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Achieving sustainable greenhouse cultivation

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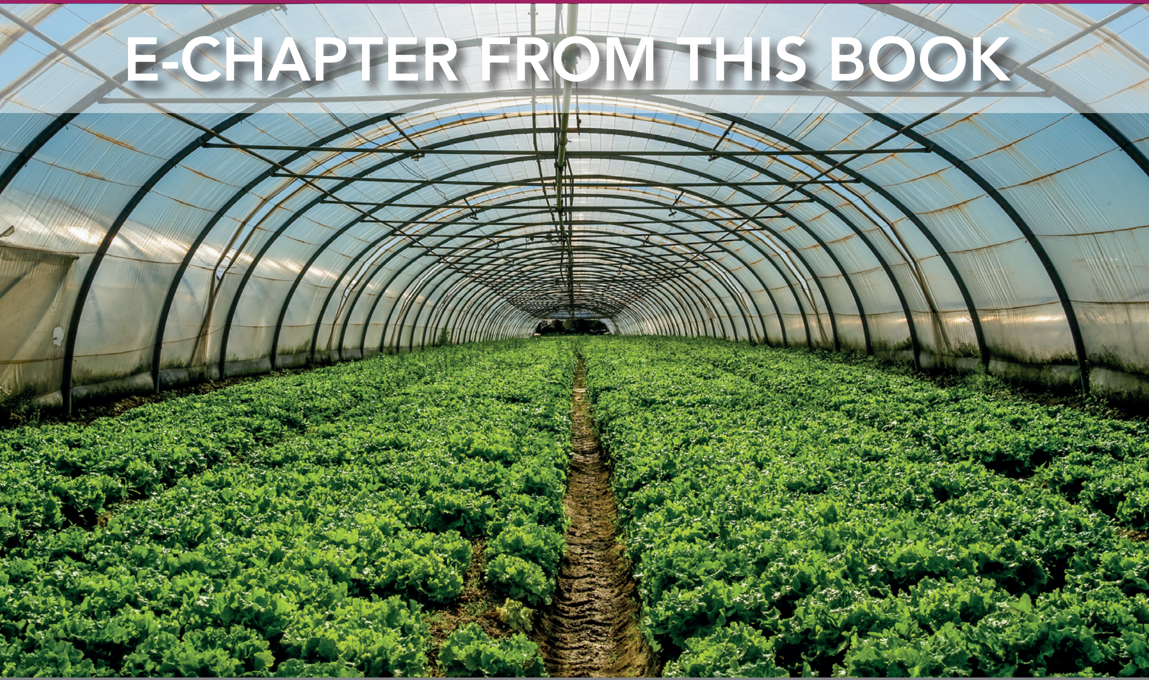

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Advances in irrigation management in greenhouse cultivation

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1 Introduction

Over the next few years, the world's horticultural systems will face an important balancing act between two needs – increasing horticultural production to sustain a rapidly increasing global population, projected to reach 10 billion by 2050, and reducing horticulture's impact on the environment by improving resource use efficiency in terms of water and nutrients (De Pascale et al., 2011; Rouphael et al., 2015). In the case of horticultural crops such as vegetables and ornamentals, maximal productivity is attained under controlled environments and indoor conditions where production may expand vertically and microclimate factors such as air and root zone temperature, light conditions (quality and intensity), carbon dioxide enrichment as well as vapour pressure deficit can be controlled (Rouphael et al., 2018). Besides the advantages of protected cultivation in terms of increasing off-season product and buffering against external climatic conditions, maximizing productivity by unit of water use is an urgent need among scientists, extension specialists and horticultural growers to face the shortage of water as a result of climate change (De Pascale et al., 2018). Therefore, in the years to come, greenhouse growers will have to be prepared to use less water, and in some cases that of lesser quality

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(i.e. saline water), meaning they will have to improve irrigation methods and techniques as well as management practices in order to maximize water use efficiency (WUE). In crop production systems, WUE expressed as kg m^{-3} is usually defined as '*the relationship between crop produced and the amount of water involved in crop production, expressed as crop production per unit volume of water*' (Molden, 2003; Ali and Talukder, 2008). The volume of water applied to the crop to obtain a unit of crop yield includes crop evapotranspiration (referring to the water loss by both soil evaporation and crop transpiration), leaching fraction and water present in the crop tissues. Increasing WUE under greenhouse conditions can be achieved by adopting efficient water delivery systems and irrigation methods such as microirrigation and subirrigation as well as adopting semi-closed- and closed-loop systems (De Pascale et al., 2017). Additional improvements in WUE can be attained through innovative and accurate tools and strategies able to optimize irrigation scheduling in terms of water amount and timing (De Pascale et al., 2018). Among these innovative tools and techniques, the use of soil moisture and crop water status sensors, as well as the calculation of crop water requirement and water balance through simplified models, are gaining interest among researchers and greenhouse growers (De Pascale et al., 2018). In addition to the above-mentioned technological strategies to boost WUE, several studies have revealed that adopting good agricultural practices, such as grafting and the use of natural substances and compounds as well as beneficial microorganisms, have also been reported to reduce the amount of water applied to the cropping system, enhancing WUE (Colla and Rouphael, 2015; Kumar et al., 2017).

This chapter provides an updated overview on the recent advances in water/irrigation management in controlled environments of horticultural crops including both vegetables and ornamentals. A technical design of a typical greenhouse irrigation system will be presented first. Tools and techniques (water balance and crop evapotranspiration) as well as the use of high-tech moisture sensors for irrigation scheduling will be covered. In the context of enhancing the WUE of greenhouse crops, innovative management practices (biostimulants and grafting) will also be discussed. Finally, the chapter will conclude with prospects and research breakthroughs that have to be considered in order to improve water management and WUE in greenhouse crops.

2 Irrigation systems

2.1 Introduction and reference characteristics

The irrigation system has as its main task delivering water to plants. This operation can be accomplished using different techniques and technologies that can vary largely depending on the cultivation system (soilless or soil growing conditions), production type (plant growth or propagation), environmental conditions (climate, soil and water physico-chemical characteristics etc.). The growing environment, *in toto*, is therefore of high relevance to identify the most efficient irrigation system. For instance, irrigation through water infiltration in the root zone is highly inefficient in soil cultivation and much more valuable in closed-loop soilless culture (e.g. subirrigation). On the other hand, some irrigation techniques are required for their particular characteristics, such as, for example, mist or fog systems for their effects on microclimate as well as liquid culture and aeroponics where water represents the growing medium in which nutrients are added following fertigation principles. Only irrigation systems for water nutrition and the utilization of smart and high-efficiency management methods (i.e. allowing high irrigation/WUE) will be discussed in this section. Detailed descriptions of basic components, manufacturing design, installation schemes and material characteristics have been meticulously summarized in previous works covering the main issues and potentialities of different cropping systems, structure types and growing areas of greenhouse production (Dasberg and Or, 1999; Raviv and Lieth, 2008; Baudoin et al., 2013; Thompson et al., 2018). The main intention of this section is therefore to provide an overview of those insights and novelties that in the last few years have made it possible to achieve more and more sustainable use of water and through the adoption of smart irrigation technologies in greenhouse systems.

In a strict sense, the irrigation system consists of an apparatus that allows the distribution of water, or rather, of the nutritive solution (in fertigated crops) to each single culture unit. From the perspective of achieving highly sustainable irrigation management, however, the same apparatus should be thought of and managed as part of a more complex system composed of three main sectors, that is (1) water collection for both water initial use and reuse, (2) water storage system and (3) water delivery system. An exhaustive overview of different water storage methods has been given by Thompson et al. (2018). Water collection and storage is strategic in greenhouse systems to support constant and high-quality production, especially during the hot season when water availability is limited (Fig. 1). This operation is usually accomplished by collecting water from the environment, that is by pumping municipal tap water, surface water and groundwater, and/or collecting rainfall.

However, a more circular and sustainable greenhouse management entails the collection and reuse of drainage water and transpired water vapour after condensation (Fig. 2). Both techniques allow water saving with high WUE (Thompson et al., 2018). Nevertheless, the management of recycled water can be difficult, especially of that drained from the substrate after irrigation, which may show increased (with respect to the input values) (1) nutrient

Figure 1 Examples of water silos (left) and lined water storage (right) for the collection of rain and/or drainage water.

and non-nutrient concentration, which in turn causes increasing electrical conductivity, (2) accumulation of plant protection products and (3) presence of allelopathic compounds (Baudoin et al., 2013; Thompson et al., 2018). A major concern regarding the reuse of water is the accumulation of ballast ions. Different strategies can be adopted to control growing systems that inevitably face problems due to poor quality (e.g. saline) water (Massa et al., 2010). Concerns about the reuse of condensed water has also been the subject of research in greenhouse crops due to the possible accumulation of metal elements, such as zinc, from which greenhouse structures are made (Dannehl et al., 2014).

Apart from its operational management, the reuse of water entails the adoption of additional equipment and technologies for water collection and treatment (biological and physical) with additional costs for installation and maintenance (Thompson et al., 2018). Depending on the quality and characteristics of available water, however, some of the above-mentioned apparatus are already present at farm level as basic components of the irrigation system. In this case, the technological level of the implemented equipment mostly depends on (1) the initial quality of water sources available

Figure 2 Collection of water drained from the cultivation system after irrigation (left) and water transpired by plants as vapour and successively condensed on greenhouse roof (right).

for irrigation purposes, (2) the irrigation delivery system and last but not least, (3) crop requirements and sensitivity to stress possibly caused or increased by the occurrence of inadequate water chemo-physical characteristics.

Parts that are common to all water delivery systems for irrigation are:

1 pumping station to pump water into the irrigation circuit;
2 computer station to control automatic or manual valve opening and closure;
3 water treatment station for particle removal, chemical element removal and disinfection; and
4 network of valves, tubes and emitters (Fig. 3).

The main task of filtration apparatus is to eliminate suspended solids that could damage irrigation systems and components or cause them to clog. Many methods are available (Thompson et al., 2018), however the most widespread are those based on the application of hydrocyclones, discs, sand bed (slow filtration) system and sieve filters. In general, filtration operations remove particles within the range of 0.05–1 mm while microfiltration methods are required in the range of 0.1–10 μm. Microfiltration is a filtration process that implies the use of microporous membranes but is different from nanofiltration and reverse osmosis because it does not require active pressurization and is not suitable for the removal of contaminants. To correct the chemical characteristic of water, more sophisticated techniques and technologies are required, which include reverse osmosis, nanofiltration, ion precipitation and deionization (Thompson et al., 2018).

The main task of the irrigation system is to deliver water to plants to prevent drought conditions. Such a task is accomplished by restoring field/substrate capacity through the supply of water volume evapotranspirated in the time between two irrigations. However, for the correct crop management, additional (extra) water volumes could be required to induce ad hoc leaching

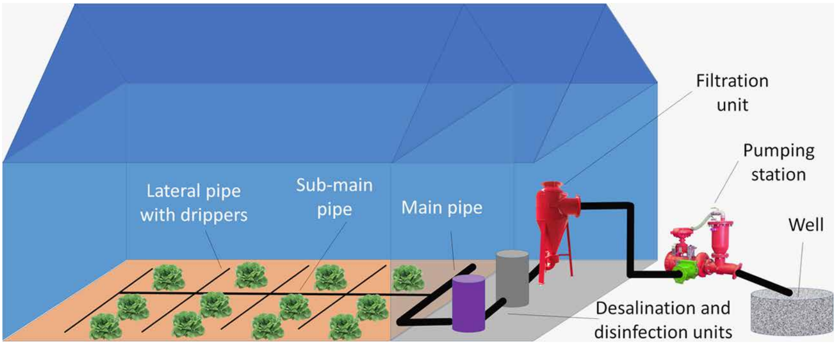

Figure 3 Schematic representation of a typical drip irrigation system for a greenhouse.

phenomena during irrigation. Depending on the cropping system, a network of valves, tubes and emitters must be realized to connect water sources to the growing environment, thereby ensuring optimal distribution of water to each growing unit. Sustainable water use in greenhouse systems mostly depends on how irrigation systems are designed in order to perform at the highest level as a function of crop needs, final production targets, soil/substrate characteristics and climatic conditions. Efficient use of water for irrigation systems is mainly concerned with the level of technology and irrigation engineering. It can be generally evaluated in terms of irrigation efficiency (IE) calculated as the ratio between 'water beneficially used' and 'total water applied' (van Halsema and Vincent, 2012). Typical uses for different irrigation systems have been reported in the literature as well as more specific indices for water distribution and conveyance efficiency (Hsiao et al., 2007; van Halsema and Vincent, 2012).

2.2 Microirrigation

The highest levels of efficiency and distribution precision in irrigation can be achieved in greenhouse systems, through the application of microirrigation (Evans and Sadler, 2008; Levidow et al., 2014). This technique can be adopted in a very broad variety of cultivation systems, from soil to soilless conditions, and different crop types from ornamental species to edible plants. Microirrigation implies the adoption of irrigation systems characterized by low flow rate and low pressure (i.e. 0.5–4 bar) in which water is delivered within a very limited area surrounding the plant thereby maximizing the interception of water by roots while limiting evaporation and percolation phenomena. The main advantages of microirrigation are

1. high IE due to the low risk of water runoff and evaporation;
2. indirect control of weeds;
3. lower risk of the occurrence of pathogens;
4. improved irrigation scheduling and water supply that can be accomplished over the day including during the warmest hours;
5. reduced soil compaction and erosion; and
6. fertigation.

Moreover, this technique is the only one that can be applied to carry out particular irrigation strategies such as, for example, deficit irrigation (Evans and Sadler, 2008) or other agronomic practices to improve WUE and other crop performances (Dasberg and Or, 1999). The combination of drip irrigation and plastic mulching is, for example, one of the most reliable strategies to ensure efficient nutrient, water and weed management (Vázquez et al., 2005, 2006).

The very high theoretical uniformity performed by microirrigation systems (up to 90%) is sometimes not achieved on farm level due to poor maintenance and insufficient system design (Hsiao et al., 2007). Therefore, microirrigation systems often perform at levels lower (as little as 75%) than expected when evaluated under operational conditions (Levidow et al., 2014). Indeed, high precision in the working principle implies high precision in the design of irrigation systems. For this purpose, mathematical models have been developed for spacing tubing and emitters as a function of soil hydrological characteristics (Schwartzman and Zur, 1986; Amin and Ekhmaj, 2006) while soil slope is, generally, not an issue in greenhouse production as otherwise reported for open field cultivation (Baiamonte et al., 2015).

Microirrigation systems are generally composed of a station pumping water into the main and sub-main pipelines from which lateral mains branch off. Main pipes are commonly made of polyvinyl chloride (PVC) or polyethylene (PE) while drip lines are mostly made of low-density polyethylene (LDPE). Accurate water filtration and chemical treatment are both important to prevent the accumulation of inert particles and the formation of biofilm in the irrigation circuit that may eventually cause clogging of the emitters due to the reduced dimension of nozzles (Yan et al., 2009). For this purpose, pipes manufactured recently aim at achieving antimicrobial and anti-root characteristics that, however, are often performed through the addition of chemicals potentially harmful to the environment (Thompson et al., 2018).

In microirrigation systems, water can be supplied to the crop by different aerial, surface and subsurface techniques, depending on the choice of equipment (Fig. 4).

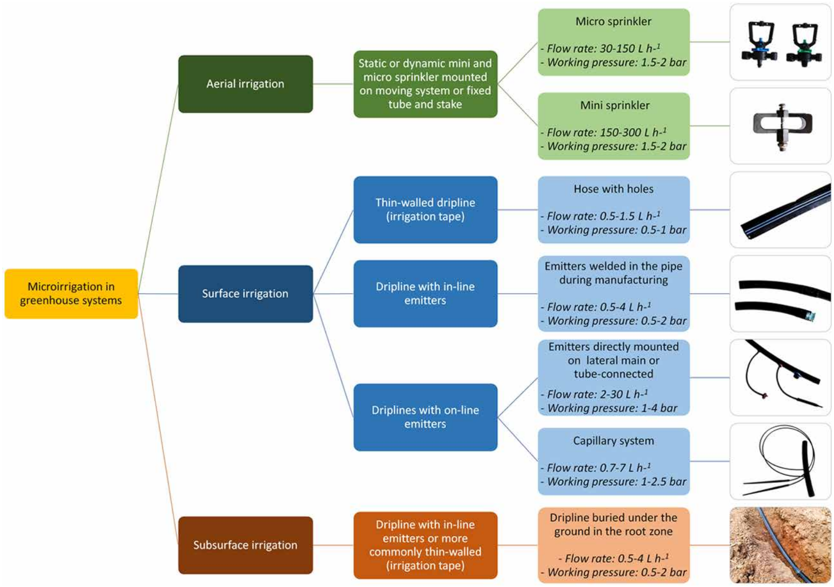

Figure 4 Overview and main characteristics of different microirrigation systems for greenhouses.

Depending on the type of water distribution, two main techniques can be distinguished, that is by spray and by drop. Mini- and microsprinklers are both spray emitters that allow the advantages of sprinkler irrigation to be combined with those typical of microirrigation techniques. Mini- and microsprinklers can be static or dynamic bodies depending on whether parts of the emitter move or not during water supply. Moreover, they can be mounted on moving and semi-moving bars or directly on static PVC pipelines. The application of microsprinklers is sometimes preferred to drippers for their effects on canopy microclimatic conditions (Dasberg and Or, 1999).

Drip irrigation is probably the most widespread form of greenhouse microirrigation, allowing very high WUE through smart and precise irrigation control (Dasberg and Or, 1999; van Halsema and Vincent, 2012). Two types of lateral mains can be adopted that differ depending on how the emitters are installed, that is (1) in-line emitters or driplines and (2) online emitters (Thompson et al., 2018). The simplest form of microirrigation (in-line emitters) is represented by the thin-walled dripline, or irrigation tape, consisting of a hose with prefixed holes without any flow rate control. More advanced dripline types entail the presence of emitters in the pipe welded during manufacturing, so that emitters and pipe together form a single entity. Online emitters are instead mounted on top of lateral pipes, can be installed directly on the lateral main, spacing as preferred, for example, as a function of plant density. In this case, a hole is made on the LDPE pipe and then the emitter barb is pushed in the hole. However, the emitters can be installed nearby the pipeline using auxiliary tubes, which connect the emitter to the lateral pipe (Fig. 3). In this case, the position of the emitters can be changed as preferred thus matching different plant spacing, therefore this technique is often chosen for container productions (Dasberg and Or, 1999; Raviv and Lieth, 2008).

Emitters can differ for the flow rate (volume of water supplied per unit time) and the method to control it. Two working principles are the most common in the manufacturing of emitters. In one case, a labyrinth causing water turbulence inside the emitter reduces the flow rate to the target value. In diaphragm emitters, instead, a flexible diaphragm controls the flow rate; although more precise in controlling flow rate and pressure, the latter are less durable and more exposed to clogging. Emitters able to keep the flow rate constant are called pressure-compensating (Dasberg and Or, 1999; Thompson et al., 2018). In addition, anti-leak is a desirable characteristic that prevents water flows after stopping irrigation, thus ensuring no water flush from the pipe. A simpler solution, widely applied, consists of the adoption of a capillary ('spaghetti') system, which is preferred for its low cost, operational simplicity and flexibility. In this case, a capillary tube, whose internal diameter commonly varies between 0.5 and 1.5 mm, is inserted into the lateral main (usually a 15–25 mm LDPE pipe) from one side and into a passive plastic stake from the other side. Capillary internal diameter and length are the parameters used to control the flow rate other than operational pressure (i.e. 1–2.5 bar): the higher the diameter of the capillary and pressure, the higher the flow rate of supplied water, while the opposite can be observed for capillary length (Fig. 5).

Subsurface drip irrigation can be performed by driplines, usually irrigation tapes, positioned below the ground at a depth that usually varies, as a function of the cropping system, between 10 and 50 cm. Generally, the higher the water infiltration rate, the lower the depth; however, it also depends on the root depth. The tape is buried automatically from a roll mounted on customized tractors. The adoption of subsurface drip irrigation can greatly improve the use of irrigation through the supply of water directly in the root zone whereby possible evaporation from the surface becomes negligible. Besides its sustainability, the implementation of this technique allows many other advantages with respect to other drip irrigation techniques such as, for example, improved nutrient distribution and plant nutrient uptake, higher frequency of irrigation, higher practicability of the cultivation soil, lower soil compaction and indirect weed control. On the other hand, besides the risk of emitter clogging, which is one of its main operational limitations, other drawbacks can arise from the use of drip surfaces when compared with other drip irrigation systems, including higher installation costs, removal and recovery, limited tillage, tube posing, more difficult irrigation management and watering evaluation.

2.3 Subirrigation

In subirrigated crops, water comes from the bottom of the root zone and spreads throughout the substrate towards the upper layers thanks to

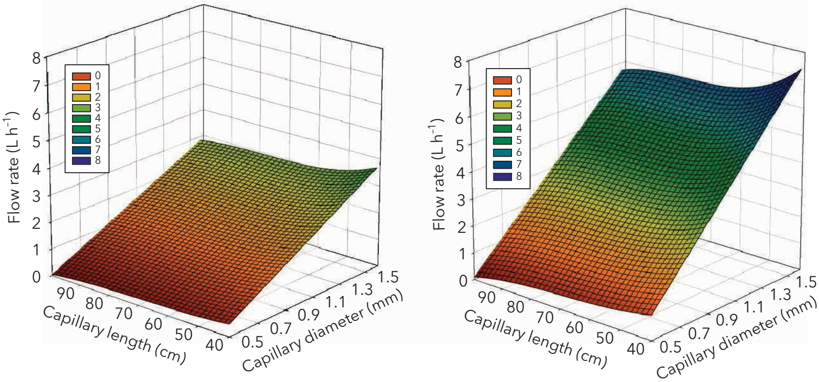

Figure 5 Irrigation system with capillary: example of flow rates simulated at 0.7 (left) and 1.4 (right) bar as a function of capillary diameter and length. Adapted from Incrocci and Riccò (2004).

capillary tension exerted by growing media. Therefore, basic conditions for successful subirrigation consist of (1) the presence of a substrate as a growing medium with high hydraulic conductivity; (2) physical continuity between the bottom of the substrate and the floor where water comes from; and (3) continuous hydration since the dry substrate capillary forces are not sufficient to ensure enough moisture in the root zone. Subirrigation is one of the most widespread techniques for water delivery in greenhouse systems that allows high uniformity for water distribution. The theoretical high WUE of subirrigation is mostly due to the fact that subirrigation practically exists only in the form of closed loop, rather than other zero-drainage systems (e.g. capillary mats), where water not absorbed by the crop during irrigation can be collected and reused in successive irrigation cycles after chemical adjustments if needed.

The effect of subirrigation in greenhouse systems has been evaluated in comparison with other irrigation systems, especially drip irrigation, on soilless ornamental (Rouphael et al., 2008a; Cardarelli et al., 2010) and vegetable crops (Rouphael and Colla, 2005; Incrocci et al., 2006; Rouphael et al., 2006). This technique demonstrates high performance in terms of plant yield and quality, allowing high nutrient and WUE, especially when water with moderate salinity is available for irrigation and discontinuous flushing of the nutrient solution arises from the management of closed-loop systems to avoid excess accumulation of undesired salts (Incrocci et al., 2006).

However, since water can evaporate from the irrigation floor, the evaporative component for evapotranspiration can be significant depending on the specific subirrigation technique, thus possibly reducing the efficiency of water. Moreover, unlike drip irrigation, in subirrigation systems the nutrient solution always tends to enter into the pot creating a unidirectional flow of nutrients from the bottom. From one point of view, this characteristic helps in closed-loop management since salts not absorbed by the crop do not accumulate in the recycled nutrient solution (Cardarelli et al., 2010). Nevertheless, along with the time, in long-cycle cultures, this may cause a heavy stratification of salts in the growing medium that, in the absence of water leaching from the pot, turns into increased electrical conductivity in the root zone (especially in the upper layer of the substrate), and uneven nutrient distribution (Rouphael and Colla, 2005; Rouphael et al., 2006). Saline irrigation water can drastically increase the accumulation of ballast ions; therefore, the use of good quality water is preferred in subirrigation systems.

Subirrigation systems usually entail the use of pots or slabs containing growing medium and can be roughly divided into three categories: flooded, trough and mat systems.

In the flooded tray or bench system, better known as the 'ebb-and-flow' system, the irrigation solution floods the bottom of the cultivation area causing a sub-immersion of the pots (roughly 5 cm). The pots are then arranged on benches periodically flooded for a period sufficient to restore optimal moisture conditions in the root zone (5–20 min). Immersion depth and time of exposure to irrigation strongly depends on the physical characteristics of the growing medium: water depth and irrigation duration have an inverse relationship with unsaturated hydraulic conductivity of substrates. Benches are usually made of plastic or metallic material, with a fluted base to facilitate water outflow after irrigation. The system is quite economical and requires moderate maintenance interventions; moreover, using mobile benches it is possible to exploit up to 80–90% of the greenhouse surface for cultivation. This technique can be applied in the cultivation of containerized crops (Cardarelli et al., 2010) and for plant propagation in nurseries (Santamaria et al., 2007). A cheaper option for flooded systems is the adoption of flooded floor. In this case, the irrigation solution is dispensed directly onto the floor of the greenhouse appositely built to the scope. Water ebb and flow usually occur through a central channel. The system allows for high mechanization of the cultivation process through the adoption of machineries that distribute pots in the area according to a desired plant density. The main drawback of the flooded systems consists of potentially high air humidity at canopy level, especially when the duration of flooding is high.

The trough system entails the arrangement of pots or slabs on sloping channels (0.5–1%) where the irrigation solution flows discontinuously for a time sufficient to restore in the root zone water lost by plant transpiration; the excess volume is collected in the drainage tank and reused in a closed loop. Plastic and metallic channels can be used in trough subirrigation; it is however fundamental that they do not bend under the weight of the pots to avoid waste stagnation. Space efficiency is slightly lower than other flooded systems (70–80%). The application of trough subirrigation was found suitable for tomato crops grown under moderate salinity allowing higher nutrient and water saving compared with drip irrigation (Incrocci et al., 2006; Montesano et al., 2010).

In the case of mat systems, a plastic film isolates the base of the cultivation area (e.g. plastic or metallic benches, concrete floor or even well-levelled ground) on which a fibreglass mat is positioned. The irrigation solution is supplied from one side and flows on the mat, which will soak, thereby distributing the irrigation solution to the pots. However, manufactured mats are available that integrate driplines with the fibres to improve water distribution. In the mat system, the holes of the pots must be on the bottom of the pot to allow contact between the potting medium and the mat. Furthermore, uneven levelling can bring about low irrigation uniformity due to the different moisture tension possibly occurring in the mat due to different height levels.

3 Irrigation management strategies

Smart and efficient irrigation faces contemporaneous challenges related to climate change, water demand for human activities other than agricultural production, and consumer and market requirements. This implies sustainable management strategies in a dynamic and flexible way as a function of variables that may also vastly differ from each other, such as human tendencies and behaviours to actual (measurable) needs and/or limitations in the use of water. In fact, if improving efficiency of water use is imperative to the responsible and sustainable use of global resources, the resulting social benefits can also be exploited as a marketing strategy, as well as obtaining added-value products. The adoption of adequate irrigation strategies is therefore a priority to achieve high economic and environmental sustainability of greenhouse cropping systems. New approaches arise and old ones can be adapted or revised to modulate water management, thereby facing limitations while exploiting new opportunities in the irrigation of greenhouse crops. Different irrigation strategies, herein reported, are available (1) to face limited water availability; (2) to prevent salt accumulation in the root zone; (3) to handle different water sources (e.g. municipal reclaimed water); and (4) to reuse water in the same cropping system or recycle it for the cultivation of successive crops in cascade-production cropping systems.

3.1 Strategies to optimize free-drain systems

3.1.1 Deficit irrigation (including RDI and PRD)

Deficit irrigation (DI) is a broad term used to identify those irrigation techniques that aim to reduce crop water supply in time and/or in space. The working principle of DI lies in the main assumption that plants exposed to drought are physiologically stimulated to improve plant–soil interaction mechanisms for enhancing water relations. Plants that are undergoing drought stress promptly reduce stomatal activity and trigger metabolic processes aimed at improving the uptake of water (Golldack et al., 2014). Based on the above assumptions, it has been demonstrated that it is possible to induce temporary water stress during specific phases of the cultivation cycle and/or in specific portions of the root zone in such a way to trigger plant reactions without causing permanent (irreversible) water stress, which would otherwise result in reduced produce yield and quality (Jones, 2004; Costa et al., 2007).

It should be highlighted that DI was primarily developed for tree crops in which the botanical characteristics of plants allow the safe management of this technique since ligneous organs, typically present in those species, generally make plants less sensitive to water stress compared with herbaceous plants. Moreover, the cultivation phases of tree crops include plant phenological stages from vegetative to reproductive phases during which water supply can be regulated *ad hoc* taking into account production targets. In practice, water stress is induced in these crops mainly during the vegetative phase. Such conditions and characteristics are not always present in the cultivation of vegetable and ornamental species such as, for example, leafy vegetables in which vegetative organs represent the harvested produce.

From an operational point of view, DI is more viable in soil-grown crops since applications in containerized production systems are highly risky due to the very limited volume of the root zone and relatively limited water buffer capacity available per plant. DI can be effectively managed by irrigation systems that allow high precision in water delivery and distribution, such as that of drip irrigation systems. The adoption of sensing techniques and technologies for monitoring crop water stress is strategic to carry out DI safely and fruitfully. This task can be accomplished in horticultural systems by the use of remote and proximity touch sensors for monitoring canopy or root zone water status (Incrocci et al., 2017; Tripodi et al., 2018).

The term DI is classically associated with a technique that implies irrigation volumes lower than actual crop evapotranspiration. However, for the sustainability of intensive protected cultivation, such a generalization would not be compatible with farmer economic targets due to the potential reduction in yield and quality depending on the extent of water limitation and crop-specific characteristics (Pulupol et al., 1996; Dorji et al., 2005). DI has two main principles of application, which consist of the regulated DI (RDI) and partial root zone drying (PRD). Table 1 reports a critical overview of different DI techniques tested for the irrigation of various greenhouse crops; in many experimental works, the application of DI results in enhanced WUE but lower yield. In summary, DI can be adopted in greenhouse cropping systems, although careful management and meticulous crop monitoring must be taken into account for successful application.

The physiological justification for the adoption of RDI lies in the fact that plant response to water stress varies during the cultivation cycle. Therefore, irrigation can either be regulated to cause plant reactions through a moderate water stress, or to reduce water supply when the plant is less sensitive; the two strategies or their combination would lead to enhanced crop WUE. The main difficulty consists in the identification of water stress thresholds as a function of the crop-specific response over the cultivation period. The main risk is that the narrow limits between light and severe stress could be suddenly surpassed if the greenhouse climate is not well controlled due to the high correlation between crop evapotranspiration and temperature or other correlated climatic variables (Jones, 2004).

In the PRD approach, water is applied to obtain the same effects of RDI in terms of plant response and water saving but alternately to different sides of the root zone. This expedient allows safer and more cost-effective plant watering since potential errors in the technique are counteracted by the well-watered

Table 1 Overview of works assessing the effects of different deficit irrigation (DI), regulated deficit irrigation (RDI) and partial root zone drying (PRD) strategies on produce yield and quality of typical greenhouse vegetable crops. The table reports a non-exhaustive compendium of experiments published in the period 2000–18

Crop	Strategy	Growing conditions/Treatments	Main results	Reference
Cucumber	PRD	Glasshouse, container experiment, perlite PRD 65% full irrigation in open and closed system	Comparable produce yield and quality in open system, 12% lower yield in closed system	Dasgan et al. (2012)
Green bean	RDI	Plastic greenhouse, soil experiment, sandy-loam soil covered with 0.3-m layer of loamy soil, 0.02-m layer of manure, 0.1-m mulch layer of coarse sand	Comparable yield in the autumn–winter season, 31% lower yield in the spring season	González et al. (2009)
Hot pepper	RDI	Plastic greenhouse, soil experiment, sandy-loam soil, drip and furrow irrigation RDI 33% and 66% full irrigation in three different growth stage = six treatments + control	Comparable yield in the drip irrigation with exception when applied during 'late fruit bearing and harvesting' stage, comparable yield in the drip irrigation only if applied during 'flowering and fruit setting' stage	Yang et al. (2017)
	PRD	Greenhouse, sand-loam-peat substrate PRD 70% full irrigation	Comparable yield and quality, significantly higher WUE	Sharma et al. (2015)
	RDI PRD	Greenhouse, soil experiment, clay-loam soil PRD × RDI 50% full irrigation in four different growth stages = eight treatments + control	Comparable yield only when PRD × RDI not imposed during 'bloom and fruit setting stage' or 'vigorous fruit-bearing stage'	Guang-Cheng et al. (2010)
	DI PRD	Glasshouse, soil experiment, clay-loam soil DI 75% and 50% commercial irrigation PRD 50% applied to one side or alternately	Comparable yield only for DI 75% significantly reduced otherwise, 21% higher WUE	Shao et al. (2008)
	PRD DI	Glasshouse, container experiment, bark-pumice-peat substrate PRD 50% commercial irrigation DI 50% commercial irrigation	PRD: 19% yield reduction, higher TSS, lower fruit number DI: 35% yield reduction, higher TSS, lower fruit number	Dorji et al. (2005)

Tomato	PRD	Multi-tunnel greenhouse, container experiment, sandy-silty substrate PRD 70% full irrigation PRD 50% full irrigation	PRD 70%: comparable yield, 27% higher water use efficiency PRD 50%: comparable yield, 65% higher water use efficiency	Affi et al. (2014)
	PRD	Glasshouse, container experiment PRD 70% and 50% full irrigation in open and closed system	Comparable yield and quality	Dasgan et al. (2009)
	DI PRD	Glasshouse and plastic tunnel, soil experiment DI and PRD 50% full irrigation	22% lower yield on average	Sirigu et al. (2007)
	PRD DI	Plastic greenhouse, soil experiment, clay soil PRD 50% ETc vs. full irrigated DI 50% ETc vs. full irrigated	PDR: 20% yield reduction, 50% water saving, reduced gaseous exchanges DI: 30% yield reduction, 38% water saving, reduced gaseous exchanges	Topcu et al. (2007)
	DI PRD	Plastic greenhouse, soil experiment, clay soil DI and PRD 50% full irrigation	Comparable yield	Kaman et al. (2006)
	DI PRD	Plastic greenhouses, soil experiment, clay soil DI and PRD 50% full irrigation	No significant difference for the statistics in yield, although 23% decrease was observed on average	Kirda et al. (2004)
Watermelon	RDI	Plastic greenhouse, soil experiment, sandy-loam soil RDI upper and lower limitations and sole upper limitation	Comparable yield in the winter-spring and autumn season, 11% lower yield in the winter season, comparable or better fruit quality	Yang et al. (2017)
	RDI	Plastic greenhouse, soil experiment, sandy-loam soil covered with 0.3-m layer of loamy soil, 0.02-m layer of manure, 0.1-m mulch layer of coarse sand	Comparable marketable yield	González et al. (2009)

part of the root zone; therefore, also less precision in monitoring crop water status is possible (Jones, 2004; Costa et al., 2007). By contrast, PRD requires a more complex irrigation net due to the duplication of sub-main pipes to allow switching irrigation from one dripline to another during cultivation (Thompson et al., 2018).

3.1.2 Leaching fraction control

Plant water uptake is driven by the difference in salt concentration between the water contained in the plant root and in the soil. If the concentration of the salts in the soil water is too high, the plant water uptake is reduced or stopped, leading to plant dehydration, yield reduction or, even, death of the plant. Another important issue of soil salinity is also the ion toxicity (mainly chloride) that could cause leaf necrosis.

The salt tolerance is well-studied in literature (Maas and Hoffman, 1977; Shannon and Grieve, 1999; Cassaniti et al., 2012) and crops show different sensibility to salt stress. Maas and Hoffman introduced in 1977 a general linear model to describe the general salt tolerance of a crop in terms of reduction of relative yield (Y) versus the electro-conductivity of soil saturated extract (SSE):

$$Y = \text{Min}\left[100;\ 100 - s\left(EC_{SSE} - EC_{SSE\text{-}TR}\right)\right] \tag{1}$$

therefore, salt tolerance can be adequately measured on the basis of only two parameters: (1) the threshold ($EC_{SSE\text{-}TR}$), that is the maximum salinity without yield reduction and (2) the slope (s), that is the percentage yield decrease per unit increase in salinity above the threshold (Fig. 6). According to this

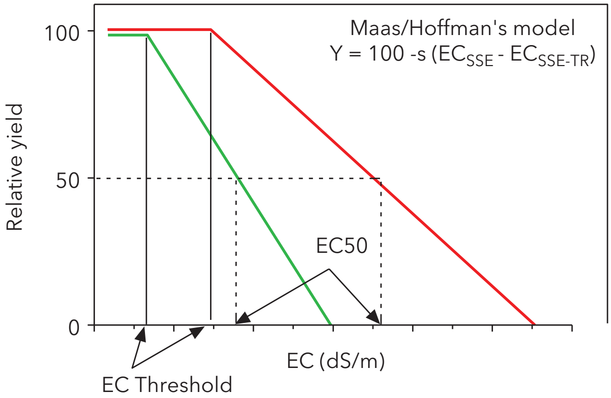

Figure 6 Schematic representation of the linear Maas and Hoffman's model. The green and red lines represent the yield-EC_{SSE} relationship of a moderately sensitive crop and a moderately salt-resistant crop, respectively.

model, the plants can be classified as sensitive, moderately salt sensitive or moderately salt tolerant: a classification of the main greenhouse crops is reported in Table 2.

The effect of salinity on soil-grown crops has been largely studied and expressed on the basis of the EC of SSE: in contrast, less information regarding the effect of substrate salinity on crop yield and quantity is present in the literature, and this information is put in relation to the EC of the substrate solution or the recirculating nutrient solution (EC_{SS}) instead of the SSE. Nevertheless, data obtained in soil salinity trials could also be used for an indicative estimate of crop salinity resistance into soilless systems using the relationship between the EC of the solution in the recirculating nutrient solution or in the substrate (SS) and the SSE, as proposed by Sonneveld (2000):

$$EC_{SS} = 1.6EC_{SSE} - 0.18 \tag{2}$$

Crop salt tolerance may depend on many environmental and genotypic factors, and sometimes the soilless culture could mitigate the negative effects of the salinity on the crop, as reported by Marcelis and Van Hooijdonk (1999) for radish.

Irrigating soil with water with a medium–high salt content (sodium and chloride – that are not essential ions for plant life – and calcium and magnesium) is one of the main causes of soil salinization. Control of salt build-up in the root zone is possible by leaching the salt accumulated in the soil/substrate: the correct calculation of the leaching fraction (the ratio between the drained and supplied water) can reduce crop salinity, thus minimizing the amount of water necessary.

The optimal leaching fraction (LF) can be calculated using the formula (Eq. (3)) proposed by Ayers and Westcot (1985):

$$LF = \frac{EC_I}{\left(5EC_{SSE\text{-}TR} - EC_I\right)} \tag{3}$$

where EC_I and $EC_{SSE\text{-}TR}$ are respectively the electrical conductivity of the irrigation water and the EC maximum value tolerated by the crop for the SSE.

3.2 Strategies to optimize water reuse systems

3.2.1 Closed- and semi-closed-loop systems

Closed-loop systems are growing systems where the water drained from the root zone can be collected and reused for irrigation of the same crop. Sometimes, when the water used for irrigation contains more salts than those absorbed by the crop, these will accumulate in the recirculating nutrient solution (or in the substrate) with the consequence that it is necessary to discharge (leaching) and

Table 2 Salt tolerance of the main vegetable and cut flower species grown in soil under greenhouse, according to the Maas-Hoffman model

	EC_{SSE} (mS cm^{-1})		EC_{SS} (mS cm^{-1})		
	EC_{TR}	Slope	EC_{TR}	Slope	References
Salt-sensitive crop					
Bean	1.9	19.0	2.9	11.9	Maas and Hoffman (1977)
Carrot	1.0	14.0	1.4	8.7	Maas (1986) – and instances below
Chrysanthemum	0.9	8.7	1.3	5.4	Barbieri and De Pascale (1992)
Eggplant	1.1	6.9	1.6	4.3	Maas 1986
Fennel	1.2	14.0	1.7	8.8	Graifenberg et al. (1996)
Lettuce	1.3	13.0	1.9	8.1	Shannon and Grieve (1999)
Onion	1.4	17.0	2.1	10.6	Shannon and Grieve (1999)
Pepper	1.5	14.0	2.2	8.7	Maas 1986
Radish	1.2	13.0	1.7	7.9	Shannon and Grieve (1999)
Rose	1.5	9.7	2.2	6.1	Barbieri and De Pascale (1992)
Strawberry	1.0	33.0	1.4	20.6	Maas and Hoffman (1977)
Moderately salt-sensitive crop					
Broccoli	2.8	9.2	4.3	5.8	Shannon and Grieve (1999)
Cabbage	1.8	9.7	2.7	6.1	Shannon and Grieve (1999)
Carnation	2.5	3.9	3.8	2.4	Barbieri and De Pascale (1992)
Celery	1.8	6.2	2.7	3.9	Maas 1986
Cucumber	2.5	13.0	3.8	8.1	Maas and Hoffman (1977)
Melon	2.2	7.3	3.3	4.6	Maas and Hoffman (1977)
Spinach	2.0	7.6	3.0	4.7	Maas and Hoffman (1977)
Tomato	2.5	9.9	3.8	6.2	Maas and Hoffman (1977)
Moderately salt-tolerant vegetables					
Artichoke	4.9	10.7	7.7	6.7	Graifenberg et al. (1993)
Asparagus	4.1	2.0	6.4	1.25	Maas (1986)
Cherry tomato	6.0	5.8	9.4	3.6	Gough and Hobson (1990)
Garden orach	6.4	4	10.0	2.5	Shannon and Grieve (1999)
Purslane	6.3	9.6	9.9	6.0	Shannon and Grieve (1999)
Rocket salad	3.5	9.0	5.4	5.6	Shannon and Grieve (1999)
Swiss chard	7.0	9.1	11.0	5.7	Shannon and Grieve (1999)
Table beet	4.0	9.0	6.2	5.6	Shannon and Grieve (1999)
Turnip	3.3	4.8	5.1	3.0	Shannon and Grieve (1999)
Zucchini, squash	5.1	11.6	8.0	7.2	Graifenberg et al. (1996)

Indicative data about the possible crop salt tolerance in soilless culture was also calculated applying the Sonneveld formula ($EC_{(SS)} = 1.6\ EC_{(SSE)}–0.18$).

Abbreviations: EC_{SSE} = EC (dS m^{-1}) of the soil saturated extract; EC_{SS} = EC (dS m^{-1}) of nutrient solution in the substrate; EC_{TR} = maximum EC tolerate by crop without growth reduction; slope = % of yield reduction per each dS m^{-1} increase in salinity above the EC_{TR}.

replace it with fresh nutrient solution. In this case, the system is defined as a semi-closed system.

The adoption of a closed-loop system may significantly increase water and nutrient use efficiency, and simplifies the irrigation scheduling, since potential over-irrigation events are buffered by the collection of excessive drainage. Nevertheless, four main drawbacks limit the large diffusion of closed-loop systems (Ehret et al., 2001; Bar-Yosef, 2008; Van Os, 2010): (1) the potential risks of the diffusion of root-borne diseases and the possible accumulation of plant and microbial metabolites with phytotoxic effects; (2) the difficulty in the nutrient replenishment of recirculating nutrient solution, due to the accumulation of non-essential and/or potentially harmful ions (sodium, chloride, sulphate, microelements and, in the case of hard water, calcium and magnesium as well); (3) the lack of technicians able to manage closed-loop systems; and (4) the high investment costs due to the equipment necessary to collect, disinfect and replenish nutrient elements in the recirculating nutrient solution.

In commercial soilless greenhouses, the disinfection of recirculating nutrient solution is strongly recommended to minimize risks of development of soil-borne diseases. According to Van Os (2010), the methods to disinfect the recirculating nutrient solution could be classified as physical (heat treatment, UV radiation, membrane filtration), physical-biological (slow sand filtration) and chemical (addition of ozone, hydrogen peroxide, sodium hypochlorite, chlorine dioxide, copper silver ionization and active carbon adsorption).

As a matter of fact, only four disinfection methods are commonly used: heat treatment, UV radiation, slow sand filtration and ozone addition.

Heat treatment consists of heating the drain water up to 95°C for a minimal exposure of 10 s: the method requires a cheap energy source. UV irradiation is based on the application of UV-C rays to a thin layer of nutrient solution: for a complete elimination of all possible pathogens, an irradiation dose of 250 mJ cm^{-2} is necessary. Slow sand filtration is a low-cost method to eliminate soil-borne pathogens, but *Fusarium* spp., viruses and nematodes are only partly (90–99.9%) removed by this method: pathogens are partially blocked by the sand in the upper layers of the filter, and are destroyed by a biologically active film that covers the sand grains. To ensure the filter works properly, the size of the sand particles (0.15–0.35 mm; $D10 < 0.4$ mm) and the flow rate (from 100 L m^{-2} h^{-1} to a maximum of 300 L m^{-2} h^{-1}) are fundamental parameters. Among the chemical methods, sodium hypochlorite and hydrogen peroxide are also cheap solutions, but their performance is sometimes insufficient. The addition of ozone at the dose of 10 g m^{-3} h^{-1} is a promising method to disinfect recirculating nutrient solution, since it presents no residue at the end of the treatment. Nevertheless, ozone treatment is not often used due to side effects including harmfulness to workers (irritation of mucous membranes), the inability to process large quantities of water at the same time, the investment cost (need of an ozone generator) and the partial oxidation of iron chelate.

3.2.2 Accumulation of phytotoxic substances

Another problem related to the adoption of closed soilless cultivation is the possible accumulation of phytotoxic substances from root secretion and organic substrate decomposition (Lee et al., 2006) during the long-term recycling of nutrient solution.

A lot of these compounds are simple water-soluble organic acids, straight chain alcohols, fatty acids, complex quinones, simple phenols, alkaloids, cyanogenic glycosides, phenolic acids such as benzoic acid, 4-hydroxy-benzoic acid, cinnamic acid, ferulic acid, salicylic acid, gallic acid, tannic acid, acetic acid, palmitic acid, stearic acid and so on (Lee et al., 2006). The accumulation of phytotoxic substances is one of the key factors causing continuous cropping obstacles of field and horticultural crops. Today, the removal of phytotoxic substances can be carried out using activated carbon adsorption and nano-TiO_2 photocatalysis (Qiu et al., 2013).

3.2.3 Cascade crops

The concept of the cascade cropping system is to use freshwater to irrigate the most sensitive crops (lettuce or strawberry, donor crops) and to employ the exhausted drainage (mainly for the high content in NaCl) collected from this culture for irrigating more tolerant crops such as cherry tomato, asparagus and zucchini (named user crops). Usually, greenhouse farms specialize in the cultivation of a few similar crops. It is therefore important that the crops used in the cascade belong to the same crop category (e.g. for cut flower farms a possible cascade crop could be roses or gerbera as donor crops and *Lisianthus* or Japanese limonium as user crops).

4 Irrigation scheduling

The term ‘irrigation scheduling’ identifies a systematic procedure that calculates the expected future water requirement over relatively short periods of time to meet all crop needs and avoid under- or over-application of water (Evans, 2008). Under-irrigation could result in a moderate plant wilt stress with a reduction in crop produce quality and yield, while over-irrigation could promote the development of plant diseases, an increase in energy cost for pumping as well as environmental pollution due to the large amount of water leached that also contains nutrients (Pardossi and Incrocci, 2011). For example, Thompson et al. (2007a) identified the poor management of drip irrigation in greenhouse crops as one of the main causes of nitrate leaching in the Almeria district (southeastern Spain), one of the most concentrated greenhouse areas in the world. Generally, the main cause of over-irrigation is the regulation of irrigation based on the grower's experience rather than on the real water crop needs (Incrocci et al., 2014). Since nutrient use and water are closely related, better water management generally results in improved nutrient use efficiency. Moreover, precise scheduling is crucial for the RDI, which aims to induce a mild water stress to the plant to save water and improve crop yield and produce quality (FAO, 2000; Jones, 2004).

As a matter of fact, irrigation scheduling must answer two basic questions: (1) how much water must be applied for each irrigation event (optimal irrigation volume) and (2) the timing for this application (irrigation turn or irrigation frequency). Generally, the optimal irrigation volume is quite easy to determine, while the right time of application of this volume remains the main weak point and problematic issue to solve in the farm in order to obtain a real improvement in water use in horticulture.

4.1 Determination of irrigation volume

The optimal irrigation volume (I) is divided in a net irrigation volume (I_{NET}, depending mainly on the water-holding capacity of the soil or substrate) and a second amount of water necessary to face possible (1) salinity build-up in the root zone due to the use of saline water, (2) uneven crop uniformity (i.e. differences in transpiration among plants) and (3) uneven water distribution of the irrigation system (i.e. difference in discharge rate of emitters, IE and uniformity etc.). Generally, this extra irrigation water volume is expressed as a safety percentage of the net irrigation (safety irrigation coefficient, Ks).

$$I = \mathrm{I_{NET}} \cdot \mathrm{K_S} \tag{4}$$

In other words, $\mathrm{I_{NET}}$ represents the amount of water depleted from the root zone between two subsequent irrigation events and corresponds to the water evapotranspirated by the crop during this time.

Soil and substrate moisture can be measured as volumetric water content (expressed as m^3 of water per m^3 of soil or substrate volume), or water (matric) potential (expressed as kPa or hPa). As the soil or substrate becomes drier, water potential, which is assumed to be close to zero at saturation, decreases and the value is more negative.

In soil, the amount of water available to the crop (AW) is defined as the difference between the moisture content at field capacity (water potential: –33 kPa) and at the wilting point (–1500 kPa). Water content at field capacity represents the water that the soil can hold against gravity, which is the water that remains in the soil after (over)irrigation and drainage. In general, horticultural crops are sensitive to water stress; consequently, to obtain the best productive performance the irrigation should be operated when only a fraction F (ranging from 0.30 to 0.50, depending on the crop) of AW is depleted. Another important parameter for soil irrigation scheduling is water permeability (or infiltration rate, expressed as mm rain that can be absorbed by the soil in an hour), which determines the rate of water application, especially in the case of overhead irrigation. The available water in a soil is strictly correlated with its texture, organic matter content and salt content. Some values of hydrological parameters are reported in Table 3 for different soils; a better estimation of an AW of a soil could be obtained using various online simulators (i.e. http://www.dynsystem.com/netstorm/soilwater.html) and software (i.e. SPAW software developed by the USDA-Hydrology and Remote Sensing Laboratory) able to simulate soil water tension, water conductivity and water-holding capability based on the soil texture, with adjustments to account for gravel content, compactness, salinity and organic matter.

In soilless culture, where substrates are used instead of soil, the calculation of AW is possible through the knowledge of the moisture retention curve (MRC), a relationship between the volumetric water content (θ) and the water matric potential (ψ_m). Generally, the MRC is determined in a laboratory by a suction table system (de Boodt and Verdonck, 1972; Kipp et al., 2001).

Conventionally, AW is defined as the difference between water content at –1 and –10 kPa matric potential, while easily available water (EAW) corresponds to the difference between water content at –1 and –5 kPa (de Boodt and Verdonck, 1972). Table 4 reports the main physical characteristics of some widely employed substrates in horticulture.

The range of matric potential values that define AW in a substrate is very different from those used in the soil (−1/−10 kPa compared to −33/−1500 kPa): this is due to the larger dimension of the particles of the substrate with respect to those of the soil, which results in a decrease of several orders of magnitude in the hydraulic conductance over a narrow range of suction values. In other words, when the ψm is more negative than −10/−15 kPa, the residual water

Table 3 Representative soil volumetric water content and water potential at saturation, field capacity, wilting point and infiltration rate for different soils

	Sand	Loam	Clay
Bulk density (kg L^{-1})	1.4–1.6	1.2–1.4	1.1–1.2
Soil water content at field capacity (L L^{-1})	0.10–0.18	0.25–0.35	0.35–0.45
Soil water content at wilting point (L L^{-1})	0.03–0.09	0.12–0.16	0.18–0.22
Available water (L L^{-1})	0.07–0.09	0.13–0.19	0.17–0.23
Infiltration rate (mm h^{-1})	> 40	20–40	3–15

Table 4 Physical properties of some widely used substrates in soilless culture

Substrate	Peat	Perlite	Pumice	Peat-perlite (1:1)	Peat-pumice (1:1)	Rockwool
Bulk density (kg L^{-1})	0.06–0.10	0.15–0.17	0.65–0.95	0.11–0.13	0.40–0.50	0.15–0.20
Porosity (% vol.)	92	75	68	78	77	93
Air capacity (% vol.)	38	70	29	32	20	15
AW[a] (% vol.)	33	9	4	28	18	78
EAW[b] (% vol.)	21	8	3	22	13	77

[a] Available water.

[b] Easily available water.

Source: Adapted from Reed (1996) and Kipp et al. (2001).

present in the substrate is unable to move across the substrate, and thus to reach the root system. These low values of water matric potential are consistent with the effects on water retention due to the gravimetric potential, related to the height of the water above the reference point (normally the bottom of the container). The force of gravity translates to approximately 1 kPa per 10 cm; so, at the end of an irrigation event, the layer of substrate at the bottom of the container will be completely saturated by water, while the substrate layer at the height of 10 cm will have a water retention equal to −1 kPa. Thus, the shape of the container is very important in determining the water-holding capacity of the substrate-container system. In this case, the term 'field capacity' is substituted by 'container capacity' (CC; water hold at the matric potential of –1 kPa). In general, for optimal plant growth, the water content in the container must not fall below 60% of the total container water-holding capacity (AWcc).

The knowledge of the AW of the soil and the crop root depth (RD, expressed in m) or the AW_{CC} of the container-substrate system and the container density (CD, expressed as number of containers per m^2) permits to calculate the optimal net irrigation (expressed as mm or L m^{-2}) for the soil (Eq. (5)) or the soilless (Eq. (6)) culture:

$$I_{NET} = \mathrm{AW} \cdot \mathrm{RD} \cdot F \tag{5}$$

$$I_{NET} = \mathrm{AW}_{CC} \cdot \mathrm{CD} \cdot F \tag{6}$$

where F is the percentage of the available water that could be depleted in the root zone between two subsequent irrigation events. For most greenhouse crops F ranges between 0.25 and 0.35 and 0.1 and 0.6 in soil and substrate, respectively.

The safety irrigation coefficient ranges from 1.15 (i.e. uniform crop and water distribution; use of low salinity water and salt-tolerant crops) to 2.0, which results in an LF (defined as the ratio between drainage water and applied irrigation water) from 13% until 50%. The safety irrigation coefficient could be optimized by an analytic calculation of the optimal LF according to the electrical conductivity of irrigation water (EC_I) and crop tolerance to salinity, as discussed in Section 3.2.1.

4.2 Irrigation turn or irrigation frequency

The irrigation frequency (I_F) is the number of irrigation events in a given period (generally one day or one week), while the irrigation interval (I_I) is the time (in days or hours) between two irrigation events.

In both cases, a precise hourly or daily knowledge of the crop evapotranspiration (ET_C, expressed as mm or L m^{-2}) is required:

$$I_F\left(\text{number of watering per day}\right)=\frac{E_{TC}}{I_{NET}} \tag{7}$$

$$I_I\left(\text{hours or days}\right)=\frac{I_{NET}}{ET_C} \tag{8}$$

Crop evapotranspiration is affected by many factors, either environmental (e.g. air temperature, radiation, humidity, wind speed) or plant related (e.g. growth phase, leaf area). Any method used for an accurate estimate of plant water requirements must take these environmental and plant factors into account. During the last few decades, many approaches have been proposed and tested in order to obtain robust and effective irrigation scheduling. These methods could be divided into four main groups according to how the ETc was estimated (see Table 5): (1) timer-based; (2) sensor and gravimetric-based (direct measurement of ET_C); (3) climate-based; and (4) 'speaking plant'. The first method is quite empiric and requires extensive experience of the grower. The methods belonging to the second group are based on a direct measurement of the ET_C and are generally more expensive, but easier to manage at the farm level. The third group involves methods based on an indirect measure of ET_C using models that are able to describe the ET_C through the measurements of various plant and climate parameters. Finally, in the last group the ET_C is determined by the measurement of transpiration or plant water status.

The *timer-based method* is a very cheap and easy approach to automatize irrigation, especially in soilless culture, where many irrigation events are necessary each day: it consists of the use of timers for many irrigation sectors, able to turn on and off with a pre-set time and irrigation length. The system is based on the use of highly porous media that are able to easily discharge the surplus of water supplied with irrigation. This represents the most used scheduling system, but is not very efficient in detecting the variation in ET_C during the day, resulting in high drainage percentage (sometimes above 40–50%) not justified by the water quality. The irrigations

Table 5 Values for the coefficients A and B of Baille equation (Eq. (12)) reported in the literature for some greenhouse crops

Crop	Growing conditions	LAI	A	B	Reference
Begonia	Pot plants	2.7	0.20	0.026	Baille et al. (1994)
Cyclamen		2.9	0.32	0.019	
Hibiscus		2.4	0.37	0.037	
Impatiens		5.1	0.67	0.013	
Pelargonium		5.7	0.61	0.017	
Poinsettia		2.0	0.12	0.017	
Schefflera		4.4	0.60	0.014	
Gardenia		4.5	0.46	0.019	
Gardenia		6.6	0.53	0.013	
Cucumber	Mediterranean regions (Almeria); autumn and spring; perlite pot substrate	0.5–2.6	0.26	0.034	Medrano et al. (2005)
			0.42	0.042	
			0.24	0.032	
			0.24	0.055	
Geranium	Mediterranean regions (Spain)	2.5	0.56	0.018	Montero et al. (2001)
Zucchini	Mediterranean regions (Italy); autumn and spring; pumice culture	0.5–5.5	0.63	0.009	Rouphael and Colla (2004)
Gerbera	Mediterranean regions (Almeria, Spain); autumn and spring; semi-closed rockwool culture	1.0–2.2	0.55	0.019	Carmassi et al. (2013)
Rose	Mediterranean regions (Greece); perlite pot culture	2.5–3.5	0.236	0.026	Kittas et al. (1999)
Tomato	Mediterranean regions (Spain); autumn and spring; perlite culture	2.5	0.580	0.025	Medrano, *pers. comm.*

must be distributed over 24 h, taking into account that 70%, 23% and 7% of daily ET_C is evapotranspirated respectively during the sunny hours of the day (10.00 am–6.00 pm), in the early morning and late afternoon, and, also, during the night.

4.3 Direct determination of crop evapotranspiration

An easy system to schedule irrigation is the direct and automatic measurement of the soil/substrate moisture variation in the root zone of some representative areas (sentinel plants) of the crop. The methods used are based on the measurement of the variation in weight (gravimetric method) of the root zone, the volumetric water content (dielectric sensors) or the water matric potential (tensiometers).

4.3.1 Weighing system

Irrigation scheduling may be controlled by one or more devices that measure continuously the weight of the whole substrate–plant system. This system is based on the assumption that in a short timeframe, changes in weight due to plant growth are negligible with respect to evapotranspiration losses (Fig. 7). After the end of each irrigation event, the system records the actual weight of the whole plant–substrate–container system; the user must set the maximum value of weight loss (the net irrigation volume) after which a new irrigation event will start. In the literature different examples of plant weighing systems are reported for tomato (Takaichi et al., 1996), gerbera (Baas and Slootweg, 2004), cucumber and tomato (CropAssist®, Helmer et al., 2005), Boston and coral lettuce (Chen et al., 2016). The system is very good for small potted plants, while some problems are encountered when it is applied to species with large or tall canopies: in all these cases, the oscillation of the plant canopy can result in an unstable and erroneous measurement of the plant weight. In the last few years, this system has been re-evaluated by the growers thanks to the huge reduction in the cost of load cells, and the development of specific software able to process automatically the raw data collected from the weighing.

Figure 7 Weighing gutter for automated monitoring of crop evapotranspiration and irrigation control in tomato substrate culture. The suspended trough with some tomato plants is connected to a load cell: the difference in weight between two consecutive irrigations represents the crop evapotranspiration in this interval. Photo: A. De Koning, Hortimax, Pijnacker, NL.

4.3.2 Tensiometers and dielectric sensors

Soil moisture sensors (SMSs) can be divided into two main groups: (1) sensors able to measure the matric potential of the soil/substrate (i.e. water-filled tensiometers or porous matric sensors) and (2) sensors able to measure the volumetric water content (dielectric sensors) (Pardossi et al., 2009).

A conventional tensiometer is a tube filled with water with a porous cup that maintains equilibrium between the pressure inside the cup and the suction potential in the surrounding soil: the measure of the matric potential is obtained by measuring the depression at the upper part of the water column using a pressure transducer. The hydraulic tensiometer could measure a pressure range from 0 to a theoretical value of −80 kPa (saturation vapour pressure), below which the cavitation phenomenon occurs (Nolz et al., 2013). Tensiometers are good tools for regulating irrigation in the wet band of the soil, as in the case of vegetable crops or in soilless culture (here, the wilting point is −10 kPa). Despite their sound performance and high accuracy (appreciated by scientists), tensiometers are not much used by growers due to the necessity of regular maintenance and fragileness. The matric potential limit of hydraulic tensiometers was overcome by the use of electrical resistance sensors (the most famous and economic is the Watermark® by Irrometer company, Inc.), able to measure from −10 to −20 kPa (Centeno et al., 2010), and porous matric sensors able to measure from −50 to −300 kPa (Whalley et al., 2007). These sensors have the drawback of difficult calibration, and appear to respond slowly in rapidly drying soil (Thompson et al., 2007b). The main advantages of sensors measuring the matric potential is the ability to choose a reproducible set point value of matric potential for irrigation management.

The second group of SMSs are able to estimate the volumetric water content by measuring the dielectric permittivity of the material surrounding the sensor, which is subjected to an electromagnetic field. For this reason, they are also known as 'dielectric' sensors.

There are different types of dielectric sensors, which use different types of output signal for estimating the volumetric water content (θ), and are based on time domain reflectometry (TDR), frequency domain (FD) (reflectometry and capacitance), time domain transmission (TDT), amplitude domain reflectometry or phase transmission methods. All these sensors differ in terms of use and maintenance, calibration requirements, accuracy and price.

Expensive and complex SMSs, such as TDR instruments, are available for soil and plant scientists, while low-cost and practical devices are needed for irrigation control of commercial crops. New types of SMSs that measure soil dielectric properties have opened up interesting possibilities (Pardossi et al., 2009). In particular, new dielectric SMSs based on FDR or FRC are cheaper and

Figure 8 Two examples of dielectric sensors for measuring substrate water content: SM 200™ (left) and WET™ (right), both commercialized by Delta-T device Ltd (UK). The latter sensor also measures substrate salinity (bulk EC) and temperature.

need much less maintenance and user expertise than traditional water-filled tensiometers (Fig. 8).

The main drawback of these sensors is that their calibration changes as a function of substrate and soil characteristics, and requires knowledge of the MRC for the choice of the right water capacity threshold to start the irrigation event. In any case, the grower can overcome this problem by an empirical, although quite effective, *in situ* calibration of the sensor: after placing the dielectric sensor in the soil, the grower observes the soil/substrate volumetric water content measured by the dielectric sensor during each irrigation event, in order to choose the right set point soil/substrate moisture value.

The use of dielectric sensors for fertigation management also makes possible the automatic modulation of fertilizer addition to the recirculating nutrient solution as well as the mix of different water quality sources.

Recently, an automated fertigation device was designed and successfully tested to modulate both irrigation frequency and EC of fertigation water, based on the simultaneous measurement of θ and pore water EC (EC_{PW}) of the growing medium by means of the WET sensor (Incrocci et al., 2010). Specific algorithms were implemented in the control software with the intention to activate irrigation when a pre-set θ threshold was reached and to modulate irrigation dose and/or nutrient solution EC (also by mixing different sources of water such as recirculated water, groundwater, rainwater etc.), to avoid salt accumulation in the substrate and minimize water drainage.

4.4 Modelling crop evapotranspiration in greenhouse

Crop evapotranspiration can be predicted by climatic (i.e. global radiation, air humidity and temperature, wind) and crop parameters (mainly leaf area index, LAI, and crop resistance) using different approaches as for example proposed by the FAO-56 methodology with the Penman–Monteith (PM) equation. This is commonly called the 'two-step approach', since the crop evapotranspiration (ET_C) is calculated through a previous estimation of the potential evapotranspiration (ET_0) and a successive adjustment obtained by multiplying the estimated value by a crop-specific coefficient (Kc):

$$ET_C = ET_0 \times K_C \tag{9}$$

Bacci et al. (2011) reported an exhaustive discussion on how to calculate ET_0 using the PM equation. A further useful equation for ET_0 calculation of crops with high LAI and plant density is the CIMIS equation (CIMIS, 2009), which runs on an hourly basis and therefore is more accurate than the PM equation under greenhouse or nursery conditions (Bacci et al., 2011).

In the past, the application of the FAO-ET model was strongly limited by scarce information on both daily ET_0 and crop coefficient. Today, the knowledge of the daily or hourly ET_0 is not a problem, since many commercial companies offer affordable weather stations, while the choice of the right crop coefficient still remains the main obstacle that limits the widespread use of this model.

In fact, crop coefficients depend on LAI but also on leaf stomatal resistance. This could be modelled as a function of some environmental condition, mainly irradiance and vapour pressure deficit. For example, Rouphael and Colla (2005) reported that in a pot-grown zucchini greenhouse cultivation, the stomatal resistance could be correlated to global radiation by an exponential model.

Consequently, many authors (e.g. Shuttleworth, 2007) have suggested that a better approach to ET_C evaluation would consist of directly calibrating the PM equation on the basis of crop evapotranspiration. It is called the 'one-step approach' in which the canopy surface resistance (r_s) of the crop would play the same role as the crop coefficient Kc present in the two-step approach.

4.4.1 PM model and simplified model: a case study of Gerbera evapotranspiration

Carmassi et al. (2013) compared the PM model, to estimate the evapotranspiration of a greenhouse gerbera crop under typical Mediterranean climate conditions, with the one-step PM model and other two simplified methods.

The PM equation is reported below:

$$\lambda \cdot \mathrm{ET}_C = \frac{\Delta \cdot 0.981 I \cdot \left(1 - \exp^{-k \cdot \mathrm{LAI}}\right)}{\Delta + \gamma \cdot \left(1 + r_\mathrm{c} / r_\mathrm{a}\right)^{*}} + \frac{\left(\frac{\rho \cdot c_\mathrm{p}}{r_\mathrm{a}}\right) \cdot \left(e_\mathrm{a}^{*} - e_\mathrm{a}\right)}{\Delta + \gamma \cdot \left(1 + r_\mathrm{c} / r_\mathrm{a}\right)} \tag{10}$$

where crop ET_C (kg m^{-2} s^{-1}) is based on ground area, λ (J kg^{-1}) is the latent heat of vapourization of water; I (W m^{-2}) is the global radiation over the crop; k (dimensionless, determined as 0.60 ± 0.02 with $n = 40$) is the light interception coefficient; LAI is the leaf area index; ρ (kg m^{-3}) is air density; c_p (J kg^{-1} K^{-1}) is the specific heat of air at constant pressure; e_a (kPa) is the air vapour pressure; e_a^{*} (kPa) is the saturated air vapour pressure; Δ (kPa $°\mathrm{C}^{-1}$) is the slope of the linear relation of saturation vapour pressure versus temperature, γ (kPa $°\mathrm{C}^{-1}$) is the psychrometric constant; and r_c and r_a (s m^{-1}) are, respectively, the mean canopy resistance and the aerodynamic resistance to vapour transfer.

Considering that in an unheated greenhouse I_n (net radiation) matches I during the light period (Baille et al., 1994), in Eq. (10), global radiation (I) was used instead of I_n. In another experiment, conducted in 2006 with gerbera grown in the same glasshouse (unpublished results), a close linear relationship was found between I_n and I ($I_\mathrm{n} = 0.981\ I$; $R^2 = 0.902$; $n = 487$) in the range between 25 and 545 W m^{-2}. Leaf area index was estimated as a function of growing degree days (GDD) assuming a base temperature of 8°C, using the following experimental relationship (validated in the 1–2.4 LAI value range):

$$\mathrm{LAI} = (1.043 - 2.448) \cdot \exp^{-0.0066 \cdot \mathrm{GDD}} + 2.448 \tag{11}$$

In this experiment, no clear relationship between r_a and climatic variables was found, therefore the Ra was assumed as a constant value throughout the seasonal period. The PM calibrated equation was able to predict the *Gerbera* ET_C: the slope of the regression equation between predicted and measured data was nearly 1, the intercept was negligible and the R^2 was close to 0.90.

4.4.2 The simplified models for the prediction of crop evapotranspiration

The FAO PM equation is currently considered a standard reference (Stanghellini, 1987; Allen et al., 1998; Walter et al., 2002). However, its application is not straightforward as it requires the knowledge of several variables and parameters. Therefore, several authors proposed simplified equations for predicting ET as a function of LAI, intercepted radiation (MJ m^{-2} h^{-1}) and vapour pressure deficit (kPa).

Transpiration rate was also modelled using the regression equation proposed by Baille et al. (1994):

$$ET_C = A \cdot \frac{\left(1 - \exp^{-k \cdot LAI}\right)}{\lambda} + B \cdot LAI \cdot VPD \quad (12)$$

Carmassi et al. (2013) also calibrated the above equation using the multiple regression method for the measured ET_C collected on cut flower gerbera against the variables $\left(1 - \exp^{-k \cdot LAI}\right)$ (MJ m^{-2} h^{-1}) and (LAI·VPD). They obtained the values 0.546 and 0.019 respectively for coefficients A (dimensionless) and B (kg m^{-2} h^{-1} kPa^{-1}): LAI and k values were the same as used in the previous P-M calibration.

The low value of B coefficient in Eq. (12) suggests that in the Mediterranean area, especially in unheated greenhouses, the ET_C is driven mainly from the incident global solar radiation (radiative component), and thus the aerodynamic term of the Eq. (12) (LAI·VPD) could be excluded without substantial errors in the predicted values of ET_C. Upon this evidence, Carmassi et al. (2013) proposed and validated a simplified Baille's model on gerbera, where the A value could be calculated applying a linear regression (forced by the origin) of ET_C against the light effectively intercepted by the crop:

$$ET_C = A \cdot \frac{I \cdot \left(1 - \exp^{-k \cdot LAI}\right)}{\lambda} \quad (13)$$

The equation predicted satisfactorily the ET_C during the day, while it produced some errors during the night: nevertheless, the formula is very easy to manage and requires only a radiometer to collect data.

Similar results were found on a semi-closed soilless tomato culture (Carmassi et al., 2007; Massa et al., 2011), using a similar equation to predict ET_C on a daily basis:

$$ET_C = A \cdot \left(1 - e^{-k \cdot LAI}\right) \cdot \frac{I}{\lambda} + B \quad (14)$$

where *A* (0.946, dimensionless) and *B* (0.188 L m^{-2}) are empirical constants, *k* is the canopy light extinction coefficient (0.69, dimensionless; Carmassi et al., 2007) and *λ* (2.45 MJ kg^{-1}) is the latent heat of water vaporization.

In this case LAI was assumed to obey a sigmoid function of thermal time expressed as GDD:

$$\mathrm{LAI} = a_1 + \frac{\left(a_2 - a_1\right)}{1 + e^{\left(\frac{a_3 - \mathrm{GDD}}{a_4}\right)}} \tag{15}$$

where a_1 (−0.335), a_2 (4.803), a_3 (755.3) and a_4 (134.7) are regression coefficients.

GDD was computed since sowing from *T* using 8°C as basal temperature. Eq. (15) is valid for *GDD* ranging from 400 (approximately the value at transplanting) to 1600 and LAI up to 4.8.

The use of these simplified methods instead of PM equation aims to simplify the use as well as the auto-calibration for crop evapotranspiration. Many authors have confirmed the reliability of the Baille equation, as summarized in Table 5. In practice, in many commercial greenhouses, growers supply an irrigation volume when a cumulated global solar radiation threshold is reached, and then adjust this threshold according to the information obtained from the LF measurements.

4.4.3 Methods based on plant water status

An alternative approach to irrigation management is the monitoring of plant water status, known also as 'plant stress sensing' (Jones, 2004; Fernandez and Cuevas, 2010; Ruger et al., 2010; Cahn and Johnson, 2017). According to Jones (2004), the methods based on this approach can be divided into two categories: (1) methods measuring the plant water status either as visible wilting leaf thickness, fruit or stem diameter, or by means of pressure chamber, leaf pressure probe (ZIM pressure probe), psychrometer; and (2) methods measuring some physiological responses such as stomatal conductance (using porometer, thermal sensing camera or sap flow sensor) or growth rate.

The pressure chamber is the main system used for determining the water status of the plant. The method is based on the pressure necessary to counterbalance the xylem pressure of a leaf or leafy twig. The measurement is very simple, but is time consuming and destructive, so continuous recordings cannot be carried out. A new solution for the continuous measurement of turgor pressure of plant leaves over long periods of time was proposed by Zimmermann et al. (2013), with a non-invasive, magnetic leaf patch clamp pressure probe (also known as ZIM-probe, commercialized by YARA GmbH).

The leaf thickness approach consists of the measurement of leaf turgidity. The system was tested and can be used as an alarm for potential water deficits (e.g. Leaf-Sen Irrigation Systems, Givat Hayim Ichud, Israel).

The sap flow system was developed mainly for trees. Basically, a flow sap sensor consists of a central needle that produces a heat pulse, and two additional symmetrically placed needles that act as temperature sensors. The flow of the sap is estimated by the temperature ratio of the two sensing needles, following the release of a heat pulse by the heater needle (e.g. Dynamax, Houston, TX).

In addition, the stem diameter variation has interesting applications mainly for woody plants, but is not suitable for most greenhouse crops.

By measuring the ratio of heat transported to two symmetrically placed temperature sensors, the magnitude and direction of the water flux can be calculated.

The use of infrared thermal cameras for measuring temperature differences between the air and the crop canopy is used to detect the early symptoms of a DI. At present the use of these cameras to schedule irrigation does not appear appropriate for greenhouse crops, since when the crop canopy temperature starts to increase, the water stress phenomenon has already begun. On the other hand, these devices are very interesting as a preliminary alarm to prevent the effects of irrigation failure.

Until now, most methods based on plant water status are mainly used for research purposes, and their implementation in commercial farms is limited due to the expensive investment costs and/or by necessity of qualified technicians for their use.

Nowadays, the most important irrigation companies have integrated different kinds of plant water status sensors in a control system for the management of both irrigation and climate in greenhouse production systems (e.g. Hortimax, Pijnacker, the Netherlands; PhyTech, Yad Mordechai, Israel), together with other more traditional sensors such as tensiometers or dielectric sensors. In the future, thanks to a reduction in costs and developments in electronics, these kinds of sensors could be used extensively in commercial greenhouses.

5 Coupling crop management practices with IE

5.1 Vegetable grafting

In vegetable crops, grafting was essentially rediscovered in the past 20 years and expanded on a large scale as a sustainable alternative to soil sterilization by means of methyl bromide (Kumar et al., 2017). In spite of the use of grafting as agro-technology for reducing disease damage, recent research reported the potential of this crop management practice to alleviate several abiotic factors (Colla et al., 2011; Rouphael et al., 2012) including water stress (Kumar et al., 2017). This is especially important for greenhouse vegetable cropping systems characterized by a shallow-rooted system and their high crop water requirements (Rouphael et al., 2008). Therefore, understanding how grafted plants can minimize water use without significant reduction in crop productivity (increasing WUE) is a basic requirement for the continued success of this agronomic practice. In a recent greenhouse experiment, Liu et al. (2016) demonstrated that luffa rootstock (*Luffa cylindrica* Roem. cv. Xiangfei No. 236) exhibited higher crop growth parameters, in particular leaf area and dry biomass, leading to a higher instantaneous WUE (defined as the ratio of the CO_2 assimilation rate and transpiration rate) when grafted with its own scion or with cucumber (*Cucumis sativus* L. cv. Jinyan No. 4). The beneficial effect of grafting on several fruit vegetables such as tomato, mini-watermelon and pepper onto vigorous rootstocks was also reported in a set of studies conducted mainly under greenhouse conditions. For instance, Ibrahim et al. (2014) and Al-Harbi et al. (2016) reported an increase in yield and yield WUE in tomato (*Solanum lycopersicum* L.) cv. Faridah grafted onto the interspecific tomato hybrid 'Unifort' (*Solanum lycopersicum* L.; *Solanum pimpinellifolium* L.), grown under both full (100% of crop evapotranspiration) and DI regimes (80%, 60% and 40% of crop evapotranspiration). Similarly, in watermelon Rouphael et al. (2008) observed a significant increase in marketable yield and yield WUE (by 60% and 10%, respectively) in pumpkin rootstock (*Cucurbita maxima* Duch. × *Cucurbita moschata* Duch.; cv. PS1313) grafted mini-watermelon [*Citrullus lanatus* (Thunb.) Matsum. and Nakai; cv. Ingrid] than in the non-grafted control. Moreover López-Marín and co-workers (2017) assessed the morpho-physiological responses of greenhouse sweet pepper (*Capsicum annuum* L.) cv. Herminio non-grafted or grafted onto three hybrid rootstocks, Atlante, Creonte and Terrano, under two well-watered (100% of crop evapotranspiration) and water stress conditions (50% of crop evapotranspiration). Pepper yield was higher in the three grafting combinations than in non-grafted plants, regardless of the irrigation regime used (constitutive response). However, among the three hybrid rootstocks tested, Creonte was the most effective in improving yield and yield WUE of grafted plants.

The effectiveness of vegetable grafting using vigorous rootstocks to increase yield and yield WUE of fruit vegetables has been associated with several improved traits of grafted vegetables such as (1) more vigorous root system architecture in terms of density, area and length; (2) improved water and nutrient uptake and assimilation; (3) enhanced photosynthetic capacity and water relations; (4) more resilient oxidative defence system; (5) modulation of hormonal balance; and (6) long-distance movement of mRNAs, small RNAs and proteins (Albacete et al., 2015; Kumar et al., 2017).

5.2 Plant biostimulants

The use of plant biostimulants has also been proposed as a sustainable and meaningful approach to boost yield and WUE of greenhouse vegetables and ornamentals (Colla and Rouphael, 2015). The term ‘Plant biostimulants’ has been adopted by many scientists to denote ‘*substances and/or microorganisms applied to plants with the intention to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits, regardless of its nutrients content*’ (du Jardin, 2015). Plant biostimulants include bioactive substances (humic acids, protein hydrolysates and seaweed extracts) and microorganisms (mycorrhizal fungi and plant growth promoting rhizobacteria of strains belonging to the genera *Azospirillum*, *Azotobacter* and *Rhizobium* spp.). In the last few years, plant biostimulants have been claimed to activate, under a limited irrigation regime, a series of molecular and physiological mechanisms such as the enhancement of leaf–water relations, an increase in relative water content and pigments biosynthesis as well as reducing stomatal limitation, which in turn led to higher water uptakes (Colla et al., 2013, 2014, 2015a,b, 2017; Xu and Leskovar, 2015; Abd El-Mageed et al., 2017).

In a recent research study, Abd El-Mageed et al. (2017) reported that the foliar application of leaf extract of *Moringa oleifera* (3%) was effective in increasing WUE in zucchini squash grown under mild and moderate water stress conditions (60% and 80% of crop evapotranspiration, respectively). Similarly, foliar spraying or root drench application of brown seaweed (*Ascophyllum nodosum*) extracts also improved the yield WUE of important leafy greens such as spinach (Xu and Leskovar, 2015). A putative mode of action involved in the stimulation of crop performance and increasing WUE under water stress conditions might be the capability of maintaining higher chlorophyll synthesis and fluorescence, improvement of photosynthetic activity and leaf water relations as well as a reduction in stomatal limitations. Saving water and increasing WUE could also be attained by microbial biostimulants inoculation in particular with arbuscular mycorrhiza fungi. For instance, the WUE was higher in inoculated (*Funneliformis mosseae* BEG25, *Funneliformis geosporus* BEG11 or a 50:50 mixed inoculation treatment of both species) strawberry plants than in non-inoculated plants under water stress conditions (Boyer et al., 2015).

Similarly, inoculation with a mixed inoculum of *Glomus intraradices* and *Glomus mosseae* has been reported to improve yield and WUE by 20% in watermelon under water stress regimes compared to non-inoculated plants (Omirou et al., 2013). The increase in root growth, the improvement in root system morphology (root diameter, total root length and diameter) and the development of external mycelium may have enhanced nutrient availability, uptake and translocation of the inoculated plants (Rouphael et al., 2015).

6 Future trends and conclusion

The constant pressure on vegetable growers to produce food for an increasing world population while minimizing excessive use of water and consequently fertilizers is a major challenge for the scientific community, which is expected to develop sustainable approaches and tools that increase WUE. Future studies should focus on the optimized use of water resources through the application of strategies for collection, storage and reuse. For instance, a fundamental issue for increasing the WUE of greenhouse crops will be the application of accurate irrigation scheduling, especially in soil-grown crops and in soilless open systems. In actual fact, the main problem concerning irrigation scheduling still remains the correct calculation of crop evapotranspiration: different approaches such as the direct measurements of the moisture in the root zone, the crop water balance or the monitoring of plant water status are available, each having both advantages and disadvantages. In the near future, the development of low-cost technologies for measuring crop water status could be the most important challenge in irrigation management. Another important research field will be the development of decision support systems that could help the greenhouse growers to manage soil salinity and irrigation scheduling.

Nevertheless, the main constraints to significant improvements in WUE in greenhouse crops relate to the high cost of these modern technologies and lack of knowledge of their use by the end users. As a matter of fact, in most worldwide countries, growers still decide when to irrigate their crop depending on personal experience, or at fixed intervals. In this sense, the improvement of IE seems related to a reduction in the overall cost of these technologies and to the policies adopted for their dissemination and transfer to professional growers. Finally, potential cultural practices such as vegetable grafting and the use of natural plant biostimulants can also appreciably affect the WUE of greenhouse crops. However, the knowledge about the potential benefits derived from applications of these strategies is far from being clear and widespread.

In the coming few years, future research should focus on innovative, simple and sustainable tools to control soil/plant water status and also to shed light on the genotype × environment × management practice interactions to define and select the best combination(s) that are able to enhance the water use efficiency in vegetable cropping systems. The overall impact of this chapter could be of interest for all horticultural actors including researchers, extension specialists and growers dealing with the vegetable sectors by identifying recent scientific studies regarding tools and techniques to determine the amount and timing of irrigation and of water, and thus increasing water use efficiency.

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