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Good Agricultural Practices for greenhouse vegetable production in the South East European countries

Principles for sustainable intensification of smallholder farms

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3. Irrigation management: challenges and opportunities

S. De Pascale,[a] G. Barbieri,[a] Y. Rouphael,[a] M. Gallardo,[b] F. Orsini[c] and A. Pardossi[d]

[a] *Department of Agricultural Sciences, University of Naples Federico II, Italy*
[b] *Department of Agronomy, University of Almería, Spain*
[c] *Department of Agricultural Sciences, University of Bologna, Italy*
[d] *Department of Agriculture, Food and Environment, University of Pisa, Italy*

ABSTRACT

Water, in terms of both quantity and quality, is crucial to the success of horticulture greenhouse production. This chapter covers the following aspects of irrigation of greenhouse vegetable crops:

- Water-use efficiency and water-saving strategies
- Micro-irrigation
- Irrigation scheduling
- Water quality management

Each section provides a critical overview of the principles, methods and tools used for vegetable crops in greenhouses, the main systems/components, the basic knowledge required for proper management and practical guidelines to deal with the most common issues faced by farmers.

WATER-USE EFFICIENCY AND WATER-SAVING STRATEGIES

To sustain the rapidly growing world population, agricultural production needs to increase. One means of achieving this is greenhouse cultivation, providing large quantities of high quality produce all year round and with an efficient use of resources (e.g. fertilizers and water). The last three decades have seen protected cultivation develop rapidly in many regions around the world, in particular in the South East European (SEE) countries with the production of a range of vegetable crops.[1] As water is rapidly becoming a scarce resource in several European countries, its sustainable use is an increasingly important issue among greenhouse

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[1] See Part I, Chapter 2.

Key questions

- Is water availability an issue?
- How can I understand if water is safe for irrigating crops?
- Is the installation of a micro-irrigation system expensive?
- How can I reduce water needed for cultivation?
- How can I increase the water-use efficiency?
- How should I decide when and how much to irrigate?
- Which is the appropriate technology to assist me in applying sufficient (not too much) water at the right frequency?
- Is water quality important?
- How can I check the water quality?
- What kinds of tools are needed to measure water quality for irrigation?

vegetable farmers. The traditional focus has been on maximizing total production (tonnes ha^{-1} or kg m^{-2}), but growers must now justify their water consumption. They must be prepared to use less water, improving the methods, techniques and management practices currently applied in the processes related to horticultural production. The concept of water-use efficiency (WUE), is a key term in the evaluation of sustainable use of water in greenhouse vegetable production. WUE (measured in kg m^{-3}) is defined as the ratio of marketable yield (Y_a), expressed on a fresh basis for vegetables, to the volume of water consumed by crop evapotranspiration (ET_c) (Molden, 2003).

Evapotranspiration (ET) refers to water lost by soil evaporation or crop transpiration during the growing season. Since there is no easy way of distinguishing between these two processes in soil culture, they are generally combined under the single term, ET. Evapotranspiration and irrigation volumes are generally measured in millimetres, as for rainfall: 1 mm corresponds to 1 litre m^{-2} or 10 m^3 ha^{-1}.

In comparison to the open-field crops, protected cultivation of vegetables is normally characterized by greater WUE (up to five times) for three main reasons:

- Reduced potential evaporation due to the lower solar radiation, less wind and greater relative humidity inside the greenhouse.
- Higher crop productivity attributed to better control of plant diseases and climatic parameters, in particular global radiation and air temperature.
- Localized irrigation and application of micro-irrigation and closed-loop soilless culture.

High water-use efficiency in greenhouse vegetable production can be achieved by modifying both terms: yield and water consumed. An optimal control of the cultural practices and environmental parameters will lead to higher productivity while reducing water loss. It is important to consider all climatic factors potentially affecting plant water uptake. For example, increased relative humidity inside the greenhouse will decrease the vapour pressure deficit and transpiration, leading to an increase in the WUE. Numerous interventions are possible to **increase WUE**:

- Efficient water delivery systems and irrigation methods (e.g. micro-irrigation) have a major impact. Measured efficiency varies from 25–50% in furrow-irrigation systems, to 50–70% with sprinkler systems, and 80–90% with drip irrigation. In situations of limited water supply, sprinkler and drip methods can increase the irrigated area by 20–30% and 30–40% compared with furrow irrigation.
- Irrigation scheduling can potentially halve crop water consumption (De Pascale *et al*., 2011). Irrigation scheduling aims to synchronize water delivery and crop demand, reducing water lost through runoff and drainage.
- The choice of appropriate crops/cultivars makes a difference, together with the implementation of strategies to identify the best match between crop type and time of cultivation for a specific environment.
- Mulching or bag culture reduce soil evaporation.
- Measures leading to rapid and uniform crop establishment (e.g. transplanting, choice of suitable plant density and architecture) have a positive impact.
- The introduction of closed soilless systems (reducing water loss due to drainage and runoff, by recycling part of the nutrient solution) can improve WUE in vegetable greenhouse production by as much as 70% (Savvas, 2002).
- Rainwater is of high value for crops and should be collected with effective gutter systems, stored properly and utilized. However, rainwater contamination can occur when deposits on the greenhouse roof (or lime and water whitewash) are washed off with the rain or if uncoated galvanized structures leach zinc into the water. It is, therefore, essential that quality parameters for irrigation water be respected.
- In areas with limited fresh water supply, alternative options may be explored at a watershed or regional level – for example, utilization of alternative water sources (e.g. surface water recycled from production areas, treated and untreated wastewater, desalinated water). Note that these sources may require additional treatments.

MICRO-IRRIGATION

This section presents the basic concepts of micro-irrigation to familiarize vegetable growers with the main advantages and disadvantages, and with the components, functioning and management of the principal micro-irrigation systems.

Micro-irrigation – also known as trickle or localized irrigation – is widely adopted in greenhouse vegetables in SEE countries. Studies of several vegetable crops have reported higher yields, improved WUE and higher produce quality with micro-irrigation compared with other irrigation methods. Micro-irrigation entails the slow and regular application at low pressure (< 2 bar) of water directly to the root zone of the crops through a network of valves, pipes, tubing and emitters (Barbieri and Maggio, 2013).

Micro-irrigation has numerous **advantages**:

- **Improved crop productivity.** Slow, regular, uniform application of water and nutrients to all plants improves product quality and uniformity, and increases yield.
- **Water and fertilizer savings.** Water and fertilizer losses are minimized, and fertilizer costs are thus reduced and farmers can irrigate more crop area per unit of water used.
- **Labour savings.** The labour requirements for irrigation, weeding and fertilizer application are less than for other irrigation systems.
- **High flexibility.** Micro-irrigation can be easily repaired, maintained or modified to suit changing needs.
- **Reduced risk of pathogen attacks.** The small wetted area results in both low air humidity and limited weed growth, which also results in reduced disease incidence.
- **Energy saving.** Most micro-irrigation systems are operated with low horsepower pumps, reducing energy demand for irrigation; furthermore, since humidity is low, less energy is needed to heat the greenhouse (more energy is needed to heat humid air than dry air).
- **Tolerance to salinity.** Due to slow and regular application of water by micro-irrigation, concentration of salts in particular in the root zone is reduced (provided the supply of the nutrient solution is well managed).

The numerous advantages can, however, be nullified if the delivery points become clogged. To help counteract this problem, the following measures should be considered:

- Installation of a reliable filtration system for the irrigation system.
- Regular inspection of all watering points to check for blockages, which in turn can lead to isolated dry spots in a crop.
- Regular flushing or washing of filters.

- Flushing of the whole system (ideally at least once a year) with clean water to remove any debris.
- Rinsing with a weak solution of chlorine nitric or phosphoric acid. For on-line drippers, nozzles can be removed, washed clean in a bleach solution, and then replaced. Similarly, nitric or phosphoric acids are injected in the drip lines (integrated dripper) at the end of the growing season for 24 hours in order to break up all the mineral and organic deposits before being flushed.

However, while drip irrigation systems typically result in lower water consumption because of a reduced leaching fraction, the soil or substrate moisture content may become inadequate in organic crop production for soil biological activity and the appropriate mineralization rates of organic fertilizers.

Micro-irrigation systems can be grouped into **five categories:**

- **Systems with drip lines.** This category includes the common perforated hoses, consisting of a thin tube of polyethylene (PE), diameter 0.15–0.20 mm, with holes at fixed distances. The operating pressure is 0.5–2.0 bar, the flow rate 0.5–4.0 litre h^{-1}.
- **Systems with drippers.** These systems consist of low density polyethylene (LDPE) tubes, diameter 16–25 mm, on which drippers are inserted at a proper distance based on the crop requirements. The operating pressure is 0.5–2 bar, the flow rate 1–4 litre h^{-1}.
- **Systems with intermittent drippers.** These systems are characterized by a high unitary flow rate of 6–30 litre h^{-1}, with an operating pressure of 1–3 bar. Due to the higher operating flow rate, the probability of clogging is very low.
- **Systems with capillary tubes.** These systems comprise a PE tube, 20–25 mm diameter, on which are inserted capillaries, internal diameter 0.5–1.5 mm, of sufficient length to reach the point of dispensing. The operating pressure is 1–2.5 bar, the flow rate 0.7–7 litre h^{-1}.
- **Subsurface drip irrigation.** Drip hoses are positioned 15 cm underground in order to reduce water evaporation.

Components of a micro-irrigation system

A micro-irrigation system comprises many components, each one playing an important part in the operation of the system. The main components of micro-irrigation systems are described below:

Pump

Unless the water at the source (municipal or other) is supplied at an adequate rate and pressure, a pump is needed to push the water through the pipes and drippers. Most irrigation applications comprise a centrifugal pump – a rotodynamic pump that adds energy to the water by means of a rotating impeller. It may be either horizontal- or vertical-shaft (including submersed pumps). Horizontal pumps are generally used to pump water from surface sources such as ponds.

Filter
Effective filtration prevents the irrigation water from clogging the drippers and is essential for good operation and long-term performance. The most commonly used filters in micro-irrigation are media filters (gravel or sand), disk filters and screen filters. A well-planned micro-irrigation system comprises two stages:

- **Primary filtration**
  - Filters relatively large particles near the water source.
  - Comprises a media or disk filter.
  - Includes a hydrocyclone sand separator placed before the main filter in cases where sand or other heavy particles (≥ 50 micron) are present in the source water.

- **Secondary filtration**
  - Filters relatively small particles remaining after the main filtration stage.
  - Comprises a screen or disk filter.

Pipes (main, sub-main, distribution)
Pipelines carry water through the entire irrigation system, from the pump through the filters and valves, and onwards to the drippers. All pipelines and fittings should be properly sized to withstand maximum operating pressures and to convey water without excessive pressure loss or gain. Polyvinyl chloride (PVC) piping may be used throughout the system. PVC, polyethylene (PE) or flexible pipes are used for sub-mains and distribution pipes.

Water meters
Water meters provide information about water application that is essential for irrigation scheduling and the monitoring of dripper clogging. Propeller meters are the most common type in horticultural applications.

Pressure gauges
Pressure gauges provide vital information about the irrigation system. The data gathered are used to help detect leaks and clogging, manage the filters and chemical injectors, and keep the system within its operating range. To ensure that data are as accurate as possible, always use a pressure gauge with a scale representing the pressure range of the system. The typical pressure in the system should be around the mid-point of the gauge's scale.

Valves

Precise control of the water flow rate and pressure throughout the irrigation system is important to ensure efficient and timely water application. It is, therefore, imperative to select the right valves and position them correctly. Valves play a key role in controlling pressure, flow and distribution under different conditions to optimize performance, facilitate management and reduce maintenance requirements.

Dripper lines (lateral)

Dripper lines are at the heart of a micro-irrigation system. In any irrigation system, the design process starts at the plant and proceeds to the dripper lines. There are numerous important considerations when designing the dripper lines: dripper line selection, wall thickness, dripper flow rate, spacing between drippers, and spacing between dripper lines.

Drippers

Drippers are evenly spaced along the dripper line and deliver water and nutrients directly to the plant root zone. A typical micro-irrigation system includes thousands of drippers. Each dripper should be durable and resistant to clogging and designed to emit the same amount of water. Wide water passages guarantee long-term trouble-free performance. The flow rate and spacing of the drippers determine the wetting pattern and the prevention of runoff or deep percolation. A properly operated and maintained micro-irrigation system provides water and nutrients to the crop root zone without runoff or deep percolation. Two types of integral drippers are available:

- Non-pressure-compensating drippers (which supply a flow rate on the basis of the working pressure)
- Pressure-compensanting drippers

GAP recommendations – Irrigation systems

- Ensure high water-use efficiency in greenhouse vegetable production through optimal control of cultural practices and environmental parameters.
- Adopt micro-irrigation when possible, as it is the most efficient system for vegetable irrigation under greenhouse conditions.
- Include a filtering apparatus upstream of the distribution line in micro-irrigation in order to avoid clogging of the nozzles.
- Rinse out the system with weak solution of chlorine nitric or phosphoric acid (when necessary, depending on the chemical and biological properties of the water).

IRRIGATION SCHEDULING

Irrigation scheduling determines the amount of water applied to the crop (irrigation dose) and the timing of application (irrigation frequency). The principal methods of irrigation scheduling in soil-bound crops and soilless growing systems are very similar:

- Water balance (determines crop water requirements from climatic data)
- Use of soil or plant sensors

Water balance method

The water applied at each irrigation event must compensate for the crop water uptake between two successive irrigations and should correspond to the maximum oscillation in the available water (AW, m^3/m^3 or percentage) in the soil or substrate – the so-called "management allowable depletion" (MAD) or "pre-irrigation soil/substrate water deficit" (PISWD). The amount of available water is defined as the water that the crop can absorb without suffering water stress (which would reduce yield) and it depends on the soil properties, for example, it is greater in loamy soil than in sandy soil. As a general rule, the MAD is calculated as a fraction of the AW (30–50% in soil-bound crops, 10% in soilless culture), while the irrigation dose is calculated by multiplying the MAD by the scheduling coefficient (SC) to account for the salinity of the water and the uniformity of application. Typically, irrigation water should be applied when the accumulated daily ET_c for the periods between irrigations approaches the MAD.

The SC is a measure of the extra water required because of non-uniform water application, inter-plant differences in leaf transpiration and, more importantly, to prevent salt accumulation in the root zone. Over-irrigation is crucial in container culture as the absence of a significant cation exchange capacity in most substrates allows buildup of high concentrations of ions in the rhizosphere. It ranges from 1.15 (uniform crop and water distribution; use of irrigation water with relatively low salinity; high crop tolerance to salinity) to 2.0 (large inter-plant variability in crop evapotranspiration; poor irrigation uniformity; use of saline water; salt-sensitive crop), that is a drain fraction (water leached/water applied) of 13–50%. An SC of 1.30 (drain fraction = 23%) is suitable in most conditions. For example, with MAD = 40 mm and SC = 1.3, the irrigation volume would be $40 \times 1.3 = 52$ mm and the drain fraction would be $12/52 \times 100 = 23\%$.

Most irrigation control methods determine the frequency of irrigation and use fixed irrigation doses. As crop evapotranspiration (ET_c) in greenhouse accounts for > 90–95% of the water absorbed by the roots, irrigation frequency can be computed as ET_c divided by MAD. If ET_c is expressed on a daily basis, the result is the number of irrigation events in a day. For example, a crop grown in substrate culture with MAD = 1.0 mm, SC = 1.3 and daily ET_c = 5.0 mm would be irrigated five times a day with an irrigation dose of 1.3 mm.

Determining evapotranspiration

To determine the crop water requirements of greenhouse vegetable crops, it is possible to adopt the FAO-56 Penman–Monteith method, which estimates crop evapotranspiration (ET_c) as the product of:

- reference evapotranspiration (ET_o) – equivalent to the evapotranspiration of a grass crop and quantifies the effect of climate on crop water demand; and
- crop coefficient (K_c) – quantifies the effect of crop species and stage of development.

The FAO-56 Penman–Monteith method is recommended for estimating ET_o inside greenhouses when radiation, air temperature and atmospheric humidity data are available; wind speed is negligible inside greenhouses. Simple equations can be used to estimate ET_o from the air temperature and/or radiation inside the greenhouse, and the results are easily implemented in irrigation control. The principal challenge is to determine K_c (related to leaf area).

K_c varies with species, development stage and crop management practices (vertically supported or not). For greenhouse-grown vegetable crops, there is wide variability in planting dates and lengths of crop cycles, depending on market prices, weather conditions and farm management considerations. For this reaon, the standard FAO method of calculating ET_c – using three constant K_c values, one for each fixed-length crop stage – is unsuitable for these crops. It is therefore recommended to use mathematical models that estimate K_c values as a function of thermal time inside the greenhouse. Crop coefficient (K_c) values for the main greenhouse-grown vegetable crops are presented in Table 1.

TABLE 1
Crop coefficient (K_c) values determined for the major greenhouse-grown vegetable species in Almeria, Spain

Species	Initial K_c	Maximum K_c	Final K_c[a]
Supported crops			
Sweet pepper	0.2	1.3	0.9
Tomato	0.2	1.6	
Melon	0.2	1.3	1.1
Cucumber	0.2	1.2	
Eggplant	0.2	1.2	
French bean	0.2	1.4	1.2
Non-supported crops			
Melon	0.2	1.1	1.0
Watermelon		1.1	1.0
Courgette	0.2	1.1	

Note. Values presented are the initial K_c value for transplanted seedlings, maximum K_c values, and final K_c values where appropriate.
[a] Many out-of-season crops are finished early because of low prices; in these cases final K_c values equal maximum K_c values.
Orgaz *et al.*, 2005.

For greenhouses, simplified (empirical) models for predicting ET_c have been developed. These models consider global solar radiation, vapour pressure deficit and specific crop parameters, such as the leaf area index (Baille *et al*., 1994).

One example is the method proposed by Gallardo *et al*. (2013), where the ET_c is estimated from daily values of maximum and minimum temperature inside the greenhouse, and of external solar radiation. These parameters are all easily available to farmers. ET_o is calculated using a local radiation equation calibrated for plastic greenhouses in Spain from external solar radiation measured in a nearby weather station. The crop coefficient (K_c) is estimated using simple models based on thermal time. Since the climatic variability in greenhouses is very low, historical climate data may help farmers to adopt simple irrigation scheduling techniques. Once ET_c is calculated, the irrigation frequency can be determined based on the water balance or by simple sensors (e.g. tensiometers).

Calculations can be done manually or special software can be adopted (e.g. PrHo v2.0, developed by the Research Station of the Cajamar Foundation of Almeria). For a detailed explanation of the methodology, see Gallardo *et al*. (2013).

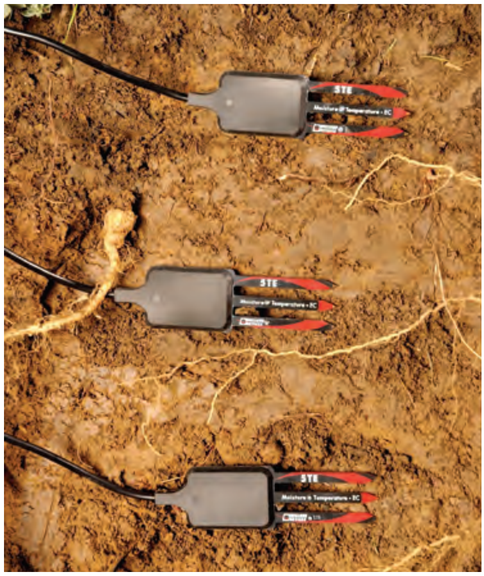
Use of sensors

Soil moisture sensors can be used to control the frequency of irrigation and, possibly, the water dose by continuously monitoring the moisture content of the growing media, expressed as moisture tension (in kPa – a negative value) or volumetric water content (as a percentage or in m^3/m^3). The tension measures the force of retention of soil water by the soil particles and indicates the availability of soil water for crops. The volumetric water content is the ratio of soil volume occupied by water. Sensors allow irrigation to be implemented on the basis of the characteristics of individual greenhouses and specific cropping conditions.

GALLARDO

Plate 1
Manual tensiometer

Nowadays, a variety of simple irrigation controllers are on the market, interfaced with one or more soil moisture sensors, usually using wireless radio technology. New kinds of soil moisture sensor have been developed to measure soil dielectric properties. These sensors are cheaper and require less maintenance and user expertise compared with traditional water-filled tensiometers. However, while the interpretation of moisture tension data for irrigation management is straightforward, the interpretation of volumetric water content requires protocols or site-specific experience. Most tensiometers usually have a working range of between 0 and –80 kPa, basically covering the range of soil moisture tension found in drip irrigated crops.



LAB-FERRER

Plate 2
Decagon probes installed in soil, placed at three different depths to measure volumetric soil moisture, soil temperature and electrical conductivity

Sensors, such as 5TE (Decagon Devices) or WET (Delta-T Device), have also been developed for simultaneous measurements of temperature, moisture content and salinity (EC) in soil or soilless media. These sensors provide the possibility of controlled fertigation.

When sensors are used for irrigation scheduling (IS), there are two important considerations: replication (≥ 2–3 sensors per crop); and location (representative of the crop). Other practical considerations include: cost, ease of use, preparation and maintenance requirements, technical support, ease of data interpretation, availability of irrigation protocols, working language, and the user-friendliness of any software.

Growing systems

The approaches to irrigation scheduling are relevant to both soil culture and soilless culture, but there are some differences between the two growing systems.

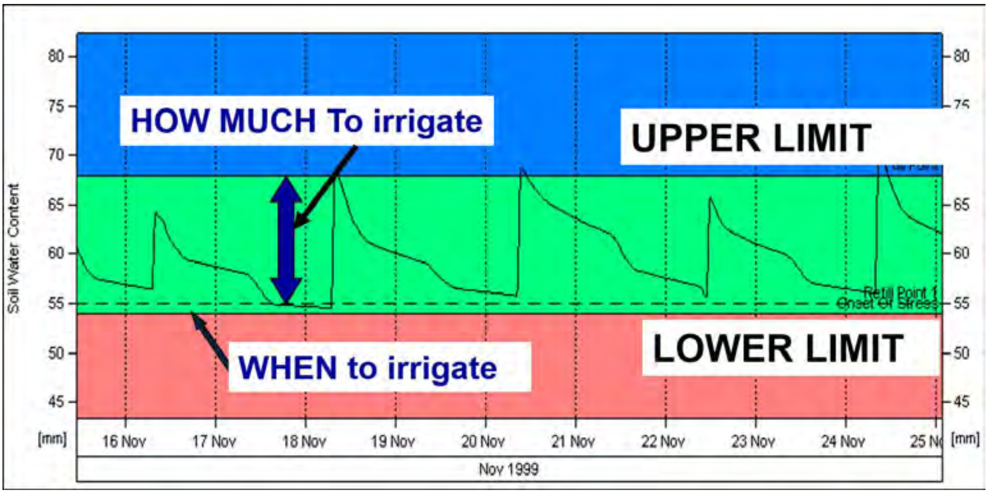
Soil culture

When calculating the water requirements of soil-bound crops, decision support systems (DSS) can assist growers and advisors. For example, the software PrHo v2.0 has been developed to calculate daily crop water requirements for the principal greenhouse vegetable crops, for cropping cycles specified by the user.[2]

Irrigation management with soil water sensors is based on maintaining the soil water between two limits: a lower limit (drier value) indicating when to start irrigating and an upper limit indicating when to stop. The difference between the two limits indicates the volume of irrigation required. Generally, the lower limit permits depletion of soil water without stressing the crop; and the upper limit prevents excessive drainage from the root zone (Figure 1).

[2] Available at http://www.publicacionescajamar.es/series-tematicas/centros-experimentales-las-palmerillas.

FIGURE 1
Example of irrigation management using a soil sensor to maintain soil water content between upper and lower limits, and their use for deciding the time of irrigation and volume to apply



Note:
Upper limit: volume of irrigation. Lower limit: date of irrigation.

Soil water sensors can be used with different configurations depending on the crop, irrigation system, cost and the characteristics of the sensors. One sensor should be placed in the zone of maximum root concentration. Additional sensors can be placed at different depths, for example, below the roots to control drainage or to the side of the plants to control the size of wetting bulbs from drip irrigation. The most widely used sensor configurations are: 1) one sensor within the zone of major root concentration; and 2) one sensor within the zone of major root concentration complemented by one or more deeper sensors.

When using tensiometers, the recommended upper and lower limits of moisture tensions are –10 and –20 kPa, –10 and –30 kPa, and –15 and –40 kPa, for soils of coarse, medium and fine texture, respectively.

Soilless culture

Either open or closed irrigation systems are used for substrate culture. In **closed systems**, the drainage water is captured and re-used following the adjustment of pH and nutrient concentration and, when necessary, disinfection to minimize the risks of root-borne diseases.

Accurate irrigation scheduling is crucial in **open systems**, as the substrate used determines the seasonal use of water and the pollution resulting from leaching of agrochemicals. However, over-irrigation or deficit irrigation can also affect crop growth and yield in closed systems, for example, by increasing incidence of physiological disorders (such as blossom-end rot in tomato and pepper) or susceptibility to root diseases.

In soilless culture, a wide range of growing media are used. For irrigation management, the ideal medium should be characterized by high porosity (> 80%) and homogenous distribution of air (oxygen) and water in order to sustain root activity.

The amount of available water ranges from 7 to 35% of total substrate volume and tends to increase with increasing substrate porosity and bulk density and with decreasing container height: the taller the container, the more drainage and the less capacity media will have to hold water. Table 2 reports values of water and air content at container capacity ($_{CC}$) and AW for different types of container and growing media widely used in greenhouse horticulture. The container AW is defined as the difference between the container water content calculated at 0 and −10 kPa matric potential at the bottom of the container (Incrocci *et al.*, 2014). AW is calculated on the basis of the water retention curve of the substrate determined in the laboratory and the geometry of the container (Bibbiani, 2002).

A good estimation of the available water in the container (AW_{cont}) can be obtained by applying the following equation:

$$AW_{cont} = + 0.64\ AW + 0.30\ P - 67\ h + 4.1$$

where AW (%) is the available water derived from the water release curve (difference between the volumetric water content at −1 and −10 kPa) of the substrate, P (%) is its porosity and h (m) is the container height.

Compared to soil culture, plants grown in substrate are generally irrigated many times during the daytime, beginning early in the morning. More than 90% ET_c occurs during the light period (i.e. ≤ 10 hours in autumn–winter and 12–14 hours in spring–summer). In heated greenhouses and in dry seasons and regions, irrigation may sometimes be necessary in the middle of the night.

Frequent watering means that the irrigation of soilless culture is generally under automatic control entailing the adoption of the following:

- Timer (based on the grower's estimate of ET_c).
- Weather station or simple light sensor (based on the grower's estimate of ET_c).
- Weighing gutter (or similar devices) to measure gravimetrically ET_c (and possibly the growth) of a few test plants over a short time (minutes or hours).
- Tray system (a similar concept to the weighing gutter method). A water level sensor is placed in a small tray where the volume of water is in

TABLE 2

Water ($_{CC}$) and air (A_{CC}) content at container capacity, and AW in different containers filled with various growing media[a]

Substrate	Porosity	AW		Unit	Slab	Bag 1	Bag 2	Bench 1	Bench 2	Bench 3	Pot 16	Pot 24	Pot 32
	%	%	height	m	0.075	0.15	0.20	0.20	0.30	0.40	0.14	0.21	0.29
			length	m	0.15	0.20	0.20	1.00	1.00	1.00	0.16	0.24	0.32
			width	m	1.00	1.00	1.00	0.40	0.30	0.40			
			volume	litre	11.25	30.0	40.0	80.0	90.0	160.0	2.81	9.50	23.31
Peat	88.0	37.0	$_{CC}$	%	82.0	76.3	72.8	72.8	66.0	60.7	77.0	72.1	66.7
			A_{CC}	%	6.0	11.7	15.2	15.2	22.0	27.3	11.0	15.9	21.3
			AW	%	47.1	41.4	38	38	31.3	26.1	42.1	37.3	32
Perlite	90.0	13.0	$_{CC}$	%	69.4	53.2	48.3	48.3	42.8	39.7	54.5	47.5	43.2
			A_{CC}	%	20.6	36.8	41.7	41.7	47.2	50.3	35.5	42.5	46.8
			AW	%	47.4	31.2	26.3	26.3	20.8	17.7	32.5	25.5	21.2
Pumice	55.0	6.0	$_{CC}$	%	49.8	45.5	44.0	44.0	42.0	40.7	45.9	43.8	42.2
			A_{CC}	%	5.2	9.5	11.0	11.0	13.0	14.3	9.1	11.2	12.8
			AW	%	14.8	10.7	9.2	9.2	7.3	6.1	11	9	7.5
Coconut	90.0	35.0	$_{CC}$	%	82.5	75.6	71.8	71.8	64.7	59.2	76.4	71	65.4
			A_{CC}	%	7.5	14.4	18.2	18.2	25.3	30.8	13.6	19	24.6
			AW	%	47.6	40.7	37	37	30	24.7	41.5	36.2	30.6
Rockwool	94.0	78.0	$_{CC}$	%	89.5	82.9	75.6	75.6	59.0	45.9	84.1	74.1	60.7
			A_{CC}	%	4.5	11.1	18.4	18.4	35.0	48.1	9.9	19.9	33.3
			AW	%	85.6	79	71.8	71.8	55.3	42.3	80.3	70.3	57
Peat-perlite	66.0	24.0	$_{CC}$	%	61.5	57.4	55.2	55.2	51.3	48.3	57.9	54.8	51.7
			A_{CC}	%	4.5	8.6	10.8	10.8	14.7	17.7	8.1	11.2	14.3
			AW	%	31.6	27.6	25.5	25.5	21.6	18.7	28	25.1	22
Peat-pumice	77.0	19.0	$_{CC}$	%	67.3	59.3	56.5	56.5	52.7	49.9	60.1	56	53
			A_{CC}	%	9.7	17.7	20.5	20.5	24.3	27.1	16.9	21	24
			AW	%	35.3	27.5	24.7	24.7	21	18.3	28.2	24.3	21.3

[a] The porosity and AW (as calculated from the water retention) for each substrate are also shown.

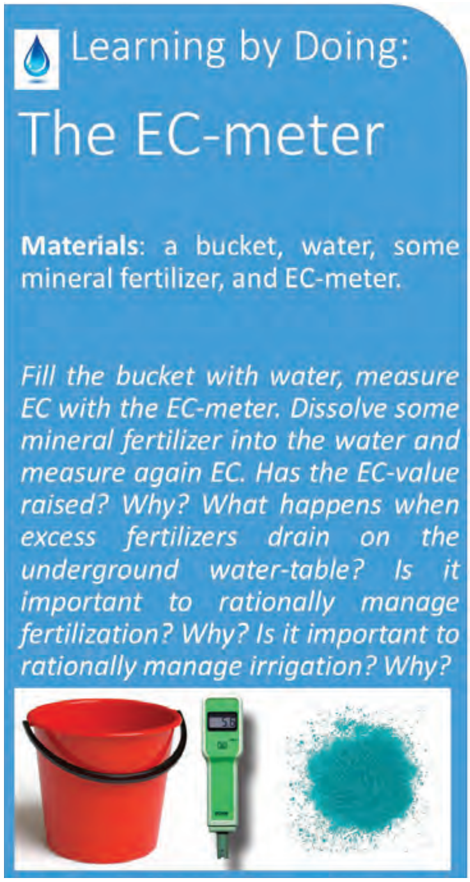
equilibrium with the water content in the substrate. When crop uptake causes the water level in the tray to decrease to the level of the sensor, the crop is irrigated.

- Soil moisture sensor(s). The sensor position is adjusted by the grower during the season on the basis of measured drainage volumes and experience.

The threshold values for moisture tension depend on crop species and growing media; typical values range from –4 to –10 kPa in substrate growing systems. This value can be converted to volumetric water content from the water release curve. For example, a moisture tension of –5 kPa corresponds to a volumetric water content of around 40% in coconut and peat and about 30% in perlite and pumice.

In substrate culture, frequent monitoring of pH and EC in the root zone is crucial in order to adjust irrigation and fertigation. The grower should, therefore, check the pH and EC of the drainage water (every 1–3 days) and of the substrate (every 4–6 weeks). When the quality of the irrigation water is poor, monitoring should be more frequent.

FIGURE 2
EC meter



GAP recommendations – Irrigation scheduling

General recommendations

- Determine both irrigation dose and frequency.
- Calculate the irrigation dose on the basis of soil or substrate hydraulic properties, crop species, water quality and irrigation system, which determine the values of the MAD (%) of the available water in the root zone and the scheduling coefficient.
- Determine irrigation frequency (either automatically or manually) on the basis of irrigation dose and ET_c, which depend, respectively, on the physical properties of the growing medium (including the volume explored by the roots) and on climatic conditions. Soil moisture sensors (tensiometers or capacitance sensors) may also be used.
- Adopt professional systems when possible to ensure optimal irrigation efficiency.
- Contact irrigation designer and company for cost-effective irrigation systems.

Soil culture

- Ascertain crop evapotranspiration ($ET_{c)}$ in crops grown in greenhouses as the product of reference evapotranspiration (ET_o) and crop coefficient (K_c) values. (Software is available to calculate ET_c.)
- Calculate crop coefficients using available models based on temperature inside the greenhouse.
- Place one soil moisture sensor in the zone of maximum root concentration. Place additional sensors at different depths (e.g. below the roots to control drainage), and to the side of the plants to control the size of wetting bulbs from drip irrigation.

Soilless culture

- Install automatic control because frequent watering is necessary.
- Adopt affordable and consistent tools (weighing gutter, tray system) for direct measurement of ET_c.
- Maintain the scheduling coefficient at ≤ 1.5 (which would result in a drain fraction of 33%).
- Check pH and EC of drainage water daily and substrate every 4–6 weeks. Intensify monitoring if poor-quality irrigation water is used.

IRRIGATION WATER QUALITY PARAMETERS

The characteristics of irrigation water depend on the source. Irrigation water can be classified on the basis of its origin as:

- surface water (from rivers, canals, natural or artificial lakes);
- subterranean water (from springs, wells etc.); or
- wastewater (from urban and industrial drains, subjected to various kinds of purification treatments).

For example, subterranean water in coastal zones may be of marginal quality for agricultural use because of the high content of dissolved salts, while municipal wastewater may also be of marginal quality because of the associated health hazards. The **parameters** characterizing irrigation water quality fall into three categories (FAO, 2013):

- **Physical:** temperature, suspended solids (soil particles, impurities etc.).
- **Chemical:** gaseous substances, pH, alkalinity, soluble salts (salinity), and concentration of sodium, chloride and toxic elements.
- **Biological:** algae, bacteria, various micro-organisms.[3]

Physical

For irrigation purposes, the **temperature** of the water must be as close as possible to that of the plants and the layer of substrate containing the root systems. Water is considered cold when its temperature is below three-quarters the air temperature. Cold water is unsuitable for irrigation as it can cause physiological disorders, especially in more delicate crops. Operative measures should be adopted, such as storing the water in basins to encourage the temperature to rise. Warm water, on the other hand, can have the dual benefits of warming the crops and supplying their irrigation requirements. Water at > 35 °C is, however, dangerous to plants. Water temperature is a particularly important consideration when growing foliage plants, because extreme water temperature (whether hot or cold) can cause leaf spotting, which reduces the value of the produce.

The **suspended solid** substances (e.g. soil particles as a result of erosion, different types of suspended matter disposed of in water courses by various industries, particulates contained in unpurified or partially purified municipal wastewater) found in water do not generally cause direct damage to the crops. However, problems may arise when plants and commercial products are stained, leading to their depreciation in terms of appearance and overall sanitary conditions, and this is particularly important in the case of flower crops. Furthermore, solids suspended in irrigation water can clog the irrigation nozzle and damage the

[3] See Part II, Chapter 9.

distribution equipment, especially in the case of micro-irrigation systems. When the presence of solid particles in the water causes the emitters in trickle irrigation systems to become obstructed, maintenance costs rise and their utilization can become compromised. Moreover, the use of wastewater containing suspended organic solids can lead to health and hygiene hazards.

Chemical

A number of **gaseous substances** may be present in the water. The presence of O_2 depends on the water temperature and the presence of biodegradable substances. Given the low solubility of air in water, however, it does not reach a high concentration, and rainwater and surface water are therefore preferred. The chlorine used to purify drinking water may be present in a gaseous form, but it becomes volatile when in contact with the environment, due to the combined action of the light and air. Gaseous contaminants (e.g. H_2S, SO_2, CH_4) may also be found and their presence can restrict possibilities to use the water.

The **pH** is an expression of the concentration of hydrogen protons (H^+) in an aqueous solution. The pH varies on a scale of 0 to 14: 7 is neutral, < 7 is acid and > 7 is basic or alkaline. The pH regulates all biological functions and can inhibit certain vital processes if it is unsuitable. The pH of the water and of the soil or various cultivation substrates influences the solubility of the ionic species and, therefore, plant nutrition. Indeed, every nutritional element has a maximum solubility for clearly defined pH intervals. The optimum pH of irrigation water is usually between 6.5 and 7.5. Water with a pH of between 6.0 and 8.0 can be used for irrigation purposes. Decidedly acid (pH < 5) or basic (pH > 8.5) water is classified as anomalous for irrigation purposes.

While pH is a measure of the hydrogen ion concentration, alkalinity is a relative measurement of the capacity of water to resist a change in pH or the ability of water to change the pH of the growing media. Alkalinity increases as the amount of dissolved carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) rises. Chemically, it is expressed in parts per million (ppm) of calcium carbonates ($CaCO_3$) equivalents. Irrigation water with high alkalinity (> 100 ppm $CaCO_3$) will tend to raise the pH of the growing media over time and will require more acid to lower the pH of the water to an acceptable level should a grower wish to do that.

Sound confusing? Well, simply stated, alkalinity affects the ability to reduce pH by neutralizing added acids. You may wish to think of alkalinity as the buffering capacity of the water – how well it resists or causes a change in pH.

Irrigation water, particularly if the source is from groundwater, usually contains some quantity of **soluble salts**. The use of saline water for irrigation may have negative effects on the overall soil–water–plant relationship, even drastically restricting the normal physiological activity and productive capacity of the crops.

Some dissolved salts are of great concern to growers, as they are directly toxic to the plants, impede root water uptake and/or cause foliar spotting that lowers the plant value. The use of saline irrigation water can lead to three kinds of problem:

- increase in the osmotic potential of the circulating solution with increasing water absorption problems for the plants (osmotic effect);
- effects on the chemistry and physics of the soil/substrate; and
- phytotoxicity.

The higher a salt concentration, the more it contributes to salinity, particularly if dissociated. The most frequently occurring ions are nitrate, chloride, sulphate, carbonates and bicarbonates of alkaline and alkaline earth elements (sodium, potassium, magnesium, calcium). Salinity can be measured by means of analytical or electrical conductivity methods. Analytical measurements give results expressed in unit of volume (g litre^{-1} or mg litre^{-1}) or as a concentration of mineral salts in parts per million (ppm), with water defined brackish whenever the salt content is > 2 g litre^{-1} (or 2 000 ppm). Electrical conductivity (EC) is expressed in milliSiemens per centimetre (mS cm^{-1}), microSiemens per centimetre (µS cm^{-1}) or deciSiemens per metre (dS m^{-1}) as measured by a conductivity meter at 25 °C (where 1 dS m^{-1} = 1 mS cm^{-1} = 1 000 µS cm^{-1}). The EC is linked to the osmotic pressure that a given saline concentration creates in the solution which, in turn, directly affects the plant's ability to absorb water (i.e. increasing the salinity of water reduces the availability of water for uptake by plants). Water is defined as brackish when the EC is ≥ 3.0 dS m^{-1}. Although a rough classification of plant species on the basis of their level of salinity tolerance is available, the response is highly variable in relation to cultivar, soil/substrate, climate conditions and the agronomic techniques used. By combining suitable agronomic strategies with careful species and cultivar selection, it is possible to minimize yield reductions. Salinity control is particularly important in the root zone, especially during germination and the early phenological phases. It can be achieved by increasing irrigation frequency or by satisfying the leaching requirement (i.e. application of extra water for leaching of salts from the root zone to prevent excessive accumulation of salts that would limit the yield potential of crops). Moreover, drip irrigation is particularly suitable for water of poor quality (saline water).

The presence of particular ions – **toxic elements** – in the water can cause phytotoxicity problems. Such problems may appear as direct toxicity for various physiological processes of the plant or in the form of nutritional imbalances, with different levels of tolerance in different plants. Toxicity problems arise when certain elements in the irrigation water build up in the plant tissue to a level which causes reductions in yield, regardless of the total solute concentration. The elements that may generate toxicity phenomena are generally chloride, sulphur, boron and sodium. Toxicity phenomena manifest themselves in a typical fashion for each element and are apparent on old leaves where the buildup is greater:

Sodium (Na) at high levels is a concern to growers since it can contribute to salinity problems, interfere with **magnesium (Mg)** and **calcium (Ca)** availability in the media and cause foliar burns.

Sulphur (S) and **chlorine (Cl)** are essential elements for plant growth. Some crops (cruciferous, leguminous, potatoes) remove significant quantities of sulphur from the soil (70 kg ha^{-1}). However, if large quantities of this element are present in the irrigation water, it can damage the crops as a result of direct toxicity. Sulphur is generally found in water in the form of sulphate (SO_4^{2-}). However, in reducing environments, sulphate can be converted into sulphide (SO_3^-), which has higher phytotoxic action; indeed, sulphides cause the precipitation of iron, leading to toxicity symptoms in plants. Chloride (Cl^-) in water derives from the dissociation of the chloride salts contained in the water and the chlorination of purified wastewater. Elevated chloride is often associated with an elevated sodium concentration. Chloride toxicity symptoms appear as leaf burning and drying (starting at the tips and continuing along the edges), browning, premature yellowing and leaf drop. The potential for chloride and sulphate to cause damage depends on the sensitivity of the irrigated species and primarily manifests itself when the vegetation is wetted (i.e. sprinkler irrigation).

Boron (B) is an essential element for plants, but it can be toxic even at very low concentrations (> 0.5 ppm). Toxic concentrations of boron are almost exclusively found in soils in arid zones and in well and spring water in geothermal and volcanic regions, while most surface water contains acceptable levels of boron. Irrigation water can sometimes contain significant quantities of boron due to outflows from residential purification plants, as it is a common component of household detergents in the form of sodium perborate. The toxic effects of boron first appear in old leaves in the form of yellowing, chlorotic spots or dried tissue at the tip and edges of the leaf. Seedlings are generally more susceptible than mature plants.

In some cases, well water may be particularly rich in **iron (Fe)**. Acid-loving plants may experience problems when grown in acid soil or substrates and irrigated with ferrous water (where iron in the form of ferrous ions does not precipitate, but increases its concentration in solution and can be toxic). Elevated iron levels (> 5 mg $litre^{-1}$) generally cause aesthetic problems on ornamental plants and greenhouse structures, but may also lead to plugged emitters. In addition to the above elements, many others react with the soil and cannot be removed by means of leaching, causing toxic buildups in the soil and in plants, despite the presence of very low concentrations in the irrigation water (trace elements). Many of these elements are heavy metals, mostly deriving from human activities (industry, traffic).

When using irrigation water with high concentrations of heavy metals, the following risks should be considered: direct damage caused by phytotoxicity, buildup of the element in the substrate or soil, and absorption, transfer and buildup in the plant, with the risk of diffusion through the food chain. In any case, as with all the salinity problems, toxicity problems also increase during the period of greatest environmental evapotranspiration demand, meaning that where good quality water is available, it is best to use it during the hottest period of the irrigation season.

WATER ANALYISIS

Analysis of irrigation water is an essential part of any rational cultivation method. It serves to:

- avoid phytotoxicity phenomena in crops;
- rationalize fertilization (especially in the case of fertigation); and
- determine the necessity (or not) of a special water treatment plant.

Sampling

Analysis may be performed at any time of year, but it is important to bear in mind that there can be high variability in the water characteristics depending on seasonal rainfall (especially in the case of surface water sources). If no information is available about the usual conditions of the well, it is advisable to carry out at least two analyses in order to be able to investigate any changes in water quality: one during a rainy and another during a dry period. It is then sufficient to repeat the laboratory test every 1–3 years, in addition to periodic pH and EC tests using user-friendly portable instruments – an essential part of any farm's equipment.

It is very simple to sample irrigation water, but it is important to follow a few basic rules:

- The well must be in regular use. If new, testing must not be done until it has been used for a few weeks; if out of use for some time, it must be used for a few days before sampling.
- The water should be allowed to flow for a few minutes before the sample is taken.
- A clean polyethylene bottle is required for the sample. The capacity must be ≥ 1 litre (to be filled completely), but a larger volume of water may be required for certain measurements, and it is recommended to contact the laboratory in advance for more detailed information.
- The sample should be sent to the laboratory as soon as possible. A label should indicate details of the farm and the crop, the water source (identified by a code), and the type of analyses to be performed. Storage prior to testing should be kept to an absolute minimum; if in excess of 1–2 days, the laboratory should be contacted for advice on the best storage methods, which may vary depending on the parameters to be investigated.

Selection of parameters to be analysed

When choosing the parameters for analysis, it is necessary to make a compromise between the need for the maximum quantity of data and the cost. A very detailed analysis can cost €100–250 (or more), depending on the geographic location and the type of laboratory. Selection of the parameters is, therefore, not easy and must be made on the basis of:

- previous analytical data;
- reason for the analysis;
- farm characteristics (species grown, cultivation technique etc.); and
- local conditions.

Chemical water characteristics may be divided into four categories:

- pH – EC. They allow an initial assessment of the water. While very important, they are insufficient for an accurate judgement.
- Concentration of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), chloride (Cl^{-}), carbonate (CO_3^{2-}), bicarbonate (HCO_3^{2-}) and sulphate (SO_4^{2-}). They enable classification of the water on the basis of its effects on the soil/substrate, the crop and the plumbing systems. They should always be measured.
- Concentration of macro- (nitric nitrogen [$N\text{-}NO_3^{-}$], ammoniacal nitrogen [$N^{-}NH_4^{+}$], phosphates [HPO_4^{2-}, PO_4^{3-}] and potassium [K^{+}]) and micronutrients (iron [Fe], manganese [Mn], copper [Cu], zinc [Zn], boron [B] and molybdenum [Mo]). They reveal the "fertilizing power" of the water and indicate the potential toxicity risks associated with the concentration of micronutrients, which also depends on the pH of the water (the risks increase as the pH falls). They permit accurate fertilization management and are necessary when the area presents particular risks.
- Concentration of toxic substances (e.g. heavy metals, anionic tensioactives contained in detergents, fluorides) and total suspended solids (TSS). They are not generally present in hazardous quantities in water, but they can present a problem. Heavy metals, for example, may be of geological origin, but can also be the result of human activity. Inorganic (sand, lime, clay) or organic suspended solids can create blockages in the plumbing. They should be measured only if pollution is suspected.

Make reference to official analysis methods when analysing water!

Table 3 presents the criteria for choosing the appropriate type of analysis. The general suggestions should be adapted to suit the individual situation. It is not possible to indicate in advance a suitable analysis type for every situation and expert advice should be sought.

TABLE 3
Guidelines for choosing the water analysis parameters

Parameter		Meaning	When to do it[a]			
			First analysis	Intensive farming	Fertigation	Water treatment system planning
pH		Expresses acidity (< 7) or basicity (> 7) of water.	*	*	*	*
Salinity	EC	Relates to the overall salt content, which in turn is linked to the osmotic pressure.	*	*	*	*
Calcium	Ca^{2+}	Absorbed in considerable quantities by plants; at high concentrations may react with carbonates and bicarbonates to form limescale and can create nozzle obstruction.	*	*	*	*
Magnesium	Mg^{2+}		*	*	*	*
Sodium	Na^{+}	Indispensable at low concentrations; tends to build up in the soil or substrate with toxic effects for plants, worsening the physical characteristics of the soil.	*	*	*	*
Chloride	Cl^{-}	Indispensable at low concentrations; tends to build up in the soil or substrate with toxic effects for the plants.	*	*	*	*
Carbonate/ Bicarbonate	CO_3^{2} HCO_3^{2-}	Also referred to with the term "alkalinity".	*	*	*	*
Sulphate	SO_4^{2-}	At high concentration cause an increase in salinity; leaf deposits may form.	*	*	*	*
Nitric nitrogen	$N\text{-}NO_3^{-}$	Indispensable for plant growth, should be taken into account in the fertilization plan.			*	*
Ammoniacal nitrogen	$N\text{-}NH_4^{+}$				*	*
Phosphate	HPO_4^{2-}, PO_4^{3-}				*	*
Potassium	K^{+}				*	*
Iron	Fe	Indispensable for plant growth; may become toxic at high concentration.	*	*	*	*
Copper	Cu			*	*	*
Zinc	Zn			*	*	*
Boron	B		o	*	*	*
Molybdenum	Mo		o	o	o	o
Toxic substances	Tensioactives, Heavy metals, Fluorides (F^{-})	May be toxic to humans and/ or plants.	o	o	o	o
Total suspended soils	TSS	Can create drip emitter blockage.				*

[a] * = always recommended; o = to be performed in zones at risk.
De Pascale *et al*., 2013.

Interpreting a laboratory report

The interpretation of an analysis certificate can appear complex:

- **Identification of "threshold values"** – i.e. the concentrations above which a certain substance can become harmful – is not simple. Cultivated species have different levels of tolerance and the growing techniques adopted affect these thresholds. For example, a given salt content may be dangerous for a greenhouse crop, but not for a field crop, which is periodically washed by the rain.
- **Assessment of irrigation water quality** involves the examination of the relationships between the various parameters. For example, a given salt content may be tolerated if the ions present are primarily calcium and magnesium, but it may be harmful if sodium and chloride predominate. The opinion of an expert with detailed knowledge of the farm in question is more reliable than fixed thresholds. The threshold values for greenhouse crops given in Table 4 are therefore indicative and are only sufficient for the purposes of an initial assessment.

TABLE 4
Assessment of water analysis results

Parameter	Unit	Threshold	Possible intervention
pH		6.0–8.0	Acidification if too high, addition of bicarbonate if too low
EC	dS m^{-1} (25 °C)	< 0.750	Reverse osmosis, dilution
Ca^{2+}	ppm	< 150	Reverse osmosis, acidification, dilution
Mg^{2+}	ppm	< 35	
Na^{+}	ppm	< 50	Reverse osmosis, dilution
Cl^{-}	ppm	< 50	
Alkalinity	ppm	< 250	Acidification
SO_4^{2-}	ppm	< 50	Reverse osmosis, dilution
Fe	ppm	< 1.0	Reverse osmosis, dilution, oxidation tanks, removal systems
Mn	ppm	< 0.6	
Cu	ppm	< 0.3	Reverse osmosis, dilution
Zn	ppm	< 0.3	
Bo	ppm	< 0.3	
Mo	ppm	< 0.05	Dilution
Tensioactives	ppm	< 0.5	
Flourides (F^{-})	ppm	< 1.0	Reverse osmosis
Cadmium (Cd)	ppm	< 0.01	
Chromium (Cr)	ppm	< 0.1	
Nickel (Ni)	ppm	< 0.2	
Lead (Pb)	ppm	< 5.0	
Mercury (Hg)	ppm	< 0.002	
TSS	ppm	< 30	Filtration

De Pascale *et al.*, 2013.

- The **units of measurement** used to express the results may differ, making it difficult to compare different analyses or an analysis and a series of threshold values. Few farms have their own laboratory and, indeed, it is not essential. However, a pH meter and a conductivity meter (to check the pH and EC levels on a regular basis) are indispensable. They are portable instruments, easily available on the market at a wide range of prices, affordable for all farms.

When using these instruments it is important to follow some fundamental rules to ensure that the readings are reliable!

GAP recommendations – Water quality

Water quality

- Ensure water quality – it is critical to successful horticulture greenhouse production.
- Know your water quality in order to plan for water treatments and avoid problems such as poor plant growth, staining, clogged watering pipes and other undesirable effects.
- Greenhouse irrigation water comes from a number of different sources and its quality varies. Nevertheless **apply the following general rules:**
  - Test water using an accredited laboratory before cultivation.
  - Seek expert advice, as it is not possible to indicate a suitable analysis type for every situation in advance.
  - Repeat analytical testing of irrigation water over time to identify composition variations which sometimes occur and may have negative effects on the crop.
  - Refer to official analysis methods when analysing water.
  - Perform periodic on-farm water pH and EC measurements as an essential part of any rational cultivation method.
  - Use portable instruments for measuring irrigation (or fertigation) water pH and EC (they are affordable, user-friendly and an essential part of correct management of greenhouse crops) and follow the fundamental rules to ensure the reliability of readings.
  - Adjust low quality waters corrected through desalination, pH correction, acidification, addition of bicarbonates and filtration.

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