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Review article – Thematic Issue

Application of soilless culture technologies in the modern greenhouse industry – A review

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Summary

Soilless culture systems (SCS) are increasingly adopted as a major technological component in the modern greenhouse industry. The core advantage of soilless culture, frequently referenced to as "hydroponics", is the independence of the crop from the soil which, as a natural medium, is heterogeneous, accommodates pathogens, tends to degrade in monoculture systems, and may be infertile, saline or sodic. The cultivation on horticultural growing media (GM) such as rockwool, perlite, and coconut is worldwide the most frequently used SCS for production of fruit vegetables and cut flowers. Water culture systems such as floating hydroponics, Nutrient Film Technique and aeroponics are mainly used for production of leafy vegetables. Modern, fully automated fertigation heads are used for the preparation and timely supply of nutrient solution (NS), which serves both the nutrition and irrigation of the plants. In soilless culture, the NS that drains out of the root zone can be easily collected and recycled, thereby considerably increasing the water use efficiency and minimizing environmental impacts arising from fertilizer residues. The spread of pathogens via the recycled effluents is a challenge that can be encountered by introducing a suitable system for their disinfection before reusing, based mainly on UV radiation, slow sand or membrane filtration, or a chemical treatment (mainly O_3, H_2O_2 or chlorination). In SCS, the NS composition has to be adapted to the composition of the water used for its preparation, the plant species and even the cultivar, the growth stage, the season of the year and the current climatic conditions, and this is a challenge that can be encountered by using modern information and computer technologies. Last but not least, the frequency of irrigation in GM-grown crops is high due to the limited volume of rooting medium per plant and has to be efficiently controlled. Suitable automation technologies are mostly based on real-time measurement of parameters related either to the greenhouse microclimate (e.g., solar radiation, vapor pressure deficit, air temperature) or to the GM water status (water tension or content).

Keywords
closed system, growing media, hydroponics, nutrient solution, substrate, water culture

Significance of this study

What is already known on this subject?

- Soilless culture is a modern cultivation technology applied mainly in greenhouses which developed rapidly during the last 30–40 years. The major objective of this cultivation technology is the elimination of problems associated with the greenhouse soil, such as soil-borne diseases, poor soil fertility, salinity, etc. These main innovations during the 30–40 years that rendered soilless culture the leading cultivation technology in modern greenhouses include the development of suitable growing media (GM) with optimal physical, hydraulic, and chemical properties, such as rockwool and coir, and the advances in plant nutrition and irrigation via modern fertigation equipment and automation technologies.

What are the new findings?

- In the last years, the research on soilless culture has mainly focused on automation of nutrient and water supply, particularly in closed systems in which the excess nutrient solution is recycled. Special efforts are in progress in order to develop plant factories based on soilless cultivation technologies. Another aspect under investigation is the complete standardization of the substrate analysis in order to obtain more reliable results that can be comparable on a common basis, and to facilitate their interpretation. The present paper, as a mini-review, provides a concise overview of both standard and new findings in soilless culture based on a detailed literature survey.

What is the expected impact on horticulture?

- The complete control of nutrition via the nutrient solution in soilless culture systems and the optimal physicochemical environment in the root zone due to the use of GM result in higher yields in comparison to soil-grown greenhouse crops, and improve the product quality, particularly in vegetable crops, such as tomato, melon, and lettuce. Furthermore, the switching over from the soil to a soilless root environment results in decreased application of pesticides and other toxic agrochemicals, which are necessary in soil-grown crops to disinfect the soil and control soil-borne pathogens. Finally, the recycling of the excess nutrient solution that drains off after each watering application may contribute to a considerable reduction of nitrate and phosphate leaching to surface- and groundwater resources.

Introduction

The term “soilless culture” generally refers to any method of growing plants without the use of soil as a rooting medium (Savvas, 2003; Gruda et al., 2016a). Besides, “hydroponics” is frequently used as a synonym to “soilless culture”. Both terms are used interchangeably in this paper, although some scientists consider hydroponics a subgroup of soilless culture which excludes the cultivation on chemically active growing media (GM) such as peat, coir, zeolite, etc. (Adams, 2002). Currently, the soilless culture systems (SCS) are considered a major technological component of modern greenhouses due to their advantages. The core advantage of SCS is the independence of the crop from the soil which, as a natural medium, is heterogeneous, accommodates pathogens, tends to degrade in monoculture systems, and may be infertile, saline or sodic. The independence from the soil as a rooting medium in SCS enables optimization of both physical and chemical characteristics in the root environment and a more efficient control of pathogens without the need to apply soil fumigation. As a result, higher yields at a reasonable production cost with minimal use of pesticides and high product quality can be attained (Gruda et al., 2018, this issue).

Soilless culture systems and equipment

The SCS include both water culture systems with merely nutrient solution as root environment and cultivation on porous growing media (GM) which create a matrix that can retain both air and water at suitable ratios for plant growth. The SCS can be either open or closed; in open systems the drainage solution (DS) is discharged while in closed systems the DS is collected and reused.

Systems of cultivation on growing media

Cultivation on pathogen-free GM allowing maintenance of a suitable balance between water and air availability to the plant roots is the most common technology to commercially produce vegetables and ornamentals independent of the soil. The substrate-based hydroponic systems dominate over water culture systems because the ability of the substrate to retain water can provide a safety reserve, if a technical failure occurs. Furthermore, substrates can provide better root aeration than water culture systems other than aeroponics due to their porous nature (Van Os et al., 2002).

The lay-out of cultivation systems on substrates may vary, depending mainly on the substrate receptor (Van Os et al., 2008). The receptors of the substrate may be bags, pots, other types of containers, or troughs (Savvas et al., 2013). Although the cost of the substrate is higher when packed in bags, the bag culture is the most widely used type of cultivation on substrates because the bags can be standardized and are easy-to-handle, thereby minimizing labor costs and errors in installation. The bags are made of UV-resistant polyethylene sheet, white on the outside to reflect radiation, thereby limiting overheating, and black inside, to prevent algal development.

Before planting a new crop, no drainage is allowed and the substrate is irrigated up to the point of saturation, to ensure a complete filling of its pores with nutrient solution (Savvas et al., 2013). Immediately after planting, full drainage has to be allowed to avoid hypoxic conditions in the root zone. In a bag culture, drainage slits are cut, which can be vertical, oblique, or horizontal, but they should extend up to the bottom level of the bag to facilitate full drainage, thereby minimizing stagnation of nutrient solution at the lowest part of the root zone.

In cultivations on GM, the particle size of the GM and the container geometry have to be properly selected to balance water availability and aeration in the root zone (Figure 1). Especially the height of the substrate layer should be high enough to allow for good drainage and aeration, depending on the hydraulic properties of the substrate (Heller et al., 2015). Overall, GM dominated by fine particles perform better when placed in tall and narrow receptors, while coarser substrates should be placed into shallow bags or channels to ensure sufficient water availability (Savvas, 2009).

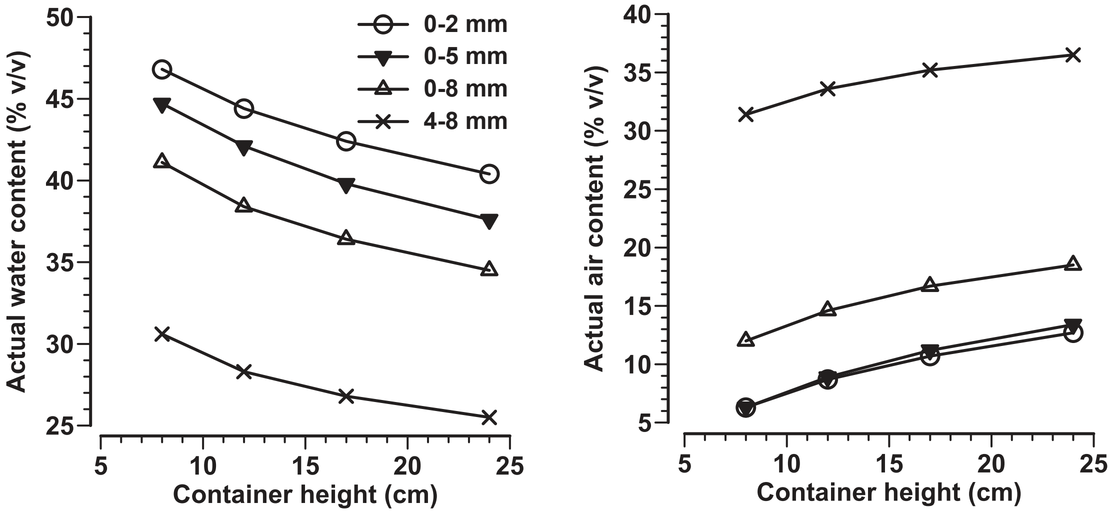

FIGURE 1. Actual water content of a containerized GM (pumice) at container capacity as influenced by container geometry (height of the substrate in the container) and the particle size range (Savvas, 2009).

TABLE 1. Typical characteristics, advantages and disadvantages of the three most important water culture systems (WCS) for commercial production of vegetables and cut flowers in greenhouses.

WCS	Short description	Advantages	Disadvantages
Floating system	Placement of plants on perforated plates consisting of lightweight plastic material such as expanded polystyrene which are left to flow above the surface of the NS (Savvas et al., 2013).	The most robust and forgiving of the available WCS systems (Brechner and Both, 2017). Due to the high volume of NS per plant, it is characterized by a high buffering capacity.	Limitations in oxygen availability in the root zone especially when the NS temperature is high. Not suitable for fruit vegetables and long-term crops.
Nutrient film technique (NFT)	Placement of plant roots in a shallow stream of NS that flows along channels (Van Os et al., 2008).	The high ratio of NS surface area to solution volume contributes to better root aeration.	Lack of buffering capacity due to the low volume of NS per plant. High risk of crop collapse in case of a technical failure. Stagnation of NS inside the channels due to excessive root biomass in long-term crops.
Aeroponics	The plant roots grow inside closed boxes or other types of containers and are continuously or periodically sprayed with fine drops of NS.	Optimal root aeration combined with sufficient supply of NS (Kratsch et al., 2006).	High risk of crop collapse in case of a technical failure.

Water culture systems

Several water culture systems (WCS) have been deviced but only the floating system (including deep flow techniques based on placement of the plants onto floating polystyrene rafts), the nutrient film technique (NFT) and the aeroponic system are important for commercial greenhouse production (Van Os et al., 2008). Of these three systems, the floating WCS is considered the most robust and forgiving (Brechner and Both, 2017), because the large amounts of available NS in the root environment provide a high buffering capacity and sufficient time to react if any failure in the system of NS supply occurs. In all three systems, the NS consumed by plants is automatically compensated for by supplying a replenishment NS. Water culture systems are predominantly used for production of leafy vegetables, such as lettuce (Van Os et al., 2008). An overview of the typical characteristics, advantages and disadvantages of the three most important WCS for commercial production is provided in Table 1.

Fertigation heads and automated control systems

The fertigation unit is of major importance for SCS since it serves as an automated system to accurately dose fertilizers to the irrigation water. Furthermore, through the fertigation heads the growers can schedule the frequency and duration of NS supply. To prepare a fresh NS, fertilizer stock solutions are diluted into irrigation water either in a mixing tank or in the main irrigation pipe (Van Os et al., 2008; Savvas et al., 2013). In most cases, the whole process of NS preparation is automatically controlled by monitoring the electrical conductivity (EC) and the pH of the outgoing solution. Thus, the injection rate can be adjusted in real time according to the measured EC and pH values. The standard practice is to use two tanks containing two different stock solutions to separate calcium from sulphate and phosphate fertilizers, thereby avoiding precipitation due to low solubility of calcium sulphates and phosphates (Sonneveld and Voogt, 2009). However, in large greenhouse enterprises, more sophisticated fertigation heads are used with a separate stock solution tank for each individual fertilizer, which are capable of automatically preparing NS of any desired composition merely by introducing the target NS characteristics into the control software (Savvas and Adamidis, 1999; Van Os et al., 2008).

In the future, the liquid stock solution of each individual fertilizer will be injected into the mixing tank in response to ion selective sensors (Rius-Ruiz et al., 2014). Ion selective sensors capable of measuring nutrient concentrations in real time are already available (Kim et al., 2013) but their use in commercial practice is still scarce due to high cost on the one and lack of reliability in the long term on the other side. The use of ion selective sensors that can be connected on-line to monitor individual nutrient concentrations in the DS is especially important for closed hydroponic systems (Katsoulas et al., 2015).

Open and closed soilless culture systems

Only crops growing on GM can operate either as open or as closed SCS. In contrast, by their nature WCS are essentially closed systems, because the NS run-off from the root zone is not controlled through the water retention capacity of a porous medium. Thus, operating a water culture as an open system would result in a huge waste of NS. The target percentage of supplied NS that runs off as DS in substrate-grown crops operated as open systems ranges from 10 to 30%, depending on water quality and crop sensitivity to salinity, while in closed systems this percentage can be higher, since the DS is not wasted (Savvas, 2002).

The reuse of the DS in hydroponic crops grown on GM restricts or even eliminates leaching of nutrients into the groundwater, thereby resulting in fertilizer savings ranging between 40–50% of the total supply (Savvas, 2002). Although the economic benefits arising from fertilizer savings are not negligible, the environmental benefits are even more significant, given that in long-term tomato crops the yearly leaching of NO_3-N via the discharged DS may exceed 380 kg ha^{-1} y^{-1} (Morard, 1997). Nevertheless, if the salt concentrations and especially those of Na^+ and Cl^- in the irrigation water are higher than 1–3 mmol L^{-1}, depending on crop sensitivity to salinity, periodic discharge of DS is inevitable to prevent significant yield losses (Katsoulas et al., 2015).

In closed SCS, the DS should be filtered and disinfected before it is recycled, to avoid spread of pathogens (Wohanka, 2002). Different technologies for DS disinfection may be applied in substrate-grown crops, such as UV-treatment, pasteurization via heating, slow sand filtration, microfiltration, and chemical treatment with ozone, H_2O_2 or chlorination (Postma et al., 2008). Novel biological methods using beneficial microorganisms are under investigation (Pagliaccia et al., 2007; Hultberg et al., 2011). However, in WCS, only chemical disinfection is economically feasible due to the high flow rate of NS through the roots (Savvas, 2002).

Growing media and their use in SCS

Classification of growing media

GM or "substrates" are defined as all solid materials, other than soil, which alone or in mixtures can guarantee better plant growth conditions than agricultural soil in one or many aspects (Gruda et al., 2013). GM have been used for both the production of high-value vegetables and ornamental plants, as well as for plant propagation, e.g., seedling and container plant production. Generally, in the horticultural industry a mixture of GM constituents and additives are used. Additives include fertilizers, liming materials and bio-control or wetting agents while GM constituents include combinations of different materials. These could be of organic or inorganic nature (Gruda et al., 2013). However, for commercial soilless production of vegetables and cut flowers, stand-alone substrates such as rockwool, perlite or coir are used, which can also be divided into organic and inorganic materials.

All inorganic GM originate from natural sources and only a part of them are subjected to industrial processing before their use. Rockwool was originally produced as insulation in the construction industry. Benefited by its light-weight and ease of handling it has become the dominant GM for fruit vegetable production in greenhouses throughout the world (Gruda et al., 2016b). Perlite is a well-established GM in Europe, while in the Mediterranean region it is more extensively used due to its lower cost (Grillas et al., 2001). Gravel and sand were used in older installations but their performance was poor due to their low porosity. Besides rockwool and perlite, different inorganic GM, such as pumice, zeolite, tuff, volcanic porous rock, expanded clay granules, and vermiculite have been used as GM (Gruda et al., 2016b).

Organic GM can be synthetic, e.g., polyurethane, or can consist of a natural organic matter, e.g., peat, wood-based substrates. The organic materials which are most available and applicable are peat (Schmilewski, 2009), composts (Raviv, 2013), bark (Maher and Thomson, 1991) and wood residues (Gruda and Schnitzler, 2004). Peat is the most widely used GM and substrate component in horticulture. Currently, peat accounts for 77–80% of GM used annually in Europe's horticultural industry (Schmilevski, 2009; Gruda, 2012a). However, peat is predominantly used in nurseries and ornamental pot plant production, while its use for vegetable and cut flower production is limited. The use of peat as a main component of GM is due to its relatively low costs, its excellent chemical, biological and physical properties with low nutrient content, low pH, high water-holding capacity, high air space and light weight (Gruda et al., 2016b). Recently, there has been an increasing interest in biochar (Nemati et al., 2014) and hydrochar. Biochar generally has a low bulk density, a high CEC and a high nutrient holding capacity. Thereby it reduces nutrient leaching (Nemati et al., 2014). On the other hand, the properties of biochar are variable, the pH is relatively high and the production costs as well.

Both inorganic and organic materials have their advantages and disadvantages when being used as raw materials or as GM constituents (Table 2).

Growing media choice

Choosing which material should be used as a growing medium or component depends on the type of crop to be grown. Therefore, GM properties have to meet the plant production needs that in turn are driven by plant biology and applied plant technology. Furthermore, the decision to use a specific GM depends also on its cost. However, recently and in the near future GM can no longer be solely production-driven. In order to survive the challenges of the future, GM should also be environmental friendly and consumer-driven (Gruda, 2012a). As a result, GM firms are no longer evaluated only according to their financial success. Nowadays, life cycle assessment is used for the classification of GM constituents, based on their environmental impact and sustainability, environmental protection, and the application of "green technologies" for their production. Generally, the use of peat substitutes, such as, e.g., compost or biochar, can substantially reduce the carbon footprint in horticulture (Martínez-Blanco et al., 2013; Steiner and Harttung, 2014).

Analyzing the growing media's performance

Performance of GM is for sure the very first prerequisite for success. When analyzing performance, one must consider the physical, chemical and biological properties.

Physical properties

The physical properties of GM are very important (i) because they have a strong impact on air and water availability to the plant roots, and (ii) these properties cannot be changed by growers. Furthermore, the volume of GM per plant is relatively small, underlining the importance of physical properties. However, two points have to be emphasized: (i) the analytical methods used to determine physical properties vary and often different definitions or terminology are used (Barret et al., 2016); (ii) the range of values for physical properties of organic media are quite different from those in mineral soils (Caron et al., 2015; Gruda et al., 2016b). To cope with the first point, an ENI method is recommended, to study the physical properties of GM. With respect to the second point, for instance the concept of particle size distribution, unlike mineral soils, has a limited use as a quality criterion with organic GM (Caron et al., 2015; Gruda et al., 2016b). Therefore, in addition to the particle size distribution, Caron et al. (2015) suggested to extend the parameters to gas diffusivity and unsaturated hydraulic conductivity for research and application purposes. According to Caron et al. (2015) and Gruda et al. (2016b) an excellent organic substrate should have an equivalent proportion of easily available water, defined as the difference of water between -1 kPa and -10 kPa. An optimal water availability is a prerequisite for good plant growth, because both the moisture tension and the hydraulic conductivity drop dramatically as the water content decreases to levels below 5–10 kPa (Raviv et al, 2002; Gizas et al., 2012).

Apart from the GM properties, the container geometry and the production process as well as the overall irrigation regime play a crucial role (Gruda and Schnitzler, 2000; Gizas and Savvas, 2007; Heller et al., 2015). The containers for plant production are much smaller and more shallow than the soil profile and could become quickly saturated or dry (Gruda et al., 2013; Caron et al., 2015; Gruda et al., 2016b). Therefore, as equivalent to "field capacity" in soil, "container capacity" is recommended to be used for containerized GM. The actual container capacity of a containerized substrate, and thus the air porosity and the water holding capacity, depend on container height (Savvas, 2009). In addition, the water desorption curve described through the Van Genuchten-Durner approach should incorporate wetting angle changes during the desorption and rewetting process, taking into account the hysteresis phenomenon, which is sometimes extraordinarily large in organic media (Caron et al., 2015), such as, e.g., peat.

Table 2. Main advantages and disadvantages of inorganic and organic materials used as growing media (GM) or GM constituents (Gianquinto et al., 2006; Gruda et al., 2016b).

Material	Origin	Advantages	Disadvantages
Sand	Natural with particles of 0.05–2.0 mm	Relatively inexpensive, good drainage ability.	Low nutrient- and water holding capacity, high volume-weight (1400–1600 kg m^{-3}), low TPS (40–50% V/V).
Rockwool	Melted silicates at 1500–2000°C	Light volume weight (80–90 kg m^{-3}), high total pore space (95–97% V/V), ease of handling, totally inert, nutrition can be carefully controlled.	Disposal problems, energy consumed during manufacture.
Vermiculite	Mg+, Al + and Fe + silicate sieved and heated to 1000°C	Light volume weight (80–120 kg m^{-3}), high nutrient holding ability, good water holding ability, good pH buffering capacity, good aeration: TPS (70–80% V/V).	Compacts when too wet, energy consuming product, expensive.
Perlite	Siliceous volcanic mineral sieved and heated to 1000°C	Light volume weight (90–130 kg m^{-3}), sterile, neutral in pH (6.5–7.5), no decay, TPS (50–75% V/V).	Low nutrient capacity, energy consuming product, expensive.
Pumice	Light silicate mineral of volcanic material	Light volume weight (450–670 kg m^{-3}), good TPS (55–80% V/V), cheap and long-lasting, environmentally friendly.	High transport costs, pH may be high.
Peat	Natural anaerobically processed plant residues	Physical stability, good air and water holding capacity: TPS (85–97% V/V), low microbial activity, light volume weight (60–200 kg m^{-3}), low and easily to adjusted pH, low nutrient content.	Finite resource, environmental concerns and contribution to CO$_2$ release, increasing cost due to energy crisis, may be strongly acidic, shrinking may lead to substrate hydro-repellence.
Coconut coir	By-product of fiber coconut processing	Physical stability, light weight (65–110 kg m^{-3}), good air content TPS (94–96% V/V) and water holding capacity, subacid-neutral pH (5–6.8).	May contain high salt levels, energy consumption during transport.
Bark (well-aged)	By-product or waste of wood manufacture	Good air content and water holding capacity, good TPS (75–90% V/V), sub-acid-neutral pH (5–7), average volume weight (320–750 kg m^{-3}), long lasting.	High variability, need time to reduce C:N ratio and terpenes concentrations, increasing cost since used as an alternative to fuel and in landscaping.
Green compost	Composted plant residues	Good source of potassium and micronutrients, suppression of diseases, good moisture holding capacity, urban waste reduction.	Variable in composition, high volume weight (600–950 kg m^{-3}), may contain excess salt, need time to be composted, becomes easily waterlogged.
Biochar and hydrochar	Solid material derived from biomass pyrolysis or biomass hydrolysis	Production is energy-neutral, helps with carbon sequestration, biologically very stable, wet material can be used for hydrochar; hydrochar has low EC.	Properties vary dependent on feedstock (biochar), high production costs, biochar often has high pH, can be dusty.

TPS = total pore space.

Chemical properties

When evaluating chemical properties of GM, the most important criteria are pH, cation exchange capacity (CEC) and the nutrient concentrations (Gruda et al., 2013, 2016b). Unlike physical, chemical properties could be adjusted at a certain level by growers.

The pH plays an important role in chemically active GM as it determines the availability of various nutrients. For most plants the optimal nutrient availability occurs when the pH in the root environment is between 5.5 and 6.0. In general, a lower pH value and lower nutrient and salt concentrations are better for GM preparation and production. Initial materials with these characteristics such as, e.g., peat moss, permit substrate manufacture where: (i) the pH value can be increased easily by lime addition; (ii) it is possible to regulate and balance the relatively high pH value of other component materials; and (iii) the demands or requirements of different plants can be accurately taken into account and controlled (Gruda et al., 2013). Since the pH value of some organic materials such as compost is relatively high, Raviv (2013) recommends the use of a low-pH organic matter by composting, mixing compost with non-buffered peat moss or adding sulphur before planting or during the growing period. Furthermore, it should be considered that pH values for some organic GM, e.g., pine tree substrates, change during the storage process (Jackson et al., 2009).

CEC provides information about the sorption force and buffering ability of GM for nutrients. GM with high CEC can store more nutrients. In addition, such GM can more efficiently buffer the fertilizer or mineral materials when hard water is used (Gruda et al., 2016b).

Biological properties

GM must be free from pests, pathogens and weeds, biologically stable, and non-toxic. The use of forestry products as well as immature compost can involve problems of phytotoxicity. For instance, high potassium and manganese content (Maher and Thomson, 1991) and the presence of phenolic compounds (Ortega et al., 1996), terpenes, organic acids and fatty acids (Morel and Guillemain, 2004) can cause such problems (Gruda et al., 2009). Methods such as composting, ageing, leaching, washing, mixing and fertilization, have been used to reduce or eliminate phytotoxicity properties (Ortega et al., 1996; Gruda et al., 2000, 2013). Grunert et al. (2016) reported that mineral and organic GM have a distinct bacterial community structure, stability and functionality in SCSs. The differences in communities can be used to develop strategies to move towards a sustainable horticulture with increased productivity and quality.

All organic materials are subject to biodegradation. Although the high biodegradability of organic GM facilitates their recycling, it could be a problem during their use as GM. Apart from the material properties, a number of factors, such as, e.g., water, oxygen, temperature and light, determine the degradation rate. Biodegradability of GM can be measured based on respiration rate, i.e., the produced carbon dioxide (CO_2), or the rate of O_2 consumption. In addition, plant respiration can influence both the CO_2 and O_2 concentrations in GM (Gruda et al., 2008a, b; Dresbøll, 2010). However, although it is well known that gas exchange within the root zone could strongly affect the growth of cultivated plants (Gruda et al., 2008a), biodegradability alone cannot determine and provide information about plant growth (Gruda et al., 2008b; Dresbøll, 2010). Dresbøll (2010) investigated six different peat-based growing media as well as three mixtures of peat and perlite, compacted by 0%, 20% or 40% with short periods of low oxygen availability corresponding to fluctuations in water content during the irrigation cycles. Despite substantial differences in their composition and periods of anoxia in the bottom of the containers, plant quality or the subsequent keeping quality of roses were not affected. Furthermore, some GM, such as, e.g., wood fibers, can immobilize some nitrogen during their use (Gruda et al., 2000).

Environmental perspective

Increasing environmental awareness among consumers, constant despoiling of ecologically important peat bog areas and a pervasive waste problem forced the horticultural industry to consider changes (Gruda, 2012b). Moreover, the question concerning a replacement for peat as a horticultural substrate has become increasingly important (Gruda, 2012a; Gruda et al., 2013). Despite the high value of peat as a growing substrate, there is a concern with the fact that peat comes from peatland ecosystems, which are important for a wide range of wildlife habitats, for water quality and cycle and carbon sequestration. Consequently, a “wise use” approach of mires and peatlands and peat usage has been adopted and extensive research has been carried out (Gruda et al., 2016b). The disposal problems, and the consumption energy during manufacture of mineral wool are two main criticisms for using rockwool in the soilless culture industry.

Consequently, the international trend for GM development tends towards the use of local, natural resources and renewable raw materials. Particularly in industrialized countries the re-use of wastes has become common (Gruda, 2012b). Barrett et al. (2016) reported a detailed summary of novel materials that have been investigated as soilless GM components since1990. The majority of these materials are from industrial, agricultural and municipal waste streams. However, renewable fast-growing plants, such as *Miscanthus*, peatmoss (*Sphagnum*) from paludiculture or seaweed (*Posidonia*) can also be used as GM constituents.

Important trends that strengthened the role of local, organic GM are the advantages in their simple recycling as well as the increasing importance of organic farming and organic food production. According to Khachatryan et al. (2014), the consumer is willing to pay more for products perceived as being ‘environmentally friendly’. Nevertheless, while many waste stream materials investigated to date have the potential to offer a multitude of benefits at the experimental level, few (coir, pine bark, wood fibre, and green composts) are actually able to meet the requirement of being environment-friendly in the commercial sector (Gruda, 2012a; Barrett et al., 2016).

As the importance of SCS is likely to rise in the near future, it is essential that researchers work with GM manufacturers towards identifying new materials that are environmentally sustainable, commercially viable and able to perform as well as those they are replacing (Barret et al., 2016).

Plant nutrition and fertilization in soilless cultivation systems

Composition of nutrient solutions

In modern SCS, all essential plant nutrients are supplied via the NS, with the exception of carbon, which is acquired from the air as carbon dioxide. Most fertilizers used to prepare NSs are highly soluble inorganic salts but some acids, such as nitric and phosphoric acid, are also used.

Due to their ability to selectively take up nutrients according to their nutritional needs, different plant species can be successfully cultivated using a single NS composition as that suggested by Hoagland and Arnon (1950). Nevertheless, the need to optimize plant nutrition in commercial SCS forced scientists to fine-tune the NS composition so as to meet more precisely the special nutritional needs of each cultivated plant species. Thus, currently, specialized NS compositions for each greenhouse crop species are available (e.g., De Kreij et al., 1999; Sonneveld and Voogt, 2009; Savvas et al., 2013).

Theoretically, the composition of a NS for a particular crop species and developmental stage is optimal when the mean uptake ratios between individual nutrients are similar with the relative proportions between the same nutrients in the supplied NS. This principle should be strictly followed in closed hydroponic systems to avoid nutrient accumulation and/or depletion (Sonneveld and Voogt, 2009; Savvas et al., 2017). However, in open hydroponic systems, part of the NS runs off. Therefore, the ratios between some nutrients in solutions prescribed for open hydroponic systems are different than their uptake ratios which more or less correspond to their ratios in the whole plant tissue. This is the case for instance with the K:Ca and K:Mg ratios, which should be substantially lower in the root zone than the corresponding uptake ratios, to ensure a sufficient uptake of the bivalent cations (Sonneveld and Voogt, 2009).

Since plant transpiration, and concomitantly water consumption, are fully independent from metabolic functions associated with nutrient assimilation, the climatic parameters may differently affect the nutrient uptake rates than those of water uptake. As a result, the nutrient/water uptake ratios may alter under contrasting different climatic conditions, which means that the optimal composition of a nutrient solution may depend also on the local climatic conditions. Consequently, a fine-tuning may be needed when a NS composition, which proved to be optimal in one region, has to be applied in another region with contrasting climatic conditions. Most NS formulae suggested in the international literature are based on research carried out in temperate climates (De Kreij et al., 1999; Adams, 2002; Sonneveld and Voogt, 2009). Therefore, in the last years, several investigators attempted to develop NS formulations specialized for soilless crops grown under dry and hot climatic conditions as those prevailing in Mediterranean environments (e.g., Pardossi et al., 2004; Savvas et al., 2017; Neocleous and Savvas, 2015).

The nutrient needs of a plant species may change at different developmental stages (Sonneveld, 2002; Gianquinto et al., 2013). Therefore, in commercial SCS, the NS composition needs periodic adjustment during a cropping period. However, programmed changes in the NS composition may be insufficient in many cases because the exact nutrient needs change from crop to crop and a standard composition cannot match all individual crops. In commercial practice, this problem is tackled by frequently analysing samples of DS and adjusting the standard NS formula according to the analytical results.

The irrigation water may contain some macronutrients (Ca^{2+}, Mg^{2+}, SO_4^{2-}), micronutrients (Mn^{2+}, Zn^{2+}, Cu^{2+}, B and Cl^-) and other non-nutrient ions (HCO_3^-, Na^+) at appreciably high concentrations (Sonneveld and Voogt, 2009). These nutrients have to be taken into consideration when the amounts of fertilizers needed to prepare a NS are calculated. Hence, the fertilizer masses needed to prepare a NS of a specific composition should be individually computed for each grower.

The need for frequent changes in the composition of the supplied NS during a cropping period, which have to be performed individually for each grower, entails the use of a computational tool to easily calculate new NS formulae whenever needed. Savvas and Adamidis (1999) developed a simple computer program that can be easily applied to calculate the amounts of fertilizers needed to prepare commercial NSs taking into consideration the mineral composition of the irrigation water. This computer program is freely accessed at: http://www.ekk.aua.gr/excel/index.htm.

Adjustment of crop nutrition

As a rule, the nutrient concentrations in the root zone of plants grown in SCS cannot be maintained to similar levels as in the supplied NS, even if the composition of the latter is optimal (Sonneveld, 2002). The changes of the nutrient concentrations in the root zone with reference to those in the supplied NS occur gradually as a result of differences in ion uptake selectivity between individual nutrients (Sonneveld, 2002). Therefore, when instructions regarding the nutrition of a particular plant species in soilless cultivation systems are given, it is essential to recommend target nutrient concentrations not only for the NS supplied to the crop but also for the NS that is in contact with the plant roots, which is commonly termed root-zone solution. Due to difficulties in directly collecting a representative sample of root-zone solution, its composition is commonly estimated indirectly by measuring the composition of the DS, although the latter in most cases is not identical to the former (Sonneveld, 2000). The nutrient concentrations in the root zone are of primary importance, since the plants are in contact and respond to the nutrient status prevailing around their roots. The composition of the nutrient solution supplied to the crop is also important but its impact on crop performance is indirect, as it is the main tool to achieve and maintain the target nutrient concentrations in the root zone (Savvas, 2001; Sonneveld and Voogt, 2009). Therefore, the target nutrient concentrations in the supplied NS may be frequently modified during the cropping period in order to achieve more closely the target concentrations in the root zone, while the latter are always the same for a particular plant developmental stage. Nevertheless, the plant requirements of a particular nutrient may alter during different plant developmental stages because different plant parts (i.e., fruit *versus* leaf) may exhibit some differences in their relative nutrient composition (Adams, 2002; Gianquinto et al., 2013). Hence, for plants with a long harvesting period (e.g., tomato) it is better to suggest different nutrient solution compositions in the vegetative and the reproductive stages (Table 3).

The electrical conductivity (EC), which is an estimate of the total ionic concentration in a NS, is considered one of the most important NS characteristics, since a too low value indicates shortages in nutrient supply, while a too high value points to salt stress conditions. Due to selectivity in nutrient uptake by plants, the EC in the root zone of the crop may drop below or exceed the range for optimal plant growth and yield. Supplying a NS solution with an optimal composition, monitoring the nutrient status in the crop through frequent

TABLE 3. Recommended EC (dS m^{-1}), pH and concentrations of macronutrients (mmol L^{-1}) and micronutrients (μmol L^{-1}) in nutrient solutions (NS) supplied to tomato crops grown in open or closed soilless culture systems under Mediterranean climatic conditions as well as in the root-zone NS during the vegetative and the reproductive developmental stage (based on Savvas et al., 2013 and Savvas et al., 2017).

Desired characteristics	Vegetative stage			Reproductive stage		
	SSOS[1]	SSCS[2]	RZ[3]	SSOS	SSCS	RZ
EC*	2.80	2.30	3.20	2.70	2.10	3.40
pH	5.60	-	5.80–6.70	5.60	-	5.80–6.70
$[K^+]$	8.20	8.20	7.50	8.00	8.00	8.20
$[Ca^{2+}]$	5.00	3.50	7.80	4.80	3.00	8.00
$[Mg^{2+}]$	2.80	1.80	3.40	2.60	1.40	3.40
$[NH_4^+]$	1.40	1.60	<0.60	1.20	1.40	<0.40
$[SO_4^{2-}]$	4.30	2.40	5.00	4.40	1.80	6.00
$[NO_3^-]$	14.60	13.70	18.00	13.20	12.80	17.20
$[H_2PO_4^-]$	1.50	1.40	1.00	1.50	1.30	1.00
[Fe]	15.00	15.00	25.00	15.00	15.00	25.00
[Mn]	10.00	10.00	8.00	10.00	10.00	8.00
[Zn]	8.00	7.00	7.00	7.00	6.00	7.00
[Cu]	0.80	1.00	0.80	0.70	0.80	0.80
[B]	30.00	20.00	50.00	25.00	20.00	50.00
[Mo]	0.50	0.50	-	0.50	0.50	-

[1] SSOS: NS supplied to open systems; [2] SSCS NS supplied to closed systems; [3] RZ target concentrations in the root zone.
* EC values corresponding to 1 mmol L^{-1} NaCl in the irrigation water.

analysis of the DS and adjusting the composition of the supplied NS whenever needed, can normally prevent the occurrence of too low or too high EC levels in the root zone due to nutrient depletion or accumulation, respectively. Sometimes, the Ca and/or Mg concentrations in the irrigation water are higher than the target concentrations in the NS to be supplied to the crop, and thus the EC of the supplied NS will inevitably be higher than the target level. In such cases, the concentrations of all other cations should not change, to avoid any further increases of the EC which may reduce yield (Neocleous and Savvas, 2013). However, in most cases, increased EC levels in the root zone of soilless-cultivated plants, which expose the crop to salinity stress, occur due to accumulation of Na^+ and Cl^- originating from the irrigation water. Nevertheless, in open hydroponic systems, part of the excessive Na^+ and Cl^- ions are leached out via the DS. Therefore, in open hydroponic systems, salinity becomes a problem for the crop only if the NaCl concentration in the irrigation water exceeds a threshold level, ranging from 3 to 10 mmol L^{-1}, depending on the plant species (Sonneveld, 2000). When the EC in the root zone exceeds a threshold level but all nutrients are included at sufficient levels in the nutrient solution, the yield decreases more or less linearly (Sonneveld, 2000; Savvas, 2001). The impact of increased EC on plant growth in hydroponics depends also on the prevailing climatic conditions. As a rule, the detrimental salinity effects are more profound under high light intensity and/or low air humidity (Sonneveld and Voogt, 2009).

The most efficient strategy to prevent excessively high EC levels in the root zone of soilless cultivated plants is to use irrigation water of good quality for NS preparation, if this is possible. In some cases, a too high EC in the root zone may be corrected by increasing the irrigation frequency (Sonneveld, 2000). Nevertheless, the use of plain irrigation water to wash out salts from substrates is an erroneous practice, which results in excessively high pH levels and nutrient imbalances in the root zone, unless rainwater is available (Savvas et al., 2013).

The optimal pH in the root zone of hydroponically grown plants ranges from 5.5–6.5, although values between 5.0–5.5 and 6.5–7.0 may not cause problems in most crops (Adams, 2002). However, in SCS, the pH may quickly increase or fall below the safety range due to the limited volume of NS per plant in the root zone. Most plants, when exposed to external pH levels above 7 or below 5, show growth restrictions (Sonneveld, 2002). If the root-zone pH in SCS is higher than 7.0, P, Fe, Mn, Cu and Zn deficiencies may occur. Similarly, at pH levels below 5.0, there is a high risk for Mn and/or Al toxicity, as well a direct H^+ injury in the root tissues (Islam et al., 1980). Furthermore, if the too low pH in the root zone is accompanied by excessively high NH_4-N concentration, the uptake of Ca may be impaired (Sonneveld and Voogt, 2009).

In most cases, the control of pH in the root zone of plants grown in SCS requires measures aimed at preventing the occurrence of a too high pH. If the percentage of DS is relatively low, an increase in irrigation frequency and/or water dosage at each irrigation cycle might restore normal pH levels within the root zone. However, if the adjustment of the irrigation schedule fails to reduce the pH to normal levels, an increase in ammonium supply may be needed. Nitrogen can be supplied to plants in both anionic (NO_3^-) and cationic (NH_4^+) forms via fertigation, while the uptake rates of both N forms are influenced by their external concentrations. Thus, the manipulation of NH_4-N/NO_3-N in the supplied nutrient solution without altering the total-N concentration may considerably modify the total cation to anion uptake ratio. As previously stated, changes in this ratio have a profound impact on the root-zone pH. Indeed, the imbalance of total cation over anion uptake in the rhizosphere originating from enhanced NH_4^+ uptake (Figure 2) is electrochemically compensated for by release of protons, and this results in a lowering of the medium pH (Lea-Cox et al., 1996; Savvas et al., 2010). Similarly, the excess of anion over cation uptake due to increased supply of NO_3^- is compensated for by H^+ influx or equivalent anion extrusion (OH^- and HCO_3^-), which increases the pH of the external solution.

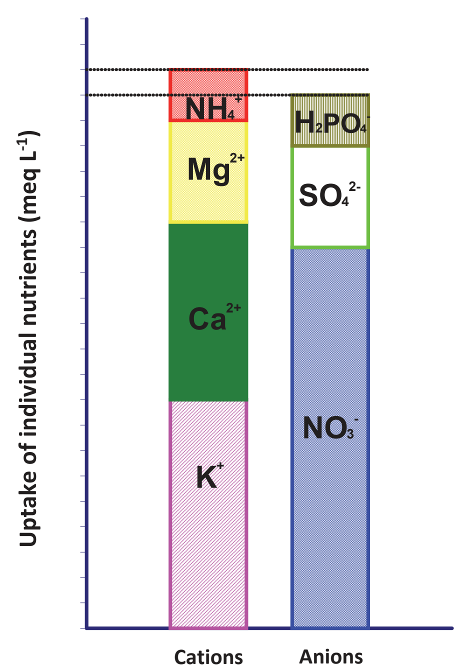

FIGURE 2. Schematic representation of the balance deficit between the uptake of nutrient cations and anions by plants when the NH_4-N/total-N in the supplied nutrient solution is high, which is compensated for by release of $[H^+]$ by the root cells (Savvas et al., 2013).

In SCS, it is much easier and safer than in soil-grown crops to improve the produce quality by properly manipulating the composition of the NS. The most typical example is the increase of the EC in the root-zone of soilless-grown fruit vegetable crops above the upper threshold level for optimal growth, in order to improve the produce quality (Dorais et al., 2001; Sonneveld and Voogt, 2009). In tomato, the main favorable effects of salinity on fruit quality include increases in dry matter content, sugar content, and titratable acidity in the fruit juice (Schnitzler and Gruda, 2002). In other studies, the shelf life of tomato was also prolonged by NS salinity whilst the incidence of the physiological disorders blotchy ripening, gold specks and russeting were decreased (Sonneveld, 2000; Savvas, 2001). Furthermore, a moderate increase of the EC in the root zone enhances vitamin C and total carotene levels in tomato fruit and increases fruit firmness (Schnitzler and Gruda, 2002). In contrast to vegetables, the quality of cut flowers does not benefit from a moderate increase of the EC in the root zone (Sonneveld et al., 1999).

Another example of improving the produce quality in SCS is the reduction of nitrate contents in leafy vegetables by lowering or eliminating the NO_3-N supply a few days before harvesting, or alternatively by using NH_4-N as a partial substitute for NO_3-N in the NS (Liu et al., 2012).

Nutritional control in closed soilless cultivation systems

In closed SCS, the nutrient concentrations in the supplied NS depend not only on the composition and the injection rates of stock solutions to water but also on the nutrient concentrations in the recycled DS. However, the latter change during the cropping period and hence the injection of nutrients via stock solutions cannot be constant but needs frequent adjustment based on sound estimations of the nutrient uptake rates (Savvas et al., 2017). To address this need, various automation techniques involving measurements of DS characteristics and adjustments in real time are used in modern closed-cycle SCS (Katsoulas et al., 2015).

A standard recycling technique applied in closed SCS involves mixing of DS and water at an automatically adjustable ratio by aiming at a preset EC (E_m) in the outgoing mixture (Figure 3A). Subsequently, a standard injection rate of stock solutions is needed to raise the EC from E_m to the target level suggested for this particular crop species (E_t). The E_t adjusted in closed systems is usually similar to that suggested in open SCSs.

An alternative technique (Figure 3B) is to inject the stock solutions of fertilizers into the irrigation water at standard rates aiming at a preset EC (E_u) and subsequently mixing the obtained solution with the DS to be recycled at an automatically adjustable ratio by aiming at a preset EC which is equal to that suggested for this particular crop species (E_t).

Both techniques require the use of a mixer which is capable of automatically adjusting the mixing ratio so as to

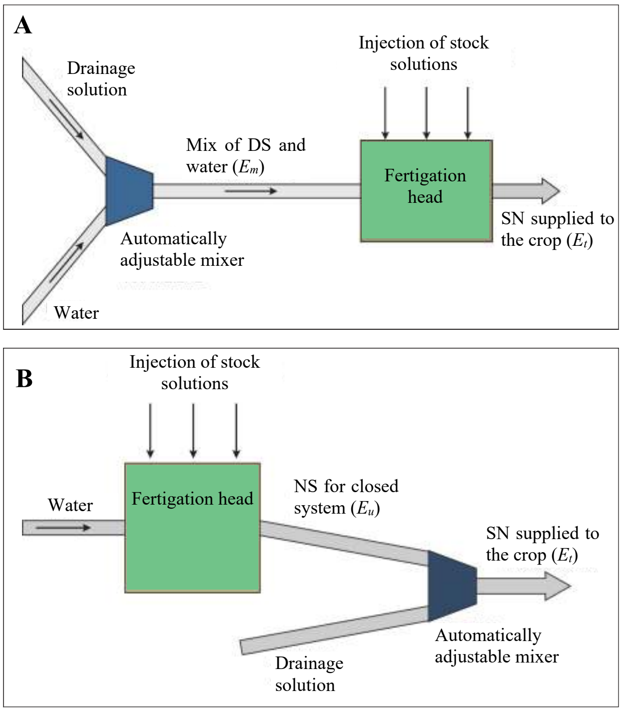

FIGURE 3. Schematic representation of two alternative methods of automatically recycling the drainage solution (DS) in closed hydroponic systems. A: mixing DS and water at an automatically adjustable ratio by aiming at a preset EC (E_m) in the outgoing mixture and subsequently injecting fertilizers to the mix via a fertigation head aiming at a target EC (E_t). B: injecting fertilizers to water via a fertigation head to prepare a NS suitable for closed systems with a target EC of E_u and subsequently mixing this NS with DS at an automatically adjustable ratio by aiming at a preset EC (E_t) in the outgoing solution.

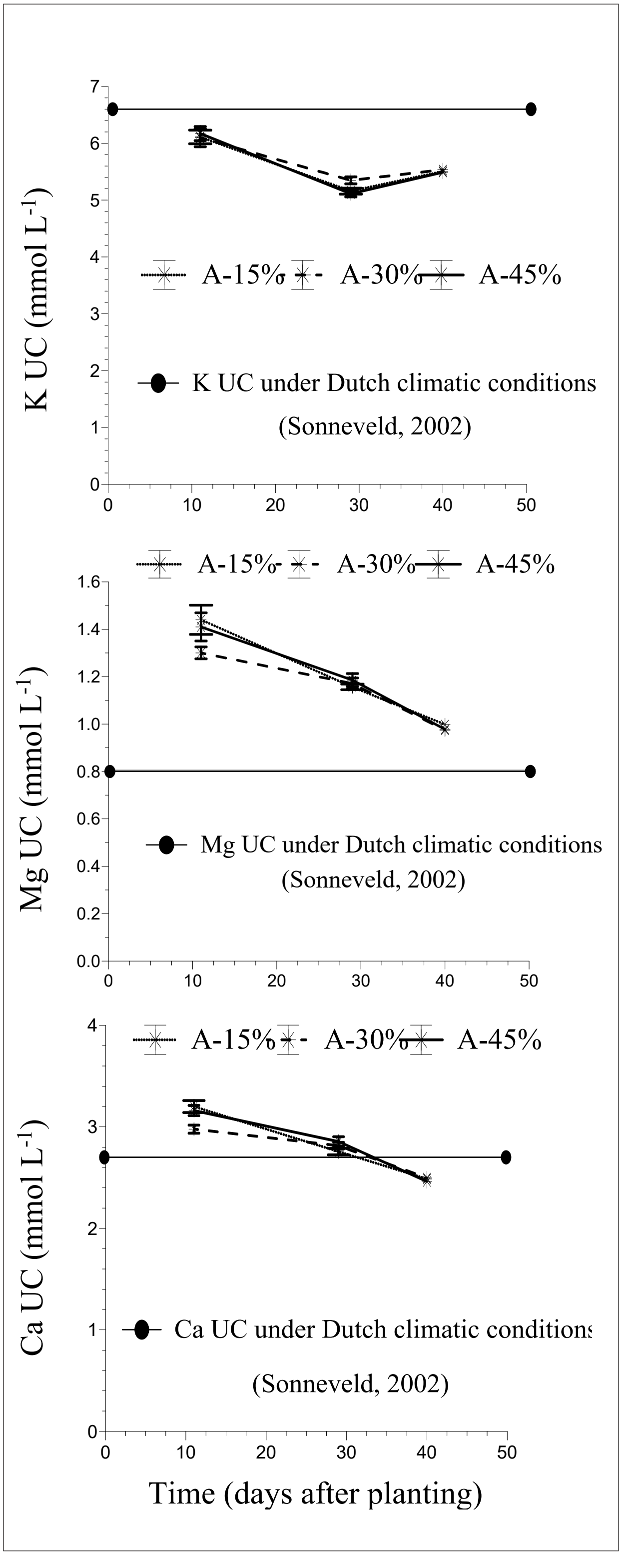

FIGURE 4. Mean uptake concentrations (UC) of K, Mg, and Ca (mmol of nutrient uptake per liter of water uptake) in a hydroponic cucumber crop during three successive time intervals, calculated on the basis of nutrient and water removal from the recirculating nutrient solution (Savvas et al., 2014). Data are provided for three different irrigation frequencies which resulted in three different mean drainage percentages (A), particularly 15%, 30% and 45% of the total supply.

achieve a target EC (E_m or E_u) in the outgoing solution. The E_m (dS m^{-1}) is estimated through the equation:

$$E_m = aE_d + (1-a)E_w \qquad (1)$$

where E_d is the EC of the DS, E_w is the EC of the irrigation water and a is the fraction of recycled DS. The E_u corresponds to the EC of a NS with concentrations equal to the anticipated mean ratios of nutrient to water uptake, which are commonly termed "uptake concentrations" (Sonneveld and Voogt, 2009). Irrespective of the applied technique, the composition of the stock solutions is computed by aiming at NS concentrations corresponding to the anticipated mean uptake concentrations for this particular crop species. The uptake concentrations exhibit some stability over time for a particular plant species but may change under contrasting climatic conditions (Figure 4). Therefore, the uptake concentrations constitute a good basis for nutrient input in closed SCS (Sonneveld, 2002; Savvas et al., 2014). Mean uptake concentrations for many greenhouse crops have been estimated experimentally by several investigators (e.g., Sonneveld and Voogt, 2009; Neocleous and Savvas, 2015; Savvas et al., 2017).

If the Na$^+$ and Cl$^-$ concentrations in the irrigation water are high, the EC in the root zone and concomitantly in the DS tends to increase due to their accumulation. However, if the target EC in the supplied NS is maintained constant, the increase of the EC in the DS due to salt accumulation imposes a decrease in the percentage of DS that is mixed with fresh nutrient solution and a corresponding increase in the discharged DS (Katsoulas et al., 2015). Furthermore, if the EC of the supplied DS is maintained constant while the concentrations of salt ions increase, the nutrient concentrations will inevitably decrease, as shown in Figure 5A. To minimize DS discharge and to prevent a progressive decrease of nutrient concentrations in the supplied NS, the target EC of the latter should be gradually elevated up to a maximum acceptable level, as shown in Figure 5B.

Irrigation in SCS

The total amounts of available water and nutrients are smaller in the root zone of plants grown in SCS than in plants grown in the soil, due to a limited volume of the root zone, despite a greater water-holding capacity of most GM. Consequently, frequent and accurate supply of NS is needed to maximize crop productivity (Schröder and Lieth, 2002; Lieth and Oki, 2008). However, this is not a disadvantage of SCS, because the triggering and termination of water supply can be controlled fully automatically.

Methods of irrigation in soilless cultivation systems

Overhead, surface and subsurface irrigation can be applied to deliver NS to the plants in SCS (Lieth and Oki, 2008). However, irrigation in SCS and especially in substrate-grown crops is dominated by surface and particularly drip irrigation systems. In drip systems, the NS is supplied via drippers pinned or laid on the upper surface of the GM and the excess solution is discharged or recirculated. The most common type of dripper in SCS is the spaghetti tube. Overhead systems, which apply NS to the aerial part of the plants via sprinklers, result in excessive waste of water while they favor fungal attacks due to frequent wetting of the foliage (Goodwin et al., 2003). Therefore, overhead systems are mainly applied in nurseries, while their use in productive hydroponic crops is scarce. Subirrigation has been also tested experimentally (Incrocci et al., 2006; Rouphael et al., 2006). However, it is rarely applied in commercial cultivations of vegetable and cut flower crops because it favours salt accumulation in the upper portion of the root zone due to lack of salt leaching (Schröder and Lieth, 2002; Lieth and Oki, 2008).

Adjusting the irrigation dosage

In plants grown on substrates, irrigation has to be applied before the easily available water (EAW) in the GM is consumed by plants. Consequently, irrigation events have to be triggered before the moisture tension in the GM falls below -5 kPa. However, in most GM, the transition from moisture tensions at which the water is easily available to tensions at which the water is unavailable needs only a small decrease of the moisture content (Raviv et al., 2002). In addition, the water availability depends not only on the moisture tension but also on the hydraulic conductivity in the GM, which diminishes rapidly as the moisture content decreases (Raviv et al., 2004). Therefore, for safety reasons, irrigation events have to be initiated as soon as a certain fraction of the EAW

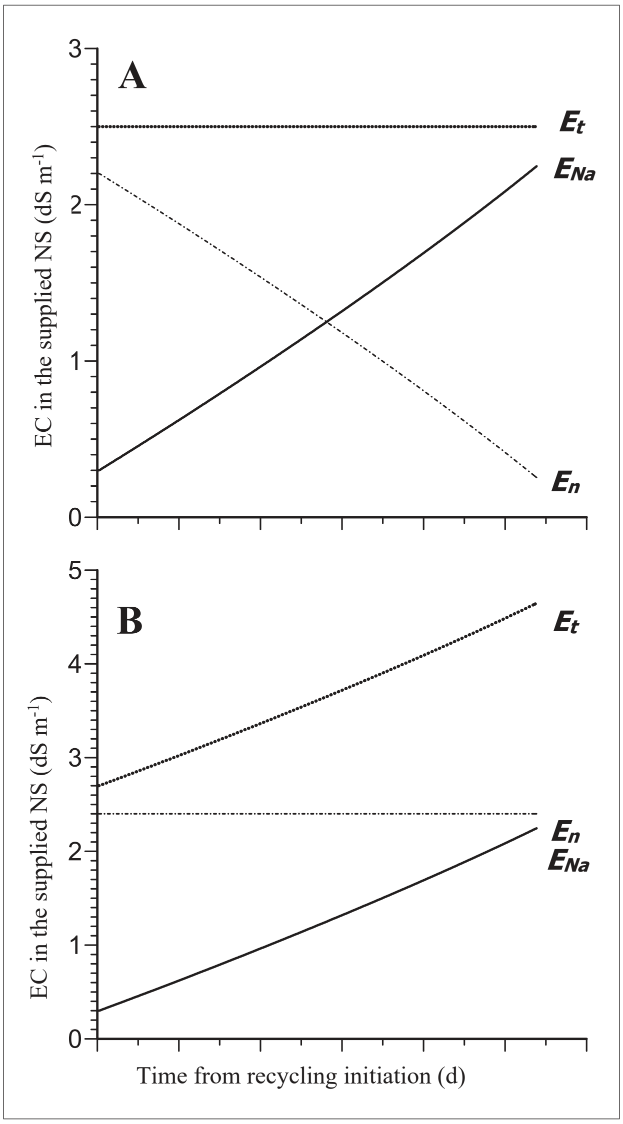

FIGURE 5. Changes in the contribution of the injected nutrients (E_n) and NaCl (E_{Na}) to the EC of the NS supplied to plants (E_t) in a closed hydroponic system: A) when the E_t is maintained constant and B) when the injection rates of nutrients (and thus the E_n) are maintained constant during the cropping period.

is consumed (indicatively from 0.2 to 0.4) and terminated as soon as container capacity is achieved. Consequently, the amount of water to be replenished at each irrigation event is constant for a particular type and volume of GM, irrespective of climatic conditions and other factors that determine the rate of water consumption. Thus, the duration of each irrigation event (T_i in min) depends on the volume and type of GM which determine the volume of EAW, the particular fraction of EAW that has to be replenished, and the flow rate of the drippers. Mathematically, this can be expressed using the following formula:

$$T_i = \frac{60 W_f V_s F}{(1-a)R} \qquad (2)$$

where W_f is the volumetric fraction of EAW (values from 0 to 1) which is computed from the water retention curve of the GM, V_s is the volume (L) of GM per plant, F is the fraction of EAW that is set as threshold for triggering an irrigation event when it is consumed (values from 0 to 1), a is the target drainage fraction (values from 0 to 1) and R is the flow rate of the drippers(L h^{-1}).

Control of irrigation frequency

The most obvious way to adjust automatically the irrigation frequency according to the rate of water consumption is to relate it to climatic parameters. Indeed, many growers use pyranometers to measure in real time the solar radiation intensity and a solar integrator to convert it into solar energy interception per cultivated area (Lieth and Oki, 2008). Then, using a suitable software, they relate triggering of an irrigation event to the accumulation of a fixed amount of solar energy per unit of cultivated area, starting with a standard value. Subsequently, the initiation of each irrigation event is set by trial and error to an appropriate value of solar energy interception that results in the delivery of as much NS as consumed by the plants in the interval between two successive irrigation events, plus an additional 20 to 30% of DS (Schröder and Lieth, 2002). The value of solar energy interception at which irrigation is triggered should be frequently adjusted as long as plants are growing up and the leaf area index of the crop changes.

A more sophisticated approach to automatically trigger irrigation events according to the actual crop water consumption, as determined by the current weather conditions, is to estimate the crop transpiration. Indeed, several models have been developed to estimate the evapotranspiration in greenhouse crops. A simple but accurate enough model for commercial applications derived from the Penman-Monteith equation by Baille et al. (1994) to calculate the evapotranspiration (E, kg m^{-2} h^{-1}) of greenhouse crops is based on the following equation:

$$E = A[1-\exp(-K * LAI)]G + B * LAI * D \qquad (3)$$

where G is solar radiation (MJ m^{-2} day^{-1}), D is the air vapour pressure deficit (kPa), LAI is the leaf area index (m^2 m^{-2}), K is a light attenuation coefficient related to the reduction of light in the canopy with LAI, and A (dimensionless) and B (W m^{-2} kPa^{-1}) are parameters which must be calibrated for any particular crop and stage of plant development.

An alternative approach to automatically schedule the irrigation frequency is to measure the water status in the GM using sensors to monitor either the moisture tension (tensiometers) or the moisture content (TDR or FDR probes, see Kizito et al. [2008] and Pardossi et al. [2009]). The sensor is located in the root zone of a plant that is representative of the entire crop. The irrigation control system continually monitors the moisture tension or content in the GM and triggers an irrigation event once a set-point value is measured. In SCS the set-point of moisture tension is a value higher than -5 kPa, while the set-point of moisture content is a value that corresponds to a moisture tension higher than -5 kPa according to the water retention curve of the particular GM. Nevertheless, the control of the irrigation frequency through sensors that monitor the moisture tension or content in GM is currently a research objective rather than a reality in commercial SCS due to their inadequate performance and their high cost. The main reason for their poor performance is the sharp decrease of the moisture tension in GM with small changes in the moisture content even within the range of moisture tension that corresponds to EAW (>-5 kPa). As a result, the measurements are fully dependent on the height from the bottom at which the sensor is placed. An additional reason for their poor performance is the heterogeneity within the crop and even within one bag or container.

Conclusions and perspectives

The rapid expansion of SCS all over the world in the last three decades may be ascribed to their ability to uncouple the crop from the soil and its drawbacks, including the soil-borne pathogens. Soilless culture seems currently the safest and most effective alternative to soil disinfection by means of methyl bromide. As a result, SCS are becoming increasingly important in protected cultivation including not only modern, fully equipped glasshouses, but also simple greenhouse constructions aimed to utilize favorable climatic conditions. Moreover, the cultivation of greenhouse crops and the achievement of high yields and good quality are possible with SCS even in saline, sodic or non-arable soils with poor structure, which represent a major proportion of the agricultural land throughout the world. Cultivation on high quality and consumer-oriented GM with focus on environmental issues and sustainability will remain also in the near future the standard choice for soilless production of edible vegetables, cut flowers, seedlings, and container plants in greenhouses.

In countries dominated by large and modern greenhouses but less favorable climatic conditions, high investment costs are needed to maximize yield and optimize product quality by completely controlling all growing conditions. Hence, the inclusion of equipment for hydroponics, which is a small aliquot of the total investment, constitutes the necessary supplement to exclude the last imponderable factor that could restrict yield and quality, namely the soil. In contrast, when the greenhouse is a simple construction mainly aimed at exploiting the favorable climatic conditions, even a small increase in the installation and operation costs that is required to switch over to hydroponics can often not be recouped by higher yields because another factor may be limiting. It is acceptable only when the problems originating from the soil become critical, water resources are limited, or the environmental pollution by nutrient leaching is serious. This seems to be the main reason for the lower expansion of commercial SCS in countries characterized by, e.g., a Mediterranean-type climate.

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