRAC, NF, AENOR, etc.).

11.5.6. Which technologies are in competition with this one?

Soil solution analysis.

11.5.7. Is the technology transferable to other crops/climates/cropping systems?

Soil analyses can be used on all crops grown in soil.

11.5.8. Description of the regulatory bottlenecks

Growers with field located in nitrate vulnerable zones are required to carry out regular soil analyses to manage N fertilisation.

11.5.9. Brief description of the socio-economic bottlenecks

Soil analysis is often encouraged by advisors and agricultural certification schemes (organic, integrated management etc.). Additionally, some clients (supermarkets, distributors) oblige or at least encourage growers to regularly conduct soil analyses as part of the conditions of their contracts.

11.5.10. Techniques resulting from this technology

Fertiliser recommendation schemes (see technology described in section 11.4 of this chapter on N fertiliser recommendation schemes for horticultural crops, and section 11.5 on P recommendation schemes, respectively. See also the technology described in section 11.13 on Decision Support Systems for soil-grown crops.

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11.6. Dutch 1:2 soil: water extraction method

(Authors: Matthijs Blind[24], Rodney Thompson[23])

11.6.1. Used for

- Preparation of irrigation water
- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

11.6.2. Region

All EU regions.

11.6.3. Crops in which it is used

Numerous vegetable species.

11.6.4. Cropping type

- Soil-bound
- Protected
- Open air

11.6.5. Description of the technology

11.6.5.1. Purpose/aim of the technology

The 1:2 volume water extract method can be used to determine the available nutrients in the soil to optimise fertiliser use, by supplying just the amount of fertilisers that is needed for maximum production.

11.6.5.2. Working Principle of operation

By use of the 1:2 volume water extract method (Figure 11-8); the available nutrients in the soil are measured. The electric conductivity (EC) of the soil is also determined. The extract is the filtrate of a suspension obtained by adding one volume of field-moist soil to two volumes of water; giving a suspension in which soil and water are mixed in a ratio of 1:2 on a volume basis. In the subsequent soil analysis report, the concentrations of available nutrients and reference values are listed. Before starting the growing season, soil samples are taken using an auger (Figure 11-7). These soil samples are taken following a W pattern within a field. At each sampling location, soil from different depths is taken, for example 0-20 cm, 20-40 cm and 40-60 cm. In a greenhouse, the soil samples are taken about 20 cm below the soil surface. During the growing season, samples can be taken every 2-3 weeks.

Figure 11-7. Taking a soil sample with an auger

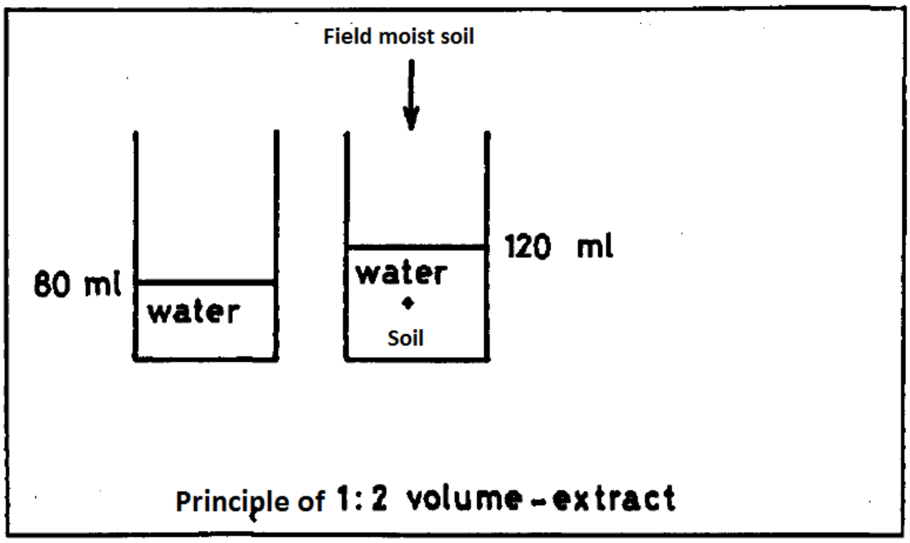

Figure 11-8. Schematic representation of the soil and water volumes used in the 1:2 volume extract method

The 1:2 volume water extract method is widely used in The Netherlands. It is commonly used in combination with global positioning systems (GPS). Many Dutch growers use GPS systems on their farms to produce yield or biomass maps. The available nutrients in the soil can also be stored in these biomass maps using GPS. In this way, it is possible to supply a variable nutrient amount to the crop. The amount of fertiliser applied for a given section of a field depends on the supply of available nutrients in the soil and the amount of biomass.

11.6.5.3. Operational conditions

The extract is made by adding sufficient field-moist soil to two parts of water until the total volume increases by one part. The analytical data for electrical conductivity, chloride, nitrogen, phosphate, potassium and magnesium in this extract are very closely related to data obtained by the saturation extract. This method is commonly used by soil-testing laboratories in The Netherlands. For the precise preparation of the 1:2 volume soil-water extract, it is necessary to use soil samples at field capacity. Most soil-testing laboratories in The Netherlands have the capacity to process a large number of samples within a short time but, the suitability of the 1:2 volume water extract method for assessing available P is questionable. Often, another extractant is used for assessing soil available P.

11.6.5.4. Cost data

Generally, the costs of analysis for the major and secondary nutrients are 110-140 €/ha. Results of the analysis of soil samples can generally be provided within a week. Accurate automated equipment for a soil analysis can be expensive; therefore, the analyses are conducted by professional analytical laboratories. The 1:2 volume water extract method is relatively cheap. The cost for analysis can vary depending on the how much the grower participates in the sampling process and the number of nutrients for which analyses are conducted. If the grower collects the samples by himself, he needs an auger and bags for the soil. Furthermore, the grower needs time as well.

11.6.5.5. Technological bottlenecks

A disadvantage of soil testing methods, such as this, is that the method only estimates the availability of nutrients to crops. There is no guarantee that the available nutrients in the root environment will be absorbed by plants.

11.6.5.6. Benefit for the grower

Advantages

- Optimisation of profit by saving on fertiliser costs
- Lower environmental impact: less leaching of nutrients results in less pollution of ground and surface waters
- Assists to determine the amount of nutrients which are needed by the crop during the growing season

Disadvantages

- Sometimes the available nutrients may not be absorbed by the plants
- This occurs because of effects of low temperatures, diseases, excess or insufficient soil water
- Electrical conductivity determinations are less reliable in soil with appreciable amounts of gypsum, which may be more of an issue in drier regions
- Knowledge of the soil organic matter content required for good interpretation of the analytical data

11.6.5.7. Supporting systems needed

If the grower collects the samples by himself, he needs an auger and bags for the soil.

11.6.5.8. Development phase

Commercialised.

11.6.5.9. Who provides the technology

A grower can collect soil samples by himself or he can hire a consultant to collect the soil samples. For collecting the soil samples, an auger and bags are needed. Once collected, the grower needs to take or send the soil samples to the laboratory. The 1:2 volume water extract method has to be carried out in a well-equipped laboratory. For example in The

Netherlands there are two laboratories, Eurofins Agro and Groen Agro Control that provide this service. Following analysis, the grower receives a report with the results.

11.6.5.10. Patented or not

The 1:2 volume water extract method is not patented. Any certified laboratory that has the equipment for this method and properly qualified staff, can conduct analysis of samples obtained with this method.

11.6.6. Which technologies are in competition with this one?

The 1:2 volume water extract method is a soil test that can also be used with substrate. In addition to soil and substrate analysis, tissue tests and sap analysis are alternative methods for assessing the adequacy of nutrient supply. Tissue tests are widely used in horticulture and when compared to soil testing procedures have their advantages and disadvantages (see 5.5 technological bottlenecks).

11.6.7. Is the technology transferable to other crops/climates/cropping systems?

This water extract method can be used with different soils, water quality, climate and cultivation practices. However, the optimal phosphorus fertiliser supply has to be estimated by other methods or in combination with the 1:2 volume water extract method.

11.6.8. Description of the regulatory bottlenecks

Regarding regulation, there are no bottlenecks for the grower. Regulation is applicable for the research companies, regarding ISO norms etc.

11.6.9. Brief description of the socio-economic bottlenecks

When collecting the soil samples, the grower has to consider the time and the equipment which are needed (see section 5.9). When hiring a consultant, the additional costs have to take into account. Furthermore, it is necessary to transport the soil samples to the laboratory. In general, these costs are not bottlenecks, because finally they will be paid back because of a more efficient use of fertilisers and less environmental impact due to leaching.

11.6.10. Techniques resulting from this technology

In The Netherlands there are two laboratories that analyse soil samples; Eurofins Agro and Groen Agro Control. Both laboratories use the 1:2 volume water extract method. In other countries there are other laboratories. It depends on the country.

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11.7. Soil solution analysis

(Authors: Claire Goillon[2], Benjamin Gard, Rodney Thompson[23], Juan José Magán[9], Eleftheria Stavridou[15])*

11.7.1. Used for

- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

11.7.2. Region

All EU regions.

11.7.3. Crops in which it is used

All vegetable and fruit crops grown in soil.

11.7.4. Cropping type

- Soil-bound
- Protected
- Open air

11.7.5. Description of the technology

11.7.5.1. Purpose/aim of the technology

Soil solution extraction can be used for salinity and nutrient management to optimise fertiliser application, reduce fertiliser costs and reduce the environmental impact associated with excessive nutrient supply.

11.7.5.2. Working Principle of operation

Sampling soil solution is done by collecting water directly from the soil using active or passive soil solution samplers.

Active soil solution samplers (e.g. Figure 11-9) consist of a plastic tube with a porous ceramic cup positioned in the soil and a stopper to seal the tube. A vacuum (negative air pressure) of approximately -60 kPa is maintained within the sampler, for a period of time, which draws water from soil pores through the ceramic cup into the sampler, from where it is subsequently collected using a syringe.

Passive soil solution samplers collect samples of soil solution by redirecting the downward flow of solution during irrigation into a collection device. Passive soil solution samplers only collect a sample when a wetting front moves past the device.

The sampled soil solution can be analysed with different analytical methods, the choice of which depends on the information required and how quickly the information is required. For example, salinity in the soil solution can be rapidly analysed on the farm, with an EC meter and the NO_3 concentration can also be rapidly measured, on the farm, with rapid analysis systems (see TD on Rapid on-farm analysis of nutrients) such as ion selective electrodes such as the LaquaTwin NO_3 meter or the combined use of test strips and an optical reader such as the Nitracheck system or the Merck RQFlex Reflecoquant.

Figure 11-9. Soil solution suction sampler

Soil solution analysis is commonly used for N management and is best suited for drip irrigated and fertigated crops where nutrients are applied continuously to the root zone and where soils are maintained in moist conditions for much of the crop. Regular soil solution sampling and analysis during crop cycle enable monitoring of the evolution of the concentration of the NO_3 concentration (i.e. the plant available N) in the soil solution in the root zone. With this information, the N supply can be subsequently adjusted to ensure optimal crop N nutrition.

11.7.5.3. Operational conditions

Active soil solution samplers can only collect samples of soil solution in moist soils. For soil solution to enter the ceramic cup there must be a negative pressure gradient between the inside of the ceramic cup and the surrounding soil. There must be a stronger suction within the sampler than in the soil. In scientific terms, the suction within the sampler must be more negative the matric potential of the soil.

As the maximum suction (vacuum) that can be applied to sampler is approximate -60 kPa, then the soil must be wetter than -60 kPa, i.e. it must have a soil matrix potential of between 0 and -60 kPa. Given that 1) suction within the sampler is sometimes slowly lost and 2) an appreciable suction gradient enhances the collection of soil solution; active samplers are most effective when the soil is wetter than -40 kPa, i.e. when the soil matric potential is between 0 and -40 kPa. These observations are relevant when small manual pumps are used; with these pumps, it is difficult to apply a suction of more than -60 kPa (that is more negative than -60 kPa).

Active soil solution samplers are best suited for frequently irrigated crops, e.g. drip-irrigated vegetable crops where the soils are maintained moist for much of the crop. Soils in greenhouses, used for vegetable production, are suitable because the soil matric potential is usually close to field capacity (-10 to -30 kPa, depending on soil texture). These samplers can generally be used throughout a vegetable crop grown in soil in a greenhouse.

Sample collection with active soil solution samplers requires good contact between the ceramic cup and the soil. The presence of large air spaces will prevent preservation of an adequate suction within the sampler. Therefore, it is essential to follow recommended installation protocols.

An important issue with suction samplers is how to reduce the spatial variability associated with nutrient concentrations in the soil solution. It is important to select carefully the sampling locations within an area of soil and to have sufficient replicate samples in order to get a good representation of the soil solution at the scale of the farm field. The following general advice on the sampling method may help to reduce spatial variability in soil solution extracts: choose the most representative areas of the field and avoid border areas on the edge of the field, position them close to healthy not sick plants, avoid areas compacted by the passage of agricultural machinery, and also avoid hollows and mounds. Knowledge of the history of the field such as where there has been abnormal growth is very useful when choosing where to place the samplers.

Soil solution suction samplers are easy to install and the installation only disturbs a small area of the soil. The sampler is placed at a specific depth, corresponding to the main root zone of the crop, to extract a sample of the soil solution that is exploited by the root system. Full contact between the sampler and soil is required for effective sampling. Several samplers must be installed in the field or greenhouse to have representative information on the soil being monitored; three is the minimum number. For fertigated crops, the soil solution suction sampler is installed on the line of the crop, close the plant and the emitter (10 cm) at the depth of the root zone (15-30 cm). Once correctly installed, suction samplers can remain in the soil as long as is needed (for example for the duration of the growing cycle of a crop).

In practical use, the spatial variability of nutrient concentrations can make it difficult to specify absolute concentration values to be used for managing nutrients. For this reason, tendencies are often used; an on-going accumulation of NO_3 in the soil solution indicates excessive N fertilisation. A commonly-used sufficiency value is 5 mmol/L of NO_3, i.e. when the soil solution NO_3 concentration exceeds 5 mmol/L, N is not limiting crop growth.

Suction samplers are mostly used for N management, based on the concentration of soil solution NO_3. They can be used for other nutrients; however, with cations, exchange interactions with soil may need to be considered. They cannot be used with phosphorus because of fixation reactions with the soil particles.

11.7.5.4. Cost data

For a soil solution suction sampler, sampling tubes are available for 30-75 € each and a manual vacuum pump costs approximately 90-120 €.

11.7.5.5. Technological bottlenecks

A significant barrier to adoption has been the lack of information and training as well as the perceived high cost of soil solution extraction devices. Growers need to be able to understand and interpret soil solution result data.

11.7.5.6. Benefit for the grower

Advantages

- Easy and quick
- Economic method
- Provides a good indication of the immediate supply of nutrients in the root zone
- Useful for the early detection of plant nutrition problems
- Enables corrective action to be implemented before the crop is seriously affected

Disadvantages

- Only the soluble fraction of available nutrients is measured
- No information on the supply of exchangeable, mineralisable and otherwise available nutrients
- Possibly results in an excessive nutrient supply
- Little information available on the interpretation of measurements
- Advice from technical advisors familiar with soil solution analysis techniques is required
- Spatial variability can be an issue, so replication is recommended

11.7.5.7. Supporting systems needed

Soil solution analysis is best used in conjunction with other monitoring tools (e.g. Leaf analysis, soil analysis, visual crop assessment).

11.7.5.8. Development phase

Commercialised.

11.7.5.9. Who provides the technology

Soil suction samplers are produced and sold by several companies specialised in irrigation material such as SDEC (http://agronomie.sdec-france.com/accueil-agronomie.html), Sentek (http://www.sentek.com.au/products/ancillary.asp), ACMAS technologies Pty Ltd (http://www.acmasindia.com/), Irrometer (http://www.irrometer.com/ssat.html) and their national and local distributors and retailers.

The company Himarcan in Almeria, Spain (http://www.himarcan.com/en/) commercialises equipment for the automatic extraction of soil solution with a suction cup and subsequent automatic measurement of EC and pH in the extracted soil solution (Figure 11-10) (http://www.himarcan.com/redhimarcan/). The measurement frequency can be programmed by the user and the results are displayed using the supplied software. The solution may be recovered after automatic measurement for subsequent additional analysis. Himarcan also sells equipment for the manual extraction of soil solution.

Figure 11-10. Equipment for automatic suction and EC and pH measurement of soil solution produced by Himarcan, Almeria, Spain

11.7.5.10. Patented or not

The suction cup samplers are not patented. The process to produce the ceramic cups may be patented. It is likely that the automatics sampling system of Himarcan is patented.

11.7.6. Which technologies are in competition with this one?

Soil analysis.

11.7.7. Is the technology transferable to other crops/climates/cropping systems?

All soil grown cropping systems could use this method. It is particularly suited to high frequency drip irrigated crops where the soil remains moist. There are some reports that in heavy clay soils, that it can be difficult to obtain samples of the soil solution.

11.7.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks for soil solution analyses.

11.7.9. Brief description of the socio-economic bottlenecks

At this moment, no socio economic bottlenecks have been identified.

11.7.10. Techniques resulting from this technology

Zenith grille®, elaborated for 14 vegetable species, defines N plant needs. Quick Nitrachek® measures along crop cycle allow determining the concentration in nitrates in the soil solution. By comparing the Nitrachek® measure to the Zenith grille allows growers deciding if secondary fertilisation is needed or not. Grille Zenith, produced by Ctifl (France).

Assessing crop N status and management of N fertilisation in fertigated vegetable crops.

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11.8. Nutrient analysis of root zone solution and drainage in soilless systems

(Authors: Rodney Thompson[23], Els Berckmoes[21])

11.8.1. Used for

- More efficient use of water
- Minimising the impact to the environment by nutrient discharge

11.8.2. Region

All EU regions.

11.8.3. Crops in which it is used

All vegetables and ornamental crops grown in soilless media.

11.8.4. Cropping type

- Soilless
- Protected
- Open air

11.8.5. Description of the technology

11.8.5.1. Purpose/aim of the technology

Nutrient analysis of substrate drainage water is widely used by growers to monitor and adjust the composition of the nutrient solution in order to optimise recirculation.

11.8.5.2. Working Principle of operation

Nutrient analysis can be carried out to inform about the concentration of a single nutrient or to give a general overview of all nutrients (e.g. Figure 11-11). Complete analyses inform about the EC, pH and the presence of macro- and micro-elements. Specific analyses can be conducted to analyse only a single nutrient if required.

		EC mS/cm	pH	Si mmol/l	NH_4	K	Na	Ca	Mg	NO_3	Cl	SO_4	P	HCO_3	Fe µmol/l.	Mn	Zn	B	Cu	Mo
Analyseresultaten		4.4	6.7	0.3	0.0	13.6	1.0	8.8	5.1	31.7	2.9	4.2	0.9	1.7	22.8	4.9	10.2	88.7	1.2	1.9
Historisch overzicht bij ref. EC :		EC mS/cm	pH	Si mmol/l	NH_4	K	Na	Ca	Mg	NO_3	Cl	SO_4	P	HCO_3	Fe µmol/l.	Mn	Zn	B	Cu	Mo
V0115570	15-11-16	6.2	6.7	0.6	0.1	5.0	0.8	11.4	8.4	29.4	3.0	6.2	0.7	1.9	9.7	1.3	4.6	13.0	0.6	1.2
V0115614	22-11-16	6.7	6.9	0.7	0.0	3.3	0.9	12.3	9.5	31.7	2.6	7.5	0.5	2.7	10.8	0.7	4.7	17.1	0.6	1.5
V0115625	29-11-16	5.3	6.6	0.5	0.1	5.0	0.9	11.1	7.9	32.0	1.2	6.2	0.8	1.8	21.1	2.1	7.0	44.5	0.8	1.6
V0115660	06-12-16	4.4	6.4	0.3	0.0	9.6	0.8	9.4	5.3	30.9	1.1	4.1	1.5	1.1	31.3	5.0	8.3	63.2	1.1	1.5
V0115673	13-12-16	4.4	6.6	0.4	0.0	11.3	1.0	8.6	5.1	29.7	1.9	4.1	1.0	1.5	32.0	3.5	8.9	67.2	1.1	1.7
V0115764	03-01-17	4.4	6.7	0.3	0.0	12.4	0.9	8.1	4.6	28.9	2.7	3.9	0.8	1.7	20.8	4.5	9.3	80.9	1.1	1.9
Streefwaarden		4.0	6.0		<0.0	9.0	<3.0	10.3	5.2	25.8	<3.0	4.5	1.7	<0.5	38.7	15.5	9.0	77.4	0.9	

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B-8800 Roeselare
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E-mail info@pcb.be

Figure 11-11. An example of a complete nutrient analysis of the substrate (rock wool) drainage water of a Belgian tomato crop (transplant beginning of November – artificial light)

Based on the result of the analysis, growers or advisors may adjust the recipe of the applied nutrient solution or decide to discharge a part or all of the drainage water.

Figure 11-12. Example of small benchtop spectrophotometer that could be used for on-site analysis. This is the Hach DR3900 Benchtop Spectrophotometer (https://be.hach.com/spectrofotometers/)

11.8.5.3. Operational conditions

Samples of the root zone solution are obtained from the root zone area of the substrate. The samples are extracted from the substrate slab by use of a syringe. Samples are collected from different slabs homogeneously spread over the growing area until at least 1 litre of root solution is collected. In cases where crops are grown without any substrate, the samples are taken from the drainage pits where the excess nutrient water is stored. After sampling, the solution is stored in a fridge until the time of analysis.

The analyses can be carried out by a laboratory or at the farm. In the latter case, continuous monitoring is possible or manual measurement.

11.8.5.4. Cost data

Analysis carried out by credited laboratories:

- Complete analyses (advise excluded): 39 € (BDB, Belgium), 34 € (Eurofins Agro, The Netherlands)
- Costs to send/bring the samples to the lab (approx. 15 € for a package of 7 kg when sent by post)

Analysis carried out on the farms:

- Continuous monitoring of elements:
  - Analyser kit for N and P:
    - sc200 Controller (Hach Lange) : 1520 €
    - N-ISE Nitrate probe (Hach Lange): 4430 €
    - PHOSPAX P-probe (1-50 mg/L) : 12810 €
- Manual measurements of single elements:
  - Analyser:
    - DR3900 photo spectrometer (Hach Lange; Figure 11-12): 4105 €
    - DR1900 portable photo spectrometer (Hach Lange): 2260 €
    - Tests for the analyser (Hach-Lange cuvette tests): 80 €/25 tests = 3 €/test
- Other analytical systems are described in the TD on Rapid on-farm analysis of nutrients, in this chapter

11.8.5.5. Technological bottlenecks

In the case of continuous monitoring, there is a need for frequent calibration of the sensors.

In case of some hand-held sensors, dilution is required before carrying out the measurement. In these cases, the analytical range of some held tools may be much lower compared to the concentration of the sample, e.g. the Merck RQFlex Reflectoquant system where the range for NO_3 measurements is between 22-155 mg/L whereas the NO_3 concentration of drainage water from a tomato crop is around 1200 mg/L. There are various ion selective electrode systems (e.g. Horiba LaquaTwin nitrate sensor, Clean Grow Nutrient Analyzer) available that have analytical ranges suitable for most solutions obtained from horticulture (nutrient solutions, substrate drainage).

11.8.5.6. Benefit for the grower

Advantages

- Easy to conduct
- Accurate
- Provides useful information on nutrient availability in the root area of the substrate slabs

Disadvantages

- Where laboratory analysis used, there may be an appreciable time delay before receiving the results. In this time, the nutrient status of medium may have changed appreciably
- In the case of continuous monitoring:
    - Expensive (investment + yearly maintenance costs)
    - Need for frequent calibrations
    - Sensors are not avail. for some specific elements
- In the case of on-site manual analyses of single elements: solutions sometimes have to be diluted before the measurement can occur (time-consuming, increased risk for of error)

11.8.5.7. Supporting systems needed

Syringes and bottles to collect the drainage water samples. Fridge to store the samples.

11.8.5.8. Development phase

Commercialised.

11.8.5.9. Who provides the technology

Analytical laboratories with or without certification, examples in Belgium are Blgg, Groen Agro control, Bodemkundige Dienst België.

On-site analysis for specific elements, e.g. Hach Lange (http://be.hach.com/quick.search-quick.search.jsa?keywords=lck+kuvettentest), Hanna instruments (http://www.hannainstruments.be/be-nl/analyse-meet-instrumenten-apparatuur/afvalwateranalyse-meters/item/hi-83224-02-foto-meter-afvalwater-analyse-barcode-lezer-geheugen.html?category_id=346).

On-site analysis of multiple nutrients:

- Clean Grow Nutrient Analyzer (http://www.cleangrow.com/product/nutrient-analyzer) for simultaneous analysis of NH_4, NO_3, Ca, Cl, K, Na, Mg
- NT Sensors Multi ION sensor (http://www.ntsensors.com/en/products/multiion.html), for NH_4, NO_3, Ca, Cl, K, Na, Mg

Also, see the technology described in this chapter on Rapid on-farm analysis of nutrients.

11.8.5.10. Patented or not

Analysis laboratories with certification; it is very advisable that the laboratories use certified methods of analysis. Many of the systems used for on-farm analysis for nutrients are patented.

11.8.6. Which technologies are in competition with this one?

None.

11.8.7. Is the technology transferable to other crops/climates/cropping systems?

The systems can be transferred to all types of crops where nutrient extractions are applied.

11.8.8. Description of the regulatory bottlenecks

The European Water Framework and Nitrates Directives are forcing farmers, with soilless growing systems, to reconsider their methods of management. For example, in Belgium and The Netherlands, it is forbidden to discharge nutrient water into surface waters. Spreading of this waste water on grassland or removing nutrients from the waste water is expensive and time-consuming. Therefore, growers in Belgium and The Netherlands are increasingly interested in knowing the nutrient composition of drainage water in order to optimise the use of this water.

Implementation of the nutrient and water legislation on both the national and regional level differs considerably.

11.8.9. Brief description of the socio-economic bottlenecks

Some growers are interested in the on-line monitoring of for example Ca and K. Although these sensors are available, the costs are very high. Additionally, these sensors require frequent calibration. This is preventing growers from using these sensors for the moment.

Hand-held analytical systems for specific nutrients are appreciably cheaper and require less maintenance. Growers are increasingly familiar with these kinds of tools, especially for N and K. They may be very useful tools for technical advisors with some scientific training.

11.8.10. Techniques resulting from this technology

Advisory services offered by laboratories:

- Bodemkundige dienst België/ Soil Service of Belgium (www.bdb.be)
- Eurofins Agro (http://eurofins-agro.com)

Devices to measure nutrient elements on site:

- Hach Lange: cuvette test for specific elements:
- Calcium: range of 5-50 mg/L (costs 80 € for 25 tests)
- Horiba LaquaTwin selective ion electrode sensors for specific ions, namely NO_3, K, Ca, Na (http://www.horiba.com/laquatwin/en/lineup/index.html)
- Clean Grow Nutrient Analyzer (http://www.cleangrow.com/product/nutrient-analyzer) for simultaneous analysis of NH_4, NO_3, Ca, Cl, K, Na, Mg
- NT Sensors Multi ION sensor (http://www.ntsensors.com/en/products/multiion.html), for NH_4, NO_3, Ca, Cl, K, Na, Mg
- Also, see technology description (TD) on Rapid on-farm analysis of nutrients

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11.9. EC measurement in soil by conventional methods

(Authors: José Miguel de Paz[14], Rodney Thompson[23])

11.9.1. Used for

- Minimising the impact of salinity on crop production
- More efficient use of water

11.9.2. Region

All EU regions; particularly, in drier regions.

11.9.3. Crops in which it is used

All vegetable, fruit and ornamental crops.

11.9.4. Cropping type

- Soil-bound
- Open air
- Protected

11.9.5. Description of the technology

11.9.5.1. Purpose/aim of the technology

The EC at 25 °C (EC25) of soil solution provides an assessment of soil salinity. The main aim of this technology is to evaluate the soil salinity in order to be able to recommend irrigation management that minimises the negative effects of salinity on crop production.

11.9.5.2. Working Principle of operation

EC is measured by applying a potential difference between two electrodes in a sample of soil solution. Dissolved salts increase the ability of soil to conduct an electrical current in the soil solution. Therefore, the higher the EC, the higher is the soil salinity. However, because the EC of aqueous solutions increases with temperature, this is also measured with a built-in temperature sensor in the same instrument. All EC measurements are standardised to 25°C which is presented as EC25. Conventional methods measure the EC25 of soil solution obtained under controlled conditions; various different procedures are used to obtain the soil solution which is extracted in the laboratory or by suction cups in the field.

EC measured in soil samples

The reference method to evaluate soil salinity is the measurement of the EC25 in the saturated paste soil extract. For this, a soil sample is saturated with water by mixing soil with laboratory grade de-ionised water until the soil saturation point is reached. Next, the solution within the paste is extracted using a vacuum pump. Finally, the EC25 is measured in this solution with an EC-meter. Since the saturation extract is inadequate for large numbers of samples, it is usually replaced by other soil extracts, such as the 1:5, 1:2 or 1:1 (ratios of soil to water) from which it is easier to extract the soil solution. For example, the $EC_{1:5}$ is determined by mixing 1 part of soil with 5 parts of de-ionised water. After mixing the sample and allowing the sediment to settle, either filtering or centrifuging is used to obtain a clear solution and the EC_{25} of the solution is then measured with an EC-meter. However, these measurements are not directly related to soil salinity and plant response because the ratio (1:5, 1:2, etc.) is more dilute than is normally found under field conditions, and interferences from cation exchange, mineral dissolution (carbonates, gypsum, etc.) and anion exclusion occur which can influence the reading. To be meaningful, the $EC_{1:5}$ is related to the EC_{25} measured in the saturation extract (EC_{se}) because the EC_{se} is the standard method for which reference values are available. In this case, several different empirical equations are available, which can be used to transform the $EC_{1:5}$ (or another dilution ratio) to EC_{se}.

An example of this conversion for soils with no gypsum is:

- For Mediterranean loamy clay soils, the conversion proposed by Visconti et al (2010):

$$EC_{se} = 5{,}7\ EC_{1:5} – 0{,}2$$

- Another conversion of $EC_{1:5}$ to EC_{se} was proposed by Shaw, (1994) for Australian soils depending on the clay content: Table 11-4

Table 11-4. ECse/$EC_{1:5}$ convert factors depending on the clay content

Clay (%)	5	6	8	13	25	33	38	43	50	60	70
Ratio EC_{se} / $EC_{1:5}$	12,4	12,1	11,7	10,7	8,9	8,0	7,4	6,9	6,2	5,3	4,5

EC measured in soil solution

Some *in situ* methods for in-field use are alternatives to the laboratory methods for obtaining a solution for EC measurement. Porous suction cup samplers installed directly in field enable the soil solution to be obtained from different soil depths and at different times during the growing season. This is a simple method that involves minimal disturbance of the soil profile. The soil solution is extracted at a soil matric potential close to field capacity water content; these samplers are effective when the soil matric potential is in the range of -10 to -50 kPa suction. The EC of the extracted soil solution is then measured with a hand-held EC-meter. In coarser soils with larger soil pores, relatively less water is available compared with finer soils; at lower (more negative, i.e. drier) soil matric potential values, the volumes of soil solution obtained from coarser soils may be small. Since the soil solution extracted by suction cups reflects field conditions, the electrical conductivity of the soil solution or soil water (EC_{sw}) is a likely to be a more realistic measure of soil salinity than the EC of the saturation extract (EC_{se}), given that suitable reference values are available to assist in the interpretation of the EC_{sw} data.

As with the $EC_{1:5}$ to EC_{se} conversion, the EC measured in the field-extracted soil solutions, using suction cups, can be converted to the EC_{se} by using equations. Biswasi et al (2007) proposed the following equation:

$$EC_{sw}\ (dS/m) = 2{,}1 * EC_{se}\ (dS/m);\ \text{where}\ EC_{se} < 10\ dS/m$$

where EC_{sw} is the EC_{25} measured in the soil solution extracted with a soil solution sampler.

Units.

Electrical conductivity is measured in siemens (S) per length units; S/m is the SI unit. However, several units are commonly used for EC measurement, which can be converted from one to another:

$$0,1\ S/m = 1\ dS/m = 1\ mS/cm = 1000\ \mu S/cm$$

Other units used for soil salinity evaluation is the concentration of the total dissolved solids (TDS, mg/l), whose ratio for conversion to EC_{se} (dS/m) is 1/640.

$$EC_{se}\ (dS/m) = TDS\ (mg/L)\ /\ 640$$

Interpretation of results

The EC_{se} can be interpreted in terms of crop tolerance to soil salinity. The equation to calculate the yield loss due to the salinity of many crops is the well-known threshold-slope function given by:

Yr (relative yield, %) = 100 - b (EC_{se} - a); (Maas & Hoffman, 1977),

where “a” and “b” are, respectively, the EC_{se} threshold and slope values and are specific for each crop. Crops can be broadly grouped for their tolerance to salinity in relation to their threshold or “a” value which indicates the salinity at which salnity-induced yield reduction occurs, and the slope or “b” value which indicates the degree of reduction as salinity increases. This can be seen in Figure 11-13 which demonstrates the relative yield reduction with increasing salinity (EC_{se} referred to here as EC_e) for crops classed as being Sensitive, Moderately Sensitive, Moderately tolerant, and Tolerant to salnity.

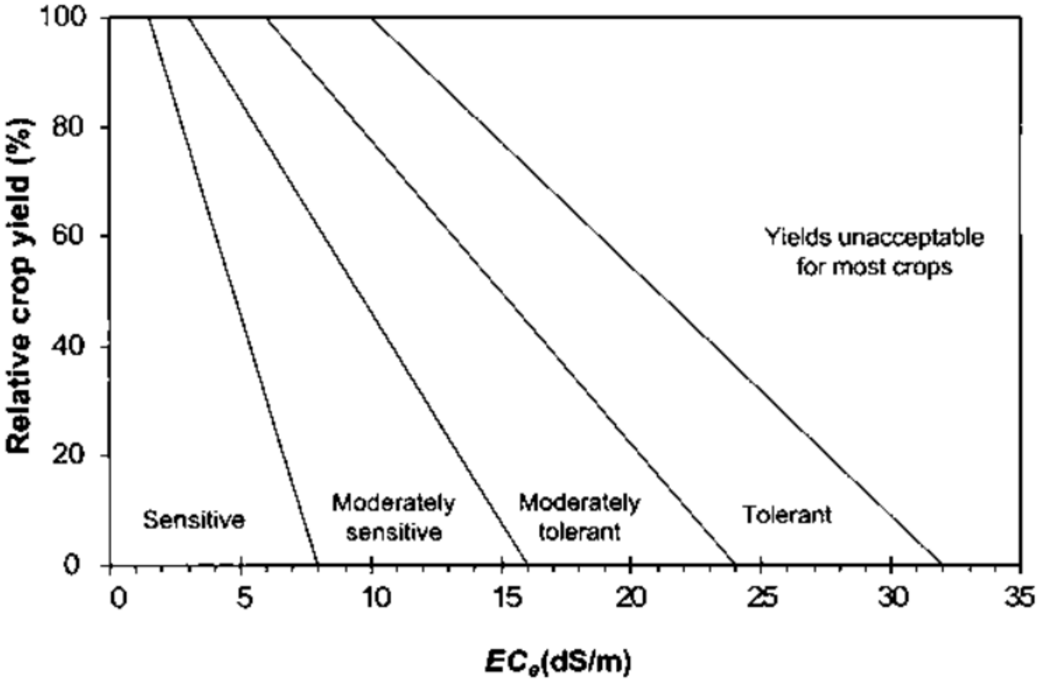

Figure 11-13. Broad classification of crop tolerance to salinity using the Maas & Hoffman (1977) approach

In Table 11-5, the salinity sensitivity/tolerance parameters (threshold and slope values using the Maas & Hoffman (1977) approach) and the sensitivty/tolerance class are provided for some common vegetable species.

Table 11-5. Soil salinity sensitivity/tolerance parameters and classification of selected vegetable crops using the Maas and Hoffman (1977) approach.

Species	Threshold EC_{se} value (dS/m)	Slope (% change per dS/m)	Sensitivity/tolerance class
Bean, common	1.0	19.0	Sensitive
Broccoli	2.8	9.2	Moderately sensitive
Muskmelon	1.0	8.4	Moderately sensitive
Pepper (capsicum)	1.5	14.0	Moderately sensitive
Strawberry	1.0	33.0	Sensitive
Tomato	2.5	9.9	Moderately sensitive
Zucchini	4.9	10.5	Moderately tolerant

More detailed information for specific crops can be obtained in Maas and Hoffman (1977).

11.9.5.3. Operational conditions

The determination of EC in the paste of a saturated extract is a time-consuming and labour-intensive procedure. This limits its practical use for regular and frequent monitoring. It is more suited to the characterisation of a soil at the start of a crop. It is the established, standard method for determining soil EC, so it is valuable for general soil characterisation.

For regular and rapid monitoring of soil EC during a crop, the determination of the EC in samples of soil solution (EC_{sw}) obtained with soil solution suction samplers is more suitable, because once the samplers are installed, it is relatively little work to periodically obtain the samples of the soil solution. A number of samplers should be installed in each field or greenhouse to ensure that the average obtained value is as representative as possible.

The installation of the suction samplers is critical and must ensure contact between the ceramic suction cup and the soil. The soils must be moist, as the maximum suction that can be applied with manual suction pumps is approximate -60 kPa. In lighter textured soils, higher (i.e. less negative) suctions can be applied.

11.9.5.4. Cost data

Cost of commercial soil samplers can be consulted in Table 11-6 (80-175 €), although a cheaper option is to make them by yourself. The cost of a manual vacuum pump is approximately 90-120 €.

11.9.5.5. Technological bottlenecks

There are several technological bottlenecks in the use of this technology for salinity monitoring:

- EC measured in soil sample: The conventional procedure of soil sampling, analysis in the laboratory and results interpretation to determine the EC_{se} is tedious, time-consuming and requires an expert soil laboratory. Management decisions sometimes require information faster than this procedure can provide

- EC measured in soil solution (EC_{sw}): Some problems may occur when using the suction cup method. The process of extracting the soil solution using a vacuum may alter the composition of the salts compared to those in the root zone soils solution because of different interactions with soil colloids. Extracting soil water from soil at different soil matric potentials may also influence the concentration and composition of the salts in the soil solution. This increases the uncertainty when comparing the measured EC_{sw} value to the EC_{se} reference value

11.9.5.6. Benefit for the grower

Advantages

- EC_{sw}: Provides real-time information on soil salinity
- EC_{sw}: Good tool for soil or irrigation management

Disadvantages

- EC_{se}: Long time between soil sampling to obtain results and interpretation
- EC_{se}: Processing of samples is time-consuming
- EC_{sw}: Limited number of soil samples or suction cups can be installed
- EC_{sw}: Not representative of the spatial variability of soil salinity
- EC_{sw}: The spatial variability should be considered to determine the number and distribution of soil samples or suction cups to be installed in the field

11.9.5.7. Supporting systems needed

For EC_{se}, soil equipment to take soil samples at several soil depths is required and a laboratory, a nearby laboratory that deals with soil analysis is needed.

For the suction cups, a pump, a handheld EC-meter are required to perform measurements in the field.

11.9.5.8. Development phase

- Research: The technique to measure EC_{se} has been researched for a long time and it is well developed. More research is required to relate the EC_{sw} to EC_{se}
- Experimental phase: There has been considerable applied experimental work to further develop and adapt these methods
- Field tests: These techniques have been widely tested in different conditions of soil, climate and irrigation systems

11.9.5.9. Who provides the technology

Suction cups can be bought from several companies; they also can be made from purchased component parts.

Table 11-6. Commercial soil solution samplers (prices are approximate)

Name	Company	Price (€)	Weblink
Ceramic suction lysimeter	SDEC France	≈80	http://environnement.sdec-france.com/index.php?lg=en&numpage=14&spec=&numfamille=10&numgamme=1&numrub=30&numcateg=43&numsscateg=95
Pressure/ vacuum soil water sampler	Soil moisture Equipment	≈175	http://www.soilmoisture.com/Soil-Water-Samplers/
Pore water samplers	DECAGON	≈170	http://www.decagon.com/en/hydrology/pore-water-sampling/pore-water-samplers/
SoluSAMPLER	Sentek	≈150	http://www.sentek.com.au/products/ancillary.asp

11.9.5.10. Patented or not

This technology is not patented.

11.9.6. Which technologies are in competition with this one?

This technology is in competition with the EC measured by sensors installed in the field. The conventional methods for EC_{se} determination are used as reference methods for sensor readings. Sensors provide faster and updated information on soil solution salinity and conventional methods provide a more accurate but tedious and time-consuming measurement. With EC measurement by sensors, there are issues of calibration and the conversion from bulk soil EC, as measured by the sensors, to EC_{se} or EC_{sw}.

11.9.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, this technology is fully transferable to other soils or cropping systems.

11.9.8. Description of the regulatory bottlenecks

There are no relevant regulatory bottlenecks.

11.9.9. Brief description of the socio-economic bottlenecks

For EC_{se}, there are bottlenecks in the time required for soil sampling, sample shipment to the laboratory, sample preparation, measurement, and in the interpretation of results.

For the use of suction cups to obtain EC_{sw}, an important issue is the selection of the location in the field where the sample cups are installed and he number of soil samples taken. Another issue is the possible interference of sampling cups with normal field operations.

It is advisable that advisors/consultants assist with the interpretation of results.

The cost of the laboratory analyses or number of suction cups installed depends on the number of samples being analysed.

In case of quick determinations of soil solution to be carried out on the field, this requires some training of this procedure for farm personnel.

11.9.10. Techniques resulting from this technology

Irrigation management may be influenced the determination of EC in the soil or the soil solution, requiring that additional irrigation may need to be applied to control salt accumulation in the soil. The information provided by this technology could be used in an irrigation recommendation system to provide management guidelines for farmers.

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11.10. EC measurement in soil using sensors

(Authors: José Miguel de Paz[14], Rodney Thompson[23])

11.10.1. Used for

- Minimising the impact of salinity in crop production
- Minimising the impact to the environment by nutrient discharge
- More efficient use of water

11.10.2. Region

All EU regions.

11.10.3. Crops in which it is used

All vegetable, fruit and ornamental crops.

11.10.4. Cropping type

- Soil-bound
- Open air
- Protected

11.10.5. Description of the technology

11.10.5.1. Purpose/aim of the technology

Electrical Conductivity sensor technology is used to quantify the salinity of the soil solution in order to manage irrigation to limit soil salinity to levels that can be tolerated by crops.

11.10.5.2. Working Principle of operation

Dissolved salts in the soil solution have effects on plant growth, depending on their concentration. It is however time consuming and to monitor the salt concentration using traditional laboratory analyses, and there is a time delay in results being available.

EC measurements in soil can be performed with different types of sensors which can be classified according to their operating principles: 1) Electrical Resistivity, 2) Electromagnetic Induction, and 3) Reflectometry, of which there are three forms: TDR (Time domain reflectometry), Amplitude domain reflectometry, or FDR (Frequency domain reflectometry).

1) Electrical Resistivity: These measurements are based on the inverse relationship between the electrical conductivity and the resistivity of a material. By measuring the electrical resistivity of a volume of soil or water of known dimensions, the EC can then be obtained
2) Electromagnetic Induction: A transmitter coil located at one end of the instrument applies a magnetic field to the soil (Figure 11-14). This generates a secondary electromagnetic field in the soil which is detected by a receiver coil located in the instrument. This signal of this secondary field is linearly related to the apparent EC_a

Figure 11-14. Electromagnetic sensor (http://agrosal.ivia.es/evaluar.html)

3) Reflectometry is based on the effects that the soil has on primary alternating electric currents which are transmitted into the soil via embedded electrodes. The main purpose of reflectometry is measurement of the soil water content, but since conduction is one of the main mechanisms through which the electromagnetic signals transmitted into the soil lose energy, it can also be used for measuring EC:

- TDR: see Chapter 10, technology description of TDR for soil water measurement (Figure 11-15)

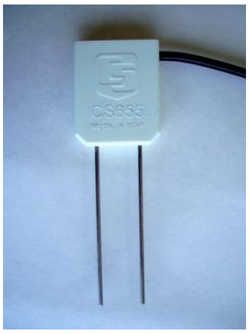

Figure 11-15. TDR sensor (http://agrosal.ivia.es/evaluar.html)

- ADR: the measurement is based on the amplitude features of the standing electromagnetic oscillation in the Transmission line. The signal generator's frequency ranges at 10-100 MHz (<< than in TDR) and instrument prices decrease
- FDR: FDR (Figure 11-16) is not based on the analysis of reflected electromagnetic pulses but on the resonance features of resistor, inductor, and a capacitor circuits in which a capacitor is formed by two electrodes and of soil in between the electrodes or surrounding the electrodes. FDR sensors are are also known as capacitance sensors

Figure 11-16. FDR sensor (http://agrosal.ivia.es/evaluar.html)

11.10.5.3. Operational conditions

Not applicable.

11.10.5.4. Cost data

The approximate prices of the more commonly-used soil EC sensors are detailed in Table 11-7.

Table 11-7. Main characteristics and the approximate prices of the more usual salinity sensors

Sensor	Manufacturer	Type	Soil Volume explored	Soil water content	Temperat.	Estimate ECp*	Cost (€)	Web site
EM38	Geonics Ltd.	EMI	≈ 1 m3	NO	NO	NO	> 10000	www.geonics.com/
Dualem 1S	Dualem Inc.	EMI	≈ 1 m3	NO	NO	NO	> 10000	www.dualem.com/
EC-probe for soil salinity measurement	Eijkelkamp	Resistivity	≈ 2 dm3	NO	YES	NO	≈ 5000	https://en.eijkelkamp.com/
5TE	Decagon Devices	Water-Capacitive, Salinity-Resistivity	≈ 100 cm3	YES	YES	NO	390	www.decagon.com
GS3	Decagon Devices	Water-Capacitive, Salinity-Resistivity	≈ 100 cm3	YES	YES	NO	< 500	www.decagon.com
WET	Delta-T Devices	FDR	≈ 100 cm3	YES	YES	YES	> 1000	www.delta-t.co.uk
CS650	Campbell Scientific	TDR	0.1 - 2 dm3	YES	YES	NO	< 500	www.campbellsci.com
CS655	Campbell Scientific	TDR	0.1 - 2 dm3	YES	YES	NO	< 500	www.campbellsci.com
TriScan	SENTEK	FDR	0.1 - 2 dm3	YES	YES	NO	609	www.sentek.com.au
Hydraprobe II	Stevens	FDR	40 cm3	YES	YES	NO	516	www.fondriest.com

*EC_p. Electrical conductivity in soil pore water.

11.10.5.5. Technological bottlenecks

Most of these sensors measure soil dielectric permittivity, which is strongly related to soil water content, but which is also affected by soil salt content. Therefore, the salinity readings are affected by soil water content, and a mathematical model is required to estimate the soil salinity represented by the electrical conductivity in the soil pore water.

An important issue is the selection of the location in the field where the sensor is installed. It should be a representative location with respect to the rest of the field, it should be possible to protect the equipment against vandalism and the sensor and accessories should not interfere with normal farming operations.

11.10.5.6. Benefit for the grower

Advantages

- Real-time information on soil salinity
- Useful for soil or irrigation management

Disadvantages

- Measurements often lack accuracy due to the effect of environmental factors
- Site-specific calibrations are needed for very accurate results
- Field soil sampling and laboratory analyses required

11.10.5.7. Supporting systems needed

Usually these sensors are connected to a logger where the data are stored. These devices are also generally used to send the information by global system for mobile communications, general packet radio services etc. to a central server where they are processed and made available to end-users (farmers, irrigator advisors etc.). Therefore, this technology requires a logger and a server where the information obtained in the field by the sensors is stored and managed.

11.10.5.8. Development phase

- Research: Research is being developed to find the best algorithms to relate the sensor readings with the electrical conductivity of the soil solution
- Experimental phase: Calibration of the sensors in different soil types
- Field tests: The sensors are being tested in different conditions of soil, climate and irrigation systems

11.10.5.9. Who provides the technology

Several companies sell salinity sensors that can be used for commercial farming applications such as, Decagon Devices, Delta-T, Dualem, Geonics, Campbell Scientific, Sentek Sensor Technologies, and Stevens Water Monitoring Systems. References and web sites of these companies are included in the Table 11-7.

11.10.5.10. Patented or not

All the commercial sensors are patented.

11.10.6. Which technologies are in competition with this one?

This technology is in competition with the traditional methods used to measure soil salinity, which requires either soil sampling or the preparation of a saturated extract in a soil laboratory or the use of ceramic cup suction samplers to obtain a sample of the soil solution that can be analysed either in the field or in the laboratory. In both of these cases, a laboratory bench or a portable hand EC meter is used to measure EC in the solution obtained either from the saturated extract or from the suction sampler.

The most established traditional method of the saturated extract requires soil sampling and laboratory manipulation of the sample and laboratory measurement of the electrical conductivity, and therefore is a time-consuming compared to sensor measurement. The other traditional method involving the use of suction samplers is quicker but is also labour intensive in that is requires application of vacuum, the collection of the sample and manual measurement. Additionally, the two traditional methods are "snap shot" measurements of one point in time, whereas sensors provide continuous measurement.

The traditional methods are discussed in the TD on EC measurement in soil using conventional methods, also in this Chapter.

11.10.7. Is the technology transferable to other crops/climates/cropping systems?

This technology is fully transferable to other soils or cropping systems. In these cases, a calibration comparing sensor readings with the reference methodology is recommended for accurate measurement.

11.10.8. Description of the regulatory bottlenecks

There are no relevant regulatory bottlenecks.

11.10.9. Brief description of the socio-economic bottlenecks

The socio-economic bottlenecks relate to time and costs. Time is required for installing the sensors and logger and also for the maintenance of the equipment.

The sensor readings should be directly interpreted or used as input for software to provide alerts or to a decision support system. This software should be user friendly so that farmers can easily interpret the sensor readings and determine the appropriate management responses.

The cost of the laboratory analyses for calibration depends on the number of samples being analysed.

11.10.10. Techniques resulting from this technology

Irrigation management based on sensor readings.

The information provided by this technology could be easily included in a decision support system to provide management recommendations for farmers.

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11.11. EC measurement of substrate drainage

(Authors: Claire Goillon[2], Benjamin Gard, Rodney Thompson[23])*

11.11.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.11.2. Region

All EU regions.

11.11.3. Crops in which it is used

- Vegetables crops
- Ornamentals

11.11.4. Cropping type

- Soilless
- Open air
- Protected

11.11.5. Description of the technology

11.11.5.1. Purpose/aim of the technology

This technology aims to provide information on the salinity of drainage water through measurement of electrical conductivity (EC). It helps to measure how the plants consume fertiliser and to monitor the risk of ion accumulation in the substrate, as well as check that what the grower thinks is happening with his feed plan, is actually happening.

11.11.5.2. Working Principle of operation

Electrical conductivity is measured by applying an alternative current to two electrodes immerged in the solution and by measuring the resulting tension. Electrical conductivity is measured in Siemens per cm (S/cm) or deci Siemens per metre (dS/m) and represents the global concentration salts in in the solution. It thus gives a useful measurement of total salt content of the root zone solution in a soilless substrate. The more salts, the higher is the electrical conductivity. Electrical conductivity measurement is done using an EC meter.

Figure 11-17. EC meter for use in water (http://www.hydroponics.com.au)

Figure 11-18. Handheld conductivity meter (http://www.eutechinst.com)

High EC readings can warn of potential problems in the crop, for example, an increase in total volume of salts (high EC) which can restrict water uptake via roots. Where drainage EC is high, it is worth examining the plant's root system to check for any root death. High chloride and sodium levels can cause root death, whereas high carbonate and bicarbonate levels can cause crop leaf yellowing, but not root death.

The conductivity of the drainage solution reflects irrigation and fertigation management practices, so it can vary over the season. The EC of the drainage is always higher than the applied nutrient solution, typically by 10-25%, although this increase can be higher when poorer quality water is used for irrigation. Higher EC values are often measured during hot weather, when water absorption by the crop increases proportionately more than nutrient absorption. Under these conditions, if nutrient concentrations are maintained in the applied solution, ions in the drainage solution will become more concentrated for the same leaching fraction. This will lead to an increase in salt levels in the substrate, resulting in prolonged higher EC readings in the drainage. To avoid this, a more dilute nutrient solution should be supplied. It is also necessary to maintain good drainage. If drainage is inadequate, it can result in increased EC.

11.11.5.3. Operational conditions

Regular measurement of EC in drainage from substrate provides an early warning of accumulating salts in the root zone. However, background conductivity (of the water source) varies from site to site and depends on the water source used. Uncontaminated rainwater has an EC of close to 0 S/cm, whereas a typical EC for mains water in the UK is 0,5 S/cm. High background EC can be reduced by blending with water sources with lower background EC e.g. rainwater. A full water analysis is needed in addition to using EC meters, as it is possible to have good EC measurements but harmful levels of sodium or chlorine.

An EC meter can be a portable device which allows measurement at several points in the greenhouse by the operator (e.g. Figures 11-17 and 11-18). An EC sensor such as a FDR meter can be permanently positioned in the substrate with automatic high frequency measurement. Results can be sent automatically to a data logger by remote data transmission. However, it is important to note that EC measured by a FDR sensor is not the real EC in the root zone solution in the substrate but bulk EC that measures EC in a volume of substrate and solution, these EC values are lower and vary appreciably with water content. Temperature of the solution can influence measurement made with an EC meter

(Table 11-8). Most of the recent devices are able to correct the for temperature of the solution. But this parameter must be taken into account.

In a soilless crop, EC measurement can be done directly in the slab, the measure allows the environment of the roots to be evaluated. Measurement can also be performed in the drain water to evaluate nutrient consumption and the risk of nutrient accumulation.

Table 11-8. Correction factor of EC (mS) for EC meters calibrated on the French norm of 20°C

Temperature (°C)	Correction factor	Temperature (°C)	Correction factor
14	1,152	20	1,000
15	1,123	21	0,979
16	1,096	22	0,958
17	1,070	23	0,938
18	1,046	24	0,919
19	1,023	25	0,902

The EC meter should be calibrated regularly using standard solutions; generally, the instructions that come with the meter recommend the frequency of calibration. The EC of the substrate drainage should be measured in a consistent manner, preferably by the same person. This person should know the acceptable EC ranges for the crop, bearing in mind the background EC of local water sources.

Yield response to moderate salinity follows the Maas and Hoffman model, according to which yield decreases linearly above a certain EC threshold value, which depends on crop species and weather conditions. An average threshold value for greenhouse-grown tomato in Mediterranean conditions is 3,3 dS/m.

Measurements should be plotted on a spreadsheet to make graphs and give insight into any trends that are occurring. The trends can be as important as individual readings. The nutrient concentrations and the EC of the applied nutrient solution can be adjusted by small amounts in response to these trends.

11.11.5.4. Cost data

Handheld portable EC meter: The costs are generally in a range of 200-500 € for a reliable sensor from an established brand. Cheaper models (e.g. 20 €) are available; however, it is recommended to purchase an established brand. More expensive models are available; however, these are intended for chemistry laboratories. All portable EC meters require regular recalibration e.g. once a year. For this calibration, a buffer solution is needed. These portable meters are suitable for making multiple individual measurements in different places at different times.

A fully-equipped EC meter station, consisting of sensors, data logger and reader, which would equip a greenhouse costs 1700-2000 €. Yearly maintenance is needed: the sensor should be replaced every 5 years; the yearly cost of a GSM data connection is approximately 150 €. These sensors are suitable for frequent, on-going measurement in one position, such as in a substrate slab.

11.11.5.5. Technological bottlenecks

EC only gives an idea about total dissolved ion content in the solution and it should be used in conjunction with regular full water analyses for optimal fertigation management.

11.11.5.6. Benefit for the grower

Advantages

- Easy and quick measurement
- Very useful for salinity management in fertigation
- Fine control of fertigation and of the quality of water being recirculated
- Reduces risk of salinity problems

Disadvantages

- No measurement of the quantity of each ion
- No pH assessment
- Installation and interpretation support is often needed
- Calibration and maintenance are essential

11.11.5.7. Supporting systems needed

Technical assistance and an easy-to-use friendly software for the EC meter station.

11.11.5.8. Development phase

Commercialised.

11.11.5.9. Who provides the technology

Portable EC meters and EC meter stations can be purchased from many suppliers of agricultural equipment for intensive horticulture. They can be purchased from supplies of scientific equipment. They can even be purchased from local affiliates of Amazon.com who generally offer a large range. Numerous companies specialised in sensors for agricultural and chemistry applications produce these portable EC meters, e.g. Hanna Instruments, Delta Ohm, Thermofisher Scientific, and Spectrum Technologies. EC meter stations are produced by GRODAN, HORTAU, and IRROLIS amongst others.

11.11.5.10. Patented or not

Some EC meters are patented.

11.11.6. Which technologies are in competition with this one?

Devices measuring total dissolved ion concentration in the solution (the measurement is directly given in a concentration unit (ppm, g/L)).

11.11.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

11.11.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

11.11.9. Brief description of the socio-economic bottlenecks

The cost of the sensors will be an issue for some growers.

11.11.10. Techniques resulting from this technology

Management of the fertigation and water drainage in closed tomato soilless system.

11.11.11. References for more information

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11.12. Plant tissue analysis

(Authors: Eleftheria Stavridou[15], Ana Quiñones[14])

11.12.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.12.2. Region

All EU regions.

11.12.3. Crops in which it is used

All crops.

11.12.4. Cropping type

All cropping types.

11.12.5. Description of the technology

11.12.5.1. Purpose/aim of the technology

Plant analysis is the chemical evaluation of essential element contents in plant tissue. It is used to:

- Predict nutrient problems likely to affect crop production between sampling and harvest
- Monitor crop nutrient status for optimal crop production
- Evaluate fertiliser efficiency
- Determinate availability of elements for which reliable soil tests are not avail.
- Determinate key ratios between nutrients, which often affect post-harvest life

There are also other, less common applications, such as crop-quality measurements, regional nutrient status evaluations, assessment of crops for animal and human nutrition, and environmental protection.

11.12.5.2. Working Principle of operation

It is usually suggested that samples from both good and problem areas be submitted for comparison when the diagnosis is the goal. Because experience and knowledge are vital in sampling plants correctly, agricultural advisors or consultants often do the job.

The interpretation of the results of plant tissue analysis results is based on the scientific principle that healthy plants contain predictable concentrations of essential elements. A number of researchers have offered schematics showing the relationship between maximum yield and concentrations of essential elements. Test values are compared with established values for deficient, optimum and excess nutrient levels for a specific plant species. In this way, the nutritional health of the plant can be assessed and the supply and availability of nutrients to crops during the growing season can be evaluated and modified to maximise yield and yield (Figure 11-19). This system uses a previously established set of standards for nutrients in a specific plant part, sampled at a particular growing stage; the results are then compared to established reference values to interpret the results. The principle of this system lies in the relationship between nutrient content and crop yield.

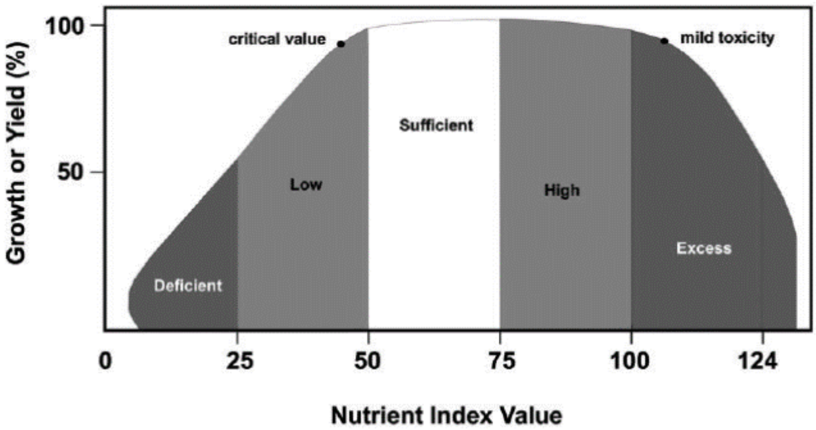

Figure 11-19. Schematic of yield or growth in response increasing nutrient concentration and interpretation

11.12.5.3. Operational conditions

Plant composition varies with age, the part of the plant sampled, the condition of the plant, the variety, the weather and other factors. Therefore, it is necessary to follow established sampling instructions; most commonly young fully expanded leaves are sampled. Most laboratories offering tissue analysis provide instruction sheets for sampling various crops, plus information sheets and directions for preparing and submitting samples.

11.12.5.4. Cost data

It takes approximately 30-45 minutes to take representative petiole/leaf samples; there is no financial cost apart from that of time.

Shipping costs vary but often if a large number of samples analysed at once, shipping costs are paid by the analytical lab (and later included in the total cost).

An analysis cost depends of the number of nutrients that the sample is analysed for. Broad spectrum analysis (N, P, K, Mg, Ca, S, Mn, Cu, Fe, Zn, Mo, B) costs 35-40 € and the basic analysis (N, P, K, Mg) costs 25-30 €. Prices may vary between analytical labs in different countries.

11.12.5.5. Technological bottlenecks

Interpretation difficulties: Plant nutrient content is determined by a number of factors in addition to crop nutrition. Genetics, plant part sampled, climate, soil properties, and soil amendments all influence the contents of nutrients within plants. Interpretations of plant analysis must take these factors and their relationships into consideration to avoid misleading interpretation.

- Plant sample: Nutrient levels in plants differ depending on the plant part sampled, stage of maturity, and position. Correct sampling is a critical factor for correct interpretation
- Climate: For example, an increase in temperature affects plant composition by stimulating nutrient movement and utilisation within the plant

- Soil properties: Soil pH affects the availability of plant nutrients. Low soil pH increases availability of aluminium, boron, copper, iron, manganese, and zinc, but decreases availability of molybdenum
- Location: Compacted soil layers can result in reduced nutrient uptake even though the nutrient supply in the soil would be considered adequate under normal conditions as they can restrict root growth

Progressive deficiencies. Another limitation of plant analysis is that it the content of a particular nutrient may be influenced by another that is strongly limiting plant growth. For example, nitrogen stress can limit the uptake of phosphorus and some of the micronutrients to the extent that they also appear to be "low".

Sample contamination. Contamination of a plant sample with soil particles or pesticide residue can lead to erroneously high results for iron, aluminium, manganese, zinc, or copper. Washing the sample to remove contamination can introduce other contaminants if detergent or tap water are used. Appreciable potassium can be lost by washing.

Sample deterioration. Decomposition of a plant sample before it reaches the laboratory will result in a loss of carbon and the concomitant concentration of most other elements, thereby giving erroneously high readings.

11.12.5.6. Benefit for the grower

Advantages

- Information of the current nutrient status of a crop
- No devices needed for taking samples
- Easy to take samples

Disadvantages

- Laboratory tests take approximately a week to complete
- Destructive (problem with ornamentals)
- The results can be difficult to interpret
- Time-consuming to collect a representative sample
- The need for locally-derived or verified sufficiency values which often are not available

11.12.5.7. Supporting systems needed

It is strongly recommended that a soil test accompanies each plant analysis. The soil test often helps to explain why a particular nutrient is low or high in a plant.

11.12.5.8. Development phase

- Research: The availability of sufficiency ranges and other interpretive data indicates gaps in the research data base and additional work that is required
- Commercialised: There are specialised laboratories that offer plant analysis; see next section

11.12.5.9. Who provides the technology

There are several companies providing analytical services in UK such as Yara analytical services (http://www.yara.co.uk/crop-nutrition/agriculture-contacts/analytical-services) and NRM (http://www.nrm.uk.com) laboratories. AGQ Labs &Technological Services (http://www.agq.com.es/en) provides analytical services worldwide (Europe, Asia and USA). Many agronomic consulting companies offer nutrient management services including soil and plant sampling, nutrient analysis, result interpretation and the determination of fertilisation requirement.

Most European countries have multiple labs that are accredited for this kind of tests.

11.12.5.10. Patented or not

This technique is not patented.

11.12.6. Which technologies are in competition with this one?

Alternative approaches to plant tissue analysis are various monitoring procedures to assess crop nutrient status. These are sap analysis (see relevant TD) and the use of various proximal optical sensors such as canopy reflectance and chlorophyll meters sensors (see relevant TDs). Proximal optical sensors are used to assess crop N status.

11.12.7. Is the technology transferable to other crops/climates/cropping systems?

Plant tissue analysis can be used in various crops, in different climates, and with crops grown in different cropping systems such as crops in soil or substrate, and crops in open field or in greenhouses. However, for each application, it is necessary to obtain or verify the reference values used to interpret the nutrient contents determined.

11.12.8. Description of the regulatory bottlenecks

There are no relevant regulatory bottlenecks.

11.12.9. Brief description of the socio-economic bottlenecks

The time required to take the samples. If samples are to be sent to a laboratory, time is required to correctly prepare the samples and to organise transport to the laboratory.

The costs associated with using a laboratory to conduct the analysis are those of transporting the samples, and the actual costs of the laboratory analysis and data interpretation.

The costs of the laboratory analysis can vary depending on the number of determinations being made and samples being analysed.

The establishment of correct reference tables for all crops under their development conditions.

11.12.10. Techniques resulting from this technology

This is an established technique.

11.12.11. References for more information

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11.13. Sap analysis

(Author: Rodney Thompson[23])

11.13.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.13.2. Region

All EU regions.

11.13.3. Crops in which it is used

All vegetable, fruit and ornamental crop.

11.13.4. Cropping type

All cropping types.

11.13.5. Description of the technology

11.13.5.1. Purpose/aim of the technology

Sap analysis is used to assess the nutrient status of a crop. It is mostly used for assessing the N status of a crop, and has been used for assessing K status. There are some private companies offering sap analysis to assess crop nutrient status of more nutrients.

11.13.5.2. Working Principle of operation

Most sap analysis is conducted with sap extracted from recently-collected fresh petioles, normally from the most recently fully expanded leaf (Figures 11-20 to 11-24). It is considered that the available nutrient content (e.g. NO_3, K) of sap being transported in connective tissue to this recently fully-formed leaf reflects the nutrient status of the crop. All scientific studies have been done with petiole sap. Some commercial companies (e.g. Hortus Technical Services in Australia) work with petiole sap. One commercial company in The Netherlands, Nova Crop Control (http://www.novacropcontrol.nl/en) works with sap obtained from leaves; leaves are easier to obtain and sap extraction is easier.

It is generally recommended with petiole sap analysis that 20-30 petioles from representative plants, from throughout a production unit, e.g. field or greenhouse, be collected at the same time to adequately represent the crop being sampled. These petioles are bulked. Similar sampling procedures (Figure 11-21, Figure 11-22, Figure 11-23) are used for leaf analysis.

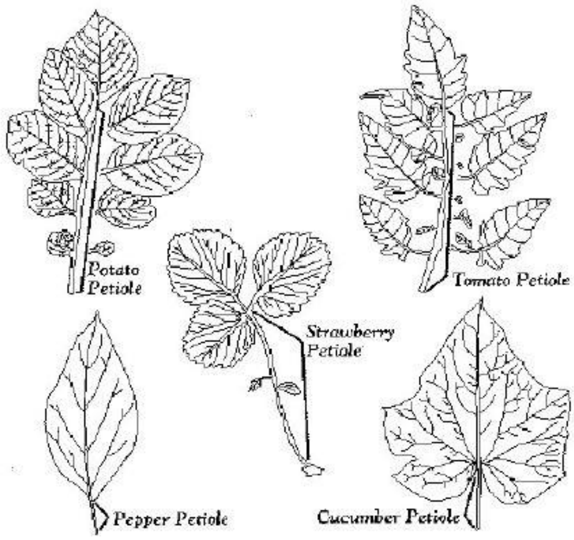

Figure 11-20. Identification of petioles of important vegetable species (Hochmuth 2012)

Figure 11-21. Cutting compound tomato leaf for later removal of petioles

Figure 11-22. Cutting petioles into small pieces prior to sap extraction

Figure 11-23. Squeezing sap from cut petioles using garlic press

Analysis of the nutrient concentration of sap can be conducted in two ways: 1) samples of petioles or leaves are sent to a laboratory where the sap is extracted and analysis conducted to determine the nutrient concentration, or 2) sap is extracted on the farm and small portable rapid analysis systems are used to analyse the nutrient concentration in-situ immediately after extraction. Suitable rapid analysis systems are described in the TD "Rapid, on-farm analysis of nutrients", also in this Chapter.

Once nutrient analysis has been conducted, the nutrient concentration is compared with reference values to determine if the determined nutrient content is deficient, sufficient or excessive. Subsequently, the nutrient supply is adjusted to ensure that it is optimal.

In addition to analysis of individual nutrients, there are commercial services that also determine the EC, pH and sugar content of sap, and use these data as part of their nutrient management service. An example is the Dutch firm Nova Crop Control. Whereas normally only the most recently fully expanded leaves are used, Nova Control additionally samples a lower leaf; composite samples of upper and of lower leaves are analysed separately. Nova Crop Control suggests that lower older leaves are useful for early detection of deficiencies of nutrients that are mobile within plants such as N, P, K and Mg. Whereas, there is considerable publicly available on the use of sap analysis for NO_3, K; the procedures used by private companies for these and other nutrients are proprietary information and cannot be independently verified.

11.13.5.3. Operational conditions

Generally, the limitations will be the time required for sampling and for sap extraction where that is done on-farm. The availability of appropriate reference values will limit the suitability of this method for given crops and cropping systems. This is further discussed in the subsequent sub-section of "Technological bottlenecks".

Considerable care must be taken to quickly refrigerate the petiole or leaf samples after removal from the plant. Extraction of sap from petiole samples should be conducted soon after removal from the plant. Fresh, whole (un-chopped) petioles can be stored for up to 8 hours on ice or in a refrigerator. Once sap is extracted, it should be analysed as quickly as possible. Published guidelines are not available for handing leaf samples; presumably they are similar. Also, companies dealing with analysis of sap from leaves will have their own guidelines.

11.13.5.4. Cost data

For taking samples: Approximately 30-45 min to take the petiole/leaf samples; there is no financial cost apart from that of the time.

For sap extraction: If done on farm, the time required is 5-10 min. It is necessary to purchase a cutting board, a large sharp knife, to cut petioles into small pieces, and a press to squeeze the petiole pieces to extract the sap. Commonly, domestic garlic presses are used. Total economic cost is approximately 10 €.

For analysis: If done on farm, 5 min. For on-farm analysis, it is necessary to purchase a small portable rapid analysis system. These are described in the TD "Rapid, on-farm analysis of nutrients" where costs are provided. For a lab analysis that will provide information on N, P, K and a wide range of trace elements, it will be approximately 60 € (based on UK prices). It can be cheaper if less information is required.

11.13.5.5. Technological bottlenecks

There are various technical bottlenecks that influence the possible adoption of sap analysis. If a grower wishes to use a laboratory that is specialised in conducting and interpreting sap analyses, there are very few such laboratories in the EU. For growers wishing to conduct on-farm analysis, appropriate sufficiency values are required in order to interpret the results. Ideally, these should be determined or verified locally. Commonly, such relevant local information is not avail. Otherwise, published values determined elsewhere can be used, but they should be used with care as indicative values. Where reference values are available in scientific and Extension literature, commonly the values are for NO_3 and sometimes for K. There are very few published reference values that are generally available, for other nutrients. Another technical bottleneck affecting on-farm analysis is the availability of suitable rapid analysis systems. There are a limited number of commercially-available suitable analytical systems. More information of these analytical systems is provided in the TD "Rapid, on-farm analysis of nutrients".

11.13.5.6. Benefit for the grower

Advantages

- Provides information of the current nutrient status of a crop
- Information can be available rapidly, enabling rapid corrective action is required

Disadvantages

- Time-consuming to collect the required number of petioles/leaves for a representative sample
- The need for locally-derived or verified sufficiency values which often are not avail.
- The need to rapidly process the petiole/leaf samples
- The need to rapidly analyse the extracted sap

- Laboratories do not always operate on a "first sample in, first sample processed" policy
- Costs: you have to pay per sample
- When using an analytical laboratory, there is a time delay to obtain the results

11.13.5.7. Supporting systems needed

If samples are to be analysed by a laboratory, there is a requirement for a specialised laboratory that conducts sap analysis and provides interpretation of results. Where petioles/leaf samples are sent to a laboratory, they must be sent refrigerated in sealed air-tight bags by a rapid messenger (e.g. overnight) service. The specialised laboratory must have procedures to minimise the times between receipt of samples and sap extraction and between extraction and analysis.

If samples are to be analysed on the farm by the grower or a technical advisor, a suitable rapid analysis system is required. These are described in the TD "Rapid, on-farm analysis of nutrients". For on-farm sap extraction, a press is required to extract sap from petiole tissue; conventional kitchen garlic presses are commonly used.

11.13.5.8. Development phase

- Research: Some research is on-going to assess sensitivity and to develop sufficiency values for new crops, varieties and locations. New approaches are also being used for these evaluations
- Experimental phase: As with research, more applied experimental work is on-going.
- Field tests: Field testing is often being conducted to adapt sap testing to particular crops and regions
- Commercialised: There are specialised laboratories that offer services of sap analysis; see next section. For on-farm analysis, small rapid analysis devices are commercially available

11.13.5.9. Who provides the technology

For laboratory analysis, the Dutch company Nova Crop Control (http://www.novacropcontrol.nl/en) is specialised in sap analysis and provides a comprehensive service. They analyse sap from leaves.

For on-farm analysis, several companies manufacture commercially-available small rapid analysis systems. More information of these analytical systems is provided in the TD "Rapid, on-farm analysis of nutrients.

11.13.5.10. Patented or not

The guideline used for interpretation by Nova Crop Control, in the Netherlands, is proprietary information and is not publicly available. For sap analysis, the procedures are widely available. Guidelines for interpretation of sap analysis are widely available when developed by public institutions. However, when developed by private companies, they are not publicly available.

11.13.6. Which technologies are in competition with this one?

Alternative approaches to sap analysis are various monitoring procedures to assess crop nutrient status. These are foliar analysis (see relevant TD in this Chapter), and the use of various proximal optical sensors such as canopy reflectance and chlorophyll meters (see relevant TDs in this Chapter). Foliar analysis can be used for various nutrients. Proximal optical sensors can be used to assess crop N status.

11.13.7. Is the technology transferable to other crops/climates/cropping systems?

Sap analysis can be used in various crops; although most work has been done with vegetable crops. It can be used in different climates and with crops grown in different cropping systems such as crops in soil or substrate and crops in open field or in greenhouses. However, for each application, it is necessary to obtain or verify the reference values used to interpret the nutrient concentrations determined.

11.13.8. Description of the regulatory bottlenecks

There are no relevant regulatory bottlenecks.

11.13.9. Brief description of the socio-economic bottlenecks

The socio-economic bottlenecks relate to time and costs. Time is required to take the samples. If samples are to be sent to a laboratory, time is required to correctly prepare the samples and to organise transport to the laboratory. If extraction and analysis are to be conducted on the farm, sometime is required to cut the samples into smaller pieces, extract sap using a press and then further time is required to prepare and calibrate the analytical equipment, conduct the analysis and to clean all equipment used.

The costs associated with using a laboratory to conduct the analysis are those of transporting the samples, and the actual costs of the laboratory analysis and data interpretation. Rapid transport (e.g. overnight) to the laboratory is required which will be more expensive than standard delivery.

The costs of the laboratory analysis can vary depending on the number of determinations being made and samples being analysed.

11.13.10. Techniques resulting from this technology

- Leaf or petiole samples sent to a laboratory where analysed and interpretation provided. The Dutch firm Nova Crop Control (http://www.novacropcontrol.nl/en) provides analysis and interpretation of up to 21 parameters that includes the nutrients Ca, Mg, K, Na, N (NO_3, NH′ total N), P, Cl, S, Si, Mn, Fe, Zn, Cu, B, Mo, Al, Co, Se and Ni plus Sugars (Brix), pH and electrical conductivity. This service is offered for leaf sap for numerous species including many vegetable and ornamental species, cereals and fruit trees. Nova Crop Control states that sap samples are analysed within 24 hours of receipt of the leaf samples, and that they work with clients in 15 different countries (see 09-12-2012 Acres USA: Plant sap analysis (handouts), http://www.novacropcontrol.nl/en/downloads)
- In England, the company OMEX UK offers a service of conducting sap analysis (http://www.omex.co.uk/agriculture/services/sap-analysis/)

- Petiole sap extracted and analysed on-farm. Several portable rapid analysis systems are commercially available for on-farm sap analysis. The most commonly-used are the LaquaTwin sensors produced by Horiba (http://www.horiba.com/laquatwin/en/). Sensors are available for NO_3, K, Ca, and Na. More information on rapid analysis systems suitable for on-farm use is available in the TD on rapid on-farm analysis of nutrients

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11.14. Chlorophyll meters

(Authors: Francisco Padilla[23], Georgina Key[1])

11.14.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.14.2. Region

All EU regions.

11.14.3. Crops in which it is used

All horticultural crops.

11.14.4. Cropping type

All cropping types.

11.14.5. Description of the technology

11.14.5.1. Purpose/aim of the technology

Chlorophyll meters are used to assess the N status of a crop from measurements of leaf chlorophyll. Nitrogen status refers to whether the crop has a deficient, sufficient or excessive supply of N to achieve maximum growth or yield.

11.14.5.2. Working Principle of operation

Chlorophyll meters provide an indirect assessment of leaf chlorophyll content from measurements of light transmitted through the leaf. The available scientific information concerns mostly N as leaf chlorophyll content is strongly and directly related to leaf and crop N content.

Chlorophyll meters (Figure 11-24) provide non-destructive, frequent and indirect assessment of crop N status by measuring leaf chlorophyll content. The meters clip onto a leaf and chlorophyll content is estimated by leaf transmittance of visible and near-infrared light (NIR). The different degree of transmittance of these two light types is used to calculate a numerical value or index that is proportional to the concentration of chlorophyll in the leaf.

Figure 11-24. Different chlorophyll meters

The rationale for using chlorophyll meters for N management is that crop N content, which influences the amount of chlorophyll in the leaf, differentially influences the absorption and transmittance of red and NIR light. Chlorophyll absorbs red light (Figure 11-25) and transmits NIR; N-deficient crops transmit relatively redder and less NIR than N-sufficient crops.

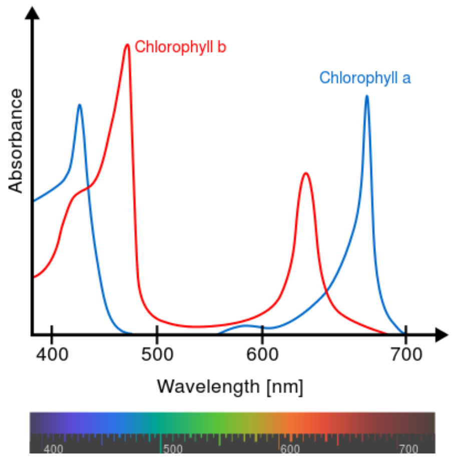

Figure 11-25. Absorbance of Chlorophyll a and b at different wave lengths (Muon Ray, 2016)

Commonly, interpretation of chlorophyll meter measurements for crop N management is conducted by comparing representative measurements from the main part of a crop with measurements taken in reference plots that have no nitrogen limitations. Where chlorophyll measurements are less than 90-95% of those in the reference plots, adjustments in N fertilisation are made. This approach is known as the Sufficiency Index. Alternatively, chlorophyll meter measurements can be compared with absolute sufficiency values (also known as reference or threshold values), that have been reported in scientific or Extension literature, to evaluate whether a crop has deficient, sufficient or excessive nitrogen with respect to that required to achieve maximum growth or yield.

11.14.5.3. Operational conditions

For N management of crops, chlorophyll meters have several attractive practical characteristics. Measurements can be made easily, quickly and periodically throughout a crop, and the results are rapidly available. There are no time delays and logistical issues as with methods involving laboratory analysis. Any required adjustments to the N supply can be made very soon after measurement, given the availability of relevant reference plots or sufficiency values.

An important consideration when using chlorophyll meters is the area of the crop that is measured. The area of leaf surface measured in a single measurement by chlorophyll meters is small (e.g. 6-64 mm^2) and therefore sufficient replication (measurements on other plants) is required to ensure that the measurements being made are representative of the field or greenhouse being assessed. Measurements should be made on the most recently fully expanded leaf (e.g. usually a leaf with ¾ of the final size) which must be well-lit, between the stalk and the tip of the leaf and midway between the margin and the mid-rib of the leaf. Between 15 and 30 representative and randomly selected plants should be used (e.g. 15-30 plants, with one leaf per plant). In general, the number of leaves and plants sampled should be higher in larger fields and where there is large variability between plants. The average value of all measurements is calculated. Care should be taken to avoid making measurements on damaged or moist leaves. Measurements are performed on the upper side of the leaf and take one second. It is recommended to follow a consistent protocol when measuring with chlorophyll meters and for instance, measure at the same time of the day each day. Where side-dressing N fertiliser applications are made, chlorophyll meter measurement may be made prior to side-dressing to adjust the rate of fertiliser application. Where N is applied throughout a crop by fertigation, measurements can be made on a regular basis (e.g. every 7-14 days) to ensure continual optical N status.

11.14.5.4. Cost data

Chlorophyll meters do not need to be installed in the crop prior to measurement. Time of measurement depends on the number of leaves/plants measured and the size of the field/greenhouse being assessed. Each measurement takes about one second; however, the time required to select the most appropriate plants and leaves also has to be also considered. In large fields and when there is large variability between plants, the time required to obtain a representative measurement may become an issue.

Most chlorophyll meters (e.g. SPAD, Yara N-Tester) cost approximately 3000 €, but some affordable meters (e.g. AtLEAF+) that cost <300 € have recently become available.

11.14.5.5. Technological bottlenecks

There are various technical bottlenecks that influence the possible adoption of chlorophyll meters. Different commercial chlorophyll meters can be used to assess crop N status, but comparing measurements taken from different meters may be difficult if the relationships between measurements of the different meters are unknown. Appropriate sufficiency values are required to interpret the results when reference plots are not available or are not used. Ideally, the sufficiency values should be either determined or verified locally. Commonly, such relevant local information is not available. Otherwise, published values determined elsewhere can be used, but they should be used with care as indicative values.

11.14.5.6. Benefit for the grower

Advantages

- Instant results
- Easy to use
- Hand-held equipment
- No need for buying a lot of devices
- Information of the current N status of a crop at the time of measurement
- Automatic data storage
- Possibility to download data to computer

Disadvantages

- Measuring is time-consuming when the field is large
- Expensive devices
- The need for locally-derived or verified sufficiency values which often are not avail.
- For certain species without flat leaves or leaflets, measurement can be difficult e.g. carrot, onion and conifers

11.14.5.7. Supporting systems needed

Most chlorophyll meters store and calculate average values of measurements; however, the internal memory of some meters is very limited. If many measurements are to be taken, a field book is recommended to write down the measured values; a standard calculator can be used to calculate average values.

Some chlorophyll meters can be connected to a computer through an USB cable for data download. If the grower is interested in downloading and then analysing data, a computer (either desktop or laptop) is required. The atLEAF+ sensor can store up to 5000 measurements and comes with Windows software to aid data management.

11.14.5.8. Development phase

- Research: Abundant research has been and is continuing to be conducted to assess sensitivity and to develop sufficiency values for new crops, varieties, and locations. New approaches are also being used for these evaluations
- Experimental phase: As with research, additional applied experimental work is on-going
- Field tests: Field testing is often being conducted to validate and adapt chlorophyll meter measurements to particular crops and regions
- Commercialised: There are a number of commercially available chlorophyll meters. The first sensor was launched in the 1980s; some new sensors have been developed recently

11.14.5.9. Who provides the technology

Several manufacturing companies sell chlorophyll meters for use by growers as hand-held sensors; some of the major companies are indicated in section 10.

11.14.5.10. Patented or not

Each chlorophyll meter is proprietary of each manufacturing company. The technology itself is not patented.

11.14.6. Which technologies are in competition with this one

Alternative approaches to chlorophyll meters are various monitoring procedures to assess crop N status. These are foliar analysis and sap analysis (see relevant TDs in this Chapter) and other proximal optical sensors such as canopy reflectance and fluorescence sensors (see relevant TDs in this Chapter). Foliar analysis can be used for various nutrients. Proximal optical sensors, including chlorophyll meters, are used to assess crop N status.

11.14.7. Is the technology transferable to other crops/climates/cropping systems?

Chlorophyll meters can be used in various crops; although most work has been done with cereals. Currently appreciable work is being conducted with vegetable crops and ornamental crops. This technology can be used in different climates and with crops grown in different cropping systems such as crops in soil or in substrate, and crops in open fields or in greenhouses. However, for each application, it is necessary to obtain or verify the sufficiency values used to relate the measurements to crop N status.

11.14.8. Description of the regulatory bottlenecks

There are no relevant directives or regulatory bottlenecks for using chlorophyll meters.

11.14.9. Brief description of the socio-economic bottlenecks

The socio-economic bottlenecks relate to time and particularly to cost of the sensor. Some time is required to measure with chlorophyll meters in larger fields and farms. The main bottleneck is the cost of sensors. Chlorophyll meters can be costly for growers (e.g. 3000 €) but some more affordable reflectance sensors (300 €) are becoming available.

11.14.10. Techniques resulting from this technology

Some of the chlorophyll meters available in the market are:

- SPAD-502Plus (http://www.konicaminolta.eu/en/measuring-instruments/products/colour-measurement/chlorophyll-meter/spad-502plus/introduction.html ; Konica Minolta, Inc., Tokyo, Japan)
- N-Tester (http://www.yara.co.uk/crop-nutrition/Tools-and-Services/n-tester/ ; Yara International ASA, Oslo, Norway)
- MC-100 Chlorophyll Concentration Meter (http://www.apogeeinstruments.co.uk/mc-100-chlorophyll-concentration-meter/; Apogee Instruments, Inc., Logan UT, USA)
- atLeaf+ (http://www.atleaf.com/Items.aspx ; FT Green LLC, Wilmington, DE, USA)

- CCM-200plus (http://www.optisci.com/ccm-200.html ; Opti-Sciences, Inc., Hudson, NH, USA)
- CL-01 Chlorophyll Content System (http://www.hansatech-instruments.com/products/cl-01/ ; Hansatech Instruments Ltd., Norfolk, UK)

11.14.11. References for more information

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http://www.konicaminolta.com/instruments/download/catalog/color/pdf/spad502plus_catalog_eng.pdf
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[3] MC-100 http://www.apogeeinstruments.co.uk/content/MC-100-spec-sheet.pdf
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11.15. Canopy reflectance for N management

(Author: Francisco Padilla[23])

11.15.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.15.2. Region

All EU regions.

11.15.3. Crops in which it is used

All vegetable, fruit and ornamental crops.

11.15.4. Cropping type

All cropping types.

11.15.5. Description of the technology

11.15.5.1. Purpose/aim of the technology

Canopy reflectance provides an indirect assessment of crop N status at the time of sampling from measurements of light reflected from the crop. Canopy reflectance can be measured with hand-held, proximal canopy reflectance sensors or with multispectral reflectance sensors fitted on unmanned aerial vehicles (commonly known as drones), small planes, or satellites to determine crop N status.

11.15.5.2. Working Principle of operation

Canopy reflectance sensors (Figures 11-26 to 11-30) provide non-destructive, frequent and indirect assessment of crop N status by using canopy reflectance sensors. This technique is a form of remote sensing in which the sensors are positioned either relatively close to the crop (e.g. 40-100 cm) or above the crop (e.g. > 30-100 m) when using drones or small planes. These reflectance sensors do not directly measure N content in crop tissue but provide measurements or indices of optical properties of crops, such as canopy reflectance, that are sensitive to crop N status. These sensors provide information on crop N status by measuring specific wavelengths of light reflected from the canopy.

Figure 11-26. A crop circle reflectance sensor

Figure 11-27. The Yara N sensor

Figure 11-28. A Greenseeker reflectance sensor and a Greenseeker hand held sensor

Figure 11-29. Measurements with reflectance sensors

The rationale for using canopy reflectance sensors for N management is that crop N content differentially influences the absorption and reflection of individual wavelengths of light, within the range of visible (390-750 nm) and NIR (750-1300 nm). Plant tissues absorb visible light and reflect NIR; N-deficient crops generally reflect more visible and reflect less NIR than N-sufficient crops. The wavelengths selected for N assessment, using canopy reflectance, are chosen because of their sensitivity to the changes in chlorophyll content, foliage density and biomass that accompany N deficiency; commonly, reflectance in four bands centred on green (495-570 nm), red (620-710 nm), red edge (light at the extreme red end of the visible spectrum, between red and infra-red light, at 710-750 nm) and NIR are used. In practice, reflectance data of 2-3 wavelengths are combined in mathematical equations to calculate vegetation indices, of which normalised difference vegetation index is one of the most commonly-used.

Commonly, the measured vegetation index in the crop is interpreted for N management by comparing with measurements taken in reference plots without nitrogen limitations, and adjustments in fertilisation is done whenever crop measurements are lower than 90-95% of those in the reference plots. Alternatively, the vegetation indices measured in the crop can be compared with available sufficiency values for those indices that have been reported in the literature to assess whether the crop has a deficient, sufficient or excessive nitrogen content to achieve maximum growth or yield.

Canopy reflectance sensors that are positioned relatively close to the crop (proximal sensors) are classified as being active or passive sensors depending on the source of light used. Passive sensor use the sun as a light source, and active sensors have their own light source thereby avoiding dependence on the variable conditions of natural radiation. Most modern proximal canopy reflectance sensors are active sensors.

11.15.5.3. Operational conditions

For N management of crops, canopy reflectance has several attractive practical characteristics. If using proximal optical sensors, measurements can be made easily, quickly and periodically throughout a crop, and the results are very rapidly available. There are no time delays and logistical issues as with methods involving laboratory analysis. Any required adjustments to the N supply can be made very soon after measurement, given the availability of relevant reference plots or sufficiency values.

Reflectance measurements are often conducted on the go on a regular basis (e.g., every 7-14 days) at walking/tractor speed if using proximal optical sensors, or at higher speed if using drones or small planes, by taking several passes along the crop. Proximal sensors are positioned either horizontal to the upper part of the crop canopy or above the canopy. Regardless of whether the sensors are measuring from a small tractor, drone or small plane, or are hand-carried, consistency in the sensor angle positioning in all measurements is important as is the height/distance of the sensor to the canopy/foliage being measured.

A major advantage of reflectance sensors is that the combination of continuous measurement with a relatively large field of view provides rapid measurement of large areas of crop canopy. The area of the crop measured depends on the field of view of the sensor and the number of passes made. In general, several square meters of crop foliage are measured with canopy reflectance sensors.

Reflectance sensors can be divided into passive and active sensors; active sensors have their own light source and therefore are not influenced by variations in ambient light conditions. Most proximal canopy reflectance sensors have their own light source, which enables reliable measurements under any light conditions. However, for proximal optical sensors, not fitted with a light source, such multispectral sensors mounted on drones or small planes, equivalent light conditions (generally clear skies) are required for canopy reflectance measurements to be comparable over time or to be comparable with reference values.

Limits:

- Most applications require specific calibrations for growing conditions or varieties
- Small field sizes can restrict the use of these techniques for remote sensing applications (plane, satellite), but not for hand-held applications
- The presence of other negative influences on crop performance e.g. other nutrient deficiencies, water stress, pests and diseases

- For satellite applications: Factors like clouds, pixel errors, etc. that affect the quantitative values derived from the image. Also, the timing of the assessment by satellite may not be sufficient for decision-making

11.15.5.4. Cost data

Reflectance sensors do not need to be installed within the crop prior to measurements. The time to make measurements depends on the sensor being used and the number of passes made in the crop; drones and small planes measure a given crop area more rapidly than proximal optical sensors that are manually supported or tractor-mounted. For a proximal optical sensor with a field of view of 34 cm height x 6 cm width, and continuous measurements along four passes consisting of 4 m long each pass at walking speed (approx. at 1,5 km/h), the time spent in measuring 16 m of linear foliage is approximately 40 seconds.

Proximal reflectance sensors can be costly (>3000-6000 €) but more affordable reflectance sensors (<1000 €) are becoming available. On large fields, proximal optical sensors can be mounted on farm tractors. Costs of drone and small plane rental need to be included for remote sensing use of reflectance sensors. Some commercial companies provide the measurement of crop canopy reflectance from drones and small planes, and provide subsequent data interpretation.

11.15.5.5. Technological bottlenecks

There are various technical bottlenecks that influence the possible adoption of canopy reflectance. The first one has to do with the necessity of homogenous sunny conditions if passive reflectance sensors are being used (i.e. sensors without their own light source). In Nordic, North-west, Central-east Europe this would be challenge particularly when trying to assess crop N status throughout a long crop cycle. Secondly, because different commercial sensors can assess crop N status, direct comparison of indices and measurements from different sensors may be difficult if the relationships between sensor measurements are unknown. Finally, for growers wishing to conduct reflectance measurements, appropriate sufficiency values are required in order to interpret the results. Ideally, these should be determined or verified locally. Commonly, such relevant local information is not avail. Otherwise, published values determined elsewhere can be used, but they should be used with care as indicative values.

11.15.5.6. Benefit for the grower

Advantages

- Information of crop N status at the time of measurement
- Faster than individual plants chlorophyll measurements

Disadvantages

- Time-consuming measurements
- The need to sample several areas of the crop when there is large variability within and/or between fields for example in large farms
- The need for locally-derived or verified sufficiency values which often are not avail.

- Similar light/timing requirements during measurements to compare data

11.15.5.7. Supporting systems needed

If the grower is going to use hand-held or tractor-mounted proximal optical sensors, there is a requirement, apart from the optical sensor itself and the tractor, for a computer (either desktop or laptop) to download and help with analysis of the reflectance data.

In the case of reflectance measurements taken by drones, planes or satellite, growers usually do not own the sensors nor the aerial vehicles but pay companies to provide a complete service.

When the objective is automatic variable rate fertiliser application, there is a requirement for variable rate fertiliser application equipment and a suitable interface. For variable rate fertiliser applications, a mathematical model or equation is required to estimate the fertiliser application rate as a function of the reflectance reading.

11.15.5.8. Development phase

- Research: Abundant research is on-going to assess sensitivity and to develop sufficiency values for new crops, varieties, and locations. New approaches are also being used for these evaluations
- Experimental phase: As with research, more applied experimental work is on-going.
- Field tests: Field testing is often being conducted to validate and adapt reflectance measurements to particular crops and regions
- Commercialised: There are a number of commercially available proximal canopy reflectance sensors. There are specialised companies that offer services of crop canopy reflectance measurements using drones or small planes; these vehicles are fitted with multispectral or hyperspectral cameras specially designed for drones and small planes (e.g. AgroCam; Norward Expert LLC, Debrecen, Hungary; http://www.agrocam.eu/)

11.15.5.9. Who provides the technology

Several companies manufacture proximal optical sensors for use by growers in hand-held or tractor-mounted modes; some of the major companies are indicated in sub section 11.16.10 of this technology description. Other companies offer canopy reflectance measurements conducted from drones or small planes; examples are also provided in sub section 11.16.10. There are companies that act as agents selling proximal canopy reflectance sensors. An example is Soil Essentials in the United Kingdom (http://www.soilessentials.com/).

11.15.5.10. Patented or not

Each reflectance sensor is proprietary of each manufacturing company. The technology itself is not patented.

11.15.6. Which technologies are in competition with this one?

Alternative approaches to canopy reflectance measurements are various monitoring procedures to assess crop N status. These are foliar and sap analyses (see relevant TDs in this chapter), and the use of other proximal optical sensors such as chlorophyll meters and fluorescence sensors (see relevant TDs in this chapter). Foliar analysis can be used for various nutrients. The various proximal optical sensors (reflectance, chlorophyll meters and fluorescence sensors) are used to assess crop N status.

11.15.7. Is the technology transferable to other crops/climates/cropping systems?

Canopy reflectance can be used in various crops; although most work has been done with cereals; currently appreciable work is being conducted with vegetable crops. This technology can be used in different climates and with crops grown in different cropping systems such as crops in soil or in substrate, and crops in open fields or in greenhouses. However, for each application, it is necessary to obtain or verify the sufficiency values used to relate the measurements to crop N status.

11.15.8. Description of the regulatory bottlenecks

There are no relevant European directives or regulatory bottlenecks.

11.15.9. Brief description of the socio-economic bottlenecks

The socio-economic bottlenecks relate to time and particularly to the cost of the sensors. Time is required to measure with canopy reflectance sensors and to process data. The main bottleneck is the cost of sensors. Proximal reflectance sensors can be costly (> 3000-6000 €) but some more affordable reflectance sensors (< 1000 €) are becoming available recently. On larger fields, proximal optical sensors can be mounted on farm tractors. Some commercial companies provide the measurement of crop canopy reflectance from drones or small planes. Costs of these services are not available.

11.15.10. Techniques resulting from this technology

Some of the proximal reflectance sensors available in the market are:

- Yara N-Sensor ALS (http://www.yara.co.uk/crop-nutrition/Tools-and-Services/n-sensor/; Yara International ASA, Oslo, Norway)
- RapidScan CS-45 (http://hollandscientific.com/product/rapidscan-cs-45/; Holland Scientific, Lincoln, Nebraska, USA)
- Crop Circle ACS-430 (http://hollandscientific.com/product/crop-circle-acs-430-active-crop-canopy-sensor/; both of which by Holland Scientific, Lincoln, Nebraska, USA)
- GreenSeeker (http://www.trimble.com/agriculture/greenseeker.aspx; Trimble Inc., Sunnyvale, California, USA)

Some of the companies providing canopy reflectance measurements from aerial craft are:

- Crop-Scan (http://www.crop-scan.es; Bioibérica S.A., Barcelona, Spain)
- SenseFly (https://www.sensefly.com/applications/agriculture.html; senseFly SA, Cheseaux-Lausanne, Switzerland)
- QuestUAV (http://www.questuav.com/; QuestUAV Ltd., Amble, Northumberland, UK)
- Falcon UAV (http://www.falconuav.com.au/; Falcon UAV Australia, Victoria, Australia)
- Agribotix (http://agribotix.com/; Agribotix, Boulder, Colorado, USA)

Some of the companies that provide fertilisation recommendation based on canopy reflectance measurements from combined platforms (satellite, plane, drone):

- Farmstar (http://www.farmstar-conseil.fr/web/fr/7-la-technologie.php)
- Smartrural (http://smartrural.net/nuestros-drones/)
- Hemav (http://hemav.com/servicio/agricultura-de-precision/)

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11.16. Fluorescence sensors

(Author: Francisco Padilla[23])

11.16.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.16.2. Region

All EU regions.

11.16.3. Crops in which it is used

All vegetables, fruit and ornamental crops.

11.16.4. Cropping type

All cropping types.

11.16.5. Description of the technology

11.16.5.1. Purpose/aim of the technology

Fluorescence sensors provide an assessment of crop N status from indirect measurements of leaf chlorophyll and flavonol contents, estimated from measurements of leaf chlorophyll fluorescence. Chlorophyll and flavonols are two N-sensitive indicator compounds.

11.16.5.2. Working Principle of operation

Fluorescence sensors (e.g. Figures 11-30 and 11-31) provide non-destructive, frequent and indirect assessment of crop N status. These sensors do not directly measure N content in the crop but assess content of indicator compounds that are sensitive to crop N status. Two N-sensitive indicator compounds are chlorophyll and flavonols. Leaf chlorophyll content is strongly influenced by leaf N since the majority of N in a leaf is contained in the photosynthetic apparatus. Flavonols, a class of polyphenols that accumulate in the leaf epidermis, are carbon-based secondary metabolites whose content increases under lower N availability. Chlorophyll content is positively related, and flavonols content inversely related, to leaf N and therefore to crop N status.

Figure 11-30. Dualex sensor (http://www.force-a.com/en/capteurs-optiques-optical-sensors/dualex-scientific-chlorophyll-meter/)

Figure 11-31. Multiplex sensor
(https://w3.ual.es/GruposInv/nitrogeno/use%20of%20proximal%20sensors.shtml)

Fluorescence sensors measure flavonols content by using the chlorophyll fluorescence screening method. The measurement principle is that leaf chlorophyll emits fluorescence in the red to far-red region of the light spectrum after being illuminated with ultraviolet (UV) and red light. Flavonols that accumulate in the leaf epidermis absorb appreciable amounts of UV light while transmitting most of the red light; the transmitted red light is subsequently absorbed by the chlorophyll in leaf chloroplasts. Flavonols reduce far red chlorophyll fluorescence under UV illumination without altering far red chlorophyll fluorescence under red illumination and so the flavonols content is estimated by comparing far red chlorophyll fluorescence under both wavelengths. Fluorescence sensors measure leaf chlorophyll content from chlorophyll fluorescence emission ratio of far red chlorophyll fluorescence and red chlorophyll fluorescence under illumination with visible light. Both chlorophyll and flavonols are considered in the Nitrogen Balance Index (NBI), which is the ratio of the chlorophyll to flavonols contents. The NBI has been considered to be a more reliable indicator of crop N status than either chlorophyll or flavonols when considered individually.

The chlorophyll and flavonols contents and the NBI index measured in the crop are interpreted for N management by comparison with measurements taken in reference plots that have no N limitation. Adjustments in fertilisation are made whenever crop measurements are less than 90-95% of those in the reference plots. Alternatively, the chlorophyll and flavonols contents and the NBI index measured in the crop can be compared with available sufficiency values (also known as reference or threshold values), that have been reported in scientific or Extension literature, to evaluate whether a crop has deficient, sufficient or excessive nitrogen with respect to that required to achieve maximum growth or yield.

11.16.5.3. Operational conditions

For N management of crops, fluorescence sensors have several attractive practical characteristics. Measurements can be made easily, quickly and periodically throughout a crop, and the results are rapidly available. There are no time delays and logistical issues as with methods involving laboratory analysis. Any required adjustments to the N supply can be made very soon after measurement, given the availability of relevant reference plots or sufficiency values.

An important consideration when using fluorescence sensors is the area of the crop that is measured. The area of leaf surface is measured in a single measurement is small (e.g. 20

mm²-50 cm²) and therefore sufficient measurements on other plants) is required to ensure that the measurements being made are representative of the field or greenhouse being assessed. Measurements should be made on the most recently fully expanded leaf (e.g. usually a leaf with ¾ of the final size) which must be well-lit, between the stalk and the tip of the leaf, and midway between the margin and the mid-rib of the leaf. Between 15 and 30, randomly selected, plants should be used (e.g. 15-30 plants, with one representative leaf per plant). In general, the number of leaves and plants sampled should be higher in larger fields and where there is large variability between plants. The average value of all measurements is calculated. Care should be taken to avoid making measurements on damaged or moist leaves. Measurements are performed on the upper side of the leaf and take one second. It is recommended to follow a consistent protocol when measuring with fluorescence sensors and for instance, measure at the same time of the day each day. Some fluorescence sensors are capable of taking continuous measurement while walking or mounted on a tractor. In this case care should be taken to ensure that the crop foliage is continuous and that no open spaces that give erroneous measurements are included.

It is well established that leaf flavonols content increases with solar radiation, therefore the use of absolute flavonols measurements for crop N monitoring is challenging whenever large fluctuations in irradiance occur throughout the crop cycle. The use of chlorophyll content and the NBI index is believed to overcome this limitation, as well as the use of reference plots within the crop.

11.16.5.4. Cost data

Fluorescence sensors do not need to be installed in the crop prior to measurements. Time of measurement depends on the number of leaves/plants measured and the size of the field/greenhouse being assessed. Each measurement takes about one second; however, the time required to select the most appropriate plants and leaves also has to be also considered. In large fields and when there is large variability between plants, the time required to obtain a representative measurement may become an issue.

Fluorescence sensors can be particularly costly (>3000-25000 €).

11.16.5.5. Technological bottlenecks

Fluorescence sensors are relatively new if compared to other optical proximal sensors. Some of the fluorescence sensors available can be considered as complex scientific instruments rather than sensors that could be adopted by farmers for routine farm use. There are simpler and more affordable versions of some fluorescence sensors and it is expected that the cost will decrease as the technology develops in the future. Finally, for growers wishing to use fluorescence sensors, appropriate sufficiency values are required in order to interpret the results. Ideally, these should be determined or verified locally. Commonly, such relevant local information is not avail. Otherwise, published values determined elsewhere can be used, but they should be used with care as indicative values.

11.16.5.6. Benefit for the grower

Advantages

- Real time measurements

- Data is immediately available
- Provides information on crop stress

Disadvantages

- Very expensive
- Time-consuming to measure a representative sample
- The need for locally-derived or verified sufficiency values which often are not available.

11.16.5.7. Supporting systems needed

Although fluorescence sensors allow local storage of measurements, writing down measurements on a field book is recommended; a standard calculator can be used to average measurements.

Data from fluorescence sensors can be downloaded to a computer; optionally, if the grower is interested in data download, a computer (either desktop or laptop) is necessary.

11.16.5.8. Development phase

- Research: Some research is on-going to assess sensitivity and to develop sufficiency values for new crops, varieties, and locations. New approaches are also being developed for these evaluations
- Experimental phase: Some experimental work is on-going
- Field tests: Some field testing is being conducted to validate and adapt fluorescence measurements to particular crops and regions
- Commercialised: There are two commercially available fluorescence sensors

11.16.5.9. Who provides the technology

One manufacturing company sells two fluorescence sensors for use by growers as hand-held or mounted on tractors; this is indicated in section 10.

11.16.5.10. Patented or not

Each sensor is proprietary of each manufacturing company.

11.16.6. Which technologies are in competition with this one?

Alternative approaches to fluorescence sensors are various monitoring procedures to assess crop nitrogen status. These are foliar analysis and sap analysis (see relevant TDs), and other proximal optical sensors such as canopy reflectance and canopy reflectance sensors (see relevant TDs). Foliar analysis can be used for various nutrients. Proximal optical sensors, including fluorescence sensors, are used to assess crop N status.

11.16.7. Is the technology transferable to other crops/climates/cropping systems?

To date, this technology has been employed for monitoring crop N status in maize, rice, turf grass and cucumber; there are no published reports for other crops. However, fluorescence sensors can be used in various crops. It can be used in different climates and with crops grown in different cropping systems such as crops in soil or substrate and crops in open field or in greenhouses. However, for each application, it is necessary to obtain or verify the sufficiency values used to interpret the nitrogen status of the crop.

11.16.8. Description of the regulatory bottlenecks

There are no relevant directives or regulatory bottlenecks for the use of fluorescence sensors.

11.16.9. Brief description of the socio-economic bottlenecks

The socio-economic bottlenecks relate to time and particularly to cost of the sensor. Some time is required to measure with fluorescence sensors in large field/greenhouses/farms. The main bottleneck is the cost of sensors. Fluorescence sensors are costly (> 3000-25000 €) and currently there are no more affordable models.

11.16.10. Techniques resulting from this technology

Some of the fluorescence sensors available in the market are:

- DUALEX Scientific (http://www.force-a.com/en/capteurs-scientifiques/dualex-scientific/; Force-A, Orsay, France; Figure 11-30)
- MULTIPLEX Research (http://www.force-a.com/en/capteurs-scientifiques/multiplex-research/; Force-A, Orsay, France; Figure 11-31)

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11.17. Rapid on-farm analysis of nutrients

(Authors: Juan José Magán[9], Rodney Thompson[23])

11.17.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.17.2. Region

All EU regions.

11.17.3. Crops in which it is used

All vegetable, fruit and ornamental crops.

11.17.4. Cropping type

All cropping types.

11.17.5. Description of the technology

11.17.5.1. Purpose/aim of the technology

This technology allows on-site and quick determination of one or several ions concentration in a solution, which can be a nutrient solution, drainage, soil solution or plant sap, what makes possible to immediately do the measurement in the farm, not being necessary to send the sample to the laboratory.

11.17.5.2. Working Principle of operation

There are two different quick on-site analysis techniques, namely: 1) portable selective ion-meters and 2) portable equipment based on colourimetry, both being based on different working principles.

Portable selective ion-meters

These devices (also called ion selective electrodes, ISE) respond selectively to an ion present in the solution (e.g. Figures 11-31 and 11-33). They frequently measure only one ion, but some equipment may measure several nutrients at the same time. These ion-meters usually have a thin membrane separating the sample to be measured and the inside of the ion-meter, where there is a solution with a known concentration of the ion to be determined. In this way a potential difference through the membrane is established, which is related to the difference in the concentration outside and inside the membrane, enabling determination of the concentration of the ion of interest in the sample.

A modified approach is to apply an electric field that is equivalent to the reference concentration; this approach is less influenced by different surface phenomena than can affect the potential difference. This enables more exact results when measuring solutions with other ions present. This technology is applied, for example, in the LaquaTwin individual selective ion-meters (http://www.horiba.com/laquatwin/en/index.html) which can be used with nutrient solutions applied by fertigation, soil solution extracted by suction cups, and even plant sap samples (Figure 11-32).

Figure 11-32. Individual selective ion-meters LaquaTwin

There are also multichannel ion-meters, which are portable devices based on the measurement with a multi-ion probe that simultaneously measures as many as seven different ions (ammonium, calcium, chloride, nitrate, potassium, sodium and magnesium) e.g. Figure 11-33. It is made from nanocarbon compounds, which allows the production very small ion-meters that are mounted together in the same probe. Examples are the CleanGrowNutrient Analyzer sensor (http://www.cleangrow.com/product/nutrient-analyzer) and the NT Sensor Multi Ion Probe (http://www.ntsensors.com/en/products/multiion.html).

Figure 11-33. Picture of the probe of a multichannel ion-meter (http://www.ntsensors.com/en/products/multiion.html)

Devices based on colourimetry

These devices use strips impregnated in a specific reagent which then reacts with the compound being measured (e.g. Figure 11-34). The intensity of the colour that develops in the test strips is related to concentration of the compound. There are different meters available that quantitatively measure the intensity of the colour of the test strip such as the Merck RQ Reflectoquant (http://www.merckmillipore.com/GB/en/products/analytics-sample-prep/test-kits-and-photometric-methods/instrumental-test-systems-for-quantitative-analyses/reflectoquant-system/ILOb.qB.OjIAAAE_Jhh3.Lxj,nav Figure 11-34). Another less technical and rigorous format is the use of simple colour strips that are visually compared against a reference colour scale.

Figure 11-34. Colourimetry-based rapid analysis device and test strips

11.17.5.3. Operational conditions

There are individual selective ion-meters for the determination of different ions (nitrate, potassium, calcium, sodium, etc.). They are calibrated quickly by using one or two calibration standard solutions; the second option provides more accurate measurement. The range of measurement is often large (1-100 mmol/L in the case of the Horiba LaquaTwin nitrate sensor) and is well adapted to the nutrient solutions handled in horticulture, so that the measurement can be carried out by directly using the undiluted sample. Comparing the readings offered by LaquaTwin ion-meters with the laboratory method, determination coefficients close to 0,9 were obtained, with the calcium sensor showing the higher deviation respect to the 1:1 line. Measurements can be made by directly immersing the sensor in the sample or by adding a few drops of solution to cover the surface of the ion-meter, as shown in Figure 11-35.

Figure 11-35. Methods of measurement with the LaquaTwin ion selective system

Regarding the multichannel probes, a pre-calibration conditioning solution and three calibration standard solutions are commonly used. Reasonably good results have been obtained with this sensor for measurement in clear nutrient solutions (M.A. Domene, Cajamar Foundation, Almeria, Spain, personal communication); the best results were obtained with the potassium sensor and the worst with the ammonium sensor (Figure 11-36). The accuracy of the calcium and chloride sensors tended to improve with increasing nutrient concentration (M.A. Domene, Cajamar Foundation, Almeria, Spain, personal communication). However, it has been observed that the measurements can be influenced by the presence of organic material. Meters with multichannel probes are relatively new, and further independent scientific evaluation is required.

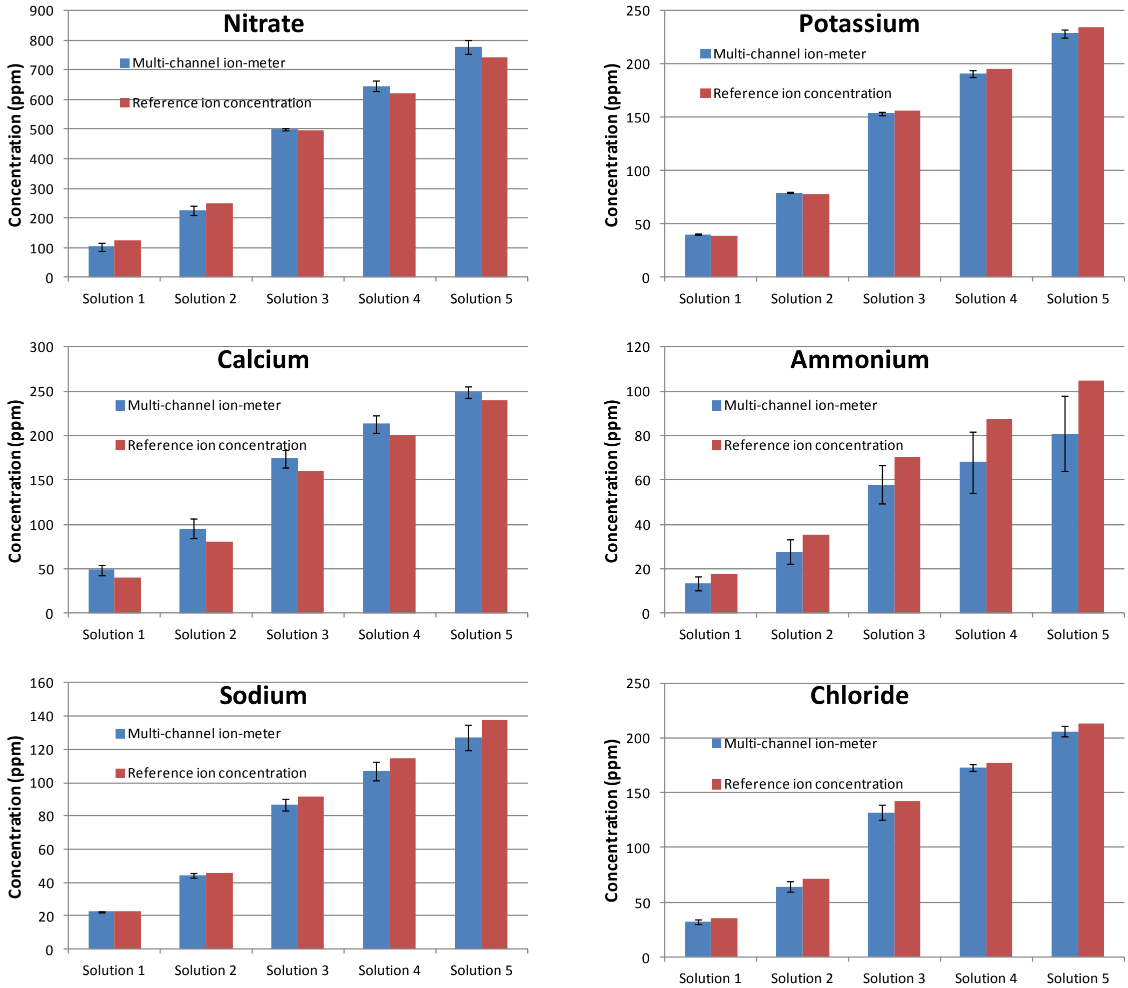

Figure 11-36. Comparison of measurements obtained by the multi-channel ion-meter respect to different reference concentrations prepared in laboratory. The bars correspond to ± standard deviation (Fundación Cajamar)

A drawback with some measuring devices is having a limited range of measurement; for example, the Merck RQ Flex Reflectoquant system has a range of 1-3,6 mmol/L for the measurement of nitrate. A limited range requires that dilution be conducted which must be done very carefully to avoid errors. The devices where the measurement range is an issue for use with fertigated horticulture, such as the Merck RQ Flex Reflectoquant generally were designed for use with natural waters, where nutrient concentrations are more dilute than in horticultural applications. The RQ Flex Reflectoquant is a versatile instrument that can be used to measure the concentrations of potassium, calcium, magnesium, ammonium, nitrates, phosphates and iron. A number of the determinations require the addition of reagents and waiting periods of several before measuring. Sometimes, colloids that colouring the sample can affect the measurement.

A mains electrical supply is usually not necessary for the use of rapid analysis equipment; most work with batteries.

11.17.5.4. Cost data

The price of a LaquaTwin selective ion-meter is around 500 €, whereas for the multi-channel ion-meter is around 1500-2000 € and for the equipment based on colourimetry RQ Flex Reflectoquant is around 900 €.

11.17.5.5. Yearly maintenance or inputs needed

For ion selective electrode systems, both single and multi-channel systems, the manufacturers recommend that the ion selective electrodes be replaced after approximately 1000 determination. In practice, in some cases, it has been necessary to change the electrodes after 500 measurements. For some systems, the cost of each replacement electrode is approximately 180-200 €. The total cost per determination with a LaquaTwin system is estimated be approximately 0,65 €.

11.17.5.6. Technological bottlenecks

Colourimetry-based equipment, such as the Merck RQ Flex Reflectoquant, requires dilution of horticultural samples for reliable measurement. This is a disadvantage when measuring on the farm where the working conditions are not the most suitable for sample processing. By contrast, selective ion-meters do not require dilution when measuring horticultural samples, although it may be advisable for sap samples (especially for K determinations).

11.17.5.7. Benefit for the grower

Advantages

- Portable devices
- Allow on farm measurement
- Quick results, thereby enabling rapid responses in nutrient management
- Generally, the operation is simple, particularly for analysis of a single nutrient
- Their use avoids sending samples to an analytical laboratory, which entails preparing parcels, shipping costs, and very importantly a time delay

Disadvantages

- Accuracy of equipment is lower than obtained in the laboratory
- Some selective ion-meters are significantly influenced by different surface phenomena, for example interference caused by the presence of colloids in the solution
- Sample dilution is necessary when using colourimetry-based equipment

11.17.5.8. Supporting systems needed

- Standard solutions for device calibration
- Laboratory material for the measurement of volumes
- Distilled or de-ionised water, for diluting samples before measurement where required

11.17.5.9. Development phase

Commercialised

11.17.5.10. Who provides the technology

Different companies manufacture this technology:

- Horiba manufactures the LaquaTwin range (http://www.horiba.com/laquatwin/en/index.html), which are the most well-known selective ion-meters
- HANNA instruments (ISEs for nitrates, potassium, calcium, chloride, sodium, etc.; http://hannainst.com/hi4113-nitrate-combination-ion-selective-electrode.html)
- HACH (AN-ISE, combined sensor for ammonium and nitrates; http://www.hach.com/an-ise-sc-combination-sensor-for-ammonium-and-nitrate/product-details?id=9296230750
- METTLER TOLEDO (perfectION™, ISEs for nitrates, potassium, calcium, sodium and chlorides (https://www.mt.com/us/en/home/perm-lp/product-organizations/ana/perfectION.html)
- NT Sensors manufactures the ion-meter Multi-ION (http://www.ntsensors.com/en/products/productslab.html)
- CleanGrow produce the multi-channel Nutrient Analyzer (http://www.cleangrow.com/product/nutrient-analyzer)
- Merck sells RQ Flex Reflectoquant device for colourmetric analysis (http://www.merckmillipore.com/ES/es /products/analytics-sample-prep/test-kits-and-photometric-methods/instrumental-test-systems-for-quantitative-analyses/reflectoquant-system/reflectometer-accessories/iUeb.qB.m1UAAAE_EPR3.Lxi,nav)
- Eijkelkamp sells the Nitracheck reflectometer for colourmetric analysis of nitrate (https://en.eijkelkamp.com/products/field-measurement-equipment/nitrachek-reflectometer.html)

11.17.5.11. Patented or not

The different devices are patented.

11.17.6. Which technologies are in competition with this one?

Chemical laboratory analysis.

11.17.7. Is the technology transferable to other crops/climates/cropping systems?

Yes.

11.17.8. Description of the regulatory bottlenecks

There no regulatory bottlenecks.

11.17.9. Brief description of the socio-economic bottlenecks

The cost of these devices may be high for their direct use by growers, taking into account that they are probably not going to intensively use them. It seems a technology more adequate for use by technical advisors who would make measurements on different farms.

11.17.10. Techniques resulting from this technology

Daily measurement of ion concentration in the recirculating solution has been used with good results for minimising water and nutrient discharge in semi-closed systems under experimental conditions.

11.17.11. References for more information

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11.18. Decision Support Systems (DSSs) for supporting nutrient management

(Authors: Rodney Thompson[23], Marisa Gallardo[23], José Miguel de Paz[14]

11.18.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.18.2. Region

All EU regions.

11.18.3. Crops in which it is used

All crops.

11.18.4. Cropping type

All cropping types.

11.18.5. Description of the technology

11.18.5.1. Purpose/aim of the technology

DSSs for crop nutrient management are user-friendly software programs that provide recommendations for the amounts and timing of nutrient applications. They are intended for practical use by growers, consultants or technical advisors. These DSSs provide site and crop specific nutrient recommendations.

The nutrient recommendations provided by DSSs consider the crop demand and the supply of nutrients from other sources (e.g. soil reserves). The objective is to match nutrient supply and demand to avoid excess nutrient application.

11.18.5.2. Working Principle of operation

After processing the relevant data of the crop in question, the DSS provides an output which will be either the amount of nutrient to apply as fertiliser or a more complete plan with the amounts and timing of multiple fertiliser application (Figure 11-37 and Figure 11-38). Some DSS provide recommendations for mineral fertilisers, others for both mineral and organic fertilisers and others for only organic fertilisers. Traditionally, DSSs for nutrient management were operated on personal computers or laptops. Now, they are increasingly being operated on tablets and smart phones. There is a current tendency for web-based DSSs that can be consulted from any device with an internet connection and access to the web page where the program is located.

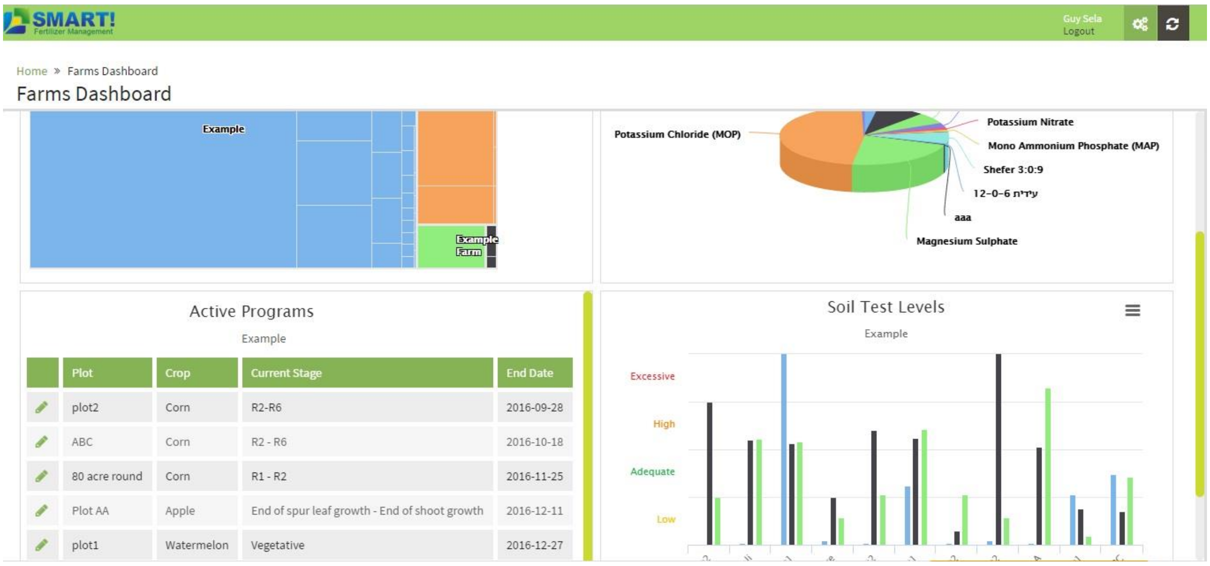

Figure 11-37. Example of SMART! FERTILIZER SOFTWARE: screenshot of the "Farm's Dashboard" (http://www.smart-fertilizer.com/)

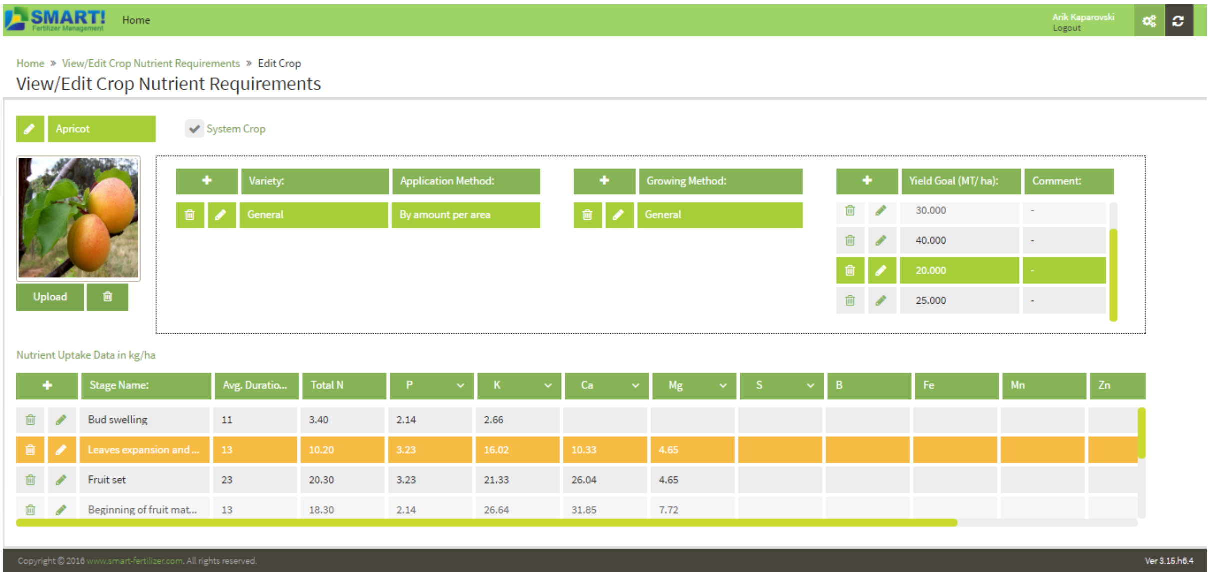

Figure 11-38. Example of SMART! FERTILIZER SOFTWARE: screenshot of the "Nutrient target values" (http://www.smart-fertilizer.com/)

Generally, DSSs for crop nutrient management have four components:

- An interface to enter data describing the crop and the cropping situation
- A simulation model that calculates crop nutrient demand in response to the dates of the crop and the expected or actual climatic conditions (see TD on Models for nutrient uptake)
- Mathematical routines that then consider the supply of available nutrients from the soil (which can include available nutrients in the soil profile, those made available from organic materials, crop residues etc.) and then calculate the additional amounts of nutrients that need to be supplied to meet the crop nutrient requirements
- The output with the recommendations that can take various forms depending on the individual DSS. The output may be the total amount of nutrient required, the individual amounts of nutrient and timing of multiple applications, the amounts of

specific forms of fertiliser, or mineral organic fertilisers. Often, the output can be stored on the device used to operate the DSS, can be saved and transferred as commonly-used file type or can be printed

Commonly, information can be stored in an internal database within a DSS and retrieved for subsequent use e.g. soil descriptions, soil analyses, descriptions of organic amendments. Crop plans can generally be saved and then modified for subsequent use.

The use of computer technology to calculate crop nutrient requirements enables numerous and frequent calculations to be made, various inputs to be considered, the use of stored data records for field and of data bases and record keeping. Frequent calculation of fertiliser requirements is essential for fertigated crops with frequent nutrient application. The use of computer technology enables a large degree of calculation to be done that would otherwise be very difficult.

A common key feature of many DSS used to calculate nutrient requirements is the use of a simulation model to calculate crop growth (dry matter production) for the dates and growing conditions of the crop. The time scale can vary; commonly for practical DSSs for horticultural crops, it is daily. From crop growth, nutrient uptake is often calculated, particularly for N. Commonly, nutrient dilution curves that relate the crop nutrient content to crop accumulated dry matter production are used. The crop nutrient uptake for a given day is obtained by multiplying the nutrient content by the accumulated dry matter production for that day. This is described more in the TD on Models for nutrient uptake. An alternative to the use of a simulation model of growth is to input expected yield and the DSS then estimates the amount and timing of nutrient uptake from an internal data base.

Most available DSSs for nutrient management are used for N, so the rest of this discussion will relate to N. DSSs for N consider N from other sources such as soil mineral in the root zone and N mineralised from soil organic matter, crop residues and manure. There are differences between different DSSs in which other sources of N are considered and how this is done. The VegSyst-DSS (web page; see references below) calculates a daily N balance in which the sum of N provided by various soil sources is subtracted from the crop N uptake. The difference is used to calculate the mineral N fertiliser requirement. The N-Expert DSS (web page), used in Germany, for all vegetable crops, is based on the KNS method, in which the total N supply (from fertiliser and soil) must meet the sum of total crop N uptake and the buffer amount of soil mineral N considered necessary to ensure optimal growth and production. A common feature of DSSs for nutrient management is to incorporate soil analysis. An alternative approach for nutrients, such as P and K, is for the DSS to interpret soil analysis results in relation to the expected growth or production.

11.18.5.3. Operational conditions

DSSs for crop nutrient management can be used with any crop or cropping; however, there is a requirement for calibration, or at least verification, for each crop and cropping situation. All such DSSs have data requirements in order to be able to operate. To make them user-friendly to growers and technical advisors, the amount of input data required to use the DSS with a given crop should be small and the data should be readily available to growers and technical advisor. The DSSs are either operated directly on personal computing devices (computer, laptop, tablet, smart phone) or on an internet site using a personal computing device to access Internet. Where the DSS is operated directly on the personal computing device, that device must have adequate technical capacity and a suitable operating system. Commonly, these DSSs are generally developed for specific crops and conditions. For use in other conditions, they should be adapted to the new conditions.

11.18.5.4. Cost data

Most of the DSS for nutrient management are produced by public institutions to assist with nutrient management and these DSS generally freely available. The private company SMART! Fertilizer Management (http://www.smart-fertilizer.com/) provides a DSS for management of all nutrients for a wide range of crops from 539 €/year for a single farm of up to 50 ha. For larger farms, the cost increases.

11.18.5.5. Technological bottlenecks

Assuming that the software is suitable and works well, possible technological bottlenecks are the availability of data and technical support for the user. Additionally, the device on which it is being used must have adequate technical capacity and a suitable operating system. An important consideration is that the software has been calibrated or verified for the crop and cropping situations being considered. Where this has not been done, the DSS can be used with some caution under for a crop which has been calibrated under similar conditions. Much care should be taken when using a DSS for a crop in conditions that are appreciably different to those for which it was calibrated.

11.18.5.6. Benefit for the grower

Advantages

- Reduced fertiliser use
- Reduced environmental impacts resulting from excessive fertiliser applications
- User-friendly interface
- Quick overview of a lot of data

Disadvantages

- The common difficulties of learning new software
- The time associated with its use
- The time required to obtain data

11.18.5.7. Supporting systems needed

Technical assistance during the first periods of use is needed. A server where host the DSS is also required.

11.18.5.8. Development phase

- Research: Research has and is being conducted to develop decision support systems for nutrient management (generally N)
- Experimental phase: As with research, applied experimental work to develop and test new DSS and to test developed DSSs is on-going
- Field tests: Field testing is often conducted to adapt the technique to particular crops and cropping systems

- Commercialised: There are some commercially-available DSS produced by private companies. The company SMART! Fertilizer Management provides a paid service with a comprehensive DSS for nutrient management

11.18.5.9. Who provides the technology

Public institutions and some companies.

11.18.5.10. Patented or not

Generally new software is registered.

11.18.6. Which technologies are in competition with this one?

There are no technologies that are in direct competition. There are several that could be complementary such as analysis of nutrients in soil solution of the root zone, sap analysis, the use of proximal optical sensors such as canopy reflectance and chlorophyll meters. Technologies such as soil analysis should be used in combination with these models when they form part of a DSS to calculate crop nutrient requirements.

11.18.7. Is the technology transferable to other crops/climates/cropping systems?

DSSs for nutrient recommendations can be developed for all crop types, climates and cropping regions.

11.18.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

11.18.9. Brief description of the socio-economic bottlenecks

The major socio-economic bottleneck is the lack of motivation of farmers to adopt technologies to optimise the use of nutrients and reduce environmental impact, particularly in countries where legislation has not been seriously implemented.

Many growers are older and will be reluctant or not interested in learning a new software program.

11.18.10. Techniques resulting from this technology

1) N-Expert: The N-Expert software assists growers and fertiliser advisers to calculate the N (and also P, K and Mg) fertiliser requirement of diverse vegetable crops in Germany. As this is a DSS, it is more fully described in the TRD on DSSs. The N-Expert 4 software and background information is freely available at: http://www.igzev.de/n-expert/?lang=en
2) Azofert: The Azofert DSS is used in France to provide crop and site specific recommendations for N for horticultural crops. It is commonly used to provide recommendations to commercial growers. This DSS was produced by INRA, the National Institute for Agronomic Research (Laon-Reims-Mons Agronomy Unit) and LDAR, the French Departmental Analysis and Research Laboratory (Aisne Agronomic Station). More information at:

http://www.npc.inra.fr/Le-centre-Les-recherches/Impacts-environnementaux/Azofert-une-aide-pour-raisonner-la-fertilisation-des-cultures and in reference [6]

3) VegSyst and VegSyst-DSS: The VegSyst simulation model is a relatively simple model developed in the University of Almeria, Spain to calculate daily values of crop N uptake as well as crop biomass production and crop evapotranspiration (ETc) for crops without water or N stress. The model has been calibrated and validated for the major vegetable crops grown in greenhouses in South-East Spain (e.g. tomato, sweet pepper, muskmelon, cucumber, zucchini, egg-plant, watermelon). The VegSyst model is a component of the VegSyst-DSS developed to calculate daily irrigation and N fertiliser requirements and nutrient solution N concentrations [N] for fertigated vegetable crops grown in greenhouses in South-East Spain. (http://www.ual.es/GruposInv/nitrogeno/VegSyst-DSS.shtml)
4) CropManage: developed in the Central Coast region of California, the on-line DSS software CropManage (https://ucanr.edu/cropmanage/login/offline.cfm, click on "About CropManage") is a DSS based on a model that estimates N fertiliser and irrigation requirements on a field-by-field basis. The N fertiliser algorithm generates recommendations based on the crop N uptake, current soil nitrate status and estimated soil N mineralization
5) EU-Rotate_N: Is a comprehensive simulation model that can be used to simulate many processes (e.g. yield, growth, N uptake and losses) of numerous vegetable species. The lack of a user-friendly interface restricts its use to scientific applications. More information is available in reference [6]
6) WELL_N DSS: The WELL_N DSS was developed as a practical DSS to determine N fertiliser recommendations in the United Kingdom. It has been used in commercial vegetable production by growers and advisors. WELL_N is based on routines of the previously developed research model N_ABLE. It considers average climate, soil mineral N, crop residues and N mineralisation from soil organic matter to calculate the minimum total amount of mineral N fertiliser required for maximum production of 25 different vegetable crops
7) SMART! FERTILISER SOFTWARE produced by SMART! Fertilizer Management (http://www.smart-fertilizer.com/). This is a private company that has various software products to assist with fertiliser and fertigation management
8) A number of other software systems developed to assist with nutrient management of horticultural crops are described in reference [6]

11.18.11. References for more information

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[7] SIDDRA: Recommendation system developed by commercial company "Fertiberia" to fertilize different crops. http://siddra.fertiberia.es/

11.19. Models for nutrient uptake

(Authors: Marisa Gallardo[23], Rodney Thompson[23])

11.19.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.19.2. Region

All EU regions.

11.19.3. Crops in which it is used

All crops.

11.19.4. Cropping type

All cropping types.

11.19.5. Description of the technology

11.19.5.1. Purpose/aim of the technology

Models for nutrient uptake that have practical applications are often models of crop N uptake that are: 1) used to estimate crop fertiliser N requirements and/or 2) for scenario analysis to demonstrate the impact of N management on crop response and N losses to the environment. In some cases, other nutrients such as P, K and Mg are also considered. Given that irrigation is commonly used in horticultural crops and that fertigation is being increasingly adopted, a number of simulation models that deal with N management of vegetables also consider irrigation.

11.19.5.2. Working Principle of operation

For the purposes of this document, nutrient uptake model refers to a series of mathematical calculations that estimate the absorption of a nutrient by a crop. There are varying levels of complexity depending on the application e.g. if is for research or practical farming use. The context here is models that have applications in farming.

The complexity of models that calculate nutrient uptake varies depending on the application. Often simple growth models are used that initially simulate dry matter production from climatic parameters (e.g. temperature and solar radiation) using empirical functions that estimate the amount of radiation intercepted by the crop and then use values of radiation use efficiency to calculate the production of plant dry matter from the amount of radiation intercepted. These calculations are made for daily or smaller time intervals. Once dry matter production is simulated (e.g. on a daily basis), the N content of the crop is then simulated; this is often done by applying a N dilution curve that relates crop N content to accumulated dry matter production.

One of the most commonly-used approaches to estimate N uptake is to simulate the critical N content which is the minimum content of N with which the crop obtains maximum growth; higher crop N contents are associated with luxury uptake. This calculation is done using the critical N dilution curve described by Greenwood et al. (1990) of: %N=a* DMP b where %N is the critical N content which is the minimum amount of N that maximise crop growth, "a" and "b" are parameters that describe the curve and dry matter production (DMP) is the dry matter production of the crop. Figure 11-39 shows an example of a critical N dilution curve for greenhouse grown tomato. The figure also presents critical N dilution curves of Tei et al. (2002) for processing tomato and the general equation of Greenwood et al. (1990) for many temperate herbaceous crops.

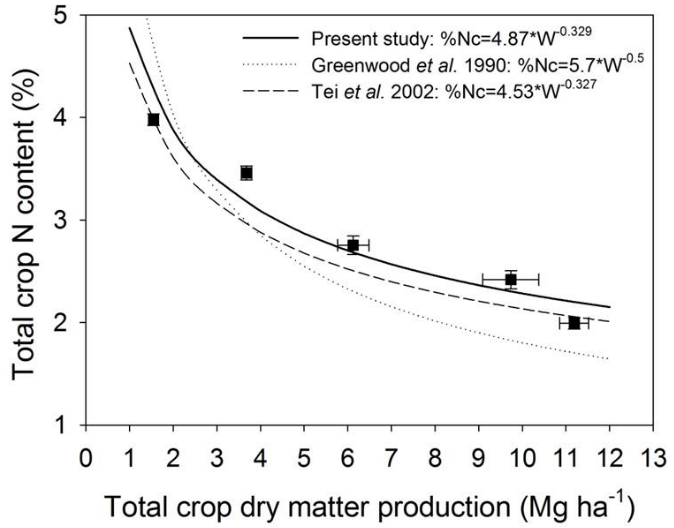


Figure 11-39. Critical N dilution curve for greenhouse tomato

The critical crop N uptake is calculated as the product of the dry matter production and the estimated crop critical N content. The critical N uptake is the minimum amount of N to be absorbed by the crop to maintain optimal growth; commonly, this is estimated daily.

Once the critical N amount by the crop is calculated, some models perform daily N balances considering N supplied by the various soil sources (soil mineral N at planting, N mineralised from organic amendments and soil organic matter) and simulated N losses (N leached, other N losses such as denitrification, volatilisation etc.). In some models, daily N fertiliser requirement is calculated as the difference between crop N uptake demand and the N supply from the various soil sources, using efficiency coefficients to avoid the complex modelling of the various N loss processes. Often the calculation of ETc is also included, particularly when N uptake models are part of DSS. With estimation of ETc and crop N uptake, the N uptake concentration can be calculated which can assist with N management of soilless crops. Some models have a soil module and simulate the root growth and the nutrient uptake by the roots; in these cases, information about the physical, chemical and hydraulic properties of the soil are required. These are generally complex models developed for scientific rather than practical farming applications.

Simulation models that estimate crop fertiliser N requirements may be incorporated into user-friendly DSSs with the aim of providing practical tools for growers and technical advisors to develop N fertiliser plans. DSSs have a user-friendly interface and incorporate models and other mathematical functions to provide practical systems to assist growers with decision making. DSSs for N management calculate crop N demand, usually for short time intervals, and importantly consider other N sources, and calculate N fertiliser requirements as supplemental N required optimising crop N status.

The use of models for scenario analysis is very useful for demonstration purposes for example with growers, advisors, administrators and policy makers. Generally, relatively simple models, with few and readily available inputs are used for practical DSSs while more complex models with more inputs tend to be used for scenarios analysis.

11.19.5.3. Operational conditions

Models of nutrient uptake are generally used for single crops in individual fields or greenhouses. Some can be used at regional level when used in combination with a Geographic Information System (GIS).

Generally, the models are included in a DSS, which provides a user-friendly interface so that nutrient uptake models can be used by growers. The use of nutrient uptake models or of DSSs that incorporate nutrient uptake models requires use of a personal computer or laptop. Commonly, internet access is required to download climatic data. In some cases, such as in greenhouses or where locally-obtained climatic data are not available, the models can be run using climatic data measured within the crop or in very similar local conditions. In this case, a simple low cost meteorological station combined with a data logger is required. Users require some aptitude in the use of computer technology. Where nutrient uptake models are part of more complex models or DSSs to calculate used to calculate crop fertiliser requirements, a soil analysis prior to planting (e.g. of soil mineral N) is required to provide input data.

For practical applications of these models, please see the TD on Decision Support Systems for soil-grown crops.

11.19.5.4. Cost data

Generally, the software to operate the model is free and provided by public research or extension centres. Some commercial companies produce DSS software or Apps that have to be paid for. The firm SMART! Fertilizer Management offers various packages of their DSS system and services for determining multiple nutrient requirements; their prices start at 539 €/year.

11.19.5.5. Technological bottlenecks

The most important technical bottleneck is that the model be available within a user-friendly DSS. This is because generally models are prepared in spreadsheets or code, and are not intended for direct use by growers. Another bottleneck is the availability a suitable model for a given cropping situation. Another fundamental limitation is that the model should be calibrated or verified for the cropping situation; if not the characteristics of the crop and cropping environment should be similar to those for which the model has been previously calibrated or validated. Given the availability of suitable calibrated models in a DSS, the availability of adequate data, particularly climate data can be a limitation. There may also be a need for data describing soil characteristics, and for soil analyses. The availability of effective technical support is a common technical bottleneck. Growers are likely to require technical support to implement and continue to use DSSs based on nutrient uptake models. It is likely that growers will require assistance when learning to use the software.

11.19.5.6. Benefit for the grower

Advantages

Can enhance DSS

- Allows calculating crop fertiliser requirements
- Contributes to improved crop nutrient management that will reduce fertiliser use and costs
- Reduces nutrient loss to the environment

Disadvantages

- Data collection is time consuming
- Climatic and soil data are not always available
- Difficulties with inputting data into the model/DSS
- Initially difficult to learn the system

11.19.5.7. Supporting systems needed

For nutrient uptake models to be used by farmers, it is necessary that 1) models are incorporated into simple and user-friendly DSS and 2) that technical support is available to assist growers to learn to use the DSS-based on these models and to incorporate them into their nutrient management programs.

11.19.5.8. Development phase

- Research: Research has and is being conducted to develop models and DSS for nutrient management (generally N). Generally, the models are specific to given crops and systems
- Experimental phase: As with research, more applied experimental work is on-going.
- Field tests: Field testing is often conducted to adapt the technique to particular crops and cropping systems
- Commercialised: Most of the models are produced by publicly funded research institutions and the models are available without cost. Most DSSs that incorporate nutrient uptake models have also been produced by publicly funded research institutions and are freely available. Some software programs and Apps have been produced by private companies and have a cost

11.19.5.9. Who provides the technology

Generally public institutions such as research/extension centres and universities develop these models. Sometimes these institutions incorporate them into a DSS. Some software programs and Apps have been produced by private companies e.g. SMART! Fertilizer Management (http://www.smart-fertilizer.com/).

11.19.5.10. Patented or not

Software produced using the models are registered according to local/national regulations.

11.19.6. Which technologies are in competition with this one?

There are no technologies that are in direct competition. There are several that could be complementary such as analysis of nutrients in soil solution of the root zone, sap analysis, the use of proximal optical sensors such as canopy reflectance and chlorophyll meters. Technologies such as soil analysis should be used in combination with these models when they form part of a DSS to calculate crop nutrient requirements.

11.19.7. Is the technology transferable to other crops/climates/cropping systems?

Models of nutrient uptake can be developed for all crop types, climates and cropping region.

11.19.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

11.19.9. Brief description of the socio-economic bottlenecks

The major socio-economic bottleneck is the lack of motivation of farmers to adopt technologies to optimise the use of nutrients and reduce environmental impact, particularly in countries where legislation has not been seriously implemented.

11.19.10. Techniques resulting from this technology

1) EU-Rotate_N model: This model was developed from an EU funded research project to optimise N management for numerous vegetable crops in Europe, and can be used for different species grown in rotation. EU-Rotate_N has been used to simulate crop N uptake as well as growth, production, ETc and soil N and water dynamics in numerous and diverse vegetable production systems. The EU-Rotate_N model has been demonstrated to be an effective scenario analysis tool of N and irrigation management for different vegetable crops grown in diverse environments (http://www2.warwick.ac.uk/fac/sci/lifesci/wcc/research/nutrition/eurotaten/)
2) N-Expert: The N-Expert software assists growers and fertiliser advisers to calculate the N (and also P, K and Mg) fertiliser requirement of diverse vegetable crops in Germany. As this is a DSS, it is more fully described in the TD on DSSs. The N-Expert 4 software and background information is freely available at http://www.igzev.de/n-expert/?lang=en
3) VegSyst: The VegSyst simulation model is a relatively simple model developed in the University of Almeria, Spain to calculate daily values of crop N uptake as well as crop biomass production and ETc for crops without water or N stress. The model has been calibrated and validated for the major vegetable crops grown in greenhouses in South-East Spain (e.g. tomato, sweet pepper, muskmelon, cucumber, zucchini, egg-plant, watermelon). The VegSyst model is a component of the VegSyst-DSS developed to calculate daily irrigation and N fertiliser requirements and nutrient solution N concentrations [N] for fertigated vegetable crops grown in greenhouses in South-East Spain (Figure 11-40 - Figure 11-43). (http://www.ual.es/GruposInv/nitrogeno/VegSyst-DSS.shtml)

Figure 11-40. Start screen of VegSyst-DSS

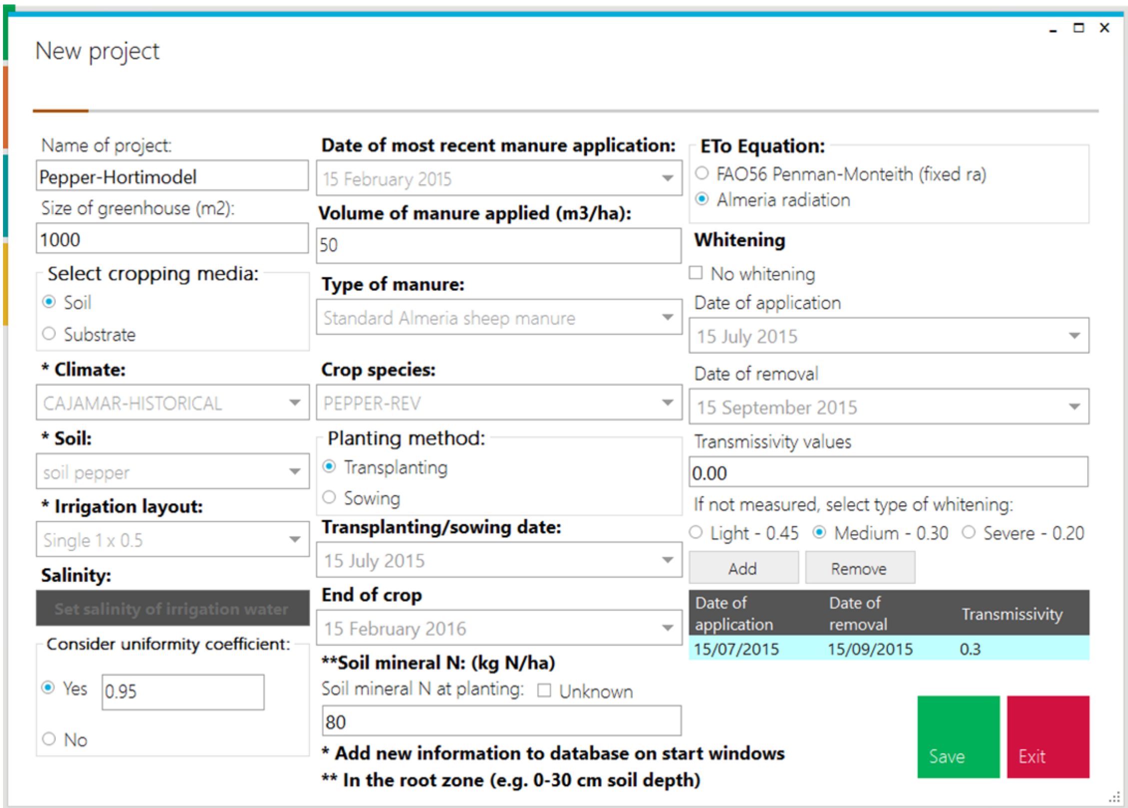
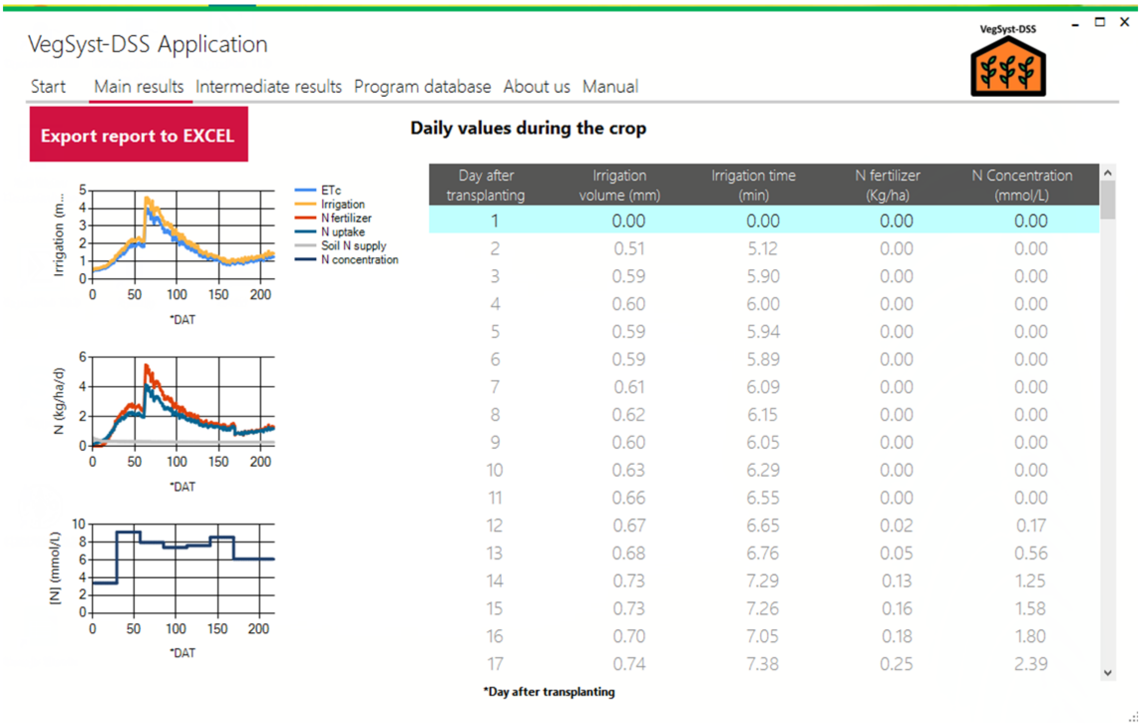


Figure 11-41. Example of input screen of VegSyst-DSS



Day after transplanting	Irrigation volume (mm)	Irrigation time (min)	N fertilizer (Kg/ha)	N Concentration (mmol/L)
1	0.00	0.00	0.00	0.00
2	0.51	5.12	0.00	0.00
3	0.59	5.90	0.00	0.00
4	0.60	6.00	0.00	0.00
5	0.59	5.94	0.00	0.00
6	0.59	5.89	0.00	0.00
7	0.61	6.09	0.00	0.00
8	0.62	6.15	0.00	0.00
9	0.60	6.05	0.00	0.00
10	0.63	6.29	0.00	0.00
11	0.66	6.55	0.00	0.00
12	0.67	6.65	0.02	0.17
13	0.68	6.76	0.05	0.56
14	0.73	7.29	0.13	1.25
15	0.73	7.26	0.16	1.58
16	0.70	7.05	0.18	1.80
17	0.74	7.38	0.25	2.39

Figure 11-42. Example of output of VegSyst-DSS

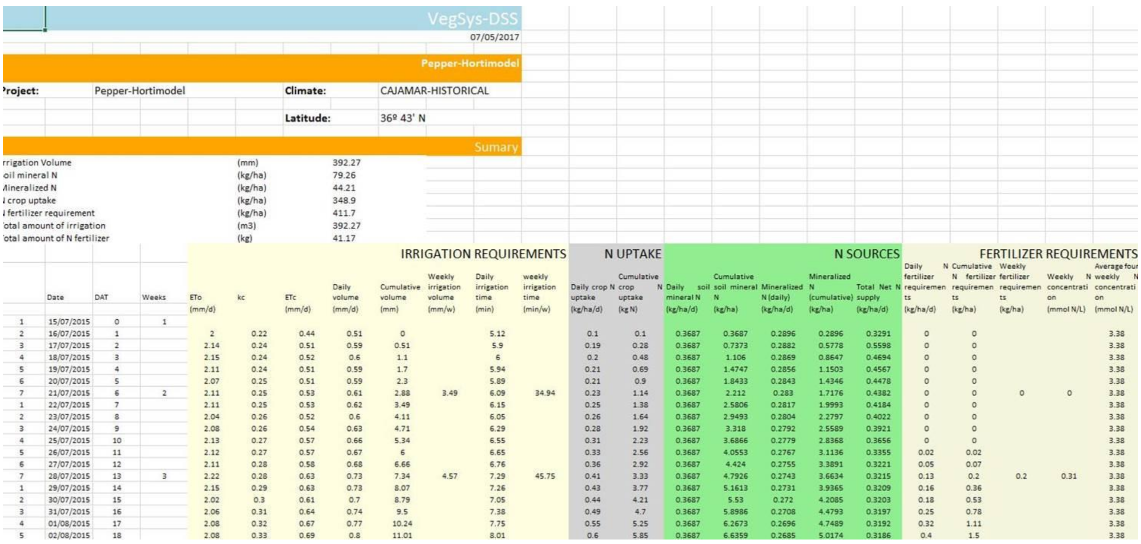


Figure 11-43. Detailed data output from VegSyst-DSS

4) CropManage: developed in the Central Coast region of California, the on-line DSS software CropManage (https://ucanr.edu/cropmanage/login/offline.cfm, click on "About CropManage") is a DSS based on a model that estimates N fertiliser and irrigation requirements on a field-by-field basis. The N fertiliser algorithm generates recommendations based on the crop N uptake, current soil NO_3 status, and estimated soil N mineralisation
5) WELL_N DSS: The WELL_N DSS was developed as a practical DSS to determine N fertiliser recommendations in the United Kingdom. It has been used in commercial vegetable production by growers and advisors. WELL_N is based on routines of the previously developed research model N_ABLE. It considers average climate, soil

mineral N, crop residues and N mineralisation from soil organic matter to calculate the minimum total amount of mineral N fertiliser required for maximum production of 25 different vegetable crops

6) SMART! FERTILISER SOFTWARE produced by SMART! Fertilizer Management (http://www.smart-fertilizer.com/). This is a private company that has various software products to assist with fertiliser and fertigation management. There is a more detailed description in the TRD on DSSs

11.19.11. References for more information

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11.20. Models for nitrate leaching

(Authors: Els Berckmoes[21], José Miguel de Paz[14], Rodney Thompson[23])

11.20.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.20.2. Region

All EU regions.

11.20.3. Crops in which it is used

All horticultural crops.

11.20.4. Cropping type

All cropping types.

11.20.5. Description of the technology

11.20.5.1. Purpose/aim of the technology

The purpose of these models is to simulate and/or predict the leaching of nitrogen to groundwater. In many cases, these models quantify the relation between the amount of fertiliser applied, soil management, soil type etc. and the amount of nutrients leached. This makes it possible to select best practices and to formulate advice and strategies for growers and advisors; it also provides valuable information for governments and authorities.

11.20.5.2. Working Principle of operation

Nitrate leaching models are software applications based on mathematical algorithms to represent nitrate movement throughout the soil to deeper layers. These algorithms are based on knowledge and research experience of water flow, solute transport and nitrogen dynamics in soil. There are various approaches to develop model algorithms following different criteria: from empirical or logistic to more physically based algorithms. The degree of model complexity and the data requirement are important issues when selecting a model to estimate N leaching.

11.20.5.3. Operational conditions

There are a lot of models with variable complexity, data and parameter requirements. The objectives and the operational conditions should be considered to properly select the model. Complex models with high data requirements are more focused on research activities at smaller scales, but simpler models with less data requirements are more suitable for screening analysis (Figure 11-44). This latter type of model is more convenient for regional estimation of nitrate leaching where the lack of data is generally the main bottleneck for this type of approach. On other hand, if the main interest is the N fertiliser recommendation (Figure 11-44) for farmers to minimise nitrate leaching losses, models with intermediate levels of detail and with moderate data requirements, while providing sufficient accuracy may be most suitable (Figure 11-45).

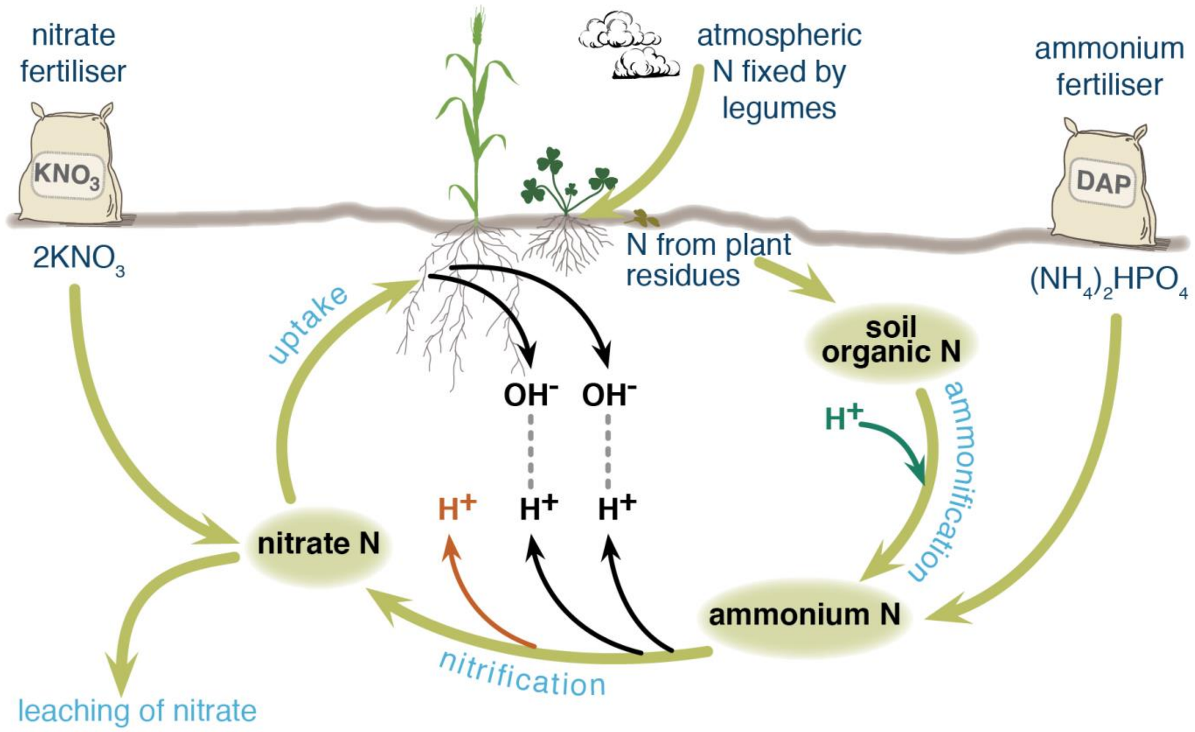

Figure 11-44. Nitrogen cycle showing the impacts of different nitrogen fertilisers (Department of primary industries and regional development, Western Australia)

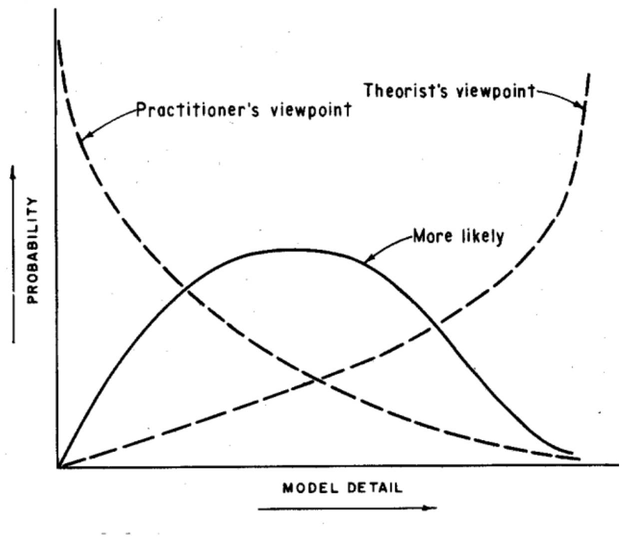

Figure 11-45. Selecting the best model for a field project (Shaffer and Delgado, 2001)

11.20.5.4. Cost data

Usually models are public and freely distributed. Some time is needed to install the model and usually a training period is required to learn how to use it.

Sometime models should be updated to newer versions, so maintenance is needed.

11.20.5.5. Technological bottlenecks

Modelling nitrate leaching is highly challenging as a result of the uncertainties associated with modelling drainage of water, the N concentrations at several soil depths, preferential water flow in soil etc. To reduce these uncertainties, the models should be calibrated and validated before being used. The calibration and validation processes are difficult, cumbersome and require considerable work to obtain sufficient data to be able to compare model output with field measurements. This is one of the main limitations to use of the models to estimate nitrate leaching. Prior to this, accurate measurement of nitrate leaching under field conditions is required. These measurements sometimes have similar uncertainties because water drainage and preferential flows can be difficult to accurately measure and additionally the soil N mineral concentration is very variable in space and time.

Currently, numerous models have been developed to predict nutrient leaching from agricultural and horticultural activities. The range of tools for assessing the contributions from these activities to non-point pollution to groundwater range from very simple to very complex models. The simple models, in general, do not take into account the annual variations in weather and are seldom able to incorporate effects of management in a realistic manner. These simple models often do not describe the soil and transport processes and may overlook certain factors. The advanced models, generally, require numerous data which requires considerable efforts to collect these data and specific skills are required to make the models run.

Upscaling of models: Generally, models work well on a small scale (e.g. field-level, greenhouse level). Where models are applied on larger scales, numerous difficulties occur. For areas with small spatial variations of landscape factors as soil, climate, crop management etc., regional application of models can simulate N leaching with better accuracy than for complex areas higher spatially variable which require obtaining information enough detailed and distributed geographically, which in many cases is difficult to obtain.

11.20.5.6. Benefit for the grower

Advantages

- Takes take into account the interactions between various elements of the immediate environment
- Considers management strategies
- Includes a characterisation of the agricultural system
- Helps achieving environmental goals set out by the policy maker (at the European, national and regional level)
- Estimates nitrate leaching losses at field scale
- Reduces fertiliser losses

Disadvantages

- Uncertainties in simulation
- Necessity for calibration and validation

11.20.5.7. Supporting systems needed

Simulation models of nitrate leaching are usually included in more complex simulation models of various processes such as EU-ROTATE_N, NLEAP, STICS, LEACHN, N-index, WELL_N, NITIRSOIL etc. Depending on the capacity of the model, they can be integrated into GIS to evaluate nitrate leaching at regional scale, or included in a Decision Support System-DSS to recommend N management.

11.20.5.8. Development phase

- Research: Research has been and is being conducted to develop models to simulate N leaching more accurately with lower data requirements and which are adapted to more diverse conditions: such as vegetable and fruits crops, flood and localised irrigation systems, new slow release N fertilisers etc.
- Experimental phase: As with research, more applied experimental work is on-going.
- Field tests: Field testing is often conducted to adapt these models to particular conditions and cropping systems
- Commercialised: Most of the models are produced by publicly funded research institutions and the models are available without cost. Most DSS that incorporate nutrient leaching models have also been produced by publicly funded research institutions and are freely available. Some software programs and Apps have been produced by private companies and have a cost

11.20.5.9. Who provides the technology

Several universities, research/extension centres, public institutions provide nitrate leaching models that are usually integrated into more complex simulation models that deal with various nutrient pathways agricultural systems. Sometimes these institutions incorporate them into a DSS for fertiliser recommendation or link them to a GIS N leaching estimation at regional scale. Several model references are cited in the section 10.

11.20.5.10. Patented or not

It is not usual for a nitrate leaching model to be patented, since numerous models are developed by public research institutes and/or universities.

11.20.6. Which technologies are in competition with this one?

Soil or soil solution sampling and analysis in laboratory are the technology that could be considered to be in competition with the nitrate leaching models. However, in reality they are complementary approaches.

11.20.7. Is the technology transferable to other crops/climates/cropping systems?

Simulation models are tools developed to estimate nitrate leaching in various conditions and are intended for use in conditions different to those in which they were developed. With suitable calibration and validation, these models can be used in other crops, climate or cropping system.

11.20.8. Description of the regulatory bottlenecks

In many European member states, policy measures have been implemented to lower the N and P emissions from agriculture and horticulture, including the emissions into groundwater and surface waters. Until now, most of the measures are based on rough risk assessments with regard to nitrate leaching. It is not always clear what the short and long term effects of regulative measures will be.

11.20.9. Brief description of the socio-economic bottlenecks

N leaching models are generally used by researchers and university staff. There is some use by public administrators and very little use by farmers. There is a tendency to increasingly develop simple, user-friendly models and also to develop web-based models, which can be accessed by smart phones, which will increase ease of use. Generally, specific skills are required to use these tools; for farmers, advisers, public staff etc. this limits the adoption of this technology.

11.20.10. Techniques resulting from this technology

Some used models are detailed as follows:

ANIMO model:

- Developed by Alterra Wageningen UR (1985); Holland
- Open source: http://www.wur.nl/en/Expertise-Services/Research-Institutes/Environmental-Research/Facilities-Products/Software-and-models/ANIMO.htm
- The ANIMO model aims to quantify the relation between fertilisation level, soil management and the leaching of nutrients to groundwater and surface water systems for a wide range of soil types and different hydrological conditions. The model comprises a large number of simplified process formulations.
- Model works on field scale

Nitrate Loss and Environmental Assessment Package (NLEAP):

- Developed by Agricultural Research Service, US Department of Agriculture, United States. https://www.ars.usda.gov/research/software/
- It a field-scale computer model developed to provide a rapid and efficient method of determining potential nitrate leaching associated with agricultural practices. The processes modelled include movement of water and nitrate, crop uptake, denitrification, ammonia volatilisation, mineralisation of soil organic matter, nitrification and mineralisation-immobilisation associated with crop residue, manure and other organic wastes. It uses basic information concerning on-farm management practices, soils and climate to project N budgets and nitrate leaching indices. NLEAP calculates potential nitrate leaching below the root zone and to groundwater supplies. Additionally, the NLEAP version 5.0 includes a GIS linkage

EU-ROTATE_N:

- Developed by a European consortium of a project entitled “Development of a model based decision support system to optimise nitrogen use in horticultural crop rotation across Europe”. QLRT-2001-01100. http://www2.warwick.ac.uk/fac/sci/lifesci/wcc/research/nutrition/eurotaten

- The EU-ROTATE_N model consists of a number of subroutines to simulate the growth both below and above ground, nitrogen mineralisation from the soil and crop residues, subsequent N uptake and balance between supply and demand to regulate growth. These will all be regulated by weather factors such as rainfall, temperature and radiation. Routines simulate the flow of water and nitrogen into the plant, subsequent evapotranspiration or leaching

Groundwater Loading Effects of Agricultural Management Systems:

- Southeast watershed research lab, US Department of Agriculture, Tifton, United States. http://www.tifton.uga.edu/sewrl/Gleams/gleams_y2k_update.htm#General%20Overview%20of%20GLEAMS
- It was developed to simulate edge-of-field and bottom-of-root-zone loadings of water, sediment, pesticides and plant nutrients from the complex climate-soil-management interactions. It has evolved through several versions from its inception in 1984 to the present 3.0 version and has been evaluated in numerous climatic and soil regions of the world. Special studies have resulted in model modifications and oftentimes the improvements in comprehension resulted in new version release

Denitrification-Decomposition model:

- Developed by Institute for the Study of Earth, Oceans and Space, University of New Hampshire. Durham, NH 03824, United States. http://www.dndc.sr.unh.edu/
- The model is a process-oriented computer simulation model of carbon and nitrogen biogeochemistry in agroecosystems

DAISY:

- Department of Plant and Environmental Science, University of Copenhagen (Denmark). http://daisy.ku.dk/
- Daisy is a well-tested dynamic model for simulation of water and nitrogen dynamics and crop growth in agro-ecosystems. The model aims at simulating water balance, nitrogen balance and losses, development in soil organic matter and crop growth and production in crop rotations under alternate management strategies

Simulateur mulTIdisciplinaire pour les Cultures Standard (STICS):

- INRA: National Institute for Agricultural Research in France. http://www6.paca.inra.fr/stics_eng/
- It is a crop model with a daily time-step, which has been developed since 1996 at INRA. Its main aim is to simulate the effects of the physical medium and crop management schedule variations on crop production and environment at the field scale. From the characterisation of climate, soil, species and crop management, it computes output variables relating to yield in terms of quantity and quality, environment in terms of drainage and nitrate leaching and to soil characteristics evolution under cropping system

CROPSYST:

- Developed by the Washington state university (United States). http://sites.bsyse.wsu.edu/cs_suite/cropsyst/index.html
- CropSyst is a user-friendly, conceptually simple but sound multi-year multi-crop daily time step simulation model. The model has been developed to serve as an analytic tool to study the effect of cropping systems management on productivity and the environment. The model simulates the soil water budget, soil-plant nitrogen budget, crop canopy and root growth, dry matter production, yield, residue production and decomposition and erosion. Management options include: cultivar selection, crop rotation (including fallow years), irrigation, nitrogen fertilisation, tillage operations (over 80 options) and residue management

WELL_N:

- Warwick Crop Centre, The University of Warwick (United Kingdom). http://www2.warwick.ac.uk/fac/sci/lifesci/wcc/resources/morph/onlinehelp/models/welln/
- This model provides estimates of the fresh and dry crop yield, Nitrogen content of crop and its residues. It also provides estimates of leaching since the start of the run and soil mineral N states at harvest, for different N fertiliser rates. This additional information enables alternate strategies of fertiliser application to be formulated

NDICEA: Nitrogen planner:

- Developed by Louis Bolk Instituut, Netherlands. http://www.ndicea.nl/indexen.php?i=enstart
- The program NDICEA nitrogen planner presents an integrated assessment on the question of nitrogen availability for your crops. This is more than a simple nitrogen budgeting for each crop: crop demand on one hand and expected availability out of artificial fertilisers and manures, crop residues, green manures and soil on the other.
    - The release of nitrogen as a result of the mineralisation of the different types of organic matter in the soil is calculated, depending on soil type, temperature and rainfall
    - Losses due to leaching and denitrification are calculated
    - During the growing season, the resulting net available nitrogen is compared with the crop demand in time steps of one week

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11.21. Use of slow and controlled release fertilisers

(Authors: Federico Tinivella[7], Rodney Thompson[23])

11.21.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.21.2. Region

All EU regions.

11.21.3. Crops in which it is used

All vegetable, fruit and ornamental crops.

11.21.4. Cropping type

- Soil bound
- Protected
- Open air

11.21.5. Description of the technology

11.21.5.1. Purpose/aim of the technology

These fertilisers allow a constant release of nutrient within a certain period of time (months) according to certain environmental conditions of the growing medium and/or to microbiological activity in the growing medium. By having a slower release of available nutrients over time, it is generally expected that one application of these fertilisers will be sufficient for an entire or an appreciable part of a growing season. Additionally, it is intended that the recovery of nutrients by crops will be higher and that nutrient losses to the environment will be smaller.

11.21.5.2. Working Principle of operation

The terms “slow release fertilisers” and “controlled release fertilisers” have been used interchangeably and also separately. Slow release fertilisers have been defined as those from which nutrient release is slower than from the commonly-used mineral fertilisers and where the rate, pattern and duration of release are not well controlled. Controlled release fertilisers have been defined as those where the factors dominating the rate, pattern and duration of release are well-known and controllable during the preparation of the controlled release fertilisers. Here these fertilisers will be considered collectively as “slow and controlled release fertilisers” (SCRF).

Controlled release fertilisers

They are granular fertilisers that are coated with a membrane formed by a semi-impermeable and biodegradable resin. The membrane allows the release of nutrients controlled by temperature. The release process is activated when water, having penetrated the granules, melts the salts that are pushed out of the granule thanks to the osmotic pressure (Figure 11-46). The thickness of the membrane determines the release period that varies between 3-4 to 16-18 months during which the fertiliser is made regularly available.

The release period is calculated making reference to a temperature of 21 °C; the increase or decrease of temperature causes a reduction or an extension of release period respectively (Figure 11-47).

Recently granules coated with double membranes have been introduced on the market; the external membrane has different chemical properties compared to the inner one and it allows a further delay in nutrients release.

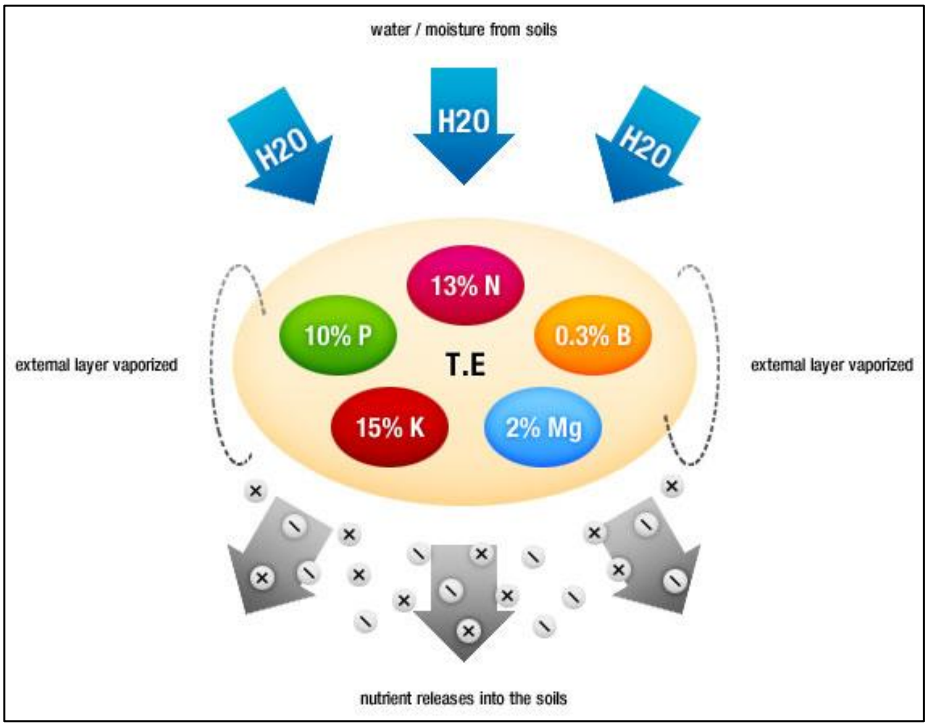

Figure 11-46. Mechanism of action of main controlled release fertilisers (www.cymax.com)

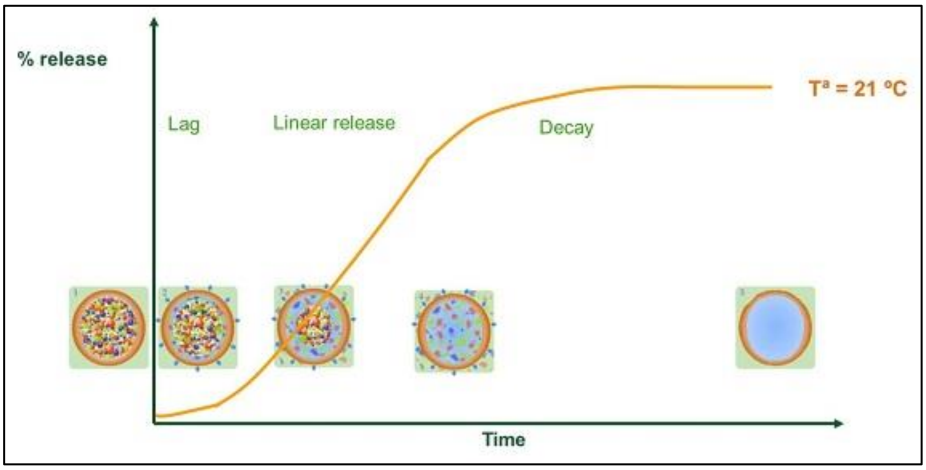

Figure 11-47. Release curve of a controlled release fertiliser (www.haifa-group.com)

Slow release fertilisers

They are basically fertilisers in granular shape that can slowly release nitrogen into the growing medium (Figure 11-48). They are obtained through a condensation reaction between urea and aldehydes of different complexity. Main typologies of slow release fertilisers are:

- Urea-formaldehyde: N release is controlled by microbiological activity (Figure 11-48), it is higher at low pH and it starts when the temperature is 5 °C gradually increasing till 32 °C. The fertilisers suitable for application in growing media are the ones characterised by small granules (< 2 mm) in order to assure an even distribution in the substrate and an average release period of 2-3 months
- Isobutylidene diurea: the release mechanism is more chemical than microbiological. First, isobutylidene diurea is solubilised then hydrolysed with urea formation and finally urea is broken down. The highest speed of hydrolysis is observed at low pH (5-6) and with granules having small dimensions
- Cyclo diurea: N release is related to a microbiological degradation and it is influenced by temperature, humidity and pH. With pH equal or lower than 6 and with a temperature lower than 10 °C N released is basically blocked

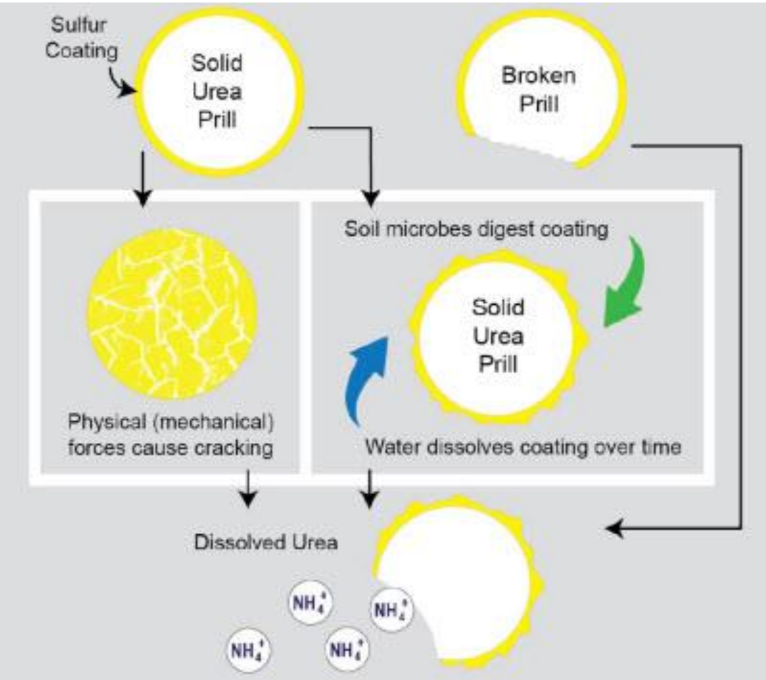

Figure 11-48. Mechanism of action of slow release fertilisers (https://www.pioneer.com/)

Slow and controlled release fertilisers are normally used for the cultivation of crops that are present for prolonged periods such as turfs, golf courses, fruit trees.

With regards to potted plants, slow and controlled release fertilisers are normally provided already mixed with the growing medium by the producers/suppliers of substrates according to the doses requested by customers.

Mixing dose:

- Controlled release fertilisers: on the average 1-3 kg/m^3 of substrate (3-4 months duration) and 3-5 kg/m^3 of substrate (12-14 months duration)
- Slow release fertiliser: 1-3 kg/m^3 of substrate

Such fertilisers are normally supplied in bags ranging from 5-25 kg.

11.21.5.3. Cost data

- Controlled release fertiliser: around 2,5 €/kg
- Slow release fertiliser: around 1 €/kg

11.21.5.4. Technological bottlenecks

The release of the fertiliser can be strongly influenced by extreme environmental conditions with specific regards to temperature, in case fertiliser (before mixing) or substrate bags are not properly stored.

It is crucial to know the different tolerance of crop species to the salts present in the fertiliser in order to avoid phytotoxic effects.

11.21.5.5. Benefit for the grower

Advantages

- Better control of fertilisation throughout the entire duration of the cultivation
- Possibility to concentrate the release of nutrients in a certain phase of crop growth
- Less fertiliser applications
- Reduced N-leaching
- Available as ready to use substrates

Disadvantages

- High costs
- Time demanding in terms of preparation of growing media

11.21.5.6. Supporting systems needed

Only in the case of growing media adopted for the cultivation of potted plants and equipment that can ease the mixing of fertiliser inside the growing medium can be of help.

11.21.5.7. Development phase

Commercialised.

11.21.5.8. Who provides the technology

Many companies are producing and/or commercialising controlled or slow release fertilisers, e.g. ICL (https://icl-sf.com/it-it/), Eurochem Agro (www.eurochemagro.com), Haifa (www.haifa-group.com), Bottos (http://www.bottos1848.com/) specialised in turf products.

11.21.5.9. Patented or not

Coating technologies applied in controlled and slow release fertilisers are normally patented.

11.21.6. Which technologies are in competition with this one?

The use of ammonium based N mineral fertilisers amended with nitrification inhibitors can be considered as being in competition with SCRF fertiliser for a prolonged N supply.

11.21.7. Is the technology transferable to other crops/climates/cropping systems?

As already mentioned above, slow and controlled release fertilisers are well suited to situations where crops are present for prolonged periods (e.g. turf, golf courses, fruit trees), where their use confers an economic advantage by reducing fertiliser application. In the case of vegetable production, where crops are commonly of short duration, vegetable growers may not perceive sufficient economic advantage, through reduced N applications, to justify the extra cost of SCRF. An additional and important issue with vegetable cropping is to ensure the N supply during periods of peak N demand; SCRF may not always be able to provide sufficient amounts of readily available N.

In general, research with SCRF in vegetable crops has shown similar but not higher production than with conventional N management and until now the economics of reduced N fertiliser application have not convinced many vegetable growers. It is possible that for environmental reasons that legislation may encourage adoption of SCRF. If there is to be appreciably increased use of SCRF in vegetable production for environmental reasons, it should be based on sound scientific research demonstrating reduced N losses under diverse realistic cropping conditions. It is likely that the potential use of SCRF in vegetable production may be influenced by the characteristics of cropping systems. Hartz and Smith (2009) commented that the use of SCRF for environmental reasons may be most suitable where appreciable in-season NO_3 leaching loss is likely and where this was beyond the control of the grower. These authors considered that this was not the case in the Mediterranean climate of California, which would also apply to vegetable crop grown in other regions with Mediterranean climates and also to greenhouse-grown crops. Examples of more suitable regions for the use of SCRF are areas with heavy rainfall events during cropping and on sandy soils.

11.21.8. Description of the regulatory bottlenecks

Regulation (EC) No 2003/2003 relating to fertilisers brings into one piece of legislation all the European Union rules that apply to fertilisers — chemical compounds that provide nutrients to plants. It ensures that these highly technical requirements are implemented uniformly throughout the EU.

11.21.9. Brief description of the socio-economic bottlenecks

Slow and controlled release fertilisers are more expensive than conventional mineral fertilisers.

11.21.10. Techniques resulting from this technology

Slow and controlled release fertilisers are generally used in specific circumstances where there is a financial advantage from reducing the number of fertiliser applications. Additionally, they may be useful in situations where there is a high risk of nutrient loss, e.g. sandy soils. These fertilisers are popular in nurseries, the production of ornamental, and in domestic gardens.

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11.22. Organic fertiliser

(Authors: Georgina Key[1], Dolors Roca[8])

11.22.1. Used for

Minimising the impact to the environment by nutrient discharge.

11.22.2. Region

All EU regions.

11.22.3. Crops in which it is used

All vegetable, fruit and ornamental crops.

11.22.4. Cropping type

All cropping types.

11.22.5. Description of the technology

11.22.5.1. Purpose/aim of the technology

In the context of supplying nutrients to reduce environmental impact and to enhance sustainability, organic fertilisers provide nutrients with an even nutrient supply throughout the crop and also can enhance soil quality with respect to both soil physical and chemical characteristics.

11.22.5.2. Working Principle of operation

Organic nutrient management involves the use of animal manures, composts, cover crops and fabricated organic fertilisers. The use of these organic materials provides a steady release of nutrients to crops as the added organic materials decompose (Figure 11-49). The added organic material that does not decompose increases the content of soil-organic matter, which enhances soil quality by improving soil chemical and physical properties. With adequate management, the large quantities of crop residues and animal manure produced annually, can be valuable sources of plant nutrients and can improve soil quality.

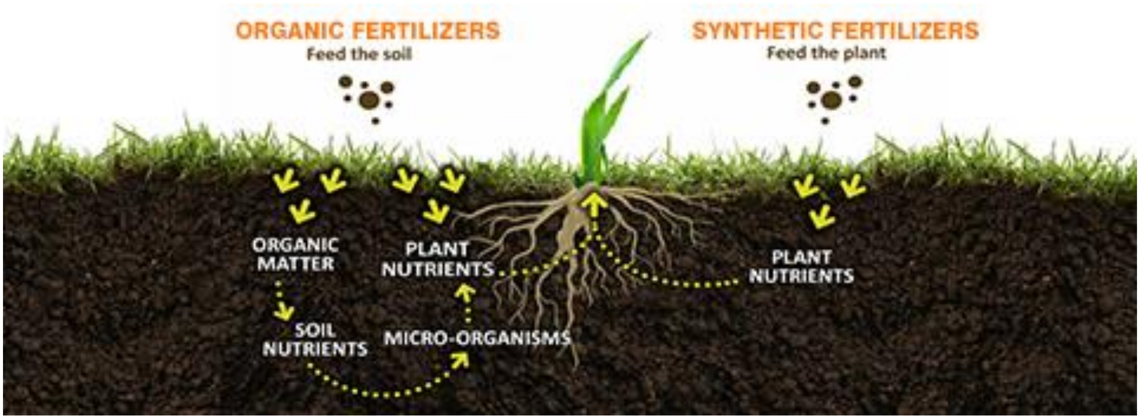

Figure 11-49.. Difference between Fertiliser Derived from Organic and Synthetic Sources (http://www.milorganite.com)

Enhanced quality of soil physical conditions can enhance root growth, facilitating more efficient nutrient uptake. The supplementary use of manures has been observed to improve the uptake efficiency of mineral fertilisers. Additionally, the application of organic fertilisers (Figure 11-50) can contribute to carbon sequestration by agricultural soils.

Figure 11-50. Example of packaged organic fertiliser (http://www.growbetter.com.au/)

11.22.5.3. Operational conditions

The major problems associated with the use of organic fertilisers include weight and bulkiness, lack of labour, insufficient quantities, high transportation and application costs, enhanced weed infestation, poor hygienic conditions and lack of storage facilities to maintain quality attributes of manure.

Both good storage and composting require active management. Larger scale businesses are more likely to require regular removal from the site, whilst composting may be a useful option for smaller ones, or where a local market exists. In all cases, the storage facility must be on hand, designed to meet the stable's particular requirements of handling the quantity of manure, the need for vehicle access must be considered and pollution avoided.

Run-off from poorly managed manure heaps is both a loss of fertility and potentially a serious pollution hazard. Maximising the nutrient value of the manure is consistent with minimising the environmental impact.

Moreover, given the diversity of compost origin, organic amendments or fertilisers, analysis is required to know the nutrient content in order to adjust application rates according to crop needs, soil tests and frequency of manure applications. Avoid applying manure at rates that exceed crop requirements for any nutrient, but especially for N on fields that receive manure on a regular basis. In addition to manure, bio solids, food processing wastes, animal by-products, yard wastes, seaweed and many types of composted materials are nutrient sources for farm fields. Bio solids contain most of the essential plant nutrients and are much “cleaner” than they were twenty years ago, but regulations for farm application must be followed to prevent the possibility of excessive trace metal accumulation. Bio solids are also not an acceptable nutrient source for certified organic production.

Applications of these products must avoid polluting water and meet minimum standards for new or improved manure stores.

11.22.5.4. Cost data

With the development of new technologies, which allow organic fertiliser production, farmers could have a fertilisation technique with a similar cost as mineral fertilisation.

11.22.5.5. Technological bottlenecks

Development of this industrial sector: Mainly, production techniques of soluble liquid organic fertiliser that can be used in fertigation.

11.22.5.6. Benefit for the grower

Advantages

- Premium for organic produce, i.e. higher prices
- Substitute for mineral fertilisers
- Reduces the risk of surface and groundwater pollution, compared to mineral fertilisers
- Improves soil quality

Disadvantages

- Uncertainty of nutrient composition
- Low nutrient content
- Large volumes have to be handled
- Special care for disease control with some materials such as slurries, manures and bio solids
- Specialised equipment needed e.g. slurry or manure spreaders

11.22.5.7. Supporting systems needed

Specialised equipment e.g. slurry or manure spreaders. Adaptation of production techniques and technical assessment during the first periods of implementation may be needed. Laboratory analysis may be required to characterise the organic materials being applied.

11.22.5.8. Development phase

- Research: Some research is on-going to match and synchronise crop demand with nutrient supply with organic fertiliser source. New approaches are also need to evaluate new sources for new crops, varieties and locations
- Experimental phase and field tests: As with research, more applied experimental work and field tests is being addressed to obtain a correct management methodology
- Commercialised: There are specialised companies which are producing different organic fertilisers

11.22.5.9. Who provides the technology

Companies that specialise in fertiliser production, particularly those that specialise in organic fertilisers, produce the products. Organic fertilisers are then sold through the general fertiliser distribution chains or through outlets specialised in organic products. Manure is supplied to horticultural growers by specialised companies who deliver the manure to the farm and commonly also apply it.

11.22.5.10. Patented or not

Some of the newer organic fertilisers, that involve the processing of materials such as algae, plants and manure, are likely to be patented by the producing company. Some of the processing procedures will be patented.

11.22.6. Which technologies are in competition with this one?

Alternative fertilisation management is in competition with organic production (mineral fertilisation); however, a mixture of these two fertilisation techniques will be adequate.

11.22.7. Is the technology transferable to other crops/climates/cropping systems?

The technology could be transferable to other crops and development situations.

11.22.8. Description of the regulatory bottlenecks

11.22.8.1. Brief description of the European directive and implications for growers at European level

- Regulation (EC) No 834/2007 set up primarily as an internal market and consumer protection regulation, describes the organic production standards and the control and labelling requirements
- Organic fertilisers are those certified as having been produced through clearly defined organic production methods (i.e. EC Regulation 834/2007). The compliance of the grower with these methods is verified by an independent organisation accredited by an authority

11.22.8.2. Implementation at the country level

Generally, there are national regulations regarding the use of organic fertilisers; often these are based on EU regulation.

11.22.8.3. Implementation at the regional level

In some regions, there are regional regulations that are often based on EU regulations.

11.22.9. Brief description of the socio-economic bottlenecks

The limited cropped area of organic agriculture will be the bottleneck for economic interest in establishing specific programs for organic farming systems.

The cost of management of the residues often used as organic fertiliser is an issue. In addition, because organic fertilisers generally have a lower nutrient content than mineral fertilisers, there are the costs involved in transporting larger volumes and their storage.

11.22.10. Techniques resulting from this technology

Not applicable.

11.22.11. References for more information

[1] Regulations:

Regulation (EC) No 2003/2003 of the European Parliament and of the Council of 13 October 2003 relating to fertilisers. This Regulation shall apply to products which are placed on the market as fertilisers designated “EC fertiliser”

- Commission Regulation (EU) 2016/1618 of 8 September 2016 amending Regulation (EC) No 2003/2003 of the European Parliament and of the Council relating to fertilisers for the purposes of adapting Annexes I and IV (Text with EEA relevance)
- REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL laying down rules on the making available on the market of CE marked fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009
- Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91. Like its predecessor, Council Regulation (EEC) No 2092/91, Regulation (EC) No 834/2007 set up primarily as an internal market and consumer protection regulation, describes the organic production standards and the control and labelling requirements
- Including amendment: COUNCIL REGULATION (EC) No 967/2008 of 29th September 2008 amending Regulation (EC) No 834/2007 on organic production and labelling of organic products
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Chapter 12. Reducing environmental impact – Nutrient removal and recovery

Coordinators: Wilfred Appelman[22], Els Berckmoes[21], Alejandra Campos[10], Jennifer Bilbao[10], Iosif Mariakakis[10], Ilse Delcour[19]

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12.1. Introduction on Reducing environmental impact – Nutrient removal and recovery

12.1.1. These techniques concern the issue

Reducing environmental impact by nutrient removal and recovery. This chapter is closely related to Chapter 3 that describes technologies to enhance the chemical quality of irrigation water.

12.1.2. Regions

All EU regions.

12.1.3. Crops in which the issue is relevant

This is not crop specific since it considers general concerns of effluent management and nutrient removal and recovery from effluents.

12.1.4. Cropping type

All cropping types.

12.1.5. General description of the issue

The adoption of fertigation was an important forward step to optimise both water and nutrient use efficiency in horticultural crops. Nevertheless, appreciable environmental impacts have been observed in regions where fertigation is used intensively. As an example, in the Flemish and Dutch soilless greenhouse areas, the threshold value for nitrate of 50 mg/L is frequently exceeded in nearby surface water bodies.

A survey conducted in the FERTINNOWA project (http://www.fertinnowa.com/project/) showed that drainage water from soilless cropping is usually collected in some European Member States, especially in North-west countries such as Belgium, The Netherlands, and the northern part of France. In recent decades, numerous research activities have been undertaken to develop technologies for nutrient removal and the recovery of some nutrients present in discharged drainage water. In this way, the environmental impact of fertigation practices could be appreciably reduced.

The problems associated with the emission of nutrients concern mostly eutrophication and nitrate contamination of aquifers. Eutrophication is a particular problem where nutrients from soilless systems enter surface water. Figure 12-1 provides an overview of the discharge of nutrient to surface water and of the possibility of nutrient recovery associated with closed soilless growing systems.

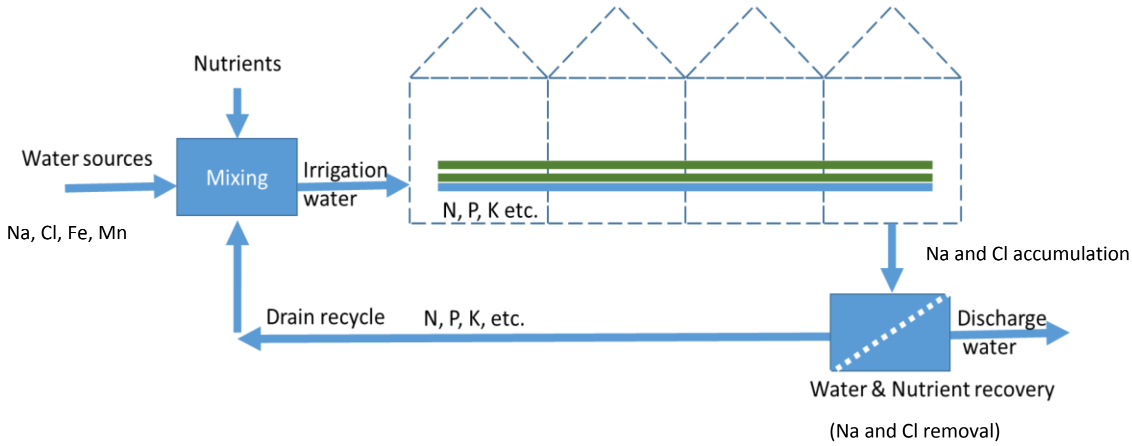

Figure 12-1. Schematic approach of a closed water system in (greenhouse) horticulture

12.1.5.1. Sub-issue A: Specific legislation regarding use of recovered nutrients

Iron Oxide Coated Sand (IOCS) can be used to adsorb P from drainage water. IOCS is a byproduct of water treatment plants. To be used as a resource for a specific application, a raw material declaration is needed (Waste Framework Directive (2008-98-EC).

12.1.5.2. Sub-issue B: Need for business models

There is a need for business models regarding end-of-pipe solutions. Removal of nutrients is costly and usually requires appreciable investment and operational costs. Consequently, it is very useful to make available sound business models that inform growers of the costs and benefits associated with using these technologies, such as the extra costs, the possible fertiliser savings associated with nutrient recovery, and to explore the options of fixed on-site, mobile or collective end-of-pipe solutions.

12.1.5.3. Sub-issue C: Need for a long-term demonstration of the nutrient recovery technologies

Most of the technologies that enhance nutrient recovery are still in the research phase. There is a need for long-term field tests and demonstrations to evaluate the regenerated fertilisers obtained.

As transport of recovered fertilisers is expensive and also would require additional legislation, it is likely that recovered nutrients would be applied at the farm from where they were recovered.

12.1.5.4. Sub-issue D: Other contaminants and need for a holistic approach

In addition to water use, the emission of nutrients and of plant protection products (PPP) to the environment are amongst the most important environmental issues associated with agriculture in Europe. Most of the technologies for removing nutrients and PPPs are end-of-pipe solutions that generally focus on the removal of specific nutrients e.g. N or P, or of PPPs. For end-of-pipe solutions, a more holistic approach would be beneficial because generally a range of discharge criteria must be satisfied to ensure good water quality e.g. chemical oxygen demand (COD), PPP, N, P, Na, Cl etc.

Various different types of treatments for limiting the emission and environmental impact of PPPs are available and are based on principles such as oxidation, adsorption or retention. Depending on the actual situation, there is a wide range of considerations concerning the effectiveness, safety and economy of different systems and technologies when used in a greenhouse or on a farm. Some highly effective systems have been shown to be costly and difficult to use and to require qualified personnel for both installation and maintenance.

In some EU member states, such as The Netherlands, where the Water Framework Directive (WFD) requirements are being increasingly applied, these types of treatment options already appear to be providing effective solutions. From the beginning of 2018, the on-farm use of a treatment technology to remove 95-99% of PPPs from drain water is compulsory in The Netherlands. Other member states, such as Belgium, are expected to follow this practice. In Work Package 4 (Deliverable 4.2) of the FERTINNOWA project (http://www.fertinnowa.com/project/), the removal of PPPs from drain water with new and integrated technologies is being examined.

When considering the increasingly strict requirements and standards for the quality of drain water, the need for a holistic approach is evident. When growers are offered end-of-pipe solutions, those solutions ideally should meet all discharge criteria. Also, an integrated solution in which drain water is collected and recirculated, so that nutrients are retained and the emission of PPPs is avoided, is a preferable option where it can be achieved, to the use of end-of-pipe solutions.

12.1.6. Brief description of the socio-economic impact of the issue

Chapter 1, section 1.7 described, in some detail, the environmental impacts of fertigated crops. In case of soil grown crops, excessive irrigation and N fertiliser application can contribute to nitrate contamination of aquifers. In soilless grown crops with recirculation, a surprising amount of drain water is discharged. Flemish and Dutch publications indicate that 5-10% of the nutrient solution is discharged per year from soilless systems with recirculation. Where the discarded recirculated nutrient solution is discharged into the surface water this can result in appreciable environmental impact. A Dutch study estimated that the Dutch soilless greenhouse sector discharges 1300 tonnes N, 200 tonnes P and 1134 kg PPPs/year (Beerling, 2014).

During the last decades, some research initiatives have been conducted to investigate the technical and economic feasibility of end-of-pipe solutions. The implementation of end-of-pipe solutions will involve dealing with a series of socio-economic issues:

- A “mind shift” of the growers will be required as growers will have to pay additional attention to the treatment of a “wastewater stream”
- At the moment, growers are not sufficiently aware of the potential value of discharged drain water. Drain water will have a residual value for both the nutrients contained as well as the value of the water itself. The value of the water will differ depending on the type of water source
- Purging of wastewater can, depending on the specific situation, require appreciable investment. Recovery of (some) nutrients and on-site production of fertilisers might cover (part) of the investment and operational cost for these installations

12.1.7. Brief description of the regulations concerning the problem

Some Directives and policy requirements have been developed by the European Union (EU) as well as the sector itself (e.g. certification schemes) that affect fertiliser use and irrigation in horticulture in the EU. Table 12-1 lists the most important directives and policy.

Table 12-1. Overview of most important directives and policy that affect fertiliser use and irrigation in horticulture

General legislation and policy	Aim and comments
Water Framework Directive (WFD), including the Nitrate Directive	To achieve good qualitative and quantitative status of all water bodies Nitrate Directive: to protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters and by promoting the use of proper farming practices
Nitrate Directive	Reduction of pollution from agricultural nitrogen
Drinking Water Directive	Mandates minimum health standards in water intended for human consumption, making linkages with other water-related policies

12.1.8. Existing technologies to solve the issue/sub-issues

Various “end-of-pipe” solutions are available for nutrient removal and recovery of specific nutrients from the drain or drainage water. The nutrient removal and recovery techniques include physio-chemical procedures such as adsorption media for phosphorus, electrochemical phosphorous precipitation, moving bed biofilm reactor, modified ion exchange, and biological approaches such as nutrient removal in constructed wetlands and the use of duckweed.

12.1.9. Issues that cannot be solved currently

12.1.9.1. Sub-issue A: Specific legislation regarding use of recovered nutrients

These should be reviewed on a case by case basis, depending on the nutrient and material used to recover the nutrient. In some cases, the legal context for the transport or use of these materials may not be clear.

12.1.9.2. Sub-issue B: Need for business models

Specific business models are required. In general, tools are available to provide the required business models.

12.1.9.3. Sub-issue C: Need for a long-term demonstration of the nutrient recovery technologies

Numerous demonstrations sites have been established throughout Europe. European projects or initiatives (like FERTINNOWA, Nuredrain, etc.), as well as numerous national projects (Apropeau (Be), SOSpuistroom (Be), Glastuinbouw Waterproof (NL), etc.), are investigating and demonstrating end-of-pipe solutions.

12.1.9.4. Sub-issue D: Need for a holistic approach

Most elements for a more holistic approach are available. They should be brought together and evaluated in a business model.

12.1.10. References for more information

[1] van Os, E., Jurgens, R., Appelman, W., Enthoven, N., Bruins, M., Creusen, R., Feenstra, L., Santos Cardoso, D. Meeuwsen, B., & Beerling, E. (2012) Technische en economische mogelijkheden voor het zuiveren van spuiwater. Wageningen UR Report GTB-1205

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[4] Lee, A., Enthoven, N., & Kaarsemaker, R. (2016) Best practice guidelines for greenhouse water management. Brochure of Grodan & Priva

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12.2. Summary of technologies subsequently presented in this chapter in individual technology descriptions (TDs)

Technology (TD)	Technology use Nutrients	Cost	Strengths	Weaknesses	Comments
Adsorption media for P	P removed, indirect recovery (has to be confirmed through research)	Not available	Removing P Less post-processing required compared to physiochemical processes No additional chlorides disposal water by adsorption	Norm of 1 mg PO_4-P/l not met in case of higher P concentrations Waste production in case saturated grains cannot be applied as fertiliser	This information is not yet available. It will be updated after showcasing the technology. This technology is still in the research phase. The potential of P saturated grains as fertiliser has to be investigated Specific legislation might be required
Electrochemical phosphorus precipitation (ePhos®)	Removing P from disposal water by precipitation, P removal, P recovery as struvite	Specific Production cost 3,4 €/kg P Energy 0,25 – 5 kWh/m^3	Modular configuration (easily expandable) On-site installation	P concentration step is required (ion exchange) Specific regulations regarding trading of struvite	This technology is still in the research phase.
Lemna minor (Duckweed)	Removal of N, P and other nutrients. Duckweed grows on the water surface and uses nutrients in that water to grow. Consequently, it consumes the amounts of nitrogen and phosphorous present	Not available	Algae prevention (through nutrient and light competition)	Specific water quality requirements The risk for clogging of filters Harvesting required in case of excessive growth	At this moment, there are no Lemna Duckweed cultures for sale however, they are available naturally

Technology (TD)	Technology use Nutrients	Cost	Strengths	Weaknesses	Comments
Moving Bed Biofilm Reactor (MBBR)	Removal of N and organic matter	5 to 10 k€ (13m³/day)	Moving Bed Biofilm Reactor (MBBR) combines the benefits of both an activated sludge process and a fixed film process. It is based on the biofilm principle with an active biofilm growing on a small specially designed plastic carriers-the threshold value of 50 mg O_3/l is met -compact installation -simple operation	MBBR reactor of 3 m³ costs 4000 € for drainage water from 2-3 ha and has a maximum flow rate of 13 m³ a day Additional costs to consider are a dosing unit (C/N/P), influent pump, and pH regulator and isolation material for the system, adding up to 5000 € Earthworks and supply of drainage water to the MBBR cost about 2000 € Sensitive to PPP residues Requires dissolved oxygen in the water	Commercial
Constructed wetlands, for example, CleanLeach	Wetland created for the purpose of treating anthropogenic discharge such as municipal or industrial wastewater, or stormwater runoff Removal of N, P, heavy metals,	Large flow wetland costs 25 €/m², Small, aerated wetlands up to 1000 €/m² Investment cost: 25 -1000 €/m² Operational cost: 150 €/yr	Commercial- efficient nutrient removal from the first year on Spore retention of Fusarium, Phytophthora and Pythium.	Proper design and careful construction required Suboptimal efficiency during winter (temperature < 15°C) Decreased efficiency after 6 years and demand for additional carbon source Large footprint (m²)	Specific conditions required: - Oxygen: min. 4mg/L - Acidity: 5,5 < pH < 9

12.3. Adsorption media for P

(Authors: Ilse Delcour[19], Joachim Audenaert[19], Elise Vandewoestijne[17])

12.3.1. Used for

Minimising the impact to the environment by nutrient discharge.

12.3.2. Region

All EU regions.

12.3.3. Crop(s) in which it is used

This is not crop specific, since it considers overall removal of phosphorus.

12.3.4. Cropping type

All cropping types.

12.3.5. Description of the technology

12.3.5.1. Purpose/aim of the technology

Removing P from disposal water.

12.3.5.2. Working Principle of operation

The technology relies on the adsorption of phosphorus onto iron. In this case, granular iron with a sand core is used as adsorption material, known as Iron Oxide Coated Sand (IOCS), see also Figure 12-2. IOCS is derived from rapid sand filters used for the preparation of drinking water from groundwater and is considered as a waste product by drinking water industry. IOCS can be used for adsorption of a variety of pollutants from wastewater, in addition to phosphates.

The removal of phosphates can be incorporated after the denitrification step of an Anoxic Moving Bed Biofilm Reactor that removes nitrates (see section 12.6).

Figure 12-2. Phosphate filter based on granular iron with a sand core

12.3.5.3. Operational conditions

- A phosphate filter with a volume of 700 L filled with 1000 kg of iron grains can treat 1 m^3 wastewater/day (with 20 mg PO_4-P/L)
- The phosphate concentration can be reduced until the norm of 1 mg PO_4-P/L at relatively low incoming phosphate concentrations (wastewater of 20 mg PO_4-P/L). At higher phosphate concentrations (until 30 mg PO_4-P/L), it decreased to 2 mg/L
- The breakthrough time of the phosphate filter is estimated at 4-6 months. Monitoring the electrical conductivity of the water can predict the breakthrough time: when the decrease in EC is appreciably reduced, the grains should be replaced
- The wastewater pH should be around 7
- The use of intermediate rest periods (16 h/day rest after 8 h feeding) significantly improves the adsorption capacity, explained by the inter-particle diffusion of phosphate towards the core of the grain during the rest periods, resulting in free adsorption sites

12.3.5.4. Cost data

This information is not yet available.

12.3.5.5. Technological bottlenecks

This information is not yet available.

12.3.5.6. Benefit for the grower

Advantages

- Less post-processing than with a conventional physicochemical phosphate removal process, which requires the highly efficient separation of the formed phosphate sludge
- No additional disposal of chlorides, which is the case when using ferric chloride
- Can be applied to smaller companies with a limited amount of wastewater, whereas biological removal processes require bigger installations
- The P-saturated grains could be reused as P fertiliser. Additional research is being carried out in Flanders to investigate P recuperation from the grains (PCS Ornamental Plant Research)

Disadvantages

- At this moment no P recovery. Further research is necessary to study the possibility of the reuse of the phosphate saturated iron grains as a fertiliser for plants
- Specific legislation

12.3.5.7. Supporting systems needed

A pump installation is required to pump the water through the coated sand bed.

12.3.5.8. Development phase

Research: Further research is necessary to study the possibility of the reuse of the phosphate saturated iron grains as a fertiliser for plants.

12.3.5.9. Who provides the technology

Currently, it is not used commercially.

12.3.5.10. Patented or not

This system is not patented.

12.3.6. Which technologies compete with this one

This information is not yet available.

12.3.7. Is the technology transferable to other crops/climates/cropping systems?

Yes. In horticulture (greenhouses), dairy farms, slaughterhouses and open field crops using underground drainage pipes. It can also be used in combination with constructed wetlands or mechanical systems to clean domestic wastewater.

12.3.8. Description of the regulatory bottlenecks

12.3.8.1. Brief description of the European directive and implications for growers at European level

To use a by-product such as IOCS as a resource for a specific application, a raw material declaration is needed (Waste Frame Directive (2008-98-EC). IOCS is originally a by-product of the purification of drinking water. It is also recognised as a resource (raw material declaration, Waste Frame Directive (2008-98-EC)) for use in various industries such as the brick industry, cement industry, fermentation plants (removal of hydrogen sulfide), water treatment (adsorption of phosphate), and drinking water treatment (removal of arsenic).

12.3.9. Brief description of the socio-economic bottlenecks

This information is not yet available.

12.3.10. Techniques resulting from this technology

No technique resulting from this technology was identified.

12.3.11. References for more information

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12.4. Electrochemical phosphorus precipitation

(Authors: Alejandra Campos[10], Jennifer Bilbao[10])

12.4.1. Used for

Minimising the impact to the environment by nutrient discharge.

12.4.2. Region

All EU regions.

12.4.3. Crop(s) in which it is used

All crops.

12.4.4. Cropping type

All cropping types.

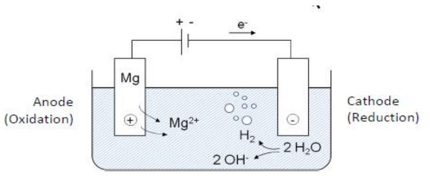
12.4.5. Description of the technology

12.4.5.1. Purpose/aim of the technology

Remove phosphorus from wastewater to minimise the impact on the environment by nutrient discharge.

12.4.5.2. Working Principle of operation

The ePhos® technology is an electrochemical phosphorus-precipitation process. It takes place in an electrolytic cell consisting of a cathode and a sacrificial anode made of magnesium (Mg). The liquid being treated flows through the cell between the two electrodes. By applying current, the electrolytic process takes place. During the cathode reduction, water splitting takes place: hydroxide (OH) ions are formed, raising the pH, while hydrogen gas (H_2) is evolved. As a result, it is not necessary for the ePhos® process to adjust the pH value by dosing chemicals. At the anode, the oxidation of metallic Mg takes place: Mg ions dissolve and react with the phosphate and ammonium or potassium contained in the water to form P-salts mainly consisting of struvite or k-struvite. Gravity then separates the P-salts. See also Figure 12-3.



$$Mg_{(s)} \rightarrow Mg^{2+} + 2e^-$$

$$2H_2O + 2e^- \rightarrow H_{2(g)} + 2OH^-$$ => No dosage of base to adjust pH

$$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O$$

Struvite

Figure 12-3. Operational principle

12.4.5.3. Operational conditions

There are no restrictions as far as the size of the wastewater treatment plant due to the modular configuration.

In the course of a feasibility study, the process was tested using a pilot plant with a flow rate of up to 1 m^3/h at a sewage treatment plant with biological phosphorus elimination in the north of Germany. It was demonstrated that the phosphorus precipitation and recovery from centrate water (water leaving a centrifuge or decanter after most of the solids have been removed) using the electrochemical ePhos® process could be carried out at the client's treatment plant. So that, in the case of a full-scale plant, major operational problems caused by the fluctuating orthophosphate concentrations would be solved.

All the trials were carried out successfully. The average phosphorus elimination rate from the centrate water of the digested sludge dewatering and the phosphorus conversion to struvite was more than 80%. The phosphorus concentration in the centrate water was reduced on average from 180 mg/L to 20,8 mg/L. The phosphorus load, that no longer had to be treated when the filtrate water was recirculated, decreased by 37%.

The design of the process for the client's plant shows that the electrochemical phosphate precipitation would require approx. 10 tons Mg in the form of sacrificial electrodes per year. From this, approx. 73 tons of struvite per year could be obtained, which can then be reused directly as a fertiliser. The total quantity of chemicals that would have to be used at the treatment plant would decrease by 40 tons or 20%/year.

Regarding its application for nutrients recovery from drainage water in fertigation, the technology has to be adapted for these conditions. Adaptation of the ePhos® technology for possible use with drainage water will be carried out within the FERTINNOWA project.

12.4.5.4. Cost data

The cost overview of ePhos® was calculated for a Wastewater Treatment Plant of 500000 Population Equivalents (Table 12-2). The capital expenditure costs amount 0,23 €/kg struvite.

Table 12-2. Cost overview

Cost overview	
Invest (€/year)	179000
Operation (€/year)	455300
Total (€/year)	634300
Specific cost (€/kg P)	3,4

Yearly maintenance or input needed are:

- Costs of Mg electrodes: about 3000 €/ton Mg. Approximately 0,25 kg/Mg/m² electrode area and hour is needed corresponding to a Mg:P stoichiometry of approximately 1,1:1, There are no restrictions of Mg recycling, except when it is in a powder form

- Costs of energy and electricity: 0,25-5 kWh/m³ depending on P-concentration and kinetic

12.4.5.5. Technological bottlenecks

For irrigation water, the system is not cost-effective because of the very low P-concentration (< 80 mg/L). P must be first concentrated using, for example, ion exchange technologies.

Also, the regulation for the use of recovered P-salts is not uniform in all European countries. This makes it difficult to sell the struvite produced.

12.4.5.6. Benefit for the grower

Advantages

- Excess nutrients can be removed from discharge water
- Removed nutrients can be used as a fertiliser
- Suitable for any company size
- Nutrients are recovered and used instead of being disposed
- No addition of chemicals necessary
- Cells or cell pathways can be switched on or off by a process control system depending on the demand

Disadvantages

- Small adaptations of the ePhos® technology are required for this application
- Precipitates have to be removed from the bottom of the clarifier by a spiral conveyor
- Energy demand, except for the pumping

12.4.5.7. Supporting systems needed

A pre-treatment with an ion exchange might be appropriate to concentrate the P.

12.4.5.8. Development phase

Field tests.

12.4.5.9. Who provides the technology

Fraunhofer IGB, Germany.

12.4.5.10. Patented or not

Yes, the process and reactor are patented. Patent numbers: DE102010050691B3 and DE102010050692B3.

12.4.6. Which technologies compete with this one

Technologies for nitrogen and phosphorus elimination and phosphorus recovery by chemical precipitation.

12.4.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, the technology is not crop or climate dependent.

12.4.8. Description of the regulatory bottlenecks

12.4.8.1. Brief description of the European directive and implications for growers at European level

There are no bottlenecks regarding regulations. On the contrary, there are initiatives in Europe for new regulations to promote the recovery and efficient use of nutrients (for example the new EU fertiliser regulation will include recovered fertilisers).

12.4.9. Brief description of the socio-economic bottlenecks

This information is not yet available.

12.4.10. Techniques resulting from this technology

ePhos®, Fraunhofer IGB.

12.4.11. References for more information

[1] Bilbao, J. (2014). Phosphorus Recovery from Wastewater Filtrates through a Novel Electrochemical Struvite Precipitation Process. Berichte aus Forschung und Entwicklung Nr. 064, Fraunhofer Verlag

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12.5. Lemna Minor (Duckweed)

(Authors: Elise Vandewoestijne[17], Ilse Delcour[19], Vanessa Bolivar Paypay[10])

12.5.1. Used for

Minimising the impact to the environment by nutrient discharge.

12.5.2. Region

All EU regions.

12.5.3. Crop(s) in which it is used

All crops.

12.5.4. Cropping type

All cropping types.

12.5.5. Description of the technology

12.5.5.1. Purpose/aim of the technology

Reducing N, P and other nutrients in the wastewater and limiting algae growth.

12.5.5.2. Working Principle of operation

Duckweed grows on the water surface and uses the nutrients in the water for growth. Consequently, it consumes appreciable amounts of nitrogen and phosphorous present in the water. After a while, the duckweed covers the water surface entirely, reducing the amount of light entering the water and consequently reducing algal growth. The reduced amount of nutrients left in the water also restricts algal growth (Figure 12-4).

Figure 12-4. Growing duckweed on nutrient-rich wastewater

12.5.5.3. Operational conditions

Water conditions

The composition of the water in which duckweed is growing has an impact on the growth and the quality of the duckweed itself. Duckweed does not grow in any (waste) water. Table 12-3 summarises the range of water parameters that allows Duckweed to grow.

Table 12-3. Summary of values where duckweed growth is limited

Parameters	Lower limit	Upper limit
pH	3,5	10,4
EC	10	10900 µS/cm
Nitrogen	0,003	345 mg/L
Phosphorus	0	135 mg/L
Potassium	0,5	100 mg/L
Magnesium	0,1	230 mg/L
Bicarbonate	8	500 mg/L
Sulphur	0,03	350 mg/L
COD	0	600 mg/L
Calcium	0,1	365 mg/L
Sodium	1,3	1000 mg/L
Chloride	0,1	4650 mg/L

The lower and upper limits which are shown in Table 12-3, are based on values from literature and should be interpreted with some caution. In the first place, interactions between various parameters are not taken into account. The pH will affect the solubility of various minerals and, consequently, also its availability for duckweed. Also, the pH also affects in which form nitrogen is present. Nitrate, ammonium, and ammonia are the forms of nitrogen which duckweed consumes. At a high pH, the ammonia-ammonium equilibrium favours the production of ammonia. As the pH drops, the equilibrium shifts to the ionised form of ammonium. Ammonia at low concentrations of 8 mg /L can cause the death of duckweed. High ammonium concentrations at lower pH, may result in growth.

Temperature

A disadvantage is that duckweed is sensitive to temperatures close to freezing; then the duckweed falls to the bottom and enters a hibernation stage. Consequently, the method is less suitable for outdoor conditions at temperatures close to and less than 0°C, because the Duckweed is unable to reduce the nutrient level in the water.

Species

Duckweed consist of a mixture of the water plant species: *Lemna minor* and *Lemna major*, obtained from natural populations. These species have good growth performance and good potential for growing in wastewaters. The balance between the two species may shift when conditions are more favourable for one of the two species. Having two species with different requirements broadens the conditions in which adequate growth of duckweed can be achieved.

Residual water from aquaculture and drain water from greenhouses is suitable for the cultivation of duckweed. Duckweed grows best at a temperature of 26-28°C, 10-50 mg N/L and a light intensity of up to 300 µmol/m²/s.

12.5.5.4. Cost data

At this moment, there are no *Lemna* cultures for sale. A wild culture (from nature) usually consists of a mixture of species, the most potent type of them will grow rapidly. Naturally-selected clones can be obtained at places in nature where polluted surface water is gathered. When there is too much duckweed, the *Lemna* can die, that way nutrients end up back in the water. Duckweed must be harvested in order to remove nutrients from the water.

On the one hand, this can be done by skimming the surface of the water. Another method works with a submersible pump which sucks water on the surface. This water (and duckweed) is pumped through a container from which the water can run at the bottom back into the lake. A mesh before the exit keeps the duckweed inside the container. The pump can be activated when the duckweed layer reaches a certain thickness. In that case, the costs will correspond to a submersible pump, a container, and some tubes.

12.5.5.5. Technological bottlenecks

Duckweed production in the open air is sensitive to damage by wind, but also by insects and aphids. The waterlily aphid *Rhopalosiphum nymphaeae* can harm duckweed. The fungus *Milothecium*, which is a parasite of the water fern *Azolla,* can also be harmful to duckweed. A closed cultivation system can avoid these problems, but is associated with higher costs.

12.5.5.6. Benefit for the grower

Advantages

- Duckweed reduces N, P, and metals in wastewater
- Duckweed grown on sewage or animal wastes normally does not contain toxic pollutants and can be fed to fish or livestock, or spread on farmland as a fertiliser
- Cheap
- Ecological
- Not labour intensive

Disadvantages

- Growth depends on the nutrient content, pH, and temperature of the water, light and biotic factors
- The duckweed biomass that results from water treatment operations must be removed from the water by, e.g. skimming
- If the duckweed is to be fed to animals, a retention period in clean water will be necessary to ensure that the biomass is free of water-borne pathogens

- Duckweed is not commercially available

12.5.5.7. Supporting systems needed

Pumps, container, and tubes to remove the duckweed from the water surface.

12.5.5.8. Development phase

This information is not yet available.

12.5.5.9. Who provides the technology

Not applicable.

12.5.5.10. Patented or not

This technique is not patented.

12.5.6. Which technologies compete with this one

- Constructed wetlands
- Moving Bed Biofilm Reactor (MBBR)

12.5.7. Is the technology transferable to other crops/climates/cropping systems?

This technique is not crop dependent. The climate may be of importance since duckweed growth is limited and hibernation might occur at lower temperatures.

12.5.8. Description of the regulatory bottlenecks

There are no regulatory bottlenecks.

12.5.9. Brief description of the socio-economic bottlenecks

None.

12.5.10. Techniques resulting from this technology

Not applicable.

12.5.11. References for more information

[1] Maréchal, T. (2016). Haalbaarheid van eendenkroosteelt: selecteren van klonen geschikt voor mestverwerking, waterzuivering en nutriëntrecuperatie. Gent, België.
[2] http://www.biobasedeconomy.nl/2014/06/16/eindeloze-mogelijkheden-met-eendenkroos/
[3] http://www.mobot.org/jwcross/duckweed/practical_duckweed.htm#Bioremediatin

12.6. Moving Bed Biofilm Reactor

(Authors: Ilse Delcour[19], Vanessa Bolivar Paypay[10])

12.6.1. Used for

Minimising the impact to the environment by nutrient discharge.

12.6.2. Region

All EU regions.

12.6.3. Crop(s) in which it is used

All crop types.

12.6.4. Cropping type

- Soilless
- Protected

12.6.5. Description of the technology

12.6.5.1. Purpose/aim of the technology

Removal of organic matter, nitrification and denitrification. It is mostly used to remove nitrates from domestic or industrial wastewater but is also used to treat water from fish farming and to a lesser extent other farming.

12.6.5.2. Working Principle of operation

Moving Bed Biofilm Reactor (MBBR) combines the benefits of both an activated sludge process and a fixed film process. It is based on the biofilm principle with an active biofilm growing on small specially designed plastic carriers (Figure 12-5). The carriers with microorganisms on it kept in motion in the water either by a blast air injection in aerobic systems or by stirrers in anoxic or anaerobic systems (Figure 12-6). Thanks to this motion, the impurities in the water are transported to the biofilm and thus reduced. The result is a high treatment capacity within a given reactor volume, resulting in a smaller footprint compared to a conventional activated sludge process. The typical operation can be seen in Figure 12-7.

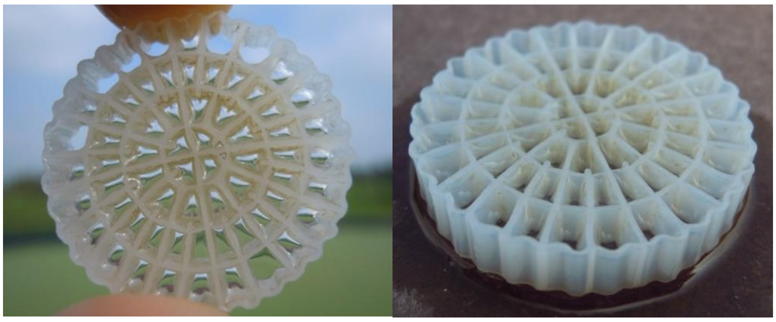

Figure 12-5. Examples of a carrier (800 m²/m³) with beginning biofilm growth (PCS, Belgium)

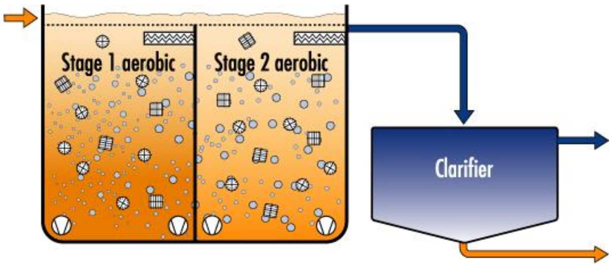

Figure 12-6. Schematic overview of an MBBR system, in this case, a 2-step biological treatment (www.lenntech.nl)

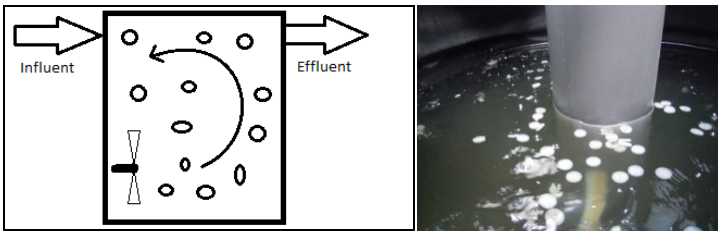

Figure 12-7. The biofilm medium is moved through the reactor and a filtered effluent is produced (PCS, Belgium: only a few carriers were already present)

Figure 12-8. MBBR at PCS (Belgium)

12.6.5.3. Operational conditions

The use of biofilm requires dissolved oxygen for the microbes to survive. It can be scaled well but is limited by the use of plant protection products, which can be harmful to the microbes. However, the capacity can be easily upgraded by simply increasing the fill fraction of biofilm carriers.

12.6.5.4. Cost data

Costs of an MBBR depend on the size and capacity. Therefore, the numbers below refer to a specific situation.

Installation costs:

An MBBR reactor of 3 m³ costs 4000 € and should be filled with 2 m³ of carriers (generally it is filled for 30-40%). In case of AnoxKalnes® K5, this costs 300 €. This MBBR is sufficient to treat the drainage water of 2-3 ha and has a maximum flow rate of 13 m³/day.

Other costs to consider are a dosing unit (C/N/P), influent pump, pH regulator and isolation material for the system, adding up to 5000 €. Earthworks and supply of drainage water to the MBBR cost about 2000 €.

If the MBBR is used on agricultural fields to reduce the nutrient load of the draining water, an off-grid energy supply (solar panels) and a switchboard should be present (10000 €).

The example below provides an estimation of the operational costs for an MBBR in case all NO_3 has to be removed for 313 m³ of drainage water with an average concentration of 193 mg NO_3/L/year or 60,5 kg NO_3/year:

- Fixed costs: depreciation (over 10 years): 2606 €/year
- Variable costs: carbon source for maintaining the biofilm (e.g., CARBO ST): 3,85 € /kg NO_3.
    - Energy costs: solid carrier: 46 €/year
    - Suspended carrier: 220 € /year
    - Carrier material on fixed bed: 0,025 kWh/m³
    - Carrier material in suspension: 0,12 kWh/m³
    - Estimate of energy rates: 5,85 € /kWh
- The total maximum variable cost amounts 452 € /year and a preliminary total cost of on average 3000 € /year

Important note: if legislation has to be met and denitrification is only required to a level of 50 mg/L (as is the case in Belgium). In this case, purification costs might be reduced by 2%.

12.6.5.5. Technological bottlenecks

The technology can only treat wastewater for nitrates and some other biological factors. Also, plant protection products can negatively affect performance.

12.6.5.6. Benefit for the grower

Advantages

- The reduction of nitrates and other nitrogen sources from drain water can allow the grower to comply with regulations
- Compact installation
- Increased durability towards toxicity
- Variable loading
- Simple operation
- System insensitive of bulking sludge

Disadvantages

Additional electricity for pumps and air pumps is required.

Some plant protection products may have adverse effects on the performance of an MBBR.

12.6.5.7. Supporting systems needed

Sieves over the outlet to separate the carriers in the treatment tank.

12.6.5.8. Development phase

- Research: There are several research projects ongoing on refining and improving the technology which might have benefits to the technology for agricultural use
- Commercialised: Wastewater treatment (several)

12.6.5.9. Who provides the technology

Several suppliers offer this technology: Lenntech (Netherlands), Veolia (Anoxkaldnes – Sweden).

12.6.5.10. Patented or not

There are several patents based on the technology, but the basic principle is not patented.

12.6.6. Which technologies compete with this one

- There are several other bioreactor technologies available, specifically Packed Bed Biofilm Reactors, which work on the same principle but do not have moving media
- Non-bio technologies that compete with MBBR are: modified ion exchange and reverse osmosis

12.6.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, the technology only requires collected drain water.

12.6.8. Description of the regulatory bottlenecks

There are no relevant regulatory bottlenecks.

12.6.9. Brief description of the socio-economic bottlenecks

Growers might not want what is mostly a growing pot of microbes close to their production out of fear that it might be a breeding ground for unwanted pests.

12.6.10. Techniques resulting from this technology

The AnoxKaldnes™ MBBR technology utilises the advantages of both activated sludge and other biofilm systems (e.g. biofilters, biorotors, etc.) without being restrained by their disadvantages. The carriers are designed to provide a large protected surface area for the biofilm to grow and optimal conditions for the bacteria culture when the carriers are suspended in water.

12.6.11. References for more information

[1] Kazmi, A., & Roorkee, T. (2013). Moving Bed Biofilm Reactor for Sewage Treatment.
[2] Lenntech (2017). http://www.lenntech.nl/processes/mbbr.htm
[3] Odegaard (1989). http://technomaps.veoliawatertechnologies.com/mbbr/en/

12.7. Constructed wetlands

(Authors: Ilse Delcour[19], Evangelina Medrano[11])

12.7.1. Used for

- Preparation of irrigation water
- Minimising the impact to the environment by nutrient discharge

12.7.2. Region

All EU regions.

12.7.3. Crop(s) in which it is used

All crops.

12.7.4. Cropping type

- Soilless
- Protected
- Open air

12.7.5. Description of the technology

12.7.5.1. Purpose/aim of the technology

Removing of organic matter and nutrients from disposal water.

12.7.5.2. Working Principle of operation

A constructed wetland (Figure 12-9) is an artificial wetland created to treat anthropogenic discharge such as municipal or industrial wastewater, or stormwater runoff. It is also often used to treat drain water from greenhouses before disposal.

Constructed wetlands are engineered ecosystems that use the natural functions of vegetation, soil, and organisms to treat different water stream (Figure 12-9). Depending on the type of wastewater that has to be treated the system has to be adjusted accordingly, which means that pre- or post-treatment may be necessary.

Constructed wetlands can be designed to emulate the features of natural wetlands, such as acting as a biofilter or removing sediments and pollutants such as heavy metals from the water. Some constructed wetlands may also serve as a habitat for native and migratory wildlife, although that is usually not their main purpose.

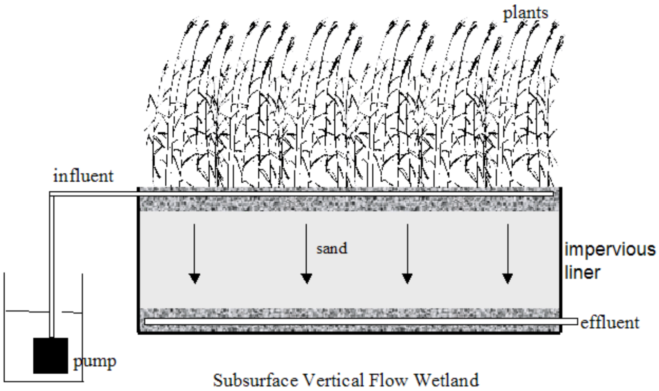

Figure 12-9. Example of a subsurface vertical flow wetland

Figure 12-10. Photo of the constructed wetlands at PCS (Belgium)

Percolation phase (helophyte sand filter)

Construction (PCS: 30 m²)

- Foil: should be smooth, impermeable, strong and thick
- Coarse gravel: (size 8/16) serves as a substrate for the influent and effluent drains
- Drainage system: drainage pipes with polypropylene fibre coating. The ends are connected to a rinsing line above the ground level to make cleaning of the drains possible. The wastewater is collected in an inspection pit which remains continuously filled with water. A filter cloth is applied on top of the gravel layer to prevent this layer from clogging with sand
- Sand: the grain size is best between 0,06 and 0,63 mm. Any clay fraction in the sand should not exceed 10% due to clogging
- Woodchips
- The main flow pipe (PVC, HDPE diameter 75-110 mm) is connected to the distributing pipes (PVC, HDPE diameter 32-40 mm). In these distributing pipes, which are closed at the end, from 6-10 mm at least one outlet opening is provided per meter. Mutual separation tubes 1 m. These tubes are in a coarse gravel layer
- The used plants are usually common reed (*Phragmites australis*)
- The percolation field is 1,25 m deep

Mode of action

- Water is brought on top of a wetland with a branched piping system so it can percolate through the reeds. Water (without floating substances) is added twice a day with a pump to switch between oxygen-rich and poor periods, which are necessary to remove nitrogen
- Oxidative reactions: ammonification of organic N by *Nitrosomonas* and nitrification of ammonium by *Nitrobacter*
- Anaerobic reaction: denitrification by *Pseudomonas*

Root zone phase

Construction (PCS: 55 m²):

- Minimum length of 5-6 m
- Depth at the inlet 60 cm and outlet 80 cm.
- Ideal slope: 1%
- Filled with coarse sand (0,63-2 mm)
- The diffuser tube is placed horizontally in a gravel layer. Other specifications for foil filter cloth and plants are identical to the percolation field (see above)

Mode of action:

- A continuous water supply takes place; therefore, the oxygen for nitrification is the limiting factor. The main reaction is denitrification, e.g., by *Pseudomonas* bacteria

2-phased wetland

- Combination of the two phases described above. Can be used for N and P rich sewage water, is advised for N removal

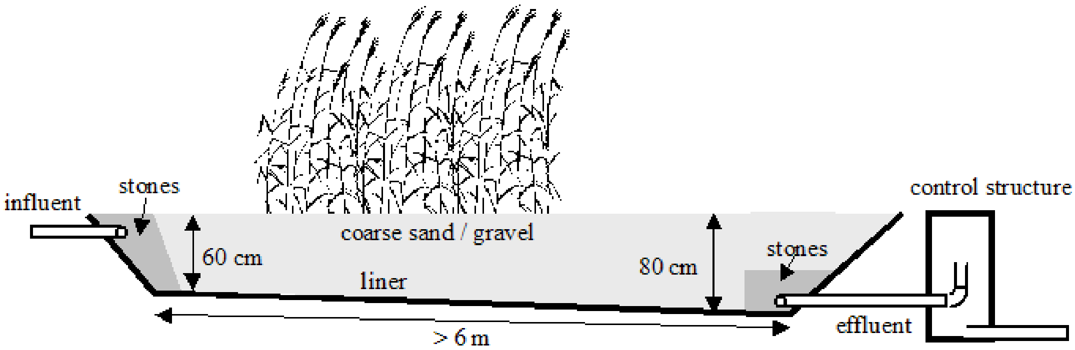

Figure 12-11. Example of the measurements of a constructed horizontal flow wetland (Source: Nico Lambert)

Figure 12-12. Horizontal flow wetland at PCS (Belgium)

CleanLeach System

A special form of a constructed wetland is the Cleanleach System.

The technology package of CleanLeach System is divided into two parts:

The first part of the system is the slow sand filter. Its main function is to filter the drain water, which can contain solid particles. The collection, filtering and recovery of drain water are done with a system consisting of a horizontal bed, which acts as a slow sand filter and is placed under the growing areas.

Constructed wetlands try to emulate natural wetlands, where pollutants such as nitrates are removed through the denitrification process. Constructed wetlands is a simple and sustainable technique with a low energy demand that is being used to purify different effluents. In the second part of the system, the treatment of drain water removed from the recirculating system is performed through a horizontal subsurface flow wetland. The wetland treatment system consists of shallow ponds or channels with wetland vegetation. In these systems, the decontamination processes take place through interactions between water, soil, plants and microorganisms. In trials of the CLEANLEACH project, a reduction of the nitrate content to below 50 mg/L and an 80% reduction of the soluble forms of phosphorus have been demonstrated.

Iris pseudacorus is commonly used in the Wetland treatment system. *Iris pseudacorus* belongs to the family of Iridaceae. It is native to Europe, West Asia and North-west Africa; nevertheless, in many areas, it is considered an invasive plant. It prefers flooded soils with exposure to full shade conditions. It tolerates aquatic conditions, low pH, and anoxic soils (not too compact). The plant spreads quickly, by both rhizome and water-dispersed seed.

This plant has been used as a form of water treatment due to the ability to take up heavy metals through its roots.

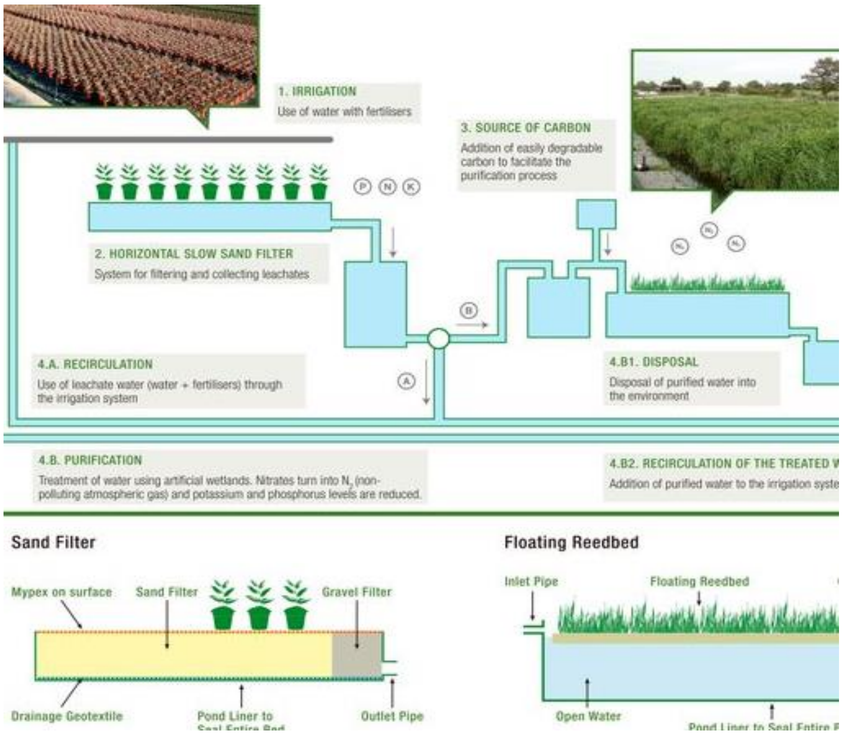

Figure 12-13. Cleanleach system

12.7.5.3. Operational conditions

If the wetland is used for P extraction before discharge of water, calcium-rich sand should be used for the sand filter. For water reuse, calcium-poor sand should be added.

Percolation phase

At PCS there was an average of 40 mg NO_3 /L in the tested drain water

Can process 60 L sewage water/m² wetland/day or about 100 L of drainwater/m² wetland/day.

Nitrification requirements:

- The temperature preferably above 15°C (>12°C is also still efficient)
- Level of oxygen in the water > 4 mg/L
- Acidity: 5,5 < pH < 9

In Belgium, the wetland has a guaranteed effect from June until August, at other times of the year, the effectiveness depends on the weather.

12.7.5.4. Cost data

Prices depend strongly on the region and surface area. For example: in Poland, near Warsaw, the Institute of Life Science has built such a constructed wetland for about 4000 €.

In Belgium, a large flow wetland costs about 25 €/m², while small, aerated wetlands can cost up to 1000 €/m². In case of PCS Ornamental Plant Research, the percolation field costs about 350 €/m² and the root zone field costs approximately 200 €/m².

A quotation from a Belgian company, that installs constructed wetlands for growers, was a total cost of 1950 € (excluding VAT) for a percolation flow field of 20 m². This included the foil (EPDM 1,15 mm), drainage system + connections, filter cloth, reed plants, distribution system and fittings, Inspection pit and adjustment pit.

Additional costs consist of the substrate (sand and gravel) and (septic and pump) wells, a submersible pump and the digging and planting the reeds.

Yearly maintenance or inputs needed:

- Yearly maintenance is 150 €
- After 6 years the N-removal diminishes because of a lack of carbon input for the anaerobic microorganisms in the wetland. The best solution is to add molasses at a dose of 0,32 L/day (for the PCS wetland dimensions)
- Cleaning of silted drains
- Removal of weeds
- Control and maintenance of the pumps
- Half-yearly check-up of pipes and nozzles

12.7.5.5. Technological bottlenecks

No technological bottlenecks have been identified until now.

12.7.5.6. Benefit for the grower

Advantages

- Potential lifespan: 15 years
- The pH of the drain water after the wetlands is constantly between 7 and 7,5
- Very efficient for nutrient removal in the first years (Table 12-4)

Table 12-4. Nutrients content during phases of water treatment

Nutrient	Water storage		Percolation wetland		Root zone reed field	
(mg/L)	2002	2003	2002	2003	2002	2003
Nitrate	57,1	16,6	26,6	3,3	1,5	0
Phosphorous	1,2	0,4	0	0	0	0
Potassium	7,8	12,1	5,9	3,4	6,3	0,1

- Biological purification by the reeds
    - Possible to purify water already in the year of installation
    - Most N and P are removed from drain water
    - Stops *Pythiaceae*, it does not have to be mowed
- Percolation phase
    - Has a filtering effect on the fungi of the *Fusarium* species
    - Can retain spores of *Phytophthora* and *Pythium*
- Root zone phase
    - Most efficient wetland for N removal
- 2-phased wetland

- The best option for removing spores of *Fusarium*, *Pythium* and *Phytophthora* (at low infection pressure)

Disadvantages

- A proper design and careful construction are essential
- The treated water cannot be reused with salt-sensitive crops (Azalea)
- Enrichment of treated water with calcium and salts, which has an effect on the water quality for reuse (hardness and EC)
- The large surface area is required
- Cannot replace disinfection in a recirculation system: capacity is too low and there is insufficient fungi removal
- Suboptimal efficiency during colder periods (no N removal)
- After 5 years, the P removing the effect of the wetland disappeared
- A source of carbon is essential to support the bacteria
- Silting of drains is possible
- During the percolation phase, the nitrate level can increase

12.7.5.7. Supporting systems needed

The activity of fungi and bacteria responsible for P and N reduction in the treated water is conditioned by the presence of carbon as many of the microorganisms involved are heterotrophic e.g. for denitrification reactions and require a carbon source. Therefore, providing a source of carbon to the wetlands is essential to have adequate microbiological activity. It is important that the wetland is close to a cheap source of carbon, e.g. by-products of the agroindustry such as molasses.

12.7.5.8. Development phase

Commercialised.

12.7.5.9. Who provides the technology

Belgium: Rietland, Rietec. A special and also commercialised form is the CleanLeach solution which is a system that recovers and treats drain water by using a combination of slow sand filtering and a constructed wetland. The CleanLeach solution is provided by IRTA (Institute of Research & Technology for Food & Agriculture, Catalonia, Spain), Bures Innova, Salix (UK), and Naturalea.

12.7.5.10. Patented or not

Not patented.

12.7.6. Which technologies are in competition with this one

- UV disinfection
- Thermodisinfection
- Chlorination
- Biofiltration

12.7.7. Is the technology transferable to other crops/climates/cropping systems?

Yes, as long as the plants in the wetland thrive in that climate.

12.7.8. Description of the regulatory bottlenecks

12.7.8.1. Implementation at the regional level

In Flanders (Belgium), the disposal of water has to comply with legal requirements (VLAREM II, The Order of the Flemish Government of 1 June 1995 concerning General and Sectoral provisions relating to Environmental Safety). This order defines all standards that the water must meet before it can be discharged. There are regional differences in the norms for surface water and groundwater. In every region, slightly different limits for the different nutrients in drain water are imposed.

12.7.9. Brief description of the socio-economic bottlenecks

Constructed wetlands are less efficient than other biological techniques used for disinfection of drain water, such as biofiltration. Constructed wetlands are used to remove excess nutrients such as N and P from drain water before releasing water into the environment. In soilless cultivation, constructed wetlands are not used with recirculating systems, but with “open”, free-draining systems. In this case, this technology can be very effective. Correct dimensioning of the basin is required to ensure that the system functions effectively. The surface area requirement of a constructed wetland may inhibit the adoption of this technique because growers may have limited space close to their greenhouse.

12.7.10. Techniques resulting from this technology

No resulting techniques were found.

12.7.11. References for more information

[1] PCS research: http://www.pcsierteelt.be/hosting/pcs/pcs_site.nsf/0/24813838411a0776c125726700328828/$FILE/De%20toekomst%20van%20rietvelden%20in%20de%20tuinbouw.pdf
[2] https://www.epa.gov/sites/production/files/2015-10/documents/constructed-wetlands-handbook.pdf
[3] https://engineering.purdue.edu/~frankenb/NU-prowd/cwetfact.htm
[4] Antón, A., Marfá, O., de Lamo, D., Sorolla, A., Figuerola, M., Viñas, M., Burés, S., López, A., Penafreta, F., Holland, D., & Cáceres, R. (2015). Providing new life to waste: cleaning of drain water and recycling industrial materials in wetland construction. Bordeaux Mainstreaming Life Cycle Management for sustainable value creation. LCM2015
[5] Guivernau, M., Viñas, M., Prenafeta, F. X., Marfá, O., & Cáceres, R. (2015). Microbial Community Assessment in a Pilot scale Construted Wetlan for Trating Horticultural Drain water. VI International Conference on Environmental, Industrial and Applied Microbiology. BioMicroWold 2015

List of abbreviations

Abbreviation	Name
$	Dolar
€	Euro
°C	Celsius
µg	Microgram
µm	Micrometre
µmol	Micromole
µS	Microsiemen
Al	Aluminium
AOP	Advanced Oxidation Process
ASR	Aquifer Storage And Recovery
ATEX	Atmosphères Explosibles
B	Boron
BPR	Biocidal Products Regulation
Ca	Calcium
$CaCO_3$	Calcium Carbonate
CAP	Common Agricultural Policy
CapDI	Capacitive Deionisation
CAPEX	Capital Expenditures
Cd	Cadmium
Cd	Concentration of the Diluted Nutrient Solution
CDI	Capacitive Deionisation
Cl	Chloride
cm	Centimetre
cm^2	Square Centimeters
Co	Cobalt
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
Cu	Copper
CV	Coefficient of Variation
CWSI	Crop Water Stress Index

Abbreviation	Name
DFT	Deep Flow Technique
DI	Deficit Irrigation
dm	Decimetre
dm^3	Cubic Decimetre
DMP	Dry Matter Production
DNA	Deoxyribonucleic Acid
DRIS	Diagnosis and Recommendation Integrated System
dS	Decisiemens
DSS	Decision Support System
DTPA	Diethylenetriaminepentaacetic Acid
EC	Electric Conductivity
EC	European Commision
ECA	Electrochemically Activated
EC_p	Electrical Conductivity in soil pore water
EC_{se}	Electrical Conductivity of the Saturation Extract
EC_{sw}	Electrical Conductivity of the Soil Water
ED	Electrodialysis
EDDHA	Ethylenediamine-N,N'-Bis(2-Hydroxyphenylacetic Acid
ED-R	Electrodialysis Reversal
EDTA	Ethylenediaminetetraacetic Acid
EMI	Electromagnetic Induction
EPDM	Ethylene Propylene Diene Monomer (M-Class) Rubber
EpF	Electrophysical Precipitation
ET	Evapotranspiration
ET_c	Crop Evapotranspiration
ET_o	Reference Evapotranspiration
EU	European Union
excl.	Excluding
FAO	Food and Agriculture Organisation
FDR	Frequency Domain Reflectometry
Fe	Iron

Abbreviation	Name
$Fe(OH)^+$	Ferrous Hydroxide
$Fe(OH)_3$	Ferric Hydroxide
Fe^{2+}	Ferrous Iron
Fe^{3+}	Ferric Iron
FO	Forward Osmosis
g	Gram
GIS	Geographic Information System
GMS	Granular Matrix Sensor
GPR	Ground Penetrating Radar
GPS	Global Positioning System
h	Hour
H	Hydrogen
H_2O	Water
H_2O_2	Hydrogen Peroxide
H_2SO_4	Sulfuric Acid
ha	Hectare
HDDW	Horizontal Directional Drilled Well
HEDTA	Hydroxyethylethylenediaminetriacetic Acid
HOCl	Hydrochlorite Acid
I	Iodine
INRA	National Institute for Agronomic Research
IOCS	Iron Oxide Coated Sand
IRT	Infrared Thermometer
ISE	Ion Selective Electrodes
ISO	International Organization for Standardization
K	Potassium
K_2O	Potassium Oxide
K_c	Crop Coefficient
K_{cb}	Basal Crop Coefficient
K_e	Evaporation Coefficient
kg	Kilogram

Abbreviation	Name
KNS	Kulturbegleitende Nmin Sollwerte
kW	Kilowatt
kWh	Kilowatt Hour
L	Litre
LDAR	French Departmental Analysis and Research Laboratory
lm	Linear Meter
LP	Low Pressure
Ltd	Limited Company
m	Metre
m^2	Square Metre
m^3	Cubic Metre
MD	Membrane Distillation
meq	Milliequivalent
mg	Milgram
Mg	Magnesium
MHz	Megahertz
min	Minute
MIX	Modified Ion Exchange
mJ	Millijoule
mL	Millilitre
mm	Millimetre
mmol	Millimole
Mn	Manganese
Mo	Molybdenum
MP	Mid Pressure
Mpa	Megapascal
mS	Millisiemens
mV	Millivolt
N	Nitrogen
n.a.	Not Applicable
Na	Sodium

Abbreviation	Name
NaClO	Sodium Hypochlorite
NBI	Nitrogen Balance Index
NDVI	Normalised Difference Vegetation Index
NF	Nanofiltration
NFT	Nutrient Film Technique
ng	Nanogram
NGS	New Growing System
NH_4	Ammonium
Ni	Nickel
NIR	Near-Infrared Light
NLEAP	Nitrate Loss and Environmental Assessment Package
nm	Nanometre
Nmin	Mineral Nitrogen
NO_2	Nitrite
NO_3	Nitrate
Not avail.	Not Available
N_{rec}	Recommended Nitrogen
NVZs	Nitrate Vulnerable Zones
NWP	Numerical Weather Prediction
O_3	Ozone
OCl	Hypochlorite Ions
OH	Hydroxyl Radical
OPEX	Operational Expenditures
P	Phosphorous
P_2O_5	Phosphorus Pentoxide
Pb	Lead
PCO	Photocatalytic Oxidation
PE	Polyethylene
pH	Potential of Hydrogen (Acidity)
PLANET	Planning Land Applications of Nutrients for Efficiency and the Environment
PO_4	Phosphate

Abbreviation	Name
ppm	Part Per Million
PPP	Plant Protection Products
PRD	Partial Root Drying
psi	Pound-Force per Square Inch
PVC	Polyvinyl Chloride
RAW	Readily Available Soil Water
RDI	Regulated Deficit Irrigation
RNA	Ribonucleic Acid
RO	Reversed Osmosis
RTK	Real-Time Kinematic
s	Second
S	Sulphur
S	Siemens
SAF	Automatic Self-Cleaning Filter
SAV	Submerged Aquatic Vegetation
SAVI	Soil Adjusted Vegetation Index
SCRF	Slow and Controlled Release Fertilisers
SDI	Subsurface Drip Irrigation
SDV	Stem or Trunk Diameter Variations
Se	Selenium
SiAR	Agroclimatic Information System For Irrigation
SNS	Soil Nitrogen Supply
SO_4	Sulfate
SRU	Sodium Removal Unit
SWC	Soil Water Content
SWRO	Desalination of Seawater
TD	Technology Description
TDR	Time Domain Reflectometry
TDS	Total Dissolved Solids
TiO_2	Titanium Dioxide
ton	Tonnes

Abbreviation	Name
TRL	Technology Readiness
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
US	United States
USA	United States of America
UV	Ultra Violet
VAT	Value Added Tax
VLAREM	Flemish Regulation Regarding Environmental Permit
VPD	Vapor Pressure Deficit
w	Watts
WFD	Water Framework Directive
WHO	World Health Organisation
wt%	Mass Fraction
WUR	Wageningen University
Zn	Zinc
ε_a	Dielectric Permittivity