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# Good Agricultural Practices for greenhouse vegetable crops

## Principles for Mediterranean climate areas

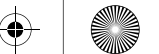


This publication capitalizes on the experience of scientists from the North Africa and Near East countries, in collaboration with experts from around the world, specialized in the different aspects of greenhouse crop production. It provides a comprehensive description and assessment of the greenhouse production practices in use in Mediterranean climate areas that have helped diversify vegetable production and increase productivity. Guidance is provided on potential areas for improvement of greenhouse cultivation. More specifically the document aims at strengthening technical capacity in the use of Good Agriculture Practices (GAP) as a means to improve product quality and safety, and achieve sustainable production intensification of greenhouse vegetables in countries in Mediterranean climate areas. The publication is also meant to be used as a reference and tool for trainers and growers as well as other actors in the greenhouse vegetables value chain in this region.



Good Agricultural Practices for Greenhouse Vegetable Crops - Principles for Mediterranean Climate Areas

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# Good Agricultural Practices for greenhouse vegetable crops

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## Principles for Mediterranean climate areas

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## 12. Soilless culture

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### TERMINOLOGY

Soilless culture can be defined as “any method of growing plants without the use of soil as a rooting medium, in which the inorganic nutrients absorbed by the roots are supplied via the irrigation water”. The fertilizers containing the nutrients to be supplied to the crop are dissolved in the appropriate concentration in the irrigation water and the resultant solution is referred to as “nutrient solution”.

In soilless crops, the plant roots may grow either in porous media (substrates), which are frequently irrigated with nutrient solution (see chapter 11), or directly in nutrient solution without any solid phase. In recent decades, supplying nutrient solution to plants to optimize crop nutrition (fertigation or liquid fertilization) has become routine cultural practice, not only in soilless culture but also in soil-grown greenhouse crops. Hence, the drastically restricted volume of the rooting medium and its uniformity are the only characteristics of soilless cultivated crops differentiating them from crops grown in the soil.

In recent years, cultivation in inorganic substrates has been characterized by a shift from open- to closed-cycle cultivation systems, involving reuse of drainage solution. The cultivation of greenhouse crops in closed hydroponic systems can substantially reduce the pollution of water resources by nitrates and phosphates stemming from fertigation effluents, and contribute to an appreciable reduction in water and fertilizer consumption (Savvas, 2002). Switching over to closed cultivation systems does not seem to restrict crop yield or product quality. However, a factor limiting the broad expansion of closed-cycle cultivation systems in substrate-grown crops is the accumulation of salt ions in the recycled nutrient solution. This phenomenon originates from the inlet of salt ions and water at higher ratios (concentrations in the irrigation water) than the corresponding ion-

to-water uptake ratios (Sonneveld, 2002). Furthermore, the reuse of the nutrient solution effluents in closed soilless culture systems is associated with the risk of disease spread via the recycled leachate, which entails the installation of a solution disinfection system (Wohanka, 2002).

The rapid expansion worldwide of hydroponic systems in the last three decades may be ascribed to their independence from the soil and its associated problems, i.e. the presence of soil-borne pathogens at the start of the crop and the decline of soil structure and fertility due to continual cultivation with the same or relative crop species. Soilless cultivation appears to be the safest and most effective alternative to soil disinfection by means of methyl bromide. It is therefore becoming increasingly important in protected cultivation – not only in modern, fully equipped glasshouses, but also in simple greenhouse constructions designed to optimize favourable climatic conditions. Hydroponic systems offer numerous advantages:

- Absence of soil-borne pathogens.
- Safe alternative to soil disinfection.
- Possibility to cultivate greenhouse crops and achieve high yields and good quality, even in saline or sodic soils, or in non-arable soils with poor structure (accounting for much of the world's cultivable land).
- Precise control of nutrition, particularly in crops grown on inert substrates or in pure nutrient solution (also in soilless crops grown in chemically active growing media, plant nutrition can be better controlled than in soil-grown crops, due to the limited media volume per plant and the homogeneous media constitution).
- Avoidance of soil tillage and preparation, thereby increasing crop length and total yield in greenhouses.
- Enhancement of early yield in crops planted during the cold season, because of higher temperatures in the root zone during the day.
- Respect for environmental policies (e.g. reduction of fertilizer application and restriction or elimination of nutrient leaching from greenhouses to the environment) – therefore, in many countries, the application of closed hydroponic systems in greenhouses is compulsory by legislation, particularly in environmentally protected areas, or those with limited water resources.

Despite the considerable advantages of commercial soilless culture, there are disadvantages limiting its expansion in some cases:

- High installation costs.
- Technical skills requirements.

Root aeration is a key factor for successful soilless cultivation. Understanding the factors influencing air availability in growing media is important for the successful management of substrate-grown crops. Oxygen deficiency may

readily occur in media with relatively low air-filled porosity, especially if the plants exhibit high growth rates and concomitantly intensive root respiration. When growing media characterized by low air-filled porosity are used, a good agricultural practice for avoiding aeration problems is to place the substrate in bags, containers or troughs in layers of at least 20 cm.

In countries where cultivation in greenhouses has reached industrial dimensions, these disadvantages are of minor importance. The average greenhouse size per enterprise is comparatively large and the investment costs per unit of greenhouse area high in order to maximize yield and optimize product quality by completely controlling all growing conditions. Therefore, the inclusion of equipment for hydroponics – a small aliquot of the total investment – constitutes the necessary supplement to exclude the last imponderable factor that could restrict yield and quality: the soil. Major greenhouse enterprises can afford the costs of specialized personnel or external advisory services and thus, the requirement for sufficient technical skills is not a problem. In contrast, when the greenhouse is a simple construction mainly based on favourable natural conditions (mild winter and increased solar irradiation), even a small increase in the installation and operation costs (as required for the introduction of hydroponics) may not be justifiable. The investment can be acceptable only when problems originating from the soil become critical, water resources are limited, or pollution of the environment by nutrient leaching is serious. The result is that commercial hydroponics is relatively limited in most Mediterranean countries.

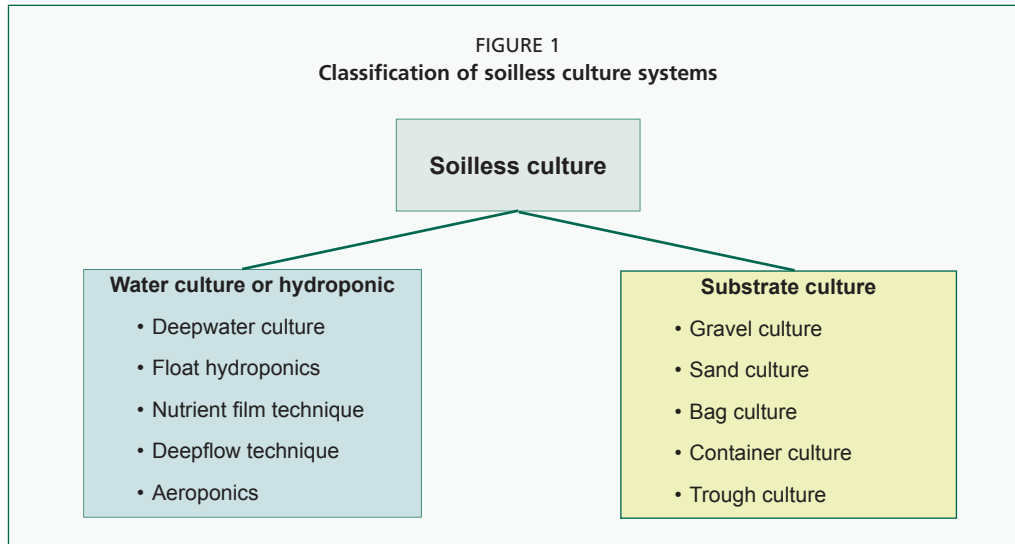
### SYSTEMS AND EQUIPMENT

Intense research and experimental activities in soilless cultivation have led to the development of numerous systems characterized by different water volume, methods of water supply, nutrition management, size and shape of growing modules, and by the presence or absence of a variety of growing media (substrates).

Soilless cultures are usually classified according to the type of plant support as substrate culture (artificial, mineral or organic growing media, or a mixture of these) and water culture or hydroponic, where roots are partially or completely dipped in the nutrient solution (Figure 1).

For several reasons – differences in nutrient supply throughout the delivery system, varying plant growth and consequent differences in rate of nutrient uptake, and the quality of irrigation water (often scarce) – the supply of nutrients and water solution must exceed the crop's needs. Excess of nutrients and water assures that all plants are adequately fed, and leaching avoids excessive concentration of salts and non-essential elements (e.g. sodium) at root level. Soilless systems are also categorized in terms of management of the leachate (drained solution) as either open- or closed-loop systems.





### Feeding plants in soilless systems

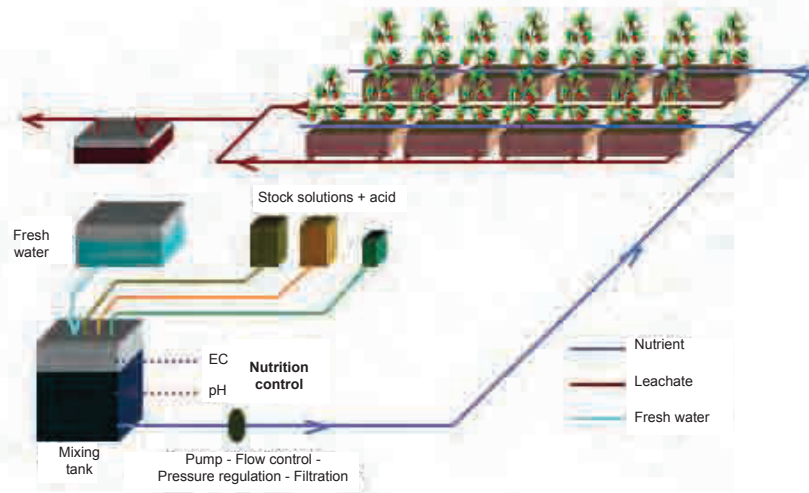
In all modern soilless systems, fertilization and irrigation are integrated into one system able to supply fertilizers and water at the same time (fertigation). Once it became evident that all nutrients essential for crops (macro- and micronutrients) could be supplied through hydrosoluble fertilizer salts, systems were developed with fertilizers dissolved at relatively high concentrations in special stock solutions. Stock solutions are injected and diluted in the irrigation water. Generally, two fertilizer tanks containing the stock solutions are used to separate fertilizers that can interact. A possible combination is a tank “A” containing essentially calcium fertilizers and a tank “B” with essentially phosphate and sulphate fertilizers. In this way, Ca is separated from P and  $\text{SO}_4\text{-S}$  to avoid precipitation of calcium phosphate or calcium sulphate, which are sparingly soluble. A third tank “C” contains a concentrated solution of an inorganic acid which is used to control the pH of the nutrient solution obtained after the injection of the stock solutions into the irrigation water, and to wash the irrigation system and avoid clogging of the nutrient solution emitters.

### Open- and closed-loop soilless systems

In open-loop systems the water and nutrients are supplied as for a conventional on-soil crop and the drained nutrient solution is thrown out of the system. The leachate may be collected and reused to fertilize on-soil crops, but in most cases it is lost causing harm to the environment (Figure 2). Open-loop systems determine the nutrient solution to supply in conjunction with leaching, i.e. the volumetric ratio of the leachate to the applied nutrient solution.

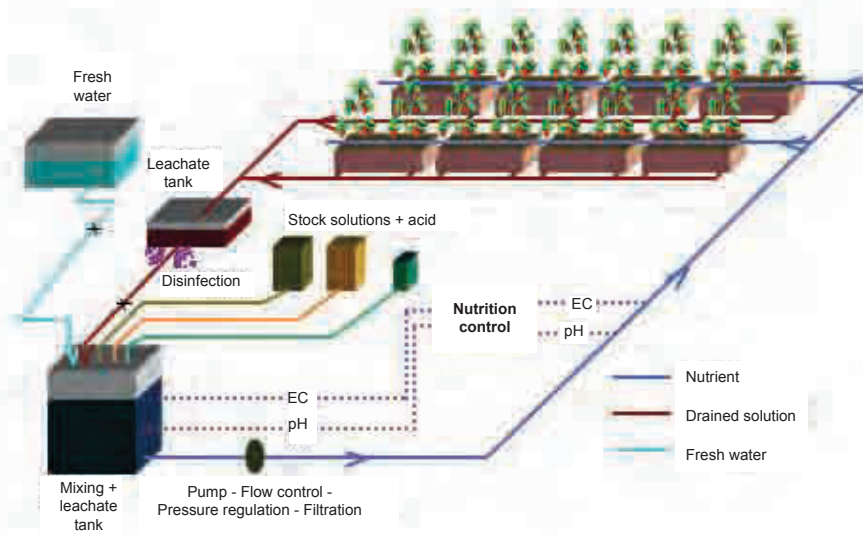
In closed-loop systems the drained nutrient solution is recovered, replenished and recycled (Figure 3). Compared with the open-loop system, it requires more

FIGURE 2  
Open-loop soilless culture system



Standard Operational Practices, Eeconomics

FIGURE 3  
Closed-loop soilless culture system



Standard Operational Practices, Eeconomics

precise and frequent control of the nutrient solution; technical know-how is needed, as it is more sensitive to operational mistakes, in particular during spring due to the possible increase of nutrient concentration in the solution with increasing temperature and solar radiation. The returned nutrient solution has to be treated to restore its original nutrient element composition and to remove any foreign substances. Moreover, spreading of root-borne diseases may occur, thus sterilization of the solution must be provided to kill pathogens.

### **Water culture or hydroponic systems**

#### *Deep water culture (DWC)*

DWC, created in 1929 by Professor W.F. Gericke of the University of California, was the first hydroponic method proposed for commercial purposes. It consists of a bucket filled with nutrient solution, covered with a net and a cloth on which a thin layer of sand (1 cm) is placed to support the plants; the roots are suspended in the nutrient solution. Alternatively, the bucket may be covered with a lid and the plants, contained in net pots, suspended from the centre of the cover. The main drawback of the system is the hypoxic conditions occurring at root level, due to the limited air-water exchange area, compared with the volume of the solution, and the low diffusion coefficient of oxygen in the water. This constraint has been overcome by means of air pumps oxygenating the nutrient solution or by applying recirculating deep water culture systems (RDWC) that use a reservoir to provide nutrient solution to multiple buckets. In RDWC, as the water is reintroduced to the reservoir it is broken up and aerated with the use of spray nozzles.

#### *Float hydroponics*

Plants are grown on trays floating in tanks filled with nutrient solution. This method has a long history but its use in greenhouse production spread following the introduction of high density polystyrene or other “ultralight” plastic (e.g. Styrofoam) trays. It was used for the first time by Professor Franco Massantini at the University of Pisa, Italy, in 1976, to grow lettuce, cardoon and strawberry. Nowadays, the technique is principally adopted for the cultivation of fresh-cut leafy vegetables (lettuce, chicory, rocket, lamb’s lettuce etc.) and aromatics (basil, mint, thyme etc.).

The system appears to be particularly interesting due to the low set-up and management costs and the little automation required for monitoring and adjusting the nutrient solution. Classic FH systems are based on tanks 0.20–0.30 m deep, made of low-cost material (concrete, bricks, wooden planks) or directly dug into the greenhouse. Tanks are sealed (e.g. waterproofing with PE film) and filled with nutrient solution (150–250 litres m<sup>-2</sup>). The large volume of nutrient solution buffers the temperature and reduces the frequency of adjustment and reintegration of the solution. During the growing season, the O<sub>2</sub> concentration in the nutrient solution should range between 5 and 6 mg per litre. The easiest way to oxygenate

**Plate 1**

*Baby leaf lettuce grown on multiple-tank system (left); basil grown on single-tank taking up the whole span (right)*

the nutrient solution is by pumps that drive part of the solution into a pipe onto which a Venturi tube is inserted to insufflate air. However, the airflow should never become very strong, to avoid root damage and recirculation of plant exudates.

In the greenhouse, a single-tank or multiple-tank system may be used (Plate 1). The former, taking up almost the whole of the span, reduces the incidence of barren areas and allows the automation of certain operations, such as the placement and removal of floating trays; the latter consists of several tanks of  $\geq 4 \text{ m}^2$  ( $2 \times 2 \text{ m}$ ), with spacing of 0.5–1.0 m, and it reduces the risk of operational mistakes and diseases.

### *Nutrient film technique (NFT)*

NFT is a hydroponic technique whereby a very thin layer (film) of nutrient solution flows through watertight channels (also known as gullies, troughs or gutters), wherein the bare roots of plants lie (Plate 2). Channels are on a slope of 1.2–3.0 percent and nutrient solution is applied at the elevated end so that the solution flows down through the channels keeping the roots completely wet. The slope may be provided by the floor itself, or benches or racks may hold the channels and provide the required elevation. The thin water stream (1–2 mm deep) ensures sufficient oxygenation of the roots, as the thick root mat which develops on the bottom of the channel has its upper surface continuously exposed to the air. At the lower end of the channels, the solution is drained to a large catchment pipe, which conducts the solution back to the cistern to be recirculated. Depressions in the channel floors must be avoided because ponds of immobile solution will lead to oxygen depletion and growth retardation.

**Plate 2**

*Nutrient Film Technique (NFT) – nutrient solution flows through the root system of tomato in a gully*

Channels generally consist of various types of plastic material, such as polyethylene liner, polyvinylchloride (PVC) and polypropylene, with a rectangle- or triangle-shaped section. The base of the channel must be flat and not curved so as to maintain a shallow stream of liquid. Depending on the crop and the size of the channels, inlet flow rates vary between 1 and 3 litres per minute (2–9 litres m<sup>-2</sup> h<sup>-1</sup>). Lower waterflow rates are recommended for crops such as lettuce, higher rates for fruiting vegetables. A distinction may also be made between the inflow rates needed for a young crop (e.g. 2–4 litres m<sup>-2</sup> h<sup>-1</sup>) and a mature crop (e.g. 5–9 litres m<sup>-2</sup> h<sup>-1</sup>).

Flow rates beyond this range are often associated either with oxygenation or nutritional problems: too rapid and the water becomes too deep and oxygenation of the roots inadequate; too slow and the result is lack of nutrients, especially for plants with roots downstream in the channel and exposed to water from which many other plants have already extracted nutrients, especially nitrogen and potassium. The rate of nutrient depletion along the channel also depends on length. As a rule, length should not exceed 12–16 m. In order to overcome these problems, a modified system called super nutrient film technique (SNFT) has been developed: nutrient solution is distributed by nozzles arranged along the channel, ensuring adequate availability of both nutrients and oxygen near the roots.

The delivery of nutrient solution may be continuous in a 24-hour cycle, or intermittent (alternating watering and dry periods to improve oxygenation of the root system). Another possibility – a compromise between these two approaches – is the continuous recirculation of the nutrient solution during daylight hours (dawn to dusk) and the automated switching off at night. Nevertheless, if recirculation of nutrient solution is intermittent, the volume capacity of the catchment tank has to be large enough to admit all the nutrient solution included in the system when recirculation is switched off. Before transplanting, the channels are usually covered with a black-on-white polyethylene film (0.15–0.25 mm thick), placing the film with the white side facing outwards (to reflect light and avoid excessive heating of the root and nutrient solution) and the black side inwards (to avoid light transmission and consequent development of algae). Plants destined for use in NFT systems are raised in small pots or plugs or in rockwool cubes and are placed in the channels when a substantial root system has formed.

The main advantages of NFT over other systems are the absence of substrate and the reduced volume of nutrient solution required, resulting in significant savings in water and fertilizers and reduced environmental impact and costs related to the disposal of the substrate. On the other hand, owing to the low water volume, the nutrient solution is subjected to major temperature changes along the channel and during growing seasons. Moreover, NFT has very little buffering against interruptions in water and nutrient supplies, and there is a considerable risk of the spread of root-borne diseases. Technically most crops could be grown

in a NFT system, but it works best for short-term crops (30–50 days), such as lettuce, because plants are ready to harvest before their root mass fills the channel.

### *Deep flow technique (DFT)*

DFT is another method where roots are continuously exposed to moving water and nutrients. While with NFT, the water stream is as thin as possible, in DFT the continuously flowing nutrient solution has a depth of 50–150 mm. The large water volume simplifies the control of the nutrient solution and buffers the temperature, making the system suitable for regions where temperature fluctuation in the nutrient solution can be a problem. The width of the channels in a DFT system are usually about 1 m. Plants are grown on polystyrene trays which float on the water or rest on the channel sidewalls.

### *Aeroponics*

Aeroponics is the growing of plants with the root system suspended in a fine mist of nutrient solution applied continuously or intermittently. Plants are secured in holes on polystyrene panels using polyurethane foam: panels are placed horizontally or on a slope, and fixed over a metal frame, arranging closed containers with a square or triangular section (Plate 3).

Water and nutrients are supplied by spraying the plant's dangling roots with an atomized nutrient solution by means of sprayers, misters or foggers inserted in PE or PVC pipes placed in the unit. The flow rate of the sprayers may range from 35 to 70 litres h<sup>-1</sup>, whereas the spacing depends on the design and size of the cropping modules. As a general indication, they should be placed about 0.50 m apart to assure homogeneous nebulization all along the aeroponic unit. Spraying usually lasts 30–60 seconds, and their frequency varies according to species, plant growth stage, growing season and time of day (e.g. in summer, during rapid vegetative growth, a crop grown in northeast Italy may require up to 80 sprayings per day). At each nebulization, the drainage is collected at the bottom of the modules and recirculated.

Aeroponics permits a major reduction in water and fertilizer consumption and ensures adequate oxygenation of the roots. However, aeroponically grown plants may experience severe thermal stresses, especially in summer. Another disadvantage is the inability to buffer interruptions in the flow of nutrient solution (e.g. power outages). Aeroponics may be used for small-sized vegetables (e.g. lettuce and strawberries) and medicinal and aromatic plants.



**Plate 3**

*Aeroponics: basil plants grown on polystyrene panels which are placed horizontally to form a square-frame system (left); lettuce plants grown on polystyrene panels placed on a slope to form an A-frame system (right)*

### Substrate culture

Substrate culture refers to soilless systems where a solid inorganic (sand, gravel, perlite, rockwool, volcanic stones etc.) or organic (peat, bark, coir, rice hulls etc.) medium offers support to the plants. Substrates retain nutrient solution reserves, thereby buffering interruptions in water and nutrient supply, and protect roots from temperature fluctuations. Cultivation on substrates is currently the primary soilless system used for the production of greenhouse peppers, cucumbers and tomatoes. Several substrates may be adopted as a growing medium in soilless cultivation and the choice is mainly based on water retention and water dynamics. Growing media for soilless systems are basically available as plastic encased slabs (e.g. rockwool, coir), prepacked substrate in plastic bags (e.g. perlite, peat, coir) or loose substrate granules placed directly in troughs, buckets or other containers made of strong and long-lasting plastic material.

### Gravel culture

Gravel culture provides growing beds on a slope of 0.2–0.3 percent built either by digging the soil or as above-ground troughs. The beds are lined with thick plastic film (e.g. 0.5 mm black PE film) with a length of up to 30–40 m. In most gravel culture systems, subirrigation is applied. Alternatively, as in NFT systems, nutrient solution is applied at the high end, it flows down the trough and is drained at the lower end to be recovered and recirculated; this modified gravel culture system is known as the gravel film technique (GFT) (Plate 4).

The best choice of gravel for both subirrigation and GFT systems is particles of porphyry or granite of irregular shape and 3–20 mm diameter (> 50 percent of particles 10–15 mm diameter). The particles should not be of calcareous material in order to avoid pH alterations. If drip irrigation is used rather than subirrigation, smaller aggregates must be used (3–10 mm diameter; > 50 percent about 5 mm).



G. GIANQUINTO

**Plate 4**  
Gravel Film Technique (GFT) – porphyry beds

### Sand culture

Plastic-lined beds are used (as for gravel culture) or sand is spread over the entire greenhouse floor. A drip irrigation system is used to feed each plant individually; waste nutrient solution is usually not recycled (open-loop system). A particular type of sand culture is *enarenado* (Plate 5): still widely used for greenhouse production in Almería, it was created to overcome the extremely poor indigenous soils in the region. *Enarenado* is prepared by levelling the soil and lining it with a layer of



G. GIANQUINTO

**Plate 5**

*Cucumbers (top); beans (middle) grown on enarenado in Almería, Spain; close-up of soil on which the plants are grown (bottom)*



G. GIANQUINTO AND VENETO AGRICOLTURA

**Plate 6**

*Strawberry grown on perlite bags (top); pepper grown on coir slabs (middle); tomato grown on rockwool slabs (bottom)*

compacted clay (about 20 cm), followed by a layer of 2–3 cm of fermented manure or organic material (composted crop residues). A layer of 10 cm of washed beach sand or coarse grit finally sits on the bed. The clay layer has a double function: preventing water leaking into the ground; stopping capillary rise from the saline watertable.

**Bag culture**

Bag culture is the cultivation of plants on plastic bags filled with either porous slabs or loose granules (Plate 6). The substrate-filled bags may be manufactured and purchased as ready-to-use bags or filled by the grower.

Slab-type growing media are either rockwool or coir; rockwool slabs are usually about 90 cm long, 8–10 cm high and 15–20 cm wide. The 15-cm-wide slabs are best suited for growing plants like pepper and tomato. The wider slabs are for crops such as cucumbers that require a strong and stable base and a large root capacity. Coir slabs expand their size after rehydration, reaching 90–110 cm in length, 15–20 cm in width and 6–12 cm in height.

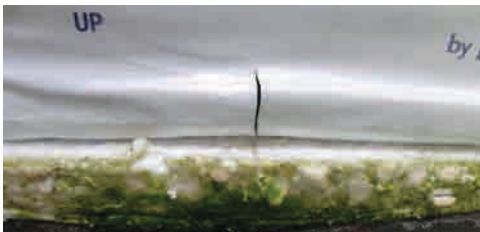




VENETO AGRICOLTURA

**Plate 7**

Holes on the top of bags/slabs for planting (top); saturation of bags with nutrient solution before transplanting (bottom)



D. SAVVAS

**Plate 8**

After saturating the substrate, vertical slits (top) or “L-shaped” slits (bottom) are incised at the basal edge of the bag, midway between two plants; each arm of the “L” is 2–3 cm long



VENETO AGRICOLTURA

**Plate 9**

Tomato transplants rooted in rockwool cubes, ready to be planted

### Bag culture

#### Advantages:

- Less substrate volume use
- Bags can be removed easily if there is any infection
- Simplicity

#### Disadvantages:

- Needs labour to fill (if ready-for-use bags not available at the market)

The granulated materials most widely used in Mediterranean countries as substrates in bag culture are perlite, peat, coir, pumice or a mixture. Bags are placed in channels or panels to collect the drainage solution. Planting holes are cut in the top (Plate 7); the number of planting holes varies depending on the crop, but as a guide, 3–5 tomatoes can be planted into a slab or bag 90–100 cm long and 15–20 cm wide. As soon as planting holes are ready, one dripper per hole is put in position, and the substrate is saturated with nutrient solution. Saturation is maintained for 24–48 hours to allow the substrate to absorb the solution. Small holes or cuts are made along the base of the plastic envelope to allow excess nutrient solution to drain (Plate 8). Saturation serves to extract the air and provide homogeneous wetting of the growing medium, providing adequate water and nutrient reserves and optimal EC and pH conditions in the plant root zone, and diluting accumulated salts (in the case of substrate reuse).

Transplants rooted in rockwool cubes or similar media are planted when the roots are about to emerge from the base of the cube (Plate 9). The nutrient solution or water

is delivered via a drip irrigation system (1 or 2 drippers per plant, dripper capacity of 2–4 litres h<sup>-1</sup>). The nutrient solution may be recycled or not, but in open-loop systems an environmentally acceptable means of disposal of the effluent from the substrate is required. Slabs and bags can be reused several times and then they must be discarded.

### *Container culture*

Different containers – PE, PVC or polystyrene buckets or pots (Plate 10) – are used. The volume of the containers varies from 12 to 18 litres and 1–2 plants per container are usually planted. The container depth is important for adequate root development and plant growth, and the deeper the container the higher the ratio of air to water in the substrate. The container depth depends on crop, length of growing season and type of substrate. In general, a depth of > 20 cm is required. A drip irrigation system is used to feed each plant individually and drainage is usually ensured by an overflow opening in the base of the container. The growing media most commonly used in container culture are peat and coir (plain or mixed with perlite, pumice, lapilli or zeolite) and perlite. The same general operating procedures are used as with bag culture.

### *Trough culture*

Plants grow on plastic or plastic-lined troughs built above ground (Plates 11 and 12). Trough depth varies from 10 to 35 cm depending on the substrate and particle size (0.3–0.5 mm particles require a depth of at least 35 cm). Troughs should have a uniform slope of 0.5 percent. A drain pipe with a diameter of at least 30 mm is placed on the bottom of the trough from one end to the other. Plants are spaced

### Container culture

#### Advantages:

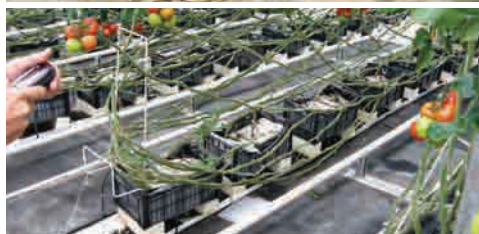
- Low substrate volume
- Containers are easily removed if there is any infection
- Simplicity

#### Disadvantages:

- Needs labour to fill
- Cost of container



G. GIANQUINTO



**Plate 10**

*Tomatoes grown on polystyrene buckets filled with coir in Morocco (above), and on PE cases filled with perlite in Turkey (below)*



G. GIANQUINTO

**Plate 11**

*Tomatoes grown in plastic-lined troughs filled with coir*



G. GIANQUINTO

**Plate 12**

*Tomatoes grown in plastic-lined troughs built above-ground and filled with coir, Morocco*

**Trough culture****Advantages:**

- Easily adapted to small scale farmers' conditions since similar to soil
- Any problems in the individual drippers could be tolerated
- Suitable for crops with high plant density (e.g. lettuce)

**Disadvantages:**

- Needs labour to fill and change substrate
- Substrate volume per plant is generally higher

normally and drip irrigation feeds each plant individually. The growing media used in trough culture and the general operating procedures are the same as those applied in container culture.

**Greenhouse layout and equipment**

As a rule, in soilless culture the soil is covered with black-on-white polyethylene film (0.20–0.25 mm thick). The film is placed with the white side facing up to maximize reflection, improve brightness at plant level and minimize the trapping of excess heat inside the greenhouse. The black side faces downwards to control weeds. Mulching reduces the relative humidity of the air, eliminating evaporation from the soil and preventing contact between plants and soil, thus reducing the risk of disease.

Soilless culture (except DWC and FH) requires fertigation systems: to mix appropriately water and fertilizers dissolved in concentrated stock solutions; and to uniformly supply feed solution to every plant. Fertigation equipment typically comprises the following:

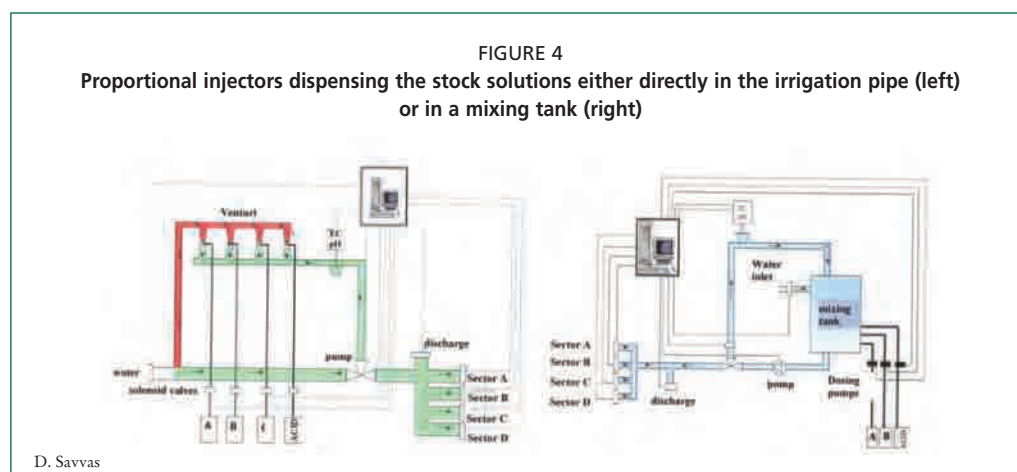
- Pressure regulators to reduce incoming water pressure to a set pressure suitable for the delivery system.
- Filters (typically 80 micron or 200 mesh) to protect from blockages caused by water impurity or precipitated salts.
- Tanks for stock and for acid solution, made of inert materials resistant to acids and salts (usually polypropylene or PVC) and typically  $\geq 1\ 000$ -litre volume for chemical storage between injection times.

- Fertilizer injection devices to take a small amount of stock solution and introduce it into the waterline for delivery to plants.
- pH and EC measuring tools – the pH (acidity or alkalinity) and electrical conductivity (EC) of water and nutrient solution are measured using pH meters and EC meters, respectively.
- Water/solution delivering system – the equipment used to supply nutrient solution in liquid hydroponic systems is illustrated above; in substrate-grown soilless crops, nutrient solution is delivered via a drip irrigation system with microtubes (commonly known as spaghetti tubes) as emitters.

The injection of stock solution in the irrigation pipe (Figure 4, left) is inappropriate with high bicarbonate concentration in the water; the pressure caused by the formation of  $\text{CO}_2$  owing to the acid-bicarbonate reaction does not allow completion of the reaction itself. Thus as the water pressure inside the line decreases (e.g. at emitter level), the acid-bicarbonate reaction stops and the solution pH increases. Injection of stock solutions into a mixing tank (Figure 4, right) ensures that all water enters into an open tank where stock and acid solutions are injected on the basis of continuously monitored EC and pH values; the feed solution is then injected into the main pipe. This system has advantages:

- The EC and pH values of the solution are fairly constant.
- The solution remains in the mixing tank for a sufficiently long time to allow for a complete reaction between acid and bicarbonate.
- An open tank allows the removal of  $\text{CO}_2$  from the solution, thus speeding up the acid-bicarbonate reaction.

The result is better pH regulation; injection into a mixing tank is the most appropriate technology for closed-loop soilless systems with nutrient solution recirculation.



Note that fertilizer injection devices can be classified into volumetric (or quantitative) and proportional injectors:

**Volumetric injectors** are relatively easy-to-use and their cost is low but they are affected by water pressure changes and cannot adjust fertilizer concentration to EC or pH fluctuations occurring in the water. The simplest volumetric injector is based on Venturi devices that reduce pressure (vacuum), sucking the fertilizer solution into the line. With other devices (e.g. Dosatron), the amount of stock solution is directly proportional to the volume of water entering the injector, irrespective of variations in waterflow or pressure which may occur in the main waterline. Volumetric dosage can also be performed by electric pumps, but in this case the cost increases.



D. SAVVAS

**Plate 13**  
*Venturi device as part of a simple volumetric injector used to prepare nutrient solution by diluting stock solutions with water*



VENETO AGRICOLTURA

**Plate 14**  
*Open mixing tank that allows completion of the acid/bicarbonate reaction*

**Proportional injectors** include electric pumps (diaphragm or piston) able to dispense stock solutions either into the waterline or into a mixing tank, depending on the EC or pH value detected downstream. The main advantages of these devices are: accuracy in obtaining a solution with fixed pH and EC – so they are suitable for water characterized by variations in chemical composition and for closed-loop soilless systems; and automation easy to apply. Their main drawback is the high cost and maintenance requirement.

## CROP NUTRITION IN SOILLESS CULTURE

### Principles

In soilless culture, all essential plant nutrients should be supplied via the nutrient solution, with the exception of carbon, taken up from the air as CO<sub>2</sub>. To prepare nutrient solutions containing all essential nutrients, inorganic fertilizers are used as nutrient sources, except for iron, which is added in chelated form to improve its availability for the plants. Most fertilizers used to prepare nutrient solutions in soilless culture are highly soluble inorganic salts but some inorganic acids are also used. A brief description of the water soluble fertilizers commonly used in soilless culture is given in Table 1.

TABLE 1  
Water soluble fertilizers commonly used in soilless culture

Fertilizer	Chemical formula	Percentage in nutrient	Molecular weight (g)	Solubility (kg litre <sup>-1</sup> , 0 °C)
Ammonium nitrate	NH <sub>4</sub> NO <sub>3</sub>	N: 35	80.0	1.18
Calcium nitrate	5[Ca(NO <sub>3</sub> ) <sub>2</sub> ·2H <sub>2</sub> O] NH <sub>4</sub> NO <sub>3</sub>	N: 15.5, Ca: 19	1 080.5	1.02
Potassium nitrate	KNO <sub>3</sub>	N: 13, K: 38	101.1	0.13
Magnesium nitrate	Mg(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O	N: 11, Mg: 9	256.3	2.79 (20 °C)
Nitric acid	HNO <sub>3</sub>	N: 22	63.0	-
Monoammonium phosphate	NH <sub>4</sub> H <sub>2</sub> PO <sub>4</sub>	N: 12, P: 27	115.0	0.23
Monopotassium phosphate	KH <sub>2</sub> PO <sub>4</sub>	P: 23, K: 28	136.1	1.67
Phosphoric acid	H <sub>3</sub> PO <sub>4</sub>	P: 32	98.0	-
Potassium sulphate	K <sub>2</sub> SO <sub>4</sub>	K: 45, S: 18	174.3	0.12
Magnesium sulphate	MgSO <sub>4</sub> ·7H <sub>2</sub> O	Mg: 9.7, S: 13	246.3	0.26
Potassium bicarbonate	KHCO <sub>3</sub>	K: 39	100.1	1.12
Iron chelates	various types	Fe: 6–13	-	-
Manganese sulphate	MnSO <sub>4</sub> ·H <sub>2</sub> O	Mn: 32	169.0	1.05
Zinc sulphate	ZnSO <sub>4</sub> ·7H <sub>2</sub> O	Zn: 23	287.5	0.62
Copper sulphate	CuSO <sub>4</sub> ·5H <sub>2</sub> O	Cu: 25	249.7	0.32
Borax	Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub> ·10H <sub>2</sub> O	B: 11	381.2	0.016
Boric acid	H <sub>3</sub> BO <sub>3</sub>	B: 17.5	61.8	0.050
Sodium octaborate	Na <sub>2</sub> B <sub>8</sub> O <sub>13</sub> ·4H <sub>2</sub> O	B: 20.5	412.4	0.045
Ammonium heptamolybdate	(NH <sub>4</sub> ) <sub>6</sub> Mo <sub>7</sub> O <sub>24</sub>	Mo: 58	1 163.3	0.43
Sodium molybdate	Na <sub>2</sub> MoO <sub>4</sub> ·2H <sub>2</sub> O	Mo: 40	241.9	0.56

In commercial soilless culture, the fertilizers needed to prepare a nutrient solution are mixed with water to form concentrated stock solutions, which are then automatically mixed with irrigation water to form nutrient solution.

### Composition of nutrient solution

To formulate the composition of a nutrient solution for a certain crop, experimental results concerning the nutritional requirements of the particular plant species should be available. Such data are also essential to check and adjust the nutritional status in the root zone during the cropping period. The composition of nutrient solutions and the optimization of nutrition in commercial hydroponics have been primary objectives of research related to soilless culture in recent decades. The pioneer work on the composition of nutrient solutions was carried out by American scientists before the Second World War and resulted in the formula of Hoagland and Arnon (1950), widely used for research purposes even today. This formula is presented in Table 2.

TABLE 2  
Composition of standard nutrient solutions

Macronutrient	H&A	S&S (cucumber)	S&S (tomato)	Micronutrient	H&A	S&S (cucumber)	S&S (tomato)
	mmol per litre				µmol per litre		
NO <sub>3</sub> <sup>-</sup>	14.0	16.00	17.00	Fe	25.00	15.00	10.00
H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>	1.0	1.25	1.50	Mn	9.10	10.00	10.00
SO <sub>4</sub> <sup>2-</sup>	2.0	1.375	2.50	Zn	0.75	5.00	4.00
K <sup>+</sup>	6.0	8.00	8.00	Cu	0.30	0.75	0.75
NH <sub>4</sub> <sup>+</sup>	1.0	1.25	1.00	B	46.30	25.00	20.00
Ca <sup>2+</sup>	4.0	4.00	5.25	Mo	0.10	0.50	0.50
Mg <sup>2+</sup>	2.0	1.375	2.00				

H&A: As proposed by Hoagland and Arnon (1950) for universal use.

S&S: As proposed by Sonneveld and Straver (1994) for commercial cultivation of cucumber and tomato in rockwool.

After the Second World War, efforts focused on adapting the basic formula of Hoagland and Arnon (1950) to the needs of individual crop species. With the support of new developments in analytical techniques and equipment, specific nutrient solutions were formulated for each greenhouse crop species. Such formulae have been published by Sonneveld and Straver (1994), Resh (1997), De Kreij *et al.* (1999), Papadopoulos (1991 and 1994), Adams (2002) etc. Two examples of formulae suggested by Sonneveld and Straver (1994) for cucumber and tomato are given in Table 2.

In commercial practice, it is not easy to implement nutrient solution formulae like those given in Table 2. The first difficulty arises from the mineral composition of the irrigation water. In most cases, irrigation water contains macronutrients (Ca<sup>2+</sup>, Mg<sup>2+</sup>, SO<sub>4</sub><sup>2-</sup>), micronutrients (Mn<sup>2+</sup>, Zn<sup>2+</sup>, Cu<sup>2+</sup>, B and Cl<sup>-</sup>) and other non-nutrient ions (HCO<sub>3</sub><sup>-</sup>, Na<sup>+</sup>) at appreciably high concentrations. When the concentration of a nutrient element in the irrigation water represents a non-negligible fraction of the target concentration in the nutrient solution, the grower has to deduct the amount that is already available in the irrigation water from the total required amount in the nutrient solution. The concentration of bicarbonates (HCO<sub>3</sub><sup>-</sup>) in the irrigation water is also very important since it determines the amount of acid required for pH adjustment. Furthermore, the concentration of Na<sup>+</sup> has to be taken into consideration, since it determines the ultimate EC of the nutrient solution supplied to the crop. However, since the concentrations of all these nutrient and non-nutrient ions are different in the irrigation water used by each individual grower, the amount of fertilizer required to prepare a nutrient solution with a standard composition differs from grower to grower. Thus, the calculations have to be performed individually for each grower. A further difficulty is the inability to supply a certain amount of a macronutrient independently of the supply of the other macronutrients, due to the lack of single-nutrient fertilizers (with the exception of N). For example, soluble potassium (K<sup>+</sup>) can be added either as KOH or as a salt (KCl, KNO<sub>3</sub>, KH<sub>2</sub>PO<sub>4</sub>, K<sub>2</sub>SO<sub>4</sub> etc.) to an

aqueous solution. However, the supply of K in the form of KOH is accompanied by the concomitant supply of OH<sup>-</sup> ions which raise the pH of the solution to harmful levels for the plants. Similarly, the supply of potassium salts results in the concomitant supply of another element in the form of an anion at a fixed molar ratio depending on the valence of this anion (normally either 1:1 or 2:1).

To overcome these complications and avoid laborious repetition, special computer programs have been developed for the calculation of the amounts of individual fertilizers required to prepare a nutrient solution with a given composition using irrigation water. Savvas and Adamidis (1999) have proposed a simple program that can be easily applied to calculate the amount of fertilizer needed to prepare commercial nutrient solutions when a target composition is available and the mineral composition of the irrigation water is known. This program, which operates via a Microsoft EXCEL<sup>®</sup> platform, is freely accessed via the Internet at: [www.ekk.aua.gr/excel/index\\_en.htm](http://www.ekk.aua.gr/excel/index_en.htm).

To calculate the amount of fertilizer needed to prepare a nutrient solution using a computer program, it is necessary to introduce input data describing its composition. When using a program based on the algorithm proposed by Savvas and Adamidis (1999), the composition of the nutrient solution has to be defined by selecting target values for the following solution characteristics:

- Electrical conductivity (EC) in dS m<sup>-1</sup> – a measure of the total salt concentration in the nutrient solution
- pH
- Levels of K, Ca and Mg, which can be alternatively introduced either as mutual ratios (K:Ca:Mg on a molar basis, denoted by X:Y:Z) or as fixed concentrations (mmol litre<sup>-1</sup>)
- Level of N, which can be defined by specifying one of the following:
  - a total nitrogen to potassium ratio (total-N/K denoted by *R*) in combination with an ammonium to total nitrogen ratio (NH<sub>4</sub>-N/total-N denoted by *N<sub>r</sub>*), both on a molar basis
  - a total nitrogen to potassium ratio (total-N/K on a molar basis, denoted by *R*) in combination with a fixed NH<sub>4</sub>-N concentration (mmol litre<sup>-1</sup>)
  - a fixed NO<sub>3</sub>-N concentration (mmol litre<sup>-1</sup>) in combination with an ammonium to total nitrogen ratio (NH<sub>4</sub>-N/total-N on a molar basis, denoted by *N<sub>r</sub>*); or
  - a fixed NO<sub>3</sub>-N concentration (mmol litre<sup>-1</sup>) in combination with a fixed NH<sub>4</sub>-N concentration (mmol litre<sup>-1</sup>)
- Concentration of H<sub>2</sub>PO<sub>4</sub><sup>-</sup> (mmol litre<sup>-1</sup>)
- Concentrations of micronutrients (μmol litre<sup>-1</sup>), specifically Fe, Mn, Zn, Cu, B and Mo



If the desired composition of a nutrient solution is given in terms of fixed target concentrations, the EC of this solution is also fixed and can be calculated using the following relationship established by Savvas and Adamidis (1999):

$$C = 9.819E - 1.462 \quad \text{Eq. 1}$$

where:

$E$  depicts the EC ( $\text{dS m}^{-1}$ )

$C$  depicts the sum of the cation concentrations ( $\text{meq litre}^{-1}$ ) in the nutrient solution, including also non-nutrient macrocations, particularly the  $\text{Na}^+$  concentration

Consequently, when only macronutrient concentrations but no macronutrient ratios are given to define the desired nutrient solution composition, it is meaningless to select a target EC, since only one fixed EC, specifically that calculated by Equation 1, is feasible. In contrast, if the desired composition of the nutrient solution is defined by selecting target macronutrient ratios, it is possible to select any desired EC.

To calculate the amount of fertilizer needed to prepare a nutrient solution, it is important to introduce also the following information to the computer program, in addition to the data describing the desired composition:

- EC, pH and concentrations of nutrients (K, Ca, Mg,  $\text{NO}_3\text{-N}$ ,  $\text{SO}_4\text{-S}$ , Mn, Zn, Cu, B, Cl) and non-nutrient ions ( $\text{Na}^+$  and  $\text{HCO}_3^-$ ) in the irrigation water used to prepare the nutrient solution
- Percentage of Fe in the Fe-chelate used as iron source
- Available source of soluble P ( $\text{KH}_2\text{PO}_4$  or  $\text{H}_3\text{PO}_4$ ) and percentage of pure  $\text{H}_3\text{PO}_4$  in the commercial-grade  $\text{H}_3\text{PO}_4$ , if the latter is used as P fertilizer (commonly 85%)
- Percentage of pure  $\text{HNO}_3$  in the commercial-grade  $\text{HNO}_3$ , if the latter is used for pH adjustment when preparing the nutrient solution
- Available source of B (see Table 1)
- Available source of Mo (see Table 1)
- Volume of stock solutions ( $\text{m}^3$ )
- Desired concentration factor, defined for a particular fertilizer as the ratio of its concentrations in the stock solution and the solution supplied to the crop (commonly 100, dictated by the least solubility of the fertilizers used)

The output obtained by implementing a computer program to calculate a nutrient solution comprises the weight of fertilizer (kg for macronutrients, g for micronutrients) to be added in the two-stock solution tanks (A and B) for the given volume. If the target nutrient solution composition introduced as input data includes macronutrient concentrations and not ratios, the computer program

also calculates the target EC. The target values of EC and pH are subsequently introduced to the controlling system of the fertigation head used to automatically prepare fresh nutrient solution by diluting the stock solutions.

As a rule, the fertilizer used as a source of calcium is calcium nitrate, because calcium phosphates and sulphates are sparingly soluble fertilizers, and calcium chloride would result in the addition of chlorides at undesirable concentrations. Magnesium and sulphates are added in the form of magnesium sulphate. If the target concentration of magnesium is higher than that of sulphate, the extra Mg is added in the form of magnesium nitrate. However, if the target concentration of sulphate is higher than that of magnesium, extra  $\text{SO}_4^{2-}$  is needed, added in the form of potassium sulphate. Phosphorus is added as monopotassium phosphate but can alternatively be added as phosphoric acid, depending on the concentration of bicarbonates in the irrigation water. Ammonium is commonly added as ammonium nitrate. Potassium is primarily added as potassium nitrate but, to compute the amount to be added, the concentration of K originating from the addition of potassium sulphate and monopotassium phosphate is deducted from the target K concentration. Nitrate-N is added in the form of calcium nitrate, magnesium nitrate, potassium nitrate, ammonium nitrate and nitric acid. The allocation of the required  $\text{NO}_3\text{-N}$  to the above referenced  $\text{NO}_3\text{-N}$  fertilizers depends on the target concentrations of Ca, Mg, K,  $\text{SO}_4^{2-}$ ,  $\text{H}_2\text{PO}_4^-$  in the nutrient solution and the concentration of bicarbonates in the irrigation water.

The concentration of  $\text{HCO}_3^-$  in the irrigation water dictates the amount of  $\text{HNO}_3$  to be added to control pH but has an impact also on the addition of  $\text{H}_3\text{PO}_4$ . When preparing fresh nutrient solution by diluting stock solutions with irrigation water, the adjustment of the target pH entails the conversion of the bicarbonates contained in the irrigation water to  $\text{CO}_2$  (Savvas and Adamidis, 1999). This reaction requires the addition of acid at an  $\text{H}^+ : \text{HCO}_3^-$  molar ratio of 1 : 1. The target P concentration in nutrient solutions rarely exceeds 1.5 mmol per litre. Hence, it is not possible to add more phosphoric acid than that resulting in a P concentration of 1.5 mmol per litre in the nutrient solution. However, the bicarbonate concentrations in most sources of irrigation water in Mediterranean countries are much higher than 1.5 mmol per litre. If the concentration of bicarbonates in the irrigation water is about 0.5–1.0 mM higher than the target P concentration in the nutrient solution, nitric acid has to be used to adjust the target pH, either in addition to phosphoric acid, or as a sole source of  $\text{H}^+$ . High  $\text{HCO}_3^-$  concentrations in the irrigation water are essentially accompanied by equally high concentrations of cations, particularly  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ . Thus, when preparing a nutrient solution using tap water with a high  $\text{HCO}_3^-$  concentration, an increased addition of  $\text{NO}_3^-$  in the form of  $\text{HNO}_3$  in order to control pH is compensated for by a decreased supply of  $\text{NO}_3^-$  in the form of  $\text{Ca}(\text{NO}_3)_2$ . If a high  $\text{HCO}_3^-$  concentration in the tap water is accompanied also by a high  $\text{Mg}^{2+}$  concentration, less  $\text{Mg}^{2+}$  is added in the form of  $\text{MgSO}_4$ . Then, the necessary  $\text{SO}_4^{2-}$  is added in the form of  $\text{K}_2\text{SO}_4$ , resulting in reduced addition

of  $\text{NO}_3^-$  in the form of  $\text{KNO}_3$ . Consequently, even if the  $\text{HCO}_3^-$  concentration in the tap water is high, there is no risk of adding too much  $\text{NO}_3^-$  to the nutrient solution when  $\text{HNO}_3$  is used to adjust the pH.

Regarding metallic micronutrients, iron is added as chelated Fe, while Mn, Zn and Cu are added in the form of their sulphate salts. The commonly used B fertilizers in soilless culture are sodium tetraborate, sodium octaborate and borax, while the commonly used Mo fertilizers are sodium molybdate and ammonium hepta-molybdate. The selection of the B or Mo fertilizer depends on current availability or market prices and not on the addition of other nutrients or the composition of the irrigation water.

An interesting aspect related to the nutrition of soilless-grown plants in greenhouses, which has received attention during the last two decades, is the inclusion of silicon in the nutrient solution. Silicon improves the growth of plants subjected to both abiotic and biotic stress conditions when supplied via the nutrient solution in hydroponics, although it seems to have no effect under non-stress conditions. Silicon is added to the nutrient solution in the form of liquid potassium silicate ( $\text{SiO}_2 \cdot 2\text{KOH}$ ), which has a strong alkaline reaction and should, therefore, be supplied to the plants from a separate stock solution tank. The high alkalinity of potassium silicate is controlled by enhancing the  $\text{HNO}_3$  injection dosage during the process of nutrient solution preparation. The extra supply of nitrogen in the form of  $\text{HNO}_3$  and K in the form of  $\text{SiO}_2 \cdot 2\text{KOH}$  to the nutrient solution is compensated for by a corresponding reduction in  $\text{KNO}_3$  injection.

### **Impact of nutrition on yield**

The EC is considered to be one of the most important properties of the nutrient solutions used in soilless culture. If the EC of a nutrient solution is too low, the supply of some nutrients to the crop may be inadequate. Similarly, when the EC is too high, the plants are exposed to salinity. However, the yield response of the plants to the EC of the nutrient solution may vary widely among different species. Therefore, for each cultivated plant species, the terms “too low” and “too high” need to be quantitatively defined based on experimental results.

In semi-arid regions such as those in the Mediterranean Basin, the presence of NaCl at relatively high concentrations in the available irrigation water is a common condition. When such irrigation water is used to prepare nutrient solutions, the concentration of NaCl is added to that of nutrients and thus the EC in the resultant nutrient solution is correspondingly increased. Furthermore, in the Mediterranean region, Ca and Mg may also occur at higher concentrations in the irrigation water than the target concentrations in the nutrient solutions. In such cases, the target Ca and Mg concentrations in the nutrient solution are essentially as high as in the irrigation water and thus higher than the desired level, thereby resulting in a correspondingly higher EC than the target EC level.

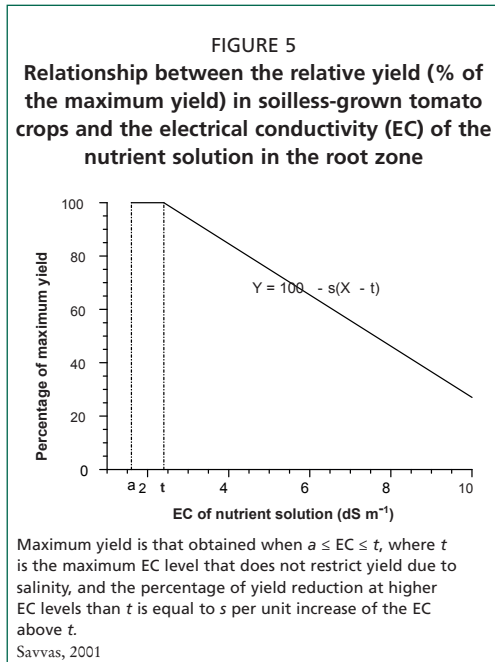
Some growers in the Netherlands and other parts of the world apply desalination by means of reverse osmosis in order to deal with the problem of high salt concentrations in the irrigation water. However, desalination technologies incur high production costs for growers and are affordable only in high-technology greenhouses used for high-value crops.

The growth and yield responses of hydroponically grown plants to the total salt concentration in the nutrient solution may be described by the generalized model presented in Figure 5. According to this model, if the EC is lower than a particular value ( $a$ ), an increase in the EC to values not exceeding ( $a$ ) enhances the yield of the crop. If the EC ranges between ( $a$ ) and ( $t$ ), where ( $t$ ) is the upper critical EC level, known as salinity threshold value (STV), the yield of the crop remains constant.

However, any further increase in the EC above ( $t$ ) results in yield decrease. If all nutrients are included at sufficient levels in the nutrient solution, the decreases in growth and yield follow a linear pattern as the EC increases to higher levels than ( $t$ ). The rate of yield decrease per unit increase of EC is termed salinity yield decrease (SYD). The impact of the increased EC on plant growth in hydroponics depends also on the prevailing climatic conditions. As a rule, the detrimental salinity effects are more pronounced under high light intensity and low air humidity.

The optimal pH in the root zone of most crop species grown hydroponically ranges from 5.5 to 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 soilless culture, when maintaining marginal values of the optimum pH range, the risk of exceeding or dropping below them for some time increases due to the limited volume of nutrient solution per plant that is available in the root zone. Most plants, when exposed to external pH levels  $> 7$  or  $< 5$ , show growth restrictions (Sonneveld, 2002). Nevertheless, there are also plant species, such as gerbera and cut chrysanthemums, which perform better at low pH due to the higher susceptibility of these species to chlorosis induced by Fe, Mn, Zn and Cu deficiencies.

Overall, values of pH above 7.0 in the root zone of soilless cultivated plants can quickly result in the appearance of P-, Fe- and Mn-, but sometimes also in Cu- and Zn-deficiency symptoms. The appearance of P-deficiency at pH values



> 6.5–7.0 is attributed to the increasing transformation of  $\text{H}_2\text{PO}_4^-$  into  $\text{HPO}_4^{2-}$ , which is not readily taken up by plants. Furthermore, the precipitation of calcium phosphate at pH values > 6.2 is an additional reason to maintain the pH below this level in the root zone of soilless-grown plants. The occurrence of Fe-, Mn-, Zn- and Cu-deficiencies at pH values > 6.5–7.0 is associated with increased conversion of these nutrients into insoluble forms which precipitate. In the case of manganese, the precipitation of water-insoluble Mn forms at relatively high pH is further accelerated by an increased activity of Mn-oxidizing bacteria. Iron is the micronutrient with the lowest solubility at high pH. In solution cultures, the free iron ions precipitate even at pH values below 6.5, mainly as iron phosphate. Therefore, Fe should always be added in the form of Fe-chelates in hydroponics, preferably as Fe-DTPA or Fe-EDDHA.

When the pH of the nutrient solution in the root zone drops to levels below 4.5–5.0, both plant growth and yield may be impaired. The detrimental effects of low pH levels on growth and yield are mainly attributed to Mn and Al toxicities due to solubilization of various oxides and hydroxides of Mn and Al, which are constituents of the substrate and remain insoluble at pH levels over 5. In addition, the uptake of Ca, Mg and K by the plants may also be restricted at  $\text{pH} \leq 4$  in the root zone, especially if the low pH was imposed by a relatively high  $\text{NH}_4\text{-N}$  concentration in the nutrient solution. At pH levels below 4 in the root zone, direct  $\text{H}^+$  injury to the roots may be observed.

Theoretically, nutrient availability is optimal when the nutrient concentrations in the root zone correspond approximately to the nutrient-to-water uptake ratio. Under such conditions, plants do not have to consume energy to take up or to actively exclude any nutrient ions, whose concentrations are lower or higher than their nutrient-to-water uptake ratios, respectively. However, the nutrient-to-water uptake ratios fluctuate widely in response to different climatic conditions, even within the same day. Therefore, it is not possible to provide a nutrient solution with nutrient concentrations which would be continuously in accordance with the corresponding nutrient-to-water uptake ratios. On the other hand, due to the very low volume of nutrient solution per plant, changes in the nutrient-to-water uptake ratio might quickly result in large alterations of the ionic concentrations in the solution. Indeed, due to a more intensive plant uptake during particular time intervals, some nutrients may become depleted while others may accumulate. Therefore, most investigators suggest higher nutrient concentrations than the expected mean nutrient-to-water uptake ratios, in order to ensure adequate supply of all nutrients. Recommended nutrient concentrations for nutrient solutions prescribed to specific plant species grown in greenhouses are given in Table 2.

Different plant species have different preferences with regard to nutrient ratios in the nutrient solution. Thus, the determination of the most favourable nutrient ratio for each species is of major importance. Most experiments concerned with

effects of nutrient ratios in nutrient solutions focused on the ratio between the metallic macronutrients (K:Ca:Mg or K:Ca), nutrient anion ratios, the N:K (or K:N) ratio and the ratio of  $\text{NH}_4^+$  to total nitrogen. The ratio between the metallic macronutrients is important for the maintenance of the EC in the root zone, since excessively high Ca:K or Mg:K may result in accumulation of these ions. Furthermore, the K:Ca:Mg ratio has a strong impact on the occurrence of physiological disorders, especially in fruit vegetables (Savvas *et al.*, 2008). The N:K and N:S proportions in the nutrient solution are important for the maintenance of a balance between vegetative and reproductive growth and fruit quality (Savvas, 2001). The proportion of  $\text{NH}_4^+$ -N to total nitrogen has no impact on the total supply of N to the crop via the nutrient solution, since both  $\text{NH}_4^+$  and  $\text{NO}_3^-$  are N sources. However, ammonium to total nitrogen ratio is very important for the regulation of pH in the root environment.

### Impact of nutrition on produce quality

Some consumers are rather mistrustful with regard to vegetables produced in soilless cultivations. This attitude is mainly based on the assumption that the soilless cultivation of plants is based on the extensive use “chemicals”, unlike plants grown in soil which acquire “natural substances” for their nutrition. However, this belief is not based on scientific knowledge. It is well known that higher plants need only inorganic substances, mainly in ionic form, to satisfy their nutritional requirements.

Plants take up N as  $\text{NO}_3^-$  and  $\text{NH}_4^+$  but not in the form of organic N substances, regardless of the content of organic matter in the soil. Actually, the organic N compounds have to be converted into inorganic N forms before they can be taken up by plants. Consequently, with respect to the quality of the edible vegetable products, it is completely irrelevant whether the nitrogen contained in the plant tissues stems from the organic substances of the soil or from inorganic fertilizers. The only factor influencing the vegetable quality is the quantity of absorbed nitrogen and the way in which it is utilized in the plant metabolism, which has an impact on the  $\text{NO}_3^-$ -N concentration in the edible plant tissues. However, both these factors are better managed in soilless culture, since the small volumes of rooting medium applied in soilless culture enable a more efficient control of the nutrient supply through the composition of the nutrient solution. Thus, reducing the nitrate nitrogen concentration in the nutrient solution supplied to lettuce or other leafy vegetables for some days prior to harvesting may considerably lower the  $\text{NO}_3^-$  content in the leaves of the plants, without significant yield losses. Moreover, since in hydroponics the plants are grown in substrates, which are free from pathogens when they are initially supplied to the grower, the pressure from soil-borne diseases is much weaker than in soil-grown crops. As a result, the demand for use of soil-disinfecting chemicals is considerably reduced in soilless culture, with obvious advantages for the quality of the vegetables produced. Finally, the taste of some fruit vegetables, such as tomato and melon, may be

substantially improved in hydroponics by manipulating the total salt and nutrient concentration in the supplied nutrient solution. Nevertheless, many other factors influencing plant growth are different in soilless cultivated crops than in soil-grown crops. Most of these factors also affect the quality of harvested vegetables.

### Monitoring and adjusting the nutrient supply

As a rule, the target nutrient concentrations in the nutrient solution supplied to soilless cultivated crops are different from the optimal concentrations in the root environment. This is the result of dissimilarities in the efficiency of plants to take up different ions owing to the involvement of different absorption mechanisms in each case. Therefore, when instructions regarding the nutrition of a particular plant species in soilless culture are given, it is essential to recommend at least two target nutrient solution compositions, particularly one for the solution supplied to the crop and another one for the solution in the root environment. The nutrient concentrations in the root environment are of paramount importance, since the plant senses and responds to the nutrient status prevailing around its roots. The composition of the nutrient solution supplied to the crop is also very important, although it has only an indirect impact on crop performance, since it is the main tool to achieve and maintain the nutrient concentrations close to the target levels in the root zone. The plant requirements for any particular nutrient may change, independently of those for other nutrients, in the different plant developmental stages. Hence, for plants with a long harvesting period (e.g. tomato) it is better to suggest different target nutrient solution compositions for different plant developmental stages.

If the nutrient concentrations in the supplied solution are balanced, monitoring the solution's EC in the root environment is a good tool to check plant nutrient status. Nevertheless, a chemical analysis in a representative sample of substrate or nutrient solution taken from the root environment at regular intervals (e.g. every month), especially in closed hydroponic systems, could contribute to better and safer nutritional management of the crop. However, the control of the EC in the root environment provides no information on the micronutrient concentrations. Therefore, care should be taken to apply proper target micronutrient concentrations in the supplied nutrient solution. As a rule, the pH maintained in the root zone is more important for micronutrient availability than the macronutrient concentrations *per se* in the supplied solution. Hence, monitoring the nutrient solution pH in the root zone provides an indirect index regarding the availability of micronutrients for the crop. However, especially for some microelements, the concentration in the supplied nutrient solution is crucial. This is the case with boron, which has a narrow range of optimal concentrations in the nutrient solutions supplied to soilless crops.

A frequent problem in soilless culture is the increase of the EC in the root zone, reaching higher levels than the salinity threshold value for the corresponding plant

species. The most efficient strategy to prevent an increase of the EC in the root zone of soilless cultivated plants to harmful levels is the use of good quality water. However, in the Mediterranean region, irrigation water of good quality may be not available. Therefore, other measures have to be deployed to adjust the EC in the root zone. In many cases, a too high EC may be corrected by increasing the irrigation frequency. Other measures to control the EC in the root zone include:

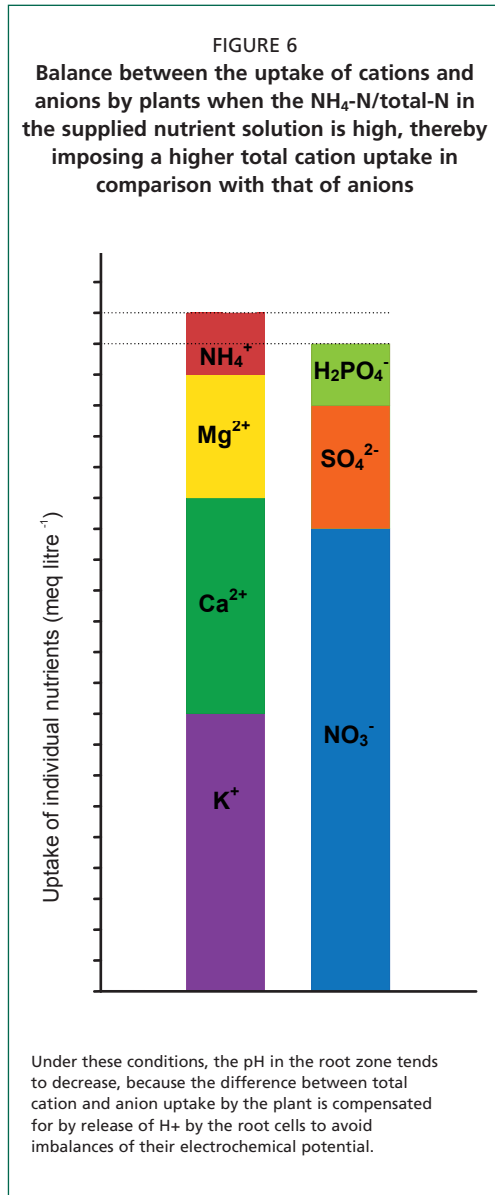
- appropriate K:Ca:Mg ratios in the nutrient solution supplied to the crop aimed at minimizing Ca and Mg accumulation;
- correct irrigation scheduling with respect to the frequency of the water supply and the target leaching fraction; and
- appropriate adjustment of the target EC in the nutrient solution supplied to the crop by taking the EC and the composition of the drainage solution into consideration.

To optimize irrigation scheduling, the frequency of irrigation should be related to the energy input (solar radiation, heating) and suitable equipment should be used. The use of raw irrigation water to wash out salts from substrates is an erroneous practice, resulting in excessively high pH levels and nutrient imbalances in the root zone, unless rainwater is available.

The composition of the nutrient solution in the root zone changes gradually, due mainly to selective ion uptake by the plants in accordance with their nutrient requirements. In periods of sufficient light intensity and rapid growth, the anion uptake usually exceeds that of cations, owing to elevated nitrate absorption and utilization in plant metabolism. In terms of electrochemical potential, anion uptake which exceeds that of cations is compensated for by the release of  $\text{HCO}_3^-$  and  $\text{OH}^-$  by the roots. As a result, the pH of the nutrient solution in the rhizosphere increases. However, under poor light conditions, the nitrate reductase activity declines, thus imposing a depression in nitrate utilization by the plant and concomitantly lower  $\text{NO}_3^-$  uptake rates. Consequently, the total anion uptake is reduced. In terms of electrochemical potential, a more rapid uptake of cations than anions is compensated for by release of  $\text{H}^+$  from the roots. Hence, under poor light conditions, the root zone pH does not tend to increase rapidly, and in some cases it may even decrease.

If the pH of the nutrient solution in the root zone drops below the optimal range, KOH,  $\text{KHCO}_3$  or  $\text{K}_2\text{CO}_3$  may be used for its adjustment, injected from a separate stock solution tank to avoid phosphate and carbonate precipitation (Savvas, 2001). The control of pH in the root environment of soilless cultivated plants usually requires measures to prevent the occurrence of a too high, rather than a too low, pH. If the percentage of drainage solution is relatively low, increased irrigation frequency or water dosage at each irrigation cycle might restore normal pH levels within the root zone. If adjustment of the irrigation schedule fails to





bring the pH to normal levels, an increase in ammonium supply may be needed. Nitrogen is the only nutrient that can be supplied to plants via fertigation in both anionic ( $\text{NO}_3^-$ ) and cationic ( $\text{NH}_4^+$ ) forms, while the uptake rates of both N forms are influenced by their external concentrations. Thus, the manipulation of  $\text{NH}_4\text{-N}/\text{NO}_3\text{-N}$  in the supplied nutrient solution without altering the total-N concentration may considerably modify the total cation to anion uptake ratio. However, changes in this ratio have a profound impact on the pH of the root zone. Indeed, the imbalance of total cation over anion uptake in the rhizosphere originating from enhanced  $\text{NH}_4^+$  uptake (Figure 6) is electrochemically compensated for by the release of protons, which results in a lowering of the medium pH. Similarly, the excess of anion over cation uptake due to increased supply of  $\text{NO}_3^-$  is compensated for by  $\text{H}^+$  influx or equivalent anion extrusion, which increases the pH of the external solution.

As a rule, the use of  $\text{NH}_4^+$  as the sole or dominating N source impairs growth and restricts yield due to the high toxicity of ammonia at intracellular level. Therefore, the current recommendation for soilless culture is that  $\text{NH}_4\text{-N}$  should not exceed 25 percent of the total nitrogen supply (Sonneveld, 2002), although individual species differ in their response to the  $\text{NH}_4\text{-N}/\text{total-N}$  supply ratio and root zone pH.

In soilless-grown crops of leafy vegetables, such as lettuce and rocket, a partial substitution of  $\text{NH}_4^+$  for  $\text{NO}_3^-$  in the nutrient solution may restrict the accumulation of  $\text{NO}_3^-$  in the edible leaves. On the other hand, an elevation of the  $\text{NH}_4\text{-N}$  supply in fruit solanaceae crops grown in soilless culture systems may increase the incidence of blossom end rot and other Ca-related disorders in fruits.

### Nutrient recycling in closed soilless culture systems

In closed systems, the nutrient concentrations in the solution supplied to the crop are largely determined by the composition of the recycled drainage solution. However, it changes during the cropping period and hence its composition is unknown. The changes in the nutrient concentration of the drainage solution complicate its recycling, because the amounts of nutrients needed to establish the target concentrations in the solution supplied to the plants are uncertain. The problem is further complicated by the fact that in commercial horticulture the replenishment process must be performed automatically. To overcome this problem, various automation techniques involving measurements of drainage solution characteristics and adjustments in real time are used in modern closed-cycle soilless culture systems. A standard technique involves mixing of drainage and water at an automatically adjustable ratio by aiming at a preset EC in the outgoing mixture. This operation enables the maintenance of a constant, desired EC in the nutrient solution supplied to the crop by dispensing nutrients at standard injection rates to the mixture of drainage solution and water, despite any fluctuations in the composition of the drainage solution. Another approach is the injection of fertilizers into water at standard rates aimed at a preset EC and the subsequent mixing of the obtained solution with the effluents to be recycled. Also in the latter case, the mixing process is automatically adjusted in real time to a ratio resulting in a constant target EC in the outgoing irrigation solution.

As stated above, both techniques are based on the injection of nutrients at standard rates, which are adjustable by the grower when the drainage solution is mixed with fertilizers and water prior to its resupply to the crop. If, for a particular crop species, experimentally established estimates of the mean uptake concentrations are known for all nutrients to be added in the nutrient solution, the rates of nutrient injection may be adjusted to equal levels with the anticipated uptake concentrations. Thus, as long as the system is closed, the rate of nutrient and water input into the closed system is equal to the rate of their removal due to plant uptake. Consequently, the supply of nutrients is adequate for optimal plant growth, but not excessive, and thus neither depletion nor accumulation of nutrients occurs in the closed system. Unfortunately, nutrient solution compositions corresponding to anticipated mean uptake concentrations, which can be used for balanced crop nutrition in closed soilless culture systems, are currently available only for the climatic conditions of the Netherlands (De Krij *et al.*, 1999). Hence, to optimize nutrient recycling in soilless culture in the Mediterranean region, there is a need to establish and validate estimates of the mean uptake concentrations for all nutrients under the specific climatic conditions.

Long-term recycling of leachate solution may result in accumulation of sparingly absorbed ions, such as  $\text{Na}^+$  and  $\text{Cl}^-$ . In order to ensure an adequate nutrient supply in closed soilless cultivations when the  $\text{Na}^+$  and  $\text{Cl}^-$  levels in the irrigation water are not low, it is important to monitor salt concentrations in the

drainage solution so as to assess their contribution to the total EC in the outgoing nutrient solution, which can then be adjusted in real time to a value that would ensure a constant nutrient supply to the crop. However, reliable tools providing real-time monitoring of specific ion levels in the drainage solution are currently not available at prices affordable to the growers. Therefore, the standard practice for coping with salt accumulation in closed systems is currently the provisional suspension of recycling and the discharge of the drainage solution until its EC returns to acceptable levels.

### **IRRIGATION MANAGEMENT IN SOILLESS CULTURE**

Irrigation management includes water transport to the root zone and the decisions “when” to irrigate the crops and “how much” to apply. Irrigation scheduling requires good knowledge of the crop’s water demand and the substrate’s physical properties. The efficiency of the irrigation method affects the precision of water application. Irrigation management is one of the main factors determining the overall performance of soilless culture systems, since both nutrients and water are supplied to the root zone via the irrigation system. One of the most important advantages of soilless culture compared with soil-grown cultures is the accurate control of water availability in the root zone. Moreover, soilless culture systems greatly improve water-use efficiency and water management in crop production. However these advantages depend on the equipment available and the system management because of the low buffering capacity in soilless culture systems.

In soilless culture, the root zone volume is much smaller than in soil-based cropping systems and thus the total volume of available water per plant is smaller, despite the higher water-holding capacity, lower moisture tension and greater hydraulic conductivity in most crops grown on substrates (Schröder and Lieth, 2002). Smaller root volume results in restricted root length and surface area and, therefore, limited capacity of the plant to take up nutrients and water. Therefore “little and frequent” irrigation and fertilization is applied to maximize yield. A standard recommendation in soilless culture is to apply a constant volume of irrigation water at each irrigation event and vary the number of irrigation applications (as opposed to keeping the number of irrigation events constant and varying the volume of irrigation water).

Some growing media may be characterized by a high water-holding capacity accompanied by suboptimal air capacity, while other media may exhibit high air capacity accompanied by suboptimal water availability. In the first case, less frequent irrigation in combination with higher watering dosages is the most appropriate strategy, while the opposite is recommended in the second case. As a general rule, the application of a specialized irrigation schedule for each growing medium, taking into consideration the physical properties, may mitigate problems relating to poor aeration or limited water availability.

### Characteristics of irrigation systems

Various types of irrigation system are used, depending mainly on the soilless culture system applied in each case. In most cases, there is more than one irrigation circuit or sector in one greenhouse aimed at reducing the necessary output capacity of the irrigation pump. System design should aim to maximize irrigation performance by optimizing all design characteristics, including system capacity, uniformity, storage capacity, pumping capacity, delivery systems, management of drainage, production unit and automation control systems.

#### *Capacity*

System capacity is the maximum flow rate that can be delivered through a particular irrigation system. It is related to the volume of water applied through each circuit and the duration of each irrigation event.

#### *Uniformity*

Uniformity is important when the irrigation water is supplied through a large number of emitters, especially when each plant receives nutrient solution through an individual emitter. Even if the capacity of the system is sufficient to cover the total water and nutrient requirements of a crop, some plants may receive insufficient amounts of nutrient solution while other plants may be overirrigated if the variation in flow rate among the emitters is very high. The variation in flow rate among individual emitters determines the uniformity of the system. Uniformity is key to the designing of irrigation systems. The uniformity of an irrigation system can be quantitatively estimated by calculating the coefficient of uniformity ( $Q$ ) using Equation 2:

$$Q = 1 - \frac{\sum_{i=1}^n |x_i - A|}{nA} \quad \text{Eq. 2}$$

where:

$x_i$  is the water supply rate in the  $i^{\text{th}}$  of the  $n$  sample plants

$A$  is the mean water supply rate to the particular plants

The coefficient of uniformity is a dimensionless quantity, independent of the water supply rate with a range of 0–1. The higher the coefficient of uniformity, the more uniform the distribution of water to the plants. Irrigation uniformity can be increased by minimizing the pressure drop in the system and pressure variation among the emitters. In order to distribute the nutrient solution uniformly in soilless-grown crops, well-designed and well-maintained irrigation systems should be established. The uniformity of an irrigation system decreases over time, due to partial or complete clogging of emitters.

#### *Storage capacity*

A storage tank or reservoir is required to supply irrigation water to the plants. The necessary volume of the storage tank depends on the size of the growing system,

namely number and type of plants and their water demand when they reach maximum size under maximum evapotranspiration conditions. A storage tank is anticipated to have sufficient capacity to supply irrigation water for at least one day to all plants. A high storage capacity minimizes the risk of crop damage due to failures in the primary water supply system.

### *Pumping capacity*

The pumping capacity needed depends on the size and type of the irrigation system, number of irrigation zones, crop species, water requirement and extent of each circuit. It is important for the grower to know the maximum potential demand for irrigation water and the pumping capacity required to satisfy this, even in a worst-case scenario (Schröder and Lieth, 2002). Soilless culture systems have small root zone buffering and, therefore, the plants need more frequent irrigation, which entails short intervals between irrigation events. Overall, irrigation timing and duration is related to environmental conditions, cultivated plant species and growth stage.

### **Delivery systems**

Irrigation systems can be grouped according to the method of water delivering to the plant, namely overhead (above the plant), drip irrigation (at the substrate surface) or subirrigation (below the root zone). Solenoid valves are used to automatically control irrigation.

If no substrate is used or the substrate has limited water-holding capacity, continuous supply of nutrient solution in closed-loop circuits enabling capture and reuse of the effluents is appropriate. In such systems, there is no need to define when to irrigate and how much water will be applied, since the roots are either constantly immersed in a continuously flowing nutrient solution (i.e. NFT) or frequently sprayed with nutrient solution (e.g. aeroponics).



B. ONICEL

**Plate 15**  
*Boom system in vegetable seedling production*

### *Overhead systems*

Water or nutrient solution is applied directly to the shoot from above. The use of overhead irrigation systems (e.g. the so-called “boom system”) is very common in nurseries for seedling and pot plant production (Plate 15). A boom system consists of a rig that moves above the plants by means of a rail. An irrigation pipe equipped with nozzles at standard intervals is fixed on the rig. The uniformity of a boom system depends on the design

and layout of the nozzles on the boom, the consistency of water pressure in the supply and the uniformity of speed at which the boom runs over the plants (Schröder and Lieth, 2002).

### *Drip irrigation*

Drip irrigation is the most widely used system in soilless culture due to its high precision and uniformity, resulting in highly efficient water use. Water is delivered slowly to the roots either on the substrate surface or directly to the root zone.

A drip irrigation system consists of one or more pumps, non-return valves, dilution equipment, filters, pressure regulators, water meters, mainline, submainlines, lateral pipes and emitters. The pump should be selected according to maximum expected flow rate and pressure. Filters are used to prevent clogging, and pressure regulators are important to provide uniform pressure in the system. Various emitters are available in a wide range of shapes and flow rates. Pressure-compensating emitters which deliver a constant amount of water per unit of time regardless of changes in pressure are a recently developed technology. Emitters should be selected on the basis of their advantages and disadvantages and their specific suitability for each type of soilless cultivation system (Table 3). The flow rate suggested for each emitter ranges between 1 and 4 litres per hour, depending on the cultivated plant species, soilless culture type and irrigation system capacity. Various emitters are available to provide this range of flow rate and most are designed to operate at a supply pressure of 0.2–1 bar. Substrate particle size also affects water availability and needs to be taken into consideration in the selection of emitters. For example, in a substrate with large particles, the use of low density emitters with high flow capacity results in a more vertical movement, while high density emitters with a low flow capacity causes more horizontal flow, which is desirable (Schröder and Lieth, 2002).

### Overhead systems

#### Advantages:

- Relatively low installation cost
- Applicability in large areas
- Cooling effect

#### Disadvantages:

- Waste of water due to unused runoff
- Disease incidence risk
- Residue risk on leaves and flowers
- Inefficient water use in substrate culture resulting in lower WUE
- Wetting the surrounding area of the plant

### Drip irrigation

#### Advantages:

- Individual irrigation of each plant
- Efficient water use
- Precision
- Uniformity
- Less runoff
- Less evaporation

#### Disadvantages:

- Emitter clogging
- Difficulty in evaluating system operation and application uniformity
- Substrate/application rate interaction
- Persistent maintenance requirements
- Smaller wetting pattern

TABLE 3  
Categories of emitters, advantages and disadvantages, and their suitability for different soilless growing systems

Emitter	Advantages	Disadvantages	Growing system
Porous pipe	Easy, low cost	Irregularity among the pores, no internal water pressure control	Surface or subirrigation systems
Punch-in emitters - drip emitters - in-line - misters	Precise, well moist root zone	Not flexible for plant spacing	Containers, pot plants Misting and air humidifying
Emitter lines	Pressure-compensating emitters can be easily installed, lower cost, long life	Life depends on quality	Trough culture
Spray emitters	Operation at low pressure	Lower water-use efficiency, water loss due to evaporation	Substrate benches, thin layer systems with high plant density

The spaghetti or tube system has a small diameter tube connected at the side. The system can be used with or without emitters. Since each plant has its own tube, it is more suitable for pot plants and containers. Pressure fluctuation could be prevented by using pressure-compensating emitters.

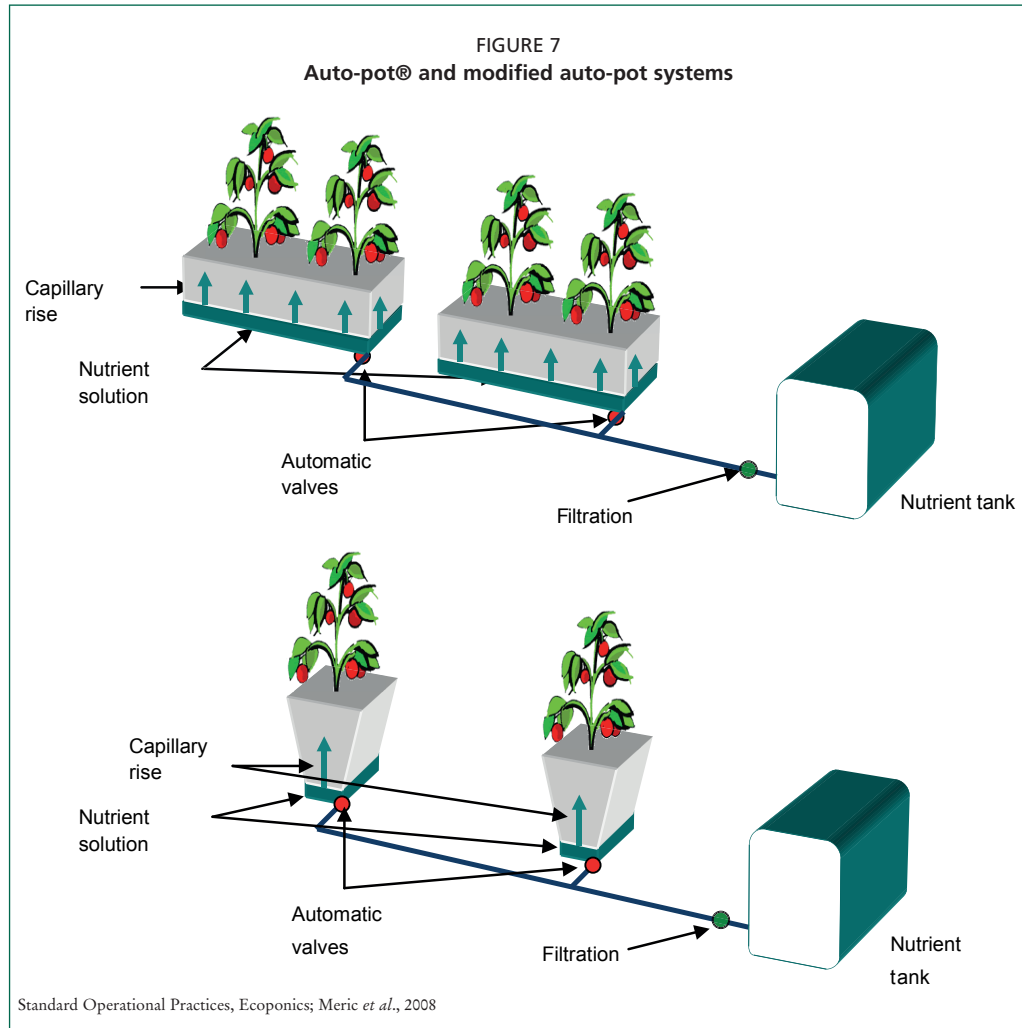
### *Subirrigation*

In subirrigated soilless cultivations, nutrient solution is applied from the base and moves up through the root zone by capillary forces – it could be called “plant-driven irrigation”. These systems consist of capillary mats, trough benches, ebb and flow systems, flooded floors (Lieth and Oki, 2008) and auto-pots® (Fah, 2000) (Table 4) (Figure 7).

In a standard subirrigation system, the nutrient solution is pumped from the fertigation head to the upper end of the crop benches, released into the troughs

TABLE 4  
Categories of subirrigated systems, advantages and disadvantages, and their suitability for different soilless culture systems

System	Advantages	Disadvantages	Crop grown
Capillary mats	Easy, cost effective	Needs good ground levelling	Pot plants
Troughs	Different amount for different plant groups	If system not closed, waste of water	Pot plants, vegetables grown on substrates
Ebb and flow system	Easy to use; uniformity	Substrate and water depth interaction; if recycling applied, spread of pathogens	Young plants, vegetables
Flooded floors	Larger scale	Needs proper design and installation; sanitation	Seedling production, big ornamental plants
Auto-pots®	No leaching of nutrients and water; no electricity-driven devices; low cost	Salt accumulation in the upper part; needs smart valves for capillary action	Vegetables, short cycle crops



and allowed to run slowly down to the lower end of the trough where the excess drains out and returns to a catchment tank for recirculation. In most cases, the supply of nutrient solution is intermittent. The troughs are filled with a substrate with good capillary properties. For better drainage after each irrigation cycle, a coarse aggregate may be placed in the bottom of the trough.

In auto-pot® systems, water and nutrients are supplied when a smart-valve is opened and the nutrient solution enters the bottom of the container to a predetermined and preset depth (usually 3.5 cm). The valve then closes, preventing further entry of nutrient solution until the original supply has been conveyed from the solution chamber to the pot and then to the plant. The solution reaches up to the higher layers of the pot and down to the root surface (essential for plant uptake) by capillary action thanks to the porosity of the substrate. Once the



solution is absorbed, the valve is reopened to supply water and nutrients to the containers (Fah, 2000).

Most subirrigation systems do not discharge nutrient solution to the environment; they are superior to other systems in terms of water and fertilizer saving, uniformity of nutrition, labour efficiency and self-scheduling. Subirrigation is mainly applied in pot plant production, given the short growing cycle and low water and nutrient requirements. Its main disadvantage is root zone salinity resulting from application of the nutrient solution from the bottom and its upward movement in the bulk of the substrate, which does not permit salt leaching. One way of reducing salt buildup and its negative effects on plants in subirrigated systems is to supply nutrient solutions with lower macronutrient concentrations (Tuzel *et al.*, 2007).

### Management of drainage

Drained nutrient solution is discarded outside the greenhouses in open systems while it is collected and reused in closed systems. In open soilless culture systems, the drained solution can be used in open field crops instead of being released into the environment. In closed systems, the drainage solution is captured and recycled. However, the accumulation of some nutrients due to dissimilarities between the rates of nutrient supply and the rates of nutrient uptake results in ion imbalance. On the other hand, the risk of root disease spreading through the recycled nutrient solution is another important problem that should be considered. Use of sand filters or UV lamps can minimize the risk of pathogen dispersal through the recycled drainage solution but the additional cost has to be taken into account.

### Control systems

There are different levels of irrigation control, from hand irrigation and simple clock timers to computer-based monitoring and control systems. With manual control, substrate selection (i.e. substrate with high water-holding capacity, good aeration and high hydraulic conductivity) is important to mitigate the impact grower error. Control parameters depend on crop species, growing stage, environmental conditions, system performance and management practices. Controls must be extremely dependable, and should have a signalling system if failure occurs. Also a backup control system or an override to manual operation is important for triggering irrigation events.

### Irrigation scheduling

#### *Irrigation scheduling approaches*

Irrigation scheduling is the decision related to “when” to irrigate and “how much” water to apply to the crop. It is based either on substrate water status, where the moisture content or potential is measured directly to determine the need for irrigation, or on plant water status, which does not indicate how much water to apply. The main advantages and disadvantages of the different irrigation

scheduling approaches are summarized in Table 5 (Jones, 2004). However, not all these approaches are as yet used in soilless culture.

In soilless culture, little and frequent irrigation is required. Thus, rapidly growing crops in the summer may need 15–20 or even more irrigation events a day. Increasing irrigation frequency reduces fruit defects, such as cracking and blossom end rot. To optimize synchronization of water supply to demand in soilless cultivated crops, frequency and rate of irrigation must be properly tuned. The quantity of supplied water is higher than anticipated plant consumption to

TABLE 5  
Main advantages and disadvantages of some irrigation scheduling approaches according to Jones (2004)

Approach	Advantages	Disadvantages
I. Substrate water status (root zone sensors)	Directly measures matric potential and water content in root zone.	Indicates plant status indirectly.
a) Substrate water potential (i.e. tensiometers)	Simple, easy to apply, quite precise, appropriate for automation.	Needs many sensors and good contact with the substrate; position should be representative for root zone.
b) Substrate water content (time domain reflectometer – TDR; frequency domain reflectometer – FDR)	Simple, easy to apply, quite precise, appropriate for automation, measures root zone EC.	FDR and TDR need calibration; position should be representative for the root zone; needs good contact with substrate; expensive.
II. Plant water status	Measures plant response to stress directly, integrates environmental conditions, potentially very sensitive.	Does not indicate “how much” water to apply; calibration required to determine “control thresholds”; still little use in commercial greenhouses.
a) Tissue water status	Appropriate measurement for physiological processes (i.e. photosynthesis); particularly measures leaf water status.	Sensitive to environmental conditions.
i) Psychrometer ( $\psi$ )	Valuable, thermodynamically based measure of water status; can be automated.	Requires sophisticated equipment and high level of technical skill, unreliable in the long term.
b) Physiological responses	Potentially more sensitive than measuring tissue (especially leaf) water status.	Require sophisticated or complex equipment; require calibration to determine “control thresholds”.
i) Stomatal conductance – Porometer	Very sensitive response. Accurate: the benchmark for research studies.	Needs replications for reliable data. Needs labour (not automated); inappropriate for commercial crops.
ii) Growth rate	Very sensitive to stress.	Instrumentation delicate and generally expensive.
III. Model-based estimation of water needs using real-time measurements of climatic parameters	Simple, sensitive, suitable for automation.	Needs efficient calibration to specific crop species, crop growth stage and environmental conditions. Accuracy may be insufficient when cultivars or cultural practices are not those used for calibration. Some coefficients are based on poorly applicable simplifications in commercial greenhouses.

compensate for lack of uniformity in supply rate among emitters and to prevent salt accumulation in the root zone. The volume ratio of drained solution to water applied is called leaching fraction. In open soilless culture systems, the leaching fraction should not exceed 25–35 percent to minimize discharge of fertilizer residues to the environment, but in closed systems, drainage water is reused and irrigation frequency can be much higher than in open cultivation systems.

Frequent irrigation resulting in high leaching fractions in closed soilless culture systems can delay salt accumulation rate in the root zone, enhance yield and improve fruit quality without any environmental impact. The only precaution regarding the application of a frequent irrigation schedule is the possible creation of excessive moisture conditions in the root zone that might reduce oxygen availability (Schröder and Lieth, 2002). Nevertheless, this problem may be tackled by selecting growing media with optimal physical characteristics in combination with proper placement of the media in the hydroponic installation.

### *Irrigation decisions*

Generally, common approaches in irrigation decisions entail timer-based, sensor-based or model-based irrigation control methods.

- Electrical timers specifically designed to control irrigation valves are used. This operation is the cheapest, simplest and easiest approach for triggering irrigation events. However, time-based irrigation needs skilled personnel and knowledge to compile a present irrigation schedule.
- Sensor-based control depends on the measurement of the water status either in the substrate (i.e. tensiometer, frequency domain reflectometer) or in the plant (i.e. sap flow meter, thermal sensing) (Table 5).
- Model-based control is based on the estimation of plant water loss related to one or more environmental variables (i.e. temperature, solar radiation). Scheduling is computerized to obtain in real time crop irrigation needs based on the data provided online by sensors. Many methods are available for the estimation of evapotranspiration and most of them use either a modified version or a combination of models originally developed by Penman and Monteith. However, the application of these models in commercial practice needs appropriate calibration for each crop.

### **Impact of irrigation on yield and quality**

Freshness and appearance, including fruit or organ size, colour and the occurrence of physiological disorders (e.g. cracking and blossom end rot, BER, in tomatoes and peppers, and tip burn in lettuce) are directly or indirectly influenced by water availability and quality, and watering frequency. Controlled watering could be used to balance vegetative growth with generative development in fruiting vegetables and to regulate fruit size (e.g. in tomatoes). Generally, increasing water availability enhances fruit size and acidity in tomato. On the contrary,

deficit irrigation enhances fruit desirability in terms of dry matter content, total soluble solids, sugar and colour intensity. Fruit sugars become concentrated under conditions of reduced water supply. However, the problem of BER is difficult to solve since the conditions contributing to increased dry matter and sugar concentrations also favour this disorder. Calcium spraying on the fruit cluster or improving environmental conditions (Gruda, 2005) are possible solutions.

Water shortage can increase the content of health-promoting substances. Water availability and irrigation timing may also influence the flavour of vegetables. Overall, water shortage generally tends to increase the ascorbic acid content in fruit; increasing the water supply reduces lycopene,  $\beta$ -carotene, vitamins and minerals, as well as total antioxidant capacity. High yields do not automatically imply high quality, therefore, a compromise needs to be established (Gruda, 2009).

### SOILLESS CULTIVATION OF MAJOR GREENHOUSE VEGETABLE CROPS

The soilless cultivation specifics of the major vegetables cultivated commercially in Mediterranean greenhouses are given below, including most used systems, layout, crop nutritional requirements and other special needs. The crops are divided into two groups: fruiting vegetables and once over-harvested vegetables. For each vegetable species, recommended nutrient concentrations in nutrient solutions are given (Savvas, 2012), based on Dutch recommendations (Sonneveld and Straver, 1994; De Kreij *et al.*, 1999) modified on the basis of mostly unpublished experimental data to adapt to Mediterranean climatic conditions. In addition to the nutrient concentrations recommended for open soilless crops of tomato grown on inert substrates, nutrient solutions for closed soilless cultivations are given, as well as target nutrient concentrations for the root zone. The recommended EC values are valid for NaCl concentrations up to 1.5 mmol litre<sup>-1</sup> in the irrigation water. If Na<sup>+</sup> and Cl<sup>-</sup> exceed this level in the irrigation water, the target EC has to be increased accordingly, taking into account that 1 mmol litre<sup>-1</sup> of NaCl raises the EC by 0.115 dS m<sup>-1</sup> (Sonneveld, 2002).

#### Fruiting vegetables

This category includes tomato, cucumber, bell pepper, eggplant, melon and bean. The general characteristic of this group is the long cropping period, 1–3 plantings per year and a small number of plants per m<sup>2</sup> (about 1–6), arranged in 2–4 rows per 3.2- or 4-m span (van Os *et al.*, 2008). Fruiting plants are characterized by a complex crop physiology, since the vegetative growth and flowering as well as the fruiting phases overlap and need to be simultaneously and continually balanced. Young plants are raised in blocks and planted either on substrates supplied regularly with nutrient solution or directly in pure nutrient solution when liquid hydroponic systems are employed.

### **Tomato**

Tomato (*Solanum lycopersicum* L.) is the most important greenhouse crop grown in soilless cultivation systems. The need to obtain high yields of high quality while considering environmental issues puts increased pressure on greenhouse tomato growers. Soilless culture systems are sustainable while increasing the net income per invested square metre; in addition, today's varieties allow growers to use a wide range of new fresh tomato types. The aim is to produce greenhouse tomatoes in periods when outdoor production is not available or competitive, thereby achieving premium-priced production with high quality and good-tasting fruit. The most widely used soilless culture system for tomato production is cultivation on rockwool slabs wrapped in polyethylene bags and supplied with nutrient solution through a drip irrigation system. Other local substrates, such as perlite, pumice and tuff, are also used, whereas the NFT-system is not very common in the Mediterranean area, although it is generally considered to be a commercially viable form of water culture with ecological benefits.

In soilless culture, tomato can tolerate total salt concentrations of up to 2.5–2.9 dS m<sup>-1</sup> in the root zone without yield losses (Sonneveld and Voogt, 2009). However, in most cases, growers maintain higher EC levels than the STV in the root zone of soilless-grown tomato in order to improve fruit quality in terms of organic acidity and soluble solid (Gruda, 2009). The increase of EC to higher values than the STV in order to improve fruit quality is economically beneficial despite the concomitant yield losses because of the relatively low rate of tomato yield decrease per unit of EC increase above the STV (Sonneveld and Voogt, 2009). Under Mediterranean conditions, EC values of up to 3.5 dS m<sup>-1</sup> in the root zone are recommended for soilless tomato in order to achieve premium fruit quality. In north European countries, even higher EC values of up to 5 dS m<sup>-1</sup> are maintained, particularly under cold and cloudy weather conditions. Nevertheless, the EC of the nutrient solution in the root zone of tomato grown in Mediterranean greenhouses has to be reduced to levels lower than 3 dS m<sup>-1</sup> under hot summer conditions. In addition to the EC adjustment in the root zone, Gruda (2009) reported several other ways to improve product quality by proper design and operation of soilless culture systems. Furthermore, a review of recent research relevant to the impact of tomato nutrition on fruit quality was written by Passam *et al.* (2007).

A crucial factor for tomato nutrition in soilless culture is the N:K ratio in the nutrient solution. Adams and Massey (1984) found that the mean daily N:K uptake ratios were 2.40 and 2.25 on a molar basis prior to setting of fruit in the first truss of tomato in February and August, respectively. However, this ratio decreased to 1.12 (molar basis) when the fruit load increased, followed by a slight increase to 1.40 after some weeks. Another important characteristic of the nutrient solution supplied to tomatoes is the NH<sub>4</sub>-N/total-N ratio. As reported by Sonneveld (2002), both growth and yield of tomato are enhanced when a small part of N ranging from 5 percent to less than 15 percent of total N is supplied in the form of

TABLE 6  
Recommended EC (dS m<sup>-1</sup>), pH and nutrient concentrations (mmol per litre) in nutrient solutions (NS) <sup>a</sup> for soilless tomato crops grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS <sup>b</sup>	SSCS <sup>c</sup>	RE <sup>d</sup>	SSOS	SSCS	RE
EC	2.80	2.50	2.00	3.20	2.40	1.85	3.40
pH	5.60	5.60	-	5.80–6.70	5.60	-	5.80–6.70
[K <sup>+</sup> ]	6.80	7.00	6.40	7.50	8.00	7.50	8.20
[Ca <sup>2+</sup> ]	6.40	5.10	3.10	7.80	4.50	2.30	8.00
[Mg <sup>2+</sup> ]	3.00	2.40	1.50	3.40	2.10	1.10	3.40
[NH <sub>4</sub> <sup>+</sup> ]	0.80	1.50	1.60	< 0.60	1.20	1.40	< 0.40
[SO <sub>4</sub> <sup>2-</sup> ]	4.50	3.60	1.50	5.00	4.00	1.50	6.00
[NO <sub>3</sub> <sup>-</sup> ]	15.50	14.30	12.40	18.00	12.40	11.00	17.20
[H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> ]	1.40	1.50	1.30	1.00	1.50	1.20	1.00
[Fe]	20.0	15.00	15.00	25.00	15.00	15.00	25.00
[Mn]	12.00	10.00	10.00	8.00	10.00	10.00	8.00
[Zn]	6.00	5.00	4.00	7.00	5.00	4.00	7.00
[Cu]	0.80	0.80	0.80	0.80	0.70	0.70	0.80
[B]	40.00	35.00	20.00	50.00	30.00	20.00	50.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

<sup>a</sup> The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

<sup>b</sup> SSOS: solution supplied to open systems.

<sup>c</sup> SSCS: solution supplied to closed systems.

<sup>d</sup> RE: target concentrations in the root environment.

Savvas, 2012

NH<sub>4</sub><sup>+</sup>. Tomato is tolerant to moderately high pH but susceptible to low pH levels in the root environment, due mainly to impairment of the Ca uptake (Savvas *et al.*, 2008). With respect to the macronutrient cations, the K requirements increase with fruit load, while Ca requirements decrease (De Kreij *et al.*, 1999). However, the Ca levels in the supplied nutrient solutions should be maintained at relatively high levels during the reproductive phase of the crop to minimize the incidence of BER. Recommended nutrient solution concentrations for tomato are given in Table 6.

### Cucumber

Cucumber (*Cucumis sativus* L.) is a semi-tropical plant originating in India and the second most important greenhouse soilless-grown crop. In Greece, Turkey, Egypt and other Mediterranean countries, a short-fruit cucumber is widely grown and is very popular in local markets. However, the most common cucumbers grown today in soilless greenhouses are the long, seedless type. Cucumber can be grown in different seasons and many growers in Mediterranean countries prefer to plant two or three crops per year instead of a single, year-round crop (standard practice in the Netherlands). After termination of the first crop, plants with roots are only partially removed and cut out from the substrate with a knife. The young plants of the second set can then be inserted with a small amount of fresh substrate, if they are grown on granular substrates. After transplanting, adequate irrigation is essential for continuous growth.

Cultivation in rockwool is very common. However, other local growing media (e.g. perlite, pumice) are also used. Slabs or bags with a width of either 15 or 30 cm are employed. Since no differences in cucumber yield were found when slabs of different width were used, it is recommended to use either single-row slabs (15 cm) or double-row slabs (20–30 cm). In the latter case, the plants have to be supported by applying a V-training system.

Cucumber is a salt-sensitive plant species; the EC in the root-zone solution should ideally be maintained at 2.7 dS m<sup>-1</sup> and in any case it should not exceed 3 dS m<sup>-1</sup> in Mediterranean greenhouses, otherwise significant yield losses are inevitable (Sonneveld and Voogt, 2009). In Mediterranean greenhouses, EC values of 2.5 dS m<sup>-1</sup> should be maintained during early plant growth, and adjusted to 2.7 dS m<sup>-1</sup> with increasing plant size (Savvas, 2012). The recommended pH level in the root zone of cucumber is 5.3–6.4 and this can be achieved by including about 10 percent of the total N in the form of NH<sub>4</sub>-N in the solution. The literature provides recommended compositions of nutrient solutions for soilless cucumber (Papadopoulos, 1994; Sonneveld and Straver, 1994; De Kreij *et al.*, 1999; Sonneveld and Voogt, 2009), but these recommendations are based on research carried out under cold-winter climatic conditions. Recommended nutrient concentrations for cucumber in Mediterranean climatic conditions are given in Table 7.

TABLE 7

**Recommended EC (dS m<sup>-1</sup>), pH and nutrient concentrations (mmol litre<sup>-1</sup>) in nutrient solutions (NS) <sup>a</sup> for soilless cucumber grown under Mediterranean climatic conditions**

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS <sup>b</sup>	SSCS <sup>c</sup>	RE <sup>d</sup>	SSOS	SSCS	RE
EC	2.40	2.20	1.95	2.50	2.10	1.85	2.70
pH	5.60	5.60	-	5.30–6.40	5.60	-	5.20–6.40
[K <sup>+</sup> ]	6.30	6.20	6.00	6.40	7.20	6.50	8.00
[Ca <sup>2+</sup> ]	5.00	4.15	3.50	6.00	3.40	2.90	5.50
[Mg <sup>2+</sup> ]	2.00	1.60	1.10	2.30	1.40	1.00	2.50
[NH <sub>4</sub> <sup>+</sup> ]	0.80	1.40	1.60	< 0.50	1.40	1.40	< 0.50
[SO <sub>4</sub> <sup>2-</sup> ]	1.90	1.30	1.00	2.20	1.40	1.00	2.60
[NO <sub>3</sub> <sup>-</sup> ]	15.60	14.75	13.10	17.00	13.75	12.00	17.20
[H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> ]	1.20	1.25	1.20	1.00	1.15	1.20	1.00
[Fe]	20.00	15.00	15.00	25.00	15.00	15.00	25.00
[Mn]	12.00	10.00	10.00	8.00	10.00	10.00	7.00
[Zn]	6.00	5.00	5.00	7.00	5.00	5.00	8.00
[Cu]	0.80	0.80	0.80	1.30	0.80	0.70	1.50
[B]	40.00	25.00	25.00	50.00	25.00	25.00	50.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

<sup>a</sup> The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

<sup>b</sup> SSOS: solution supplied to open systems.

<sup>c</sup> SSCS: solution supplied to closed systems.

<sup>d</sup> RE: target concentrations in the root environment.

Savvas, 2012

Since cucumber likes high levels of relative humidity, irrigation becomes critical at low relative humidity, because large quantities of water must be added to the growth medium without constantly flooding the roots and depriving them of oxygen. By using NFT systems or other water culture systems, additional means to improve oxygenation of the nutrient solution have to be considered (Papadopoulos, 1994).

### *Pepper*

Bell or sweet pepper (*Capsicum annuum* L.) is the third most important soilless cultivated crop species. Bell pepper is cultivated in different growing systems and different substrates. Pepper plants can be trellised following either the Dutch “V” (a two-stem pruned) system or the “Spanish” (non-pruned) system. Jovicich *et al.* (2004) compared the “V” with the “Spanish” trellis system and found no differences in total marketable fruit yield. However, the non-pruned plants produced 38 percent more extra-large fruit and less fruit with BER at the end of the spring than the pruned plants. In addition, the labour requirement for the Spanish system was reduced to 25 percent that needed for the “V” trellis system. The authors recommend a plant density of 3.8 plants m<sup>-2</sup>.

Pepper plants should be fertigated frequently with an appropriate nutrient solution. The suggested pH in the root zone during the harvesting period is 6–6.7, attainable by supplying about 5 percent of the total N in the form of NH<sub>4</sub>-N. A higher NH<sub>4</sub>-N supply during the reproductive phase is not recommended because ammonium may reduce the Ca uptake and increase the incidence of fruit with BER, to which pepper is highly susceptible. Pepper is considered a sensitive crop to salinity and the recommended EC range in the root zone is 2.7–3.0 dS m<sup>-1</sup>, depending on the season of the year and the mineral composition of the available irrigation water. Detailed information on single nutrient elements and physiological disorders of greenhouse pepper, including soilless culture, can be found in a recent review by Savvas *et al.* (2008). Recommended nutrient solutions for open and closed soilless pepper crops in Mediterranean countries are given in Table 8.

### *Eggplant*

Eggplant (*Solanum melongena* L.) is an important greenhouse crop in most Mediterranean countries. Eggplant can be grown successfully in most commercial soilless culture systems, including cultivation in substrates and nutrient solution.

When 1-m-long slabs or bags are used, two eggplant seedlings per slab or bag are usually planted. Denser spacing is not recommended because eggplant’s very large leaves may adversely affect light interception in the canopy and favour the occurrence of plant diseases. As a rule, each plant is trained to 2 or 3 stems, aiming at 4–6 stems m<sup>-2</sup>.



TABLE 8  
Recommended EC ( $\text{dS m}^{-1}$ ), pH and nutrient concentrations ( $\text{mmol litre}^{-1}$ ) in nutrient solutions (NS)<sup>a</sup> for soilless pepper grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS <sup>a</sup>	SSCS <sup>b</sup>	RE <sup>c</sup>	SSOS	SSCS	RE
EC	2.30	2.20	1.80	2.50	2.10	1.70	2.70
pH	5.60	5.60	-	5.60–6.60	5.60	-	6.00–6.70
[K <sup>+</sup> ]	5.70	5.40	5.30	6.00	5.80	6.00	5.50
[Ca <sup>2+</sup> ]	5.30	4.65	3.15	6.50	4.50	2.70	7.25
[Mg <sup>2+</sup> ]	1.65	1.60	1.10	2.00	1.40	1.00	2.00
[NH <sub>4</sub> <sup>+</sup> ]	0.50	1.20	1.40	<0.60	0.60	0.80	<0.40
[SO <sub>4</sub> <sup>2-</sup> ]	2.00	1.85	1.00	2.70	1.75	1.00	3.10
[NO <sub>3</sub> <sup>-</sup> ]	14.40	13.70	11.60	15.60	13.00	10.60	16.00
[H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> ]	1.20	1.20	1.10	1.20	1.20	1.10	1.10
[Fe]	20.0	15.00	15.00	15.00	15.00	15.00	15.00
[Mn]	12.00	10.00	10.00	6.00	10.00	10.00	5.00
[Zn]	6.00	5.00	4.00	7.00	5.00	4.00	8.00
[Cu]	0.80	0.80	0.80	0.80	0.80	0.70	0.80
[B]	45.00	30.00	30.00	80.00	30.00	25.00	80.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

<sup>a</sup> The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

<sup>b</sup> SSOS: solution supplied to open systems.

<sup>c</sup> SSCS: solution supplied to closed systems.

<sup>d</sup> RE: target concentrations in the root environment.

Savas, 2012

K requirements are lower during the vegetative developmental stage and increase during the reproductive stage, as the fruit load increases. Overall, the nutrient requirements of eggplant exhibit many similarities with those of tomato. The only important differences are eggplant's higher requirements of Mg and B and its lower requirements of K. However, the salt tolerance of eggplant is much lower than that of tomato and similar to that of pepper. Accordingly, the suggested EC in the root-zone solution of soilless eggplant grown in Mediterranean greenhouses ranges from 2.6 to 2.8  $\text{dS m}^{-1}$ . Nevertheless, values up to 3.0  $\text{dS m}^{-1}$  may be inevitable if the NaCl concentration in the available irrigation water exceeds a level of about 3.0 mM.

Recommended nutrient solutions for soilless cultivations of eggplant grown under Dutch greenhouse conditions have been published by Sonneveld and Straver (1994) and De Kreij *et al.* (1999). Table 9 gives the nutrient solution compositions for eggplants grown in Mediterranean countries.

### Melon

It is possible to cultivate two or three cropping cycles of melon (*Cucumis melo* L.) per year in substrates, such as rockwool, perlite, pumice and tuff, as well as in NFT. The transplants are raised in rockwool cubes or pots filled with a substrate, before eventually being moved into the system. As with cucumber, all emerging

TABLE 9  
Recommended EC (dS m<sup>-1</sup>), pH and nutrient concentrations (mmol litre<sup>-1</sup>) in nutrient solutions (NS) <sup>a</sup>  
for soilless eggplant grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS <sup>b</sup>	SSCS <sup>c</sup>	RE <sup>d</sup>	SSOS	SSCS	RE
EC	2.40	2.20	1.85	2.50	2.10	1.75	2.70
pH	5.60	5.60	-	5.50–6.50	5.60	-	5.60–6.60
[K <sup>+</sup> ]	5.70	5.60	5.60	5.60	6.30	6.20	6.40
[Ca <sup>2+</sup> ]	4.20	3.50	2.50	5.00	3.00	2.20	5.00
[Mg <sup>2+</sup> ]	3.00	2.50	1.65	3.70	2.30	1.25	3.80
[NH <sub>4</sub> <sup>+</sup> ]	1.00	1.50	1.80	< 0.80	1.30	1.60	< 0.80
[SO <sub>4</sub> <sup>2-</sup> ]	2.00	1.60	1.00	2.20	1.50	0.90	2.60
[NO <sub>3</sub> <sup>-</sup> ]	15.50	14.20	12.20	16.80	13.50	11.40	17.00
[H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> ]	1.10	1.20	1.00	1.00	1.20	1.00	1.00
[Fe]	20.00	15.00	15.00	25.00	15.00	15.00	25.00
[Mn]	12.00	10.00	10.00	8.00	10.00	10.00	7.00
[Zn]	6.00	5.00	5.00	6.00	5.00	5.00	7.00
[Cu]	0.80	0.80	0.80	0.70	0.80	0.70	0.80
[B]	50.00	40.00	30.00	80.00	35.00	25.00	80.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

<sup>a</sup> The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

<sup>b</sup> SSOS: solution supplied to open systems.

<sup>c</sup> SSCS: solution supplied to closed systems.

<sup>d</sup> RE: target concentrations in the root environment.

Savvas, 2012

flowers and laterals should be removed up to the eighth node on the main stem. One fruit is then allowed to form on each lateral. In order to improve fruit setting, melons are often pollinated by bumblebees. Rodriguez *et al.* (2006) successfully grew melons in containers filled with different substrates and supplied with a nutrient solution composed as follows (mg per litre): 50 N, 23 P, 44 K, 5 Mg, 0.2 B, 0.5 Cu, 0.1 Fe, 0.5 Mn, 0.005 Mo and 0.005 Zn. Based on practical experience and some preliminary research results, Savvas (2012) suggests a nutrient solution with an EC of 2.2 dS m<sup>-1</sup> and the following nutrient concentrations for melon grown in Mediterranean greenhouses: 6.8 mM K<sup>+</sup>, 4.0 mM Ca<sup>2+</sup>, 1.6 mM Mg<sup>2+</sup>, 1.1 mM NH<sub>4</sub><sup>+</sup>, 13.2 mM NO<sub>3</sub><sup>-</sup>, 1.2 mM H<sub>2</sub>PO<sub>4</sub><sup>-</sup>, 2.1 mM SO<sub>4</sub><sup>2-</sup>, 10 µM Fe, 10 µM Mn, 5 µM Zn, 0.8 µM Cu, 20 µM B, and 0.5 µM Mo. The recommended EC in the root zone of soilless melon crops is 2.9 dS m<sup>-1</sup>, but values of up to 3.2 dS m<sup>-1</sup>, particularly during fruit ripening, may be beneficial in terms of fruit quality.

### Zucchini

Zucchini squash (*Cucurbita pepo* L.) is an important plant in many Mediterranean countries for out-of-season greenhouse production and is successfully cultivated in soilless culture systems. Its nutrient requirements are similar to those of cucumber, with minor differences related to their metallic macrocation and boron requirements. In particular, zucchini has somewhat smaller requirements for K

and Ca, but a higher demand for Mg. In contrast, the B requirements of zucchini are lower than those of cucumber. Furthermore, as with cucumber, the supply of Si through the nutrient solution is beneficial for zucchini, particularly when plants are exposed to salinity and other types of abiotic stress, or when there is a risk of powdery mildew attacks.

Zucchini squash was found to be moderately sensitive to salinity under Mediterranean climatic conditions (Rouphael *et al.*, 2006). Accordingly, EC values in the root-zone solution ranging from 2.6 to 2.8 dS m<sup>-1</sup> are considered optimal for soilless zucchini squash grown in Mediterranean greenhouses. Nevertheless, if the concentrations of Na, Cl, and/or Ca in the available irrigation water are substantially higher than the optimal levels, an accordingly higher EC in the root zone of zucchini squash must be accepted to avoid shortages in nutrient supply. Nutrient solution compositions for zucchini squash crops grown under Mediterranean climatic conditions are given in Table 10.

TABLE 10  
Recommended EC (dS m<sup>-1</sup>), pH and nutrient concentrations (mmol litre<sup>-1</sup>) in nutrient solutions (NS)<sup>a</sup> for soilless zucchini grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS <sup>b</sup>	SSCS <sup>c</sup>	RE <sup>d</sup>	SSOS	SSCS	RE
EC	2.40	2.20	1.80	2.60	2.00	1.70	2.80
pH	5.60	5.60	-	5.50–6.50	5.60	-	5.50–6.50
[K <sup>+</sup> ]	6.00	5.60	5.30	6.40	6.60	6.10	7.00
[Ca <sup>2+</sup> ]	4.60	4.00	2.65	5.80	3.00	2.10	5.80
[Mg <sup>2+</sup> ]	2.60	2.10	1.50	3.00	1.70	1.20	3.20
[NH <sub>4</sub> <sup>+</sup> ]	0.70	1.30	1.60	<0.60	1.20	1.50	<0.40
[SO <sub>4</sub> <sup>2-</sup> ]	2.00	1.35	1.00	2.50	1.10	1.00	2.80
[NO <sub>3</sub> <sup>-</sup> ]	15.50	14.65	11.65	17.30	13.30	10.70	17.50
[H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> ]	1.10	1.25	1.05	1.00	1.20	1.00	1.10
[Fe]	20.00	15.00	12.00	25.00	15.00	14.00	25.00
[Mn]	12.00	10.00	10.00	8.00	10.00	10.00	7.00
[Zn]	6.00	5.00	5.00	7.00	5.00	5.00	8.00
[Cu]	1.00	1.00	1.00	1.20	1.00	1.00	1.30
[B]	45.00	35.00	30.00	60.00	35.00	30.00	60.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

<sup>a</sup> The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

<sup>b</sup> SSOS: solution supplied to open systems.

<sup>c</sup> SSCS: solution supplied to closed systems.

<sup>d</sup> RE: target concentrations in the root environment.

Savvas, 2012

**Bean**

Bean (*Phaseolus vulgaris* L.) is a fruiting vegetable and is cultivated in soilless culture systems. The recommended density is 10–14 plants m<sup>-2</sup>, when liquid hydroponic systems or substrate culture are applied. Plants can be supported either by plastic twine attached on a horizontal wire, similar to those used in greenhouse crops of other fruiting vegetables (e.g. tomatoes, cucumbers and pepper), or by stretching suitable nets along the planting lines.

Bean is sensitive to salinity. Therefore, the recommended EC values for nutrient solutions supplied to hydroponically grown bean are relatively low ( $\leq 2$  dS m<sup>-1</sup>). Furthermore, care should be taken to avoid accumulation of Na<sup>+</sup> and Cl<sup>-</sup> ions in the root zone, especially when the nutrient solution is recycled. Given bean's high sensitivity to salinity, the availability of good quality water is essential for cultivation in closed soilless culture systems. Low pH levels in the root zone have a negative impact on plant growth: the pH should never be allowed to fall below 5.5. To avoid excessively low pH in the root zone, the percentage of NH<sub>4</sub>-N/total-N in nutrient solutions supplied to bean should be relatively low (< 10%). Recommended compositions of nutrient solutions for bean crops originating from Savvas (2012) are given in Table 11.

TABLE 11  
Recommended EC (dS m<sup>-1</sup>), pH and nutrient concentrations (mmol litre<sup>-1</sup>) in nutrient solutions (NS)<sup>a</sup> for soilless bean grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS <sup>b</sup>	SSCS <sup>c</sup>	RE <sup>d</sup>	SSOS	SSCS	RE
EC	2.20	2.00	1.60	2.40	1.80	1.50	2.60
pH	5.70	5.60	-	5.70–6.50	5.60	-	5.70–6.50
[K <sup>+</sup> ]	5.40	5.30	4.80	5.80	5.80	5.60	6.40
[Ca <sup>2+</sup> ]	4.60	3.75	2.50	5.60	3.00	1.90	5.70
[Mg <sup>2+</sup> ]	2.00	1.60	1.00	2.50	1.20	0.85	2.60
[NH <sub>4</sub> <sup>+</sup> ]	0.50	1.20	1.40	<0.5	1.00	1.20	<0.3
[SO <sub>4</sub> <sup>2-</sup> ]	2.00	1.45	0.90	2.60	1.45	0.80	2.90
[NO <sub>3</sub> <sup>-</sup> ]	13.50	12.60	9.90	15.00	10.60	9.20	15.30
[H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> ]	1.10	1.20	1.00	1.00	1.20	1.00	1.00
[Fe]	15.00	15.00	12.00	15.00	12.00	10.00	15.00
[Mn]	6.00	7.00	5.00	5.00	10.00	5.00	5.00
[Zn]	6.00	5.00	4.00	7.00	5.00	4.00	7.00
[Cu]	0.70	0.70	0.60	1.00	0.80	0.60	1.00
[B]	30.00	20.00	20.00	40.00	20.00	20.00	40.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

<sup>a</sup> The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

<sup>b</sup> SSOS: solution supplied to open systems.

<sup>c</sup> SSCS: solution supplied to closed systems.

<sup>d</sup> RE: target concentrations in the root environment.

Savvas, 2012

### Once over-harvested vegetables

This category comprises leafy vegetables, such as lettuce, rocket and other salad crops, but also kohlrabi, endive, spinach etc. Literature sometimes categorizes crops as transplanted and sowing plants. The general characteristics are:

- relatively high plant density per m<sup>2</sup> (10–20 for lettuce, > 100 for spinach); and
- short cultivation period (1–4 months).

Common practice is to raise seedlings in pressed peat cubes or pots or in mineral wool cubes. At present, only a small number of enterprises produce leafy vegetables in soilless culture systems in Europe, due to the tough competition from outdoor production and the relatively high investment needed; the economic efficiency is thus questioned (Van Os *et al.*, 2008).

#### Lettuce

Due to its very short cultivation period, lettuce can be produced in more than eight cropping cycles per year in greenhouses, when grown hydroponically. For soilless cultivation of lettuce, float systems and systems based on continuous nutrient solution recirculation (e.g. NFT) are widespread; cultivation on substrates is less common. Lettuce is characterized by high K and P uptake rates, but is susceptible to Mn toxicity. It is crucial to maintain low nitrate content in the edible tissues: with soilless culture systems it is possible to properly adjust the supply of nitrates via the nutrient solution shortly before harvesting (Schnitzler and Gruda, 2002). In Table 12, recommendations are given regarding the concentrations of essential

TABLE 12  
Recommended EC (dS m<sup>-1</sup>), pH and nutrient concentrations (mmol litre<sup>-1</sup>) in nutrient solutions (NS)<sup>a</sup> for soilless lettuce grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	SSOS <sup>b</sup>	SSCS <sup>c</sup>	RE <sup>d</sup>
EC	2.50	2.40	2.30	2.60
pH	5.60	5.60	-	5.60–6.50
[K <sup>+</sup> ]	7.50	8.00	9.00	6.20
[Ca <sup>2+</sup> ]	5.40	4.80	3.75	7.30
[Mg <sup>2+</sup> ]	1.50	1.10	1.00	1.60
[NH <sub>4</sub> <sup>+</sup> ]	0.80	1.30	1.60	< 0.6
[SO <sub>4</sub> <sup>2-</sup> ]	1.50	1.40	1.15	2.00
[NO <sub>3</sub> <sup>-</sup> ]	17.20	16.40	15.50	18.00
[H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> ]	1.40	1.40	1.80	1.20
[Fe]	40.00	35.00	30.00	40.00
[Mn]	5.00	5.00	5.00	1.00
[Zn]	5.00	5.00	4.00	5.00
[Cu]	0.80	0.80	1.00	0.80
[B]	40.00	30.00	30.00	50.00
[Mo]	0.50	0.50	0.50	-

<sup>a</sup> The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

<sup>b</sup> SSOS: solution supplied to open systems.

<sup>c</sup> SSCS: solution supplied to closed systems.

<sup>d</sup> RE: target concentrations in the root environment.

Savas, 2012

nutrients in nutrient solutions for lettuce crops grown in open and closed soilless systems as well as the target concentrations in the root zone.

### *Other edible crops*

In general, it is possible to produce several other edible crops in soilless culture systems, but the cultivated area in Mediterranean countries is not extensive and, consequently, experience with such plants is limited. Nevertheless, some crops (e.g. kohlrabi, radish, endive, spinach, rocket and lamb's lettuces) are successfully produced in this area as well. The most common methods are similar to those applied for lettuce production: flat hydroponic systems, float systems and NFT. The suggested EC level is lower in comparison to lettuce (about 1.3 and 1.6 dS m<sup>-1</sup> for kohlrabi and lamb's lettuces, respectively). However, the Fe content in the nutrient solution should be higher than that suggested for lettuce, particularly in lamb's lettuce crops. Values of 4 mg per litre of Fe are, therefore, recommended (Göhler and Molitor, 2002).

### **OUTLOOK**

Although in recent decades numerous scientific papers have addressed various aspects of soilless cultivation under Mediterranean climatic conditions, only a few have focused on the systematic determination of nutrient uptake. Thus, the currently available research data are still incomplete for the establishment of nutrient solution recipes, specifically for Mediterranean climatic conditions. Accordingly, more research is needed in the near future to estimate nutrient and water requirements of soilless cultivated plants under mild winter and dry summer conditions, such as those prevailing in the Mediterranean Basin. Such data would be particularly useful for establishing nutrient solution compositions for closed or semi-closed soilless crops (Savvas, 2002), where accuracy in nutrient-to-water supply ratios is much more important than in open systems for minimizing both ion accumulation in the root zone and discharge of drainage solution.

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