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Technical Equipment in Soilless Production Systems

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5.1 INTRODUCTION

The introduction of soilless culture on a commercial scale (Steiner, 1967) was motivated by a potential for increased crop productivity and efficiency. As part of this development, technical developments were made related to problems with root diseases, root zone oxygen deficiency, fertility control and increased complexity in irrigation strategy. Technical solutions to these problems and opportunities resulted in widespread adoption of soilless container plant production in outdoor nurseries in the 1950s and 60s. In the early 1970s, production of greenhouse crops in stone wool dramatically expanded commercially viable soilless crop production (Verwer, 1978; Cooper, 1979). Technical innovations in fertilization and irrigation resulted in adoption of fertigation technologies wherein completely soluble fertilizers are dissolved in irrigation water so as to deliver to plants the nutrients they need for optimal growth.

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In all modern production systems, fertilization and irrigation have been integrated into a system that the grower seeks to optimize. Traditionally growers applied dry fertilizer products to the top of the root zone, resulting in fertilizer nutrients being carried to the root surfaces with the applied irrigation water. Once it became evident that all essential fertilizers could be supplied through completely soluble fertilizer salts, systems were developed where such salts are dissolved at relatively high concentrations in special stock solutions. By using one or more injectors, such concentrated solutions could be injected into the irrigation water (fertigation). This chapter focuses on the technical equipment associated with fertigation and irrigation in greenhouse production. In most such soilless production systems, fertilization is accomplished through injection of soluble fertilizer into irrigation water. We also discuss which system is best suited to which crop and where continued innovation is likely to result in future technical advances. Irrigation control methods are the subject of the previous chapter.

5.2 WATER AND IRRIGATION

5.2.1 WATER SUPPLY

An adequate supply of high-quality water is essential in soilless crop production, regardless of whether in outdoor nursery production or in greenhouse crop production. Potential water sources include rainwater, surface water and ground water. The latter two can be secured either directly or though municipalities as part of their drinking water supply.

The quality of irrigation water is typically evaluated through consideration of the dissolved minerals and salts in the water. Salinity is typically measured as electrical conductivity (EC) and it is known that water with high salinity ($EC > 2\,mS\,cm^{-1}$) can result in growth suppression (and perhaps also other problematic manifestations) for many plants. In some areas of the world, the available supply of water has EC nearly that high (or perhaps higher), so that this presents the grower with serious challenges.

The EC of the irrigation water results from a combination of the dissolved materials in the supply water plus any fertilizers that are dissolved in the water. It is desirable for the supply water to have an EC of less than $0.5\,mS\,cm^{-1}$ and the sodium concentration less than $0.5\,mmol\,l^{-1}$ (Sonneveld, 2000). This then allows for addition of ample fertilizer ions, so that the irrigation solution seen by the plants is below a level where problems might result. In recirculating irrigation systems, where some soluble materials will build up over time, EC management can be particularly challenging if the EC of the source water is higher than $1\,mS\,cm^{-1}$. Management of this type of situation is discussed in Chap. 9 and is an area of continued innovation in soilless production because water quality in many areas of the world is low, containing higher levels of sodium (Na^+) and other problematic elements such as SO_4^{2-}, Fe^{2+} or Mg^{2+}.

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In addition to causing problems for plants, it is also possible for materials dissolved in the water to cause problems to the irrigation system. For example, iron and carbonates can deposit in the pipes causing blockages in pipes and filters.

5.2.1.1 Rainwater

Since the advent of agriculture, rain has always played a role in crop production. This source of water has the advantage that it is generally very clean (with low EC), but has the disadvantage that its availability is generally sporadic. Many soilless production systems include full protection of the plants from precipitation because of the uncertainties and potential production problems associated with rain events imposing uncertainty on the nutritional status of the root zone. Thus, the use of rainwater in soilless production involves capture of precipitation, storage in reservoirs and pumps (along with filters) to put the water under pressure for use in the nursery.

In general, rainwater has very low EC levels relative to the needs and limitations discussed above. Sometimes Na^+ concentration in rainfall is increased by rain and wind near oceans. Rainwater can be collected from the roofs of the greenhouses. In the Netherlands, where rain throughout the year is plentiful, growers are required to have a storage capacity of at least 500 m^3 of rainwater per hectare of production facility. Rainfall averages may range from 50 to 90 mm per month, so that with a storage capacity of 500 m^3 per hectare can provide for about 60 per cent of the irrigation water needs (Van Os and Stanghellini, 2002); if the storage capacity is increased to 1500 or 4000 $m^3\,ha^{-1}$ then 75 or 95 per cent, respectively, of the necessary water can be secured this way. This rainwater is stored in basins or tanks depending on the desired capacity. Earthen basins are used for capacities of more than 1500 m^3, while tanks (Fig. 5.1) are used for smaller volumes, since this is less expensive and less production space is needed to house such tanks.

Collection of rainwater is not used in some production areas for various reasons. If the quality of other water sources is high and it can be obtained at low cost, then it may not be economically feasible to make the investment in collection equipment and water storage, since the space lost to this equipment can remove a substantial amount of production space from the nursery. Also, in areas where low-cost greenhouse structures are in use, rainwater collection may not be feasible if the greenhouses are not designed with this in mind (lacking gutters or drainage plumbing). Also, in many areas (e.g. Northern California, Mediterranean countries) precipitation patterns are more uneven, requiring that the collection reservoirs be substantially larger than those identified above for Northwest Europe.

In some regions, rainwater can be stored underground in aquifers. This saves using expensive space, and water quality is maintained. In fact, many ground water sources are such sources, although on a much larger scale.

One salient issue related to the use of collected rainwater is that it is never adequate for 100 per cent of the needs of most nurseries. Thus irrigation systems must always include another water supply. This must be considered as part of the investment cost.

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FIGURE 5.1 Rainwater storage in metal tanks (see also Plate 8).

5.2.1.2 Municipal Tap Water

Tap water may be unsuitable for use in closed soilless systems if it has been treated for human consumption to improve its flavour and kill bacteria. If calcium and chlorine have been added during processing, then it is particularly important that chlorides be present at less than 1.5 mmol l^{-1}. In arid and semi-arid regions of the world, chloride levels are typically higher than this so that growers have to manage this by using salinity-resistant cultivars and other means.

In many areas of the world, municipal drinking water is relatively cheap compared to creating such water quality and capacity on site. Where this is not the case, the greenhouse operation must use ground water or surface water, perhaps in combination with stored rainwater and captured irrigation run-off.

5.2.1.3 Surface Water

Water from surface sources (creeks, rivers and lakes) is sometimes available in large quantities at a low price. While such water can be of high quality if relatively remote from human impact, the quality can also be low, especially if the water has been inadequately treated after municipal use or due to other human environmental impacts (e.g. canal water). The water may be polluted by salts, agricultural chemicals, inadequately treated sewage or storm water run-off from nearby urban areas.

Even when surface water is generally of good quality, it should be noted that water quality might not be uniform throughout the year, requiring frequent testing by the grower to assure its continued suitability for crop production. If such water quality

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deteriorates at particular times of the year, then the grower will need water treatment equipment to improve the water quality. Alternately, a second source of high-quality water can be used to blend with poorer quality water, as is done by many growers in the Netherlands with captured rainwater. Reverse osmosis is a commonly used treatment approach; while this process is effective, it increases the net price of supply water dramatically.

Desalination of sea water has been tested in an attempt to develop water resources for greenhouse horticulture. Unfortunately, the price of fresh water resulting from this is so high that it is not economically feasible without government subsidies.

5.2.1.4 Groundwater

In regions of the world with aquifers, groundwater can be an excellent source of water. Typically such aquifers are large and well buffered so that the supply quality is relatively stable. This is important for growers since it means that the fertigation systems design does not need to change over time. Since variations in water quality can, nonetheless occur, it is wise for the grower to have the source water tested every 6–12 month to monitor water quality. Many domestic groundwater sources have been unchanged for centuries but are now experiencing changes as run-off water from agricultural operations reaches the aquifer (a process that can take decades).

Also, in many areas where intensive agriculture is practised, groundwater depletion is a problem. Along coastal areas, where agricultural production is frequently intense due to the milder climates, the salt water intrusion into the aquifer can result in groundwater too high in salt for use in plant production (e.g. EC 10–15 mS cm^{-1}). In the region of Spain around Almería, groundwater, which mainly originates from the nearby mountains, is often used (EC ranges between 0.4 and 3.5 mS cm^{-1}). Water is pumped from wells between 150 and 600 m deep and, consequently, the groundwater table is decreasing, raising environmental and political concerns (Heuvelink and da Costa, 2000). The same phenomenon has been observed in the Central Coast area of California, particularly around Watsonville and Salinas where salt water intrusion has forced some growers to find alternate sources of water or close down their cropping system.

5.2.2 IRRIGATION APPROACHES

The equipment used to convert the raw supply water into water that is suitable for use in soilless cultivation should focus on improving water quality and to put the water under pressure so that it will flow through the plumbing. Sand filtration is frequently used to clean up water to make it suitable for use. In addition to filters, pumps are needed to create water pressure. All soilless production systems require water to be pressurized so as to make it feasible to have uniform irrigation. Water delivery systems typically involve the use of pipes that are of largest inner diameter near the pumps. The further the water in the pipe is from the source, the lower the pressure. This problem can partly be mitigated by decreasing the pipe cross section as the water travels through the pipe. But ultimately the irrigation water supply system

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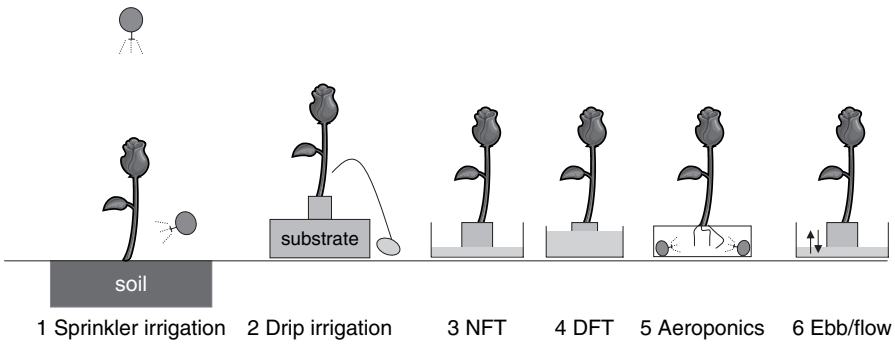

FIGURE 5.2 Various types of watering methods (see also Plate 9).

has to be divided into circuits in such a way that the pressure in each circuit is adequate to assure that the plants are irrigated uniformly.

As described in the previous chapter, irrigation can be from above the plant canopy, to the top of the root zone, or from below the root zone. Each of these irrigation approaches requires different technical equipment directly at the plant. The irrigation equipment needed in soilless production will be described below; a schematic overview is illustrated in Fig. 5.2. Generally in greenhouse soilless production, irrigation and fertilization methods are integrated.

5.2.2.1 Sprinkler Irrigation

Sprinkler irrigation systems apply irrigation water to the plants from above (Fig. 5.2). In some greenhouse and shade structures, plumbing is mounted overhead. Overhead installation does have the advantage that the plumbing is protected from mechanical damage by vehicles and persons. Installations can also have supply lines buried in the soil below the crop or mounted to the infrastructure. Movable sprinkler systems are also in use in various parts of the world. Crops for which it is undesirable to wet the foliage (e.g. some ornamental crops) can be irrigated with micro-sprinklers to the base of the plants. One positive feature of sprinkler irrigation from above is that it supplies water to most of the top of the root zone with relatively low investment and low maintenance costs (Heemskerk et al., 1997). Each sprinkler head type has a particular circular water distribution pattern; multiple sprinkler heads with short distances between emitters can be used to create a more uniform distribution pattern, but inherently sprinkler systems have uneven water distribution. For some crops, wetting of the foliage introduces a higher risk of plant disease development.

Micro-sprinkler irrigation systems, which deliver water to the base of the plants, overcome some of the drawbacks of overhead supply of water: there is no light interception due to overhead pipes and the crop becomes only partly wet. However, the plants themselves interfere with the even distribution of the water and prevent irrigation of large surface areas so that many more sprinkler heads are required, each delivering smaller amounts of water, to provide water to all plants.

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Modern sprinkler installations are typically designed for the type of cropping system and the specific demands of the grower. In outdoor nursery production, sprinkler emitters may include rotating impact sprinklers and gear-driven ones which throw a stream of water 2–20 m to ones with no moving parts which provide a circular spray pattern with a radius of 1–5 m. In greenhouse production, sprinkler systems are less common and emitters are frequently micro-sprinklers which deliver water at lower rates with greater precision to the base of the plants. Emitters have also been designed with other features that improve performance; pressure compensation assures that emitters deliver water only while the pressure is between specified minimum and maximum levels to avoid leaking of the emitters.

Due to the low expense of sprinkler systems relative to other systems, it is the most widely used system in outdoor container production. But even in these types of operations, growers typically use sprinkler irrigation only with tightly spaced plants. Plants which are spaced far apart are typically irrigated with drip or micro-sprinkler systems to reduce the amount of irrigation that misses the plants entirely. In greenhouse production, sprinkler irrigation is less commonly used due to the drawbacks mentioned above.

5.2.2.2 Drip Irrigation

Drip irrigation is currently the most common irrigation approach in soilless culture in greenhouses. Drip systems are of two types: microtube systems or in-line systems. The former generally involves many emitters and supply tubing to allow an emitter to place an irrigation solution at a specific location, generally near the base of a plant. The latter consists of supply tubing with emitters attached directly to, or embedded in, the supply pipe.

Drip irrigation with microtubing (capillaries) and drip emitters (Fig. 5.2) allow the system to operate with relatively high pressure (at the pump or source), reduced to uniform lower pressure at the emitters. This approach allows the grower to maximize uniformity of delivery of irrigation solution to every plant. This is important for crops with a low planting density or where each plant is of high value, making it financially feasible to optimize fertigation of each plant. Each emitter is typically connected either to a small stake (Chap. 4, Fig. 5.4B) or to a weight (Chap. 4, Fig. 5.4A) to assure that they release the irrigation solution at the desired spot. Emitters or nozzles with various flow rates and working pressures are available and chosen according to the requirements of the crop and substrate. Emitters are typically matched to particular types of substrates so that emitters with low flow rates are typically used with substrates that have high infiltration and drainage rates. Pressure-compensated emitters can be used to obtain even water distribution. Leakage-protected emitters assure that water is only supplied during irrigation events (Fig. 5.3) and prevent dripping at various points in the system; by keeping the irrigation system from draining between irrigation events, the system also starts up faster during an irrigation, leading to greater irrigation uniformity especially for short-duration irrigation events.

When applied to crops in beds where plants are growing at a specified spacing, in-line drip irrigation can be used by matching the planting density to the fixed in-line emitter spacing. In-line emitters can have the same properties as the standard emitters.

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FIGURE 5.3 Drip irrigation using pressure-compensated emitters to avoid leaking (see also Plate 10).

5.2.2.3 Nutrient Film Technique

Nutrient Film Technique (NFT) (Fig. 5.2) involves growing plants by maintaining a coating of nutrient solution around the roots, without the use of a substrate. When NFT first appeared, it seemed to be an ideal growing system because it seemed to offer optimal control over the watering of the roots without the expense of a substrate (Cooper, 1979; Graves, 1983). Optimization schemes were difficult to develop so that today NFT is used only for a few specific crops. Technically most crops could be grown in an NFT system (examples amongst others: Morgan, 1985; Lataster et al., 1993; Ito, 1994; Hortiplan, 2005) but widespread adoption has not occurred probably because such systems lack the ability to buffer even the slightest interruption in water and nutrient supply and there is a considerable risk of spreading root-borne diseases.

The system consists of a trough on a slope of 0.3–2 per cent; the roots of the plant lie inside the bottom of this trough. Nutrient solution is continually applied at the elevated end, so that the solution flows down through the trough at exactly the rate required to keep the roots completely wet. At the bottom end of the trough, the solution is allowed

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to drain. The nutrient solution layer should be as thin as possible, almost as a film. The width of the trough varies according to the crop; troughs of 4–8 cm are sufficient for crops such as lettuce and chrysanthemums, while for tomato and sweet pepper a trough of 15 cm is needed. The length of the trough varies from 1 to 20 m. Depending on the crop and the sizes of the troughs, various types of materials have been used: polyethylene liner, polyvinylchloride (PVC), polypropylene and coated metal. Ideal water flow rates have been identified to be between 3 and 8 $l\,m^{-2}\,h^{-1}$ for crops such as chrysanthemums and lettuce (Benoit and Ceustermans, 1989b; Ruijs et al., 1990a,b; Benoit and Ceustermans, 1994). Fruiting vegetables benefit from a faster flow rate. The slowest flow rate that is adequate to keep the roots coated with water may not be adequate in an NFT system; if the flow rate is too low, the problem is not lack of water, but lack of nutrients, especially for plants whose roots are downstream in the trough and are exposed to water from which many other plants have already extracted some nutrients. The last plants in the row get the least nutrients, especially potassium. Sometimes a distinction is made in flow rates needed for a young crop (2 $l\,m^{-2}\,h^{-1}$) versus a mature crop (5 $l\,m^{-2}\,h^{-1}$).

Plants destined for use in NFT systems are raised in small pots which are placed in the trough when a substantial root system has formed. In situations where the flow of water meanders in the trough, thus bypassing some plants, a lining of tissue in the bottom of the trough can be used to minimize this problem (Van Os and Kuiken, 1984). Shaped troughs (e.g. V-shaped) also prevent this problem (Formflex, 2005).

5.2.2.4 Deep Flow Technique

Deep Flow Technique (DFT) refers to a method that also attempts to keep the roots continuously exposed to moving water and nutrients. While with NFT the water film is as thin as possible, with DFT the continuously flowing nutrient solution has a depth of about 5–15 cm (Fig. 5.2). The large buffer of water and nutrients make it considerably simpler to control the nutrient solution. Only a relatively small fraction of the water and nutrients are actually taken up by the plants. The large volume of water also buffers the temperature, making the system practical in regions where nutrient solutions temperature fluctuations can be a problem (Ikeda, 1985; Ito, 1994; Park et al., 2001; Both, 2005). The width of the troughs in a DFT system are typically about 100–130 cm. Plants are secured in holes on polystyrene panels by means of a polyurethane foam; the panels float on the water or rest on the troughs sidewalls. The system is often installed at working height so that crops such as the lettuce or herbs can be easily planted and harvested.

5.2.2.5 Aeroponics and Aerohydroponics

In aeroponic growing systems the roots of plants are suspended in a volume where emitters continually spray the roots with nutrient solution. The construction is similar to DFT (closed square box of about 1.2 m wide and 5–10 m long) but there is no water layer; rather there is a constant misting of the roots. A similar enclosed space

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FIGURE 5.4 Aeroponics, nutrient solution is divided by sprinklers (see also Plate 11).

is created in a triangle construct of polystyrene boards, as in a Japanese commercial design (Panel, 1988) and in a research arrangement (Leoni et al., 1994). In the triangle construct, the relative humidity is 100 per cent and oxygen availability is increased around the roots (Fig. 5.4). However, care should be taken that the upper plants receive enough water. Often a thin layer of water is formed on the bottom, which acts as a buffer to the plants. Kratky (2005) showed the usefulness of the additional oxygen available in these systems by measuring higher lettuce yields in comparison to a continuous water layer around the roots. The amount of water supplied to the plants is not mentioned in the literature; often a timer is used, but the release rate of the nozzle is not given. Ruijs et al. (1990b) suggest a flow rate of $2\,l\,m^{-2}\,h^{-1}$ for chrysanthemum crops.

The NFT and aeroponic systems share the disadvantages due to lack of a buffer around the roots for water, nutrients and heat. A hybrid system was devised by Soffer and Levinger (1980) by combining aeroponics with DFT, which they called 'The Ein Gedi System' and coined the term 'aerohydroponics' for it. Here the roots of the plants extend through a panel, dangling in an airspace as with aeroponics, but into a substantial quantity of flowing nutrient solution, rather than just a thin film. One facet of this system is that the nutrient solution is continuously aerated and the rate at which the bulk flow of water and nutrients bathes the roots exceeds that of any other soilless production system.

With all variations of aeroponics, electricity is used to achieve all the bulk movement of water and this movement is critical to the survival of the plants. Evaluation of the commercial feasibility of such system requires balancing this energy cost with the enhancements in nutrient uptake and oxygen availability.

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FIGURE 5.5 Ebb and flow on a concrete floor for foliage plants (see also Plate 12).

5.2.2.6 Ebb and Flow/Ebb and Flood

In 'Ebb and Flow' or 'Ebb and Flood' systems (EF), container-grown plants are flood-irrigated on a water-tight tray or floor. During irrigation, water flows onto the tray or floor so that the base of each pot is submerged as the tray or floor is flooded (Fig. 5.5). The required duration of the flooding depends on the hydraulic conductivity of the substrate in the containers. The duration should be adequate to allow the water within the root zone to be wicked to the top of the root zone: generally 10–30 min if the substrate has high unsaturated hydraulic conductivity (longer if not). Then the tray or floor is drained which also allows the substrate to drain. Sloping surfaces and drainage grooves or channels are engineered into these systems to maximize the uniformity in water contents across a floor or tray between all pot/containers while facilitating rapid drainage. It is particularly important that the water be allowed to drain away completely so as to prevent root diseases. If wet spots remain around the plant, algae growth, root diseases and uneven watering will occur.

5.2.3 FERTIGATION HARDWARE

Water serves two important functions in plant production: it provides a vital resource for growth and also acts as a transport system for nutrients. Irrigation practices where both of these functions are actively combined in one system through the use of

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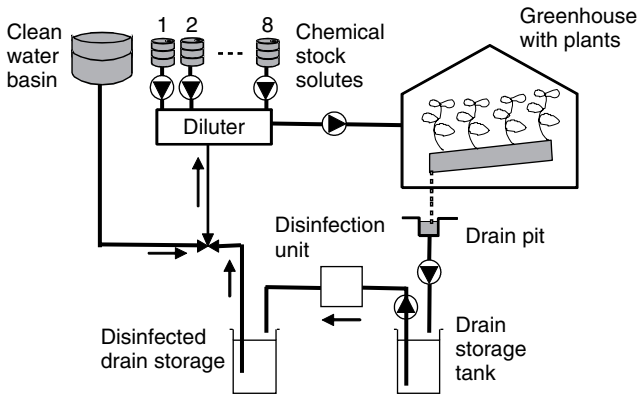

FIGURE 5.6 Schematic overview of the nutrient solutions way in a closed production system. The diluter/dispenser unit sees to it that concentrated fertilizers are diluted to a nutrient solution to be taken up by the plant.

completely soluble fertilizers are called fertigation. In this section, we focus on the dynamic control of the supply of nutrients in fertigation systems.

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A diluter/dispenser unit combines nutrients as concentrated chemical solutes in two to eight stock tanks (Fig. 5.6) with irrigation water. A system of pumps, valves and irrigation capillaries delivers the resulting nutrient solution to each individual plant.

The amount of irrigation is often controlled by time-duration operation of the supply or by a sequence of a controlled number of equal volumetric additions. Valves connect the nutrient diluter/dispenser unit to the various irrigation sections of the greenhouse. Approximately, 50 section valves can be allocated flexibly; each section is equipped with instruments to measure and log the amount of supply and drainage and daily averages of EC, pH and water usage.

Supporting programs manage the rainwater stock storage tanks or basins, the drainage storage and the storage for cleaned drain water. When additional water is needed in the system, selection criteria determine the source of the clean water. Since clean water is a highly valuable resource, water from different sources should not be mixed beforehand.

In closed growing systems the drainage water is recycled. Precipitation of crystallized salts may occur when highly concentrated stock fertilizer are directly mixed with the water from the drainage tanks. The recycled drainage water will be mixed with fresh water in a proportion selected to achieve a pre-defined EC value of the input water to the diluter/dispenser unit. An accurate control of the EC and pH of this input water should be incorporated into the unit's controller, in combination with procedures for automatic cleansing of filters in the recirculation circuit. Comprehensive and detailed fertigation management should include these techniques to prevent failures due to unexpected EC and pH values or blockages in the system due to precipitation.

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5.2.3.1 Sensors and Measurement

Electrical conductivity and pH

The EC and pH sensors are the simplest form of direct measurement in electrolyte solutions and are basic instruments for any grower using soilless production systems.

The EC sensors that are used in equipment for the processing of fertilizers measure using three equidistant ring-shaped electrodes which are mounted inside the water transport pipe at equal distances. The two end-electrodes are connected to each other and to ground. The temperature of the fluid is measured and is used to modify the value of the alternating current (AC) voltage applied between the central electrode and the ground electrodes as a means of temperature compensation. This AC voltage is typically around 1 V. The AC frequency that may range from 400 Hz to 50 kHz AC voltage is used to avoid polarization of the electrodes. The EC is determined by dividing the AC voltage by the electric current measured between the central electrode and the two end-electrodes. The current ranges from 0.1 to 10 mA. Both end-electrodes are connected to each other and to the electrical ground terminal to allow the serial or parallel connection of several EC electrodes in one water supply system. In horticultural practice, two distinct EC electrodes are used in parallel to provide a check on the functioning of both EC sensors against each other. The measuring range of an EC sensor is between 0 and 10 [dS m^{-1}].

The pH of a solution indicates how acidic or basic (alkaline) it is. The pH sensor measures the potential across a thin glass bulb or membrane caused by the difference in activity of H_3O^+ ions (protons) in the electrolyte on one side of the membrane and the measurant on the other side. In fertigation equipment, pH is measured with a standard combination type of sensor and includes a measuring electrode and a reference electrode in the same sensor body. A gel is used as an electrolyte, which means that the electrolyte needs no further replenishing. In this way, the slow deterioration of the pH sensor is avoided. The lifetime expectancy of these pH sensors is about one year. Again, two sensors can be used, so that one sensor is checked against the other. The values obtained with the EC and pH sensors are compared with the results of a bi-weekly laboratory analysis as an additional check. The laboratory analysis is also used for determination of the composition of the nutrient solution.

Sensors for individual ions

An Ion-selective Electrode (ISE) is a sensor which converts the activity of a specific ion dissolved in a solution into an electrical potential which can be measured by a voltmeter (Fig. 5.7). The voltage is theoretically dependent on the logarithm of the ionic activity, according to the Nernst equation (Chang, 1990). The sensing part of the electrode is usually made as an ion-specific membrane, along with a reference electrode. ISEs are used to measure on-line the activity of cations and anions in the root environment. ISE sensors are available for most macro-nutrients, like K^+, Ca^{2+}, NO_3^-, SO_4^{2-}, NH_4^+ and for Na^+ and Cl^-.

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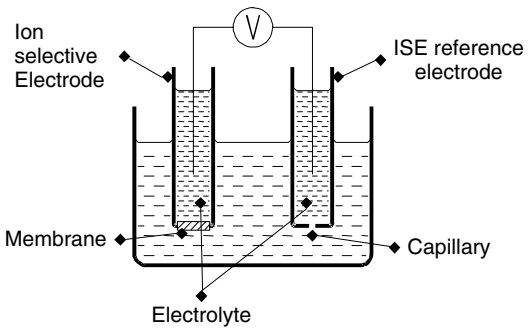

FIGURE 5.7 Basic principle of an Ion-selective Electrode.

Soil or substrate moisture

Close monitoring of soil or substrate moisture may be useful to maintain an efficient growth and to protect the environment. Waste of valuable nutrients and pollution of the surrounding environment, if open growing systems are used, is caused by the practice of providing a slight overdose of nutrient solution (10–50 per cent) and letting the excess solution run off as drainage water to wash out unused nutrients from the growing medium. Closed growing systems solve this problem by catching and recycling the drainage water.

The moisture content of the growing medium is an important variable in the uptake of water.

Sensors to measure water content determine the dielectric properties or the hydraulic properties of the growing medium, or the change of weight of the growing medium is established.

Dielectric sensors

Dielectric methods to determine water content from the dielectric constant of the substrate are rapidly gaining ground. The relationship between the dielectric constant for each specific soil type and its water content has to be established in a calibration procedure.

In time domain reflectometry (TDR), a short electrical pulse is sent into a pair of electrodes and the time-dependent reflected signal is analysed to give the water content of the medium between the electrodes. TDR equipment is commercially available. The basic principle of dielectric sensor operation is described in detail in Chap. 3.

In an alternative approach, the real and imaginary part of the complex impedance between two electrode needles is measured at one carefully chosen (high) frequency (Hilhorst et al., 1992). This Frequency Domain (FD) Method allows calculation of both water content and EC and is easier to automate and miniaturize than TDR. A commercial version is available as a sensor for *W*ater content of the substrate, *E*C of the substrate and *T*emperature of the substrate (the so-called WET sensor, Balendonck et al., 1998; Delta-T, 2006). Special designs of the two electrodes of the FD sensor

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offer opportunities to build sensors with one electrode rod (Balendonck et al., 1998; Delta-T, 2006). FD sensors are commercially available.

Hydraulic tensiometer

A porous cup filled with distilled water can be used for water potential levels near zero. When the cup is brought in contact with the growing medium, equilibrium will develop in which the pressure inside the cup equals the suction of the soil or the substrate (Slavik, 1974). The pressure inside the cup is measured with a pressure transducer. The basic principle of tensiometer operation is described in detail in Chap. 3.

The method works for suction pressures as low as −80 kPa. At lower pressures, there is a risk of air entering the cup. Errors will arise when contact between cup and soil is lost. Hydraulic tensiometers are commercially available. For more information on tensiometers in soilless production, see Chap. 4.

Gravimetric sensing

Changes in plant weight can also be sensed so that this input can be used as part of irrigation control. One example is shown in Fig. 5.8 where metal trough with approximately 16 plants (to give a representative sampling) is suspended from the greenhouse frame by wires. The wires are connected to load cells. An extra set of load cells measures the change of the fresh weight of the plants (Fig. 5.8). The weight changes are due to growth, supply of nutrient solution, the run-off of drainage water, the free evaporation of water and the transpiration of the plants. The change of weight due to growth, evaporation or transpiration is slow and over short time periods it shows itself as an almost steady signal.

The amount of supplied nutrient solution is determined by detecting the sudden change in weight when the supply is started. The exact increase in weight from that moment on till the end of supply is the accurate measuring signal for the supplied amount.

The drainage water is collected in a small break-out tank (∼50 mL), which is fixed to the through. The tank discharges when a fixed level is reached in the break-out tank. The sudden discharge of the collected drainage by the break-out tank is detected by the sudden change in the overall weight signal of the load cells. The exact decrease in weight from that moment till the end of the discharge is the accurate measuring signal for the amount of drainage water.

On the basis of this precise information, the supply of nutrient solution can be controlled with high accuracy. The change of the fresh weight of the plants and the value of the transpiration are used to inform the grower about the status of his crop. The basic principles of gravimetric sensing and examples for its use are described in detail in Chap. 3.

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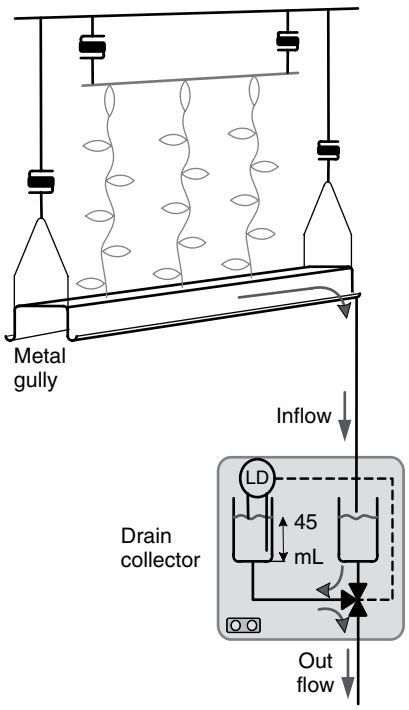

FIGURE 5.8 Measuring trough: by measuring the weight of the plants and the trough and the incoming water supply and outgoing leaching part, there is exact knowledge about the quantity of nutrient solution to be dosed to the plant at exactly the right moment.

5.2.3.2 Stock Solutions: A and B Solutions Versus Individual Liquid Fertilizers

A specific recipe of nutrients can be made for the particular crop in relation to the chemical composition of the source water. In 1970, when hydroponic production was introduced in The Netherlands, a system was developed by Verwer (1978) with one central tank to hold irrigation solution created by combining water with two stock solutions, called A and B solutions.

This type of system is still in widespread use today. The two stock solutions are prepared at concentrations 100 or 200 times higher than the average concentration of the solution to be supplied to the plants. Tank A contains all calcium compounds. In container B, all sulphates and phosphates are dissolved (Fig. 5.9). If the fertilizers in the two stock solutions were to be mixed at these concentrations, precipitation would occur in the pipes, valves and emitters, with disastrous results. For these reasons, solutes from the A and B tanks are diluted in fresh water in the mixing tank to achieve the right concentration and the appropriate EC level of the nutrient solution. An extra amount of an acid or base solute may be used to control pH of the batch of nutrient solution in the mixing tank.

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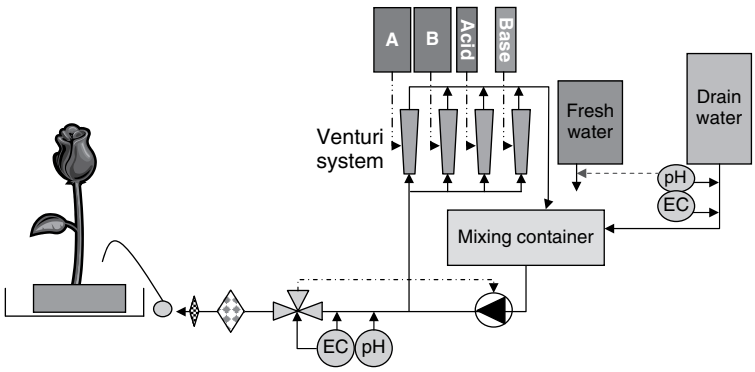

FIGURE 5.9 Example of a fertilizer diluter/dispenser unit where a Venturi fitting in the main supply pipe creates a pressure drop to transport concentrated fertilizers (courtesy Priva bv, De Lier, Netherlands).

The recipe of the A and B mixtures is selected according to the requirements of the crop to be fertigated and is based on a laboratory analysis performed every two weeks. Fertilizers are usually added to the A and B tanks by hand. This is heavy and unpleasant work, especially when the size of the greenhouse is in the range of several hectares. This is one reason for finding new methods to fill the concentrated fertilizer tanks.

One option is to deliver individual liquid fertilizers by tanker from a supplier. In general, depending on the supplying company, 6–10 liquid fertilizers are combined in a standard recipe for most commercial greenhouse crops. The tanker is equipped with separated segments, one segment for each concentrated fertilizer. A standardized discharge procedure ensures that each chemical fluid ends up in the right container, thus minimizing the chance of accidents. The need for additional manual labour is eliminated. However, significant disadvantages of this method are the cost for the transportation. Since a large quantity of water is transported, costs increase. The tanker method is only of particular interest in areas of greenhouse concentration, such as the Westland area in The Netherlands, the Almería region in Spain or the Brittany region in France. However, for most greenhouse production regions, it will be too expensive.

A second option is to manually mix solid fertilizers in the A and B stock tanks from 25 kg bags with standard fixed mixtures. The amount of labour can be decreased by the use of large plastic bags of 1 or 2 m^3, where the solid fertilizers are pre-mixed by the supplier in an A bag and a B bag, in accordance to the latest laboratory analysis. The bags are delivered on standard pallets, placed on a platform above the A and B tanks by a fork lift truck and easily emptied through an opening at the bottom of the bag. The whole content of the big bags is used at once.

New recipes of the A and B stock solution are prepared sequentially, but the release of the new recipe in both stock tanks is done at the same time to ensure that changes in the composition of the A and B solutions happen at the same time.

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The recipe of the nutrient solution must be adapted to the needs of the crop during the development of the plant from a seedling stage to a reproductive stage. Cultivation starts with a species-related standard recipe. This recipe is then adjusted in accordance with advice from a specialized laboratory after a test performed every two weeks on a sample taken from the root environment. The advice takes into account the composition of the different stock nutrients, whether they are solid or liquid stock fertilizers and information about the status of the crop. The appropriate adjustments to the recipe are calculated on the basis of this information. Not all the possible outcomes of these calculations result in recipes that the diluter/dispenser unit is capable of producing. During recent years, fertilizers have evolved from simple single- or multi element fertilizers to more sophisticated combinations of elements, fine-tuned for a specific growth strategy. In liquid fertilizers, the option of adjusting pH levels has also been introduced (Fig. 5.10) by adding acid or basic fertilizer solutions. Manual calculation of the recipe has been replaced by computerized calculation, which has made it possible to take all kinds of constraints into account. Nowadays these algorithms are also directly available to the grower as a spreadsheet or as a specialized calculation program related to a particular brand of fertilizer. Certain mixtures may lead to precipitation or to combinations of ions that cannot be produced from the available fertilizer stock solids or stock solutes. If the dilutor/dispenser units should be forced to proceed with an

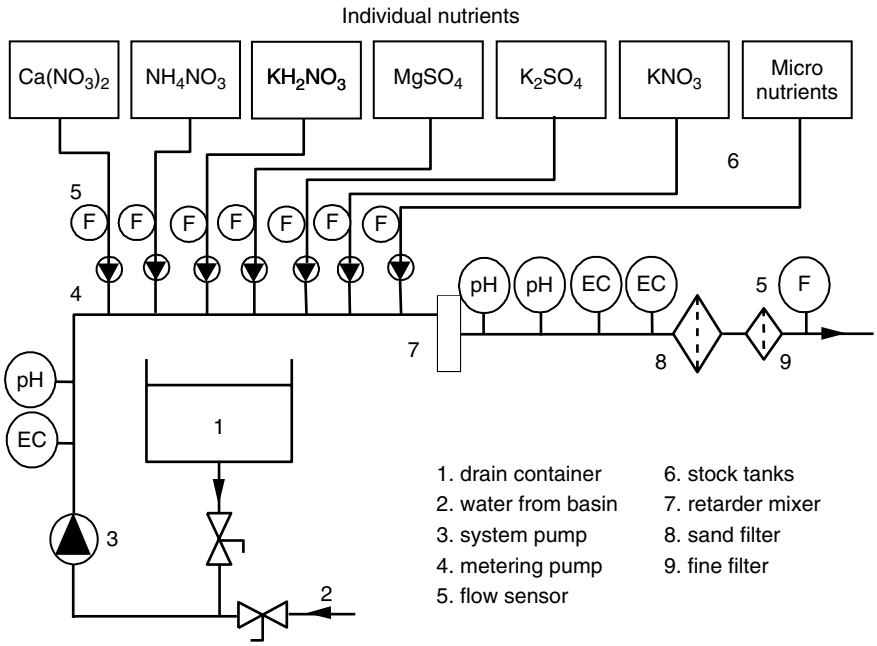

FIGURE 5.10 System with metering pumps to supply the stock liquids directly into the main supply line or into an open non-pressurized mixing tank.

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'impossible recipe', it can cause precipitations, blockages in the transport conduits or even explosions (Schrevens and Cornel, 1990). Additionally, optimization algorithms may on occasion lead to a more cost-effective choice of similar fertilizers.

5.2.3.3 Commercial Injector Systems for the Dilution of Concentrated Fertilizers

The mixing tank system

The operating principles of mixing tank diluters are as follows: A mixing tank is connected to the various fertilizer stock tanks (Fig. 5.9). In these storage tanks, solid fertilizers are dissolved in water and diluted at a standard high concentration. Quantities of the highly concentrated fertilizer solutions are fed into the tank of the nutrient dispenser system. They are mixed in accordance with a recipe, diluted with fresh water to a suitable concentration for the plants and finally pumped to the crop in the greenhouse.

There are several ways of feeding the highly concentrated stock mixtures into the mixing tank:

- Metering pumps supply the stock liquids into an open non-pressurized mixing tank or directly into the main supply line. One batch is prepared at a time in the mixing tank and then pumped to the greenhouse (Figs. 5.9 and 5.10). Examples of these systems are found in the early designs of computerized nutrient fertilizer systems (Bauerle et al., 1988; Papadopoulos and Liburdi, 1989).
- A Venturi fitting inside the main supply line creates a pressure drop which forces the stock fertilizers (Fig. 5.9) into the mixing tank or into pre-mixing chambers.
- Small container tubes (~5 L) are placed just above a mixing tank, one tube for each concentrated stock solution (Fig. 5.11). A valve at the bottom of the tube releases a precise quantity of stock solution into the mixing tank. A pressure sensor in the bottom of the tube measures the amount of stock solution released. The container tubes are filled by means of simple pumps or gravity (the stock tanks are in an elevated position).

The EC of the supply solution is controlled by altering the extent of the dilution of nutrients and water. The simplest systems are laid out to mix a small number of stock solutions, such as systems where four nutrient stock fertilizers are used with an extra acid or base solution for pH correction. EC- and pH-sensors are installed in duplicate to ensure safe operation. An embedded computer system controls the mixing process, the alarms and operator communication.

Mixing tank dispensers are used in systems with overhead sprinklers, drip irrigation systems or in ebb-flow systems. They are configurable for both in-line as well as in batched by-pass mode. The systems are available for various output capacities in the range of $1\,m^3\,h^{-1}$ to more than $40\,m^3\,h^{-1}$. A small number (4–6) of different nutrient recipes is possible. The EC set value is dependent on changes in global radiation.

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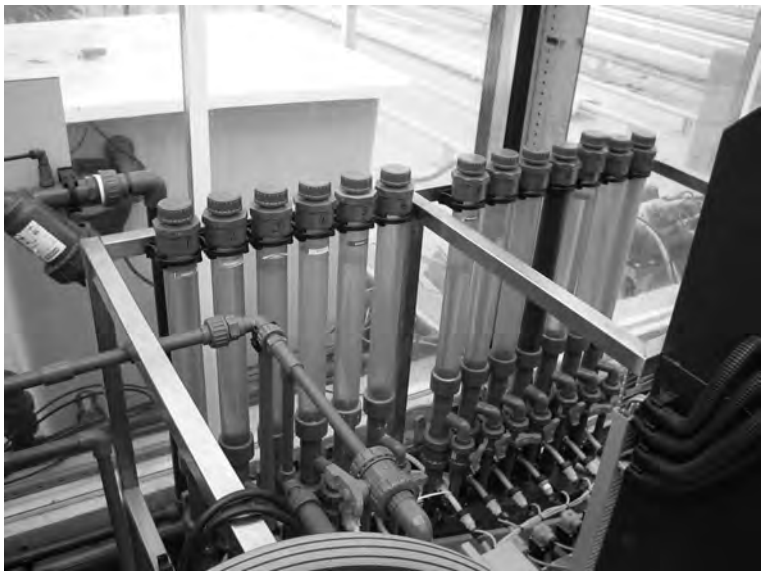

FIGURE 5.11 Small container tubes (~5 L) are placed just above a mixing tank to precisely release a quantity of stock solution into the mixing tank.

Direct injection system

The injection of concentrated fertilizers by means of a pressure drop in the main supply line is a modern and attractive alternative to the use of metering pumps. The pressure drop is created across a Venturi (Fig. 5.9). This pressure drop is the driving force to suck in the concentrated fertilizer fluids. It is a compact means of fertilizer transport, using fewer devices and moving parts that require maintenance, than a system with metering pumps. Direct injection diluter/dispenser units are available in several sizes and capacities.

Simple direct injection systems use a mixing tank to mix and dilute the stock fertilizers from the A and B tanks by using separate pre-mixing chambers into which the highly concentrated solutions of stock fertilizers are combined with supply water. This solution is then injected into the main supply line, where it is diluted to the concentration that is needed for the plants.

Systems that blend and dilute highly concentrated stock solutions of individual liquid fertilizers are more complex. The dispenser unit uses a fertilizer channel for each stock tank. A Venturi pressure drop in the main supply line is again the driving force behind the movement of the concentrated fertilizer fluids. The channel is closed off with a small ceramic insert with an orifice. The orifice ensures a fixed and limited flow rate. Ceramic inserts with different orifice sizes are used for the different channels. A flow meter and a fast-switching valve control precisely the accumulated flow over time. Four channels are connected to the mixing chamber. The amount of fertilizer transported into the mixing chamber is determined by the pulse activating the valves.

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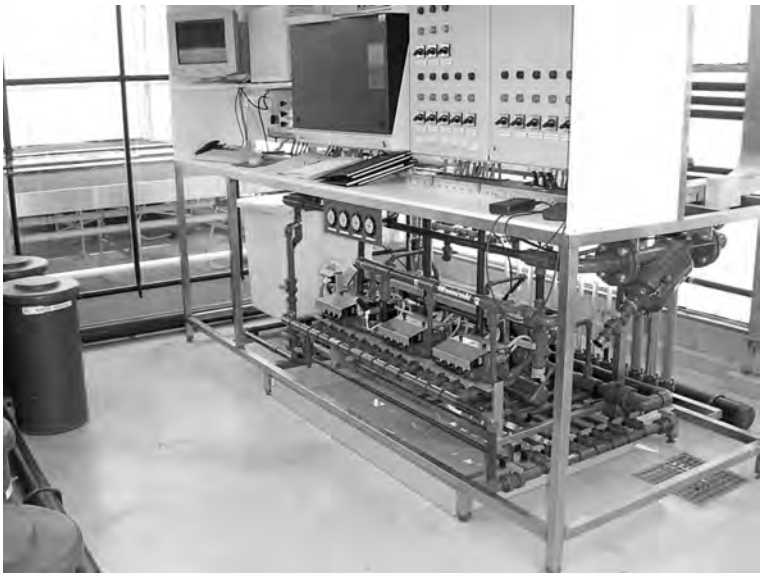

FIGURE 5.12 More sophisticated direct injection system for single element liquid fertilizers (see also Plate 13; courtesy Priva bv, De Lier, Netherlands).

A static retarder in the main supply line mixes the highly concentrated fertilizers with the supply water (Fig. 5.12) and prevents the contact of hazardous combinations of highly concentrated stock fertilizers with residues of nutrient ions in the supply water (recirculated in case of closed systems).

The process of mixing and diluting the various individual fertilizers is controlled by feeding back the measured EC value of the supply water into a computer controller. The amount of each individual fertilizer is calculated and corrected by the controller as a function of the measured water supply flow rate and the volumetric relation between the various fertilizers, as prescribed in the recipe selected by the grower. The intended pH and EC will be realized in the solution when the mixing algorithm is correctly applied. However, other factors, such as small changes in the composition of the clean input water of the system or the use of recirculated drainage water, introduce the need for fine-tuning the pH and EC value. This is carried out automatically by adjusting the output of the appropriate individual fertilizer channel in relation to its recipe value. An excess of a particular nutrient ion can be corrected in the next fertilizer supply cycle.

The concentration of the individual stock solutions is used as an input parameter in the calculation of the fertilizer recipes. The system is thus easily adjusted to accommodate all available concentrations of stock solution, such as standard industrial solutions or special stock solutions prepared for horticulture. Durable materials and a small number of moving parts ensure intrinsic reliability.

In general, eight liquid fertilizer fluids are sufficient to realize every possible recipe, including one channel for micro-nutrients. Injection dispensers are available at a capacity in the range of $100\,m^3\,h^{-1}$.

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Safety and protection

Mixing highly concentrated ionic nutrient liquids can be hazardous. Extra precautions must be built into the system to protect the grower and his staff from hazardous situations. For this purpose, extra sensors should check the process of dilution, mixing and dispensing for potential hazards, such as

- excessive or insufficient flow in the individual fertilizer channels;
- liquid fertilizer leakages;
- intake of air into the fertilizer mixing channels;
- unexpected drop in capacity;
- jamming of the channel.

General checks on the following should also be made:

- sudden or large deviations from the expected EC and pH values;
- leakage from the stock tanks (also when the equipment is switched off);
- the stock tanks should be stored in a containment pool with the capacity of at least one stock tank.

5.3 PRODUCTION SYSTEMS

Since the advent of the use of soilless culture, various types of production systems have been developed to produce specific crops. In general, crops grown this way are 'high-value' crops that have a high rate of economic return, thus ensuring that the deployed inputs-intensive system is profitable for the grower. Initial phases of this industry involved production in the ground in highly amended soils with above-ground soilless systems being a more recent development. In soilless production today, some systems sit directly on the ground, while others are raised above ground, allowing for no connection between plants and soil.

For each of these types of production systems, we will discuss the advantages and disadvantages, and the suitability for specific groups of crops (crops in rows, crops in beds). Substrates will not be discussed in this section, although a distinction will be made between solid substrates (such as stone wool or polyurethane slabs), granulated substrates (such as perlite, pumice, coir or peat) and no substrate (as in NFT and aeroponics). Most systems can be either open (all leachate flows into the subsoil without recirculation) or closed (leachate is reused).

5.3.1 SYSTEMS ON THE GROUND

5.3.1.1 Ground Preparation

Ground preparation is extremely important when installing a production system that will be placed directly on the ground, so as to minimize the incidence of pathogens

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and weeds. Steam sterilization, a chemical treatment or a solarization treatment can be used to ensure a disease-free start and to prevent the germination of weeds. Treatment of the top 10 cm of soil is generally sufficient. Production systems which sit directly on the ground also require that the ground be prepared to accommodate the hydraulic needs of the system so that the drainage water from the production system is managed correctly. Wet and dry areas will develop if the root zone is not perfectly horizontal or on an even incline. Consequently, water availability for the plants will not be uniform resulting in oxygen deficiency in some pockets, leading to root rot. Deviations from this may also lead to variations in EC levels, leading to reduced productivity and quality.

Levelling is mostly done at a slope of 0.3 to 0.5 per cent along the length of the greenhouse span. The overall length is subdivided into sections of 20–25 m to avoid excessive differences in height within the greenhouse. A moulding machine can be used to adequately shape the subsoil after levelling. The substrate bed that will make up the root zone may be lower or higher than the aisle and small canals are dug for drain water collecting tubes. Shaping by hand is impractical for larger areas, and the accuracy of the work is likely to be inadequate. Compaction of the soil may also be needed in cases where the production system is heavy.

A plastic barrier between the production system and the ground is generally used to manage weeds and excess moisture. This can take the form of a plastic film or durable woven material with a tight mesh. Selection of a liner made of a light-coloured material provides the feature that it reflects light back up towards the plants. This is especially important in latitudes with prolonged dark periods and short daylight periods. A disadvantage of a light-coloured (white) material is that it generally allows enough light to penetrate into and through the material to allow for some weed germination and UV degradation of the plastic. A black liner may be more advantageous than a white liner in areas where it is of greater value to have the ground below the liner attain slightly higher temperatures (cold greenhouses without possibilities to heat during the night) since it will store more heat during the day and release it during the night. A dark material is also generally more resistant to the degrading effects of UV radiation. Additionally, a liner prevents the movement of plant diseases from the ground into the production system.

Woven material, rather than impervious film, should be used in cases where water needs to seep into the ground below the aisle and production system. In such cases, the ground preparation should be such as to avoid excessive compaction of the ground where the aisle will be located.

There is a significant difference in the type of layout of plants within ground-based systems. Some production systems consist of long rows of individual plants spaced at some particular spacing (i.e. ‘single rows’). Other systems consist of rows of plants with several plants side by side (i.e. a ‘bed’ of plants). In this chapter, we define ‘single row’ to be a row of individual plants in a substrate and/or trough forming a root zone that is 4–25 cm wide. On the other hand, a ‘bed’ is defined as consisting of several plants growing side by side in wider arrangement (>1 m) with the root zone completely filled with substrate. AU6

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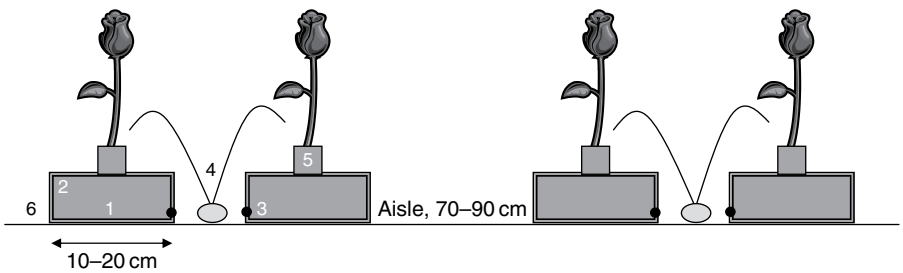
5.3.1.2 Crops in Single Rows

Single row systems are in use for crops such as roses, cucumber, tomato, pepper, strawberry and lettuce (Benoit and Ceustermans, 1989a). For crops in narrow rows, small quantities of substrates are normally used during propagation in the form of pressed peat pots or plugs. Propagules are started in these, from either seed or cuttings, and later transferred to a production system. Many times, single row systems are placed so that two single rows are adjacent (forming pairs of rows); this is done when the width of a single row is such that harvesting and plant management can be accomplished from one side of the row. This effectively eliminates a large percentage of aisle space, resulting in greater overall production efficiency.

Generally, the soilless substrate that makes up the root zone of plants grown in single rows is enveloped in plastic film so as to contain the irrigation water. Preformed materials, such as stone wool slabs, as well as some granulated substrates are generally enclosed in bags which have adequate support to allow them to be placed directly on top of the liner without the need for a reinforcing container. Substrate products which are not in these forms require some physical containment to hold the root zone in its desired form. This is either in the form of nursery containers, buckets or troughs.

Production systems which are placed directly on the ground are generally more difficult to configure as closed systems. In an open system, drainage water seeps directly from the root zone through the liner into the ground below the crop (Fig. 5.13). This traditional approach has the benefit that the required investment in materials is low, but a lot of water and fertilizer is wasted while also polluting the environment. Governmental regulations in most of Europe and North America now control the permitted amount of nitrate leaching (Agricultural Structure Memorandum, 1989; National Environmental Policy Plan, 1989) so that open systems are being phased out in many such areas. This has accelerated the development towards closed systems.



1: substrate slab or granulated substrate
2: foil around the substrate
3: drain holes are made 1–2 cm above ground level and at the non-aisle side
4: drip irrigation at the non-aisle side
5: pots for plant raising, using the same substrate
6: plastic liner covering the soil

FIGURE 5.13 Open systems for single row crops.

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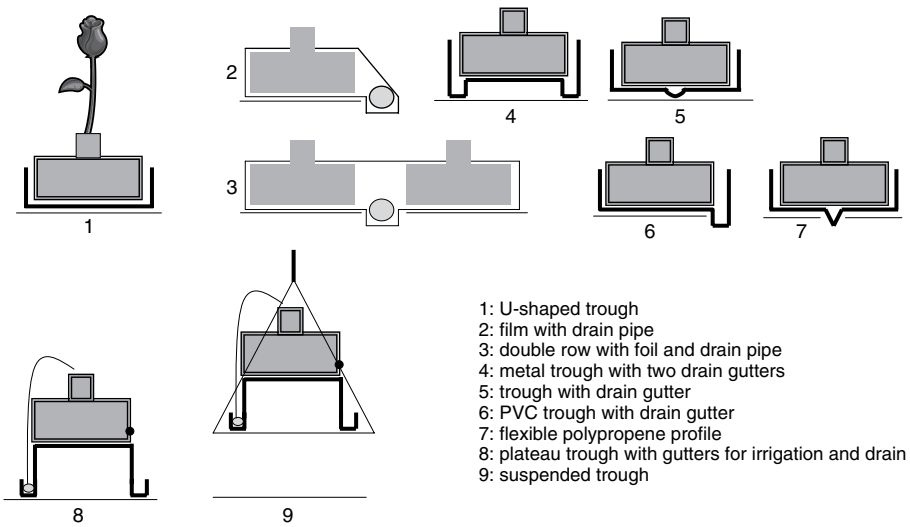

FIGURE 5.14 Troughs and profiles for closed single row systems.

A variety of materials have been used to create the troughs that collects the drainage water from slabs and bags (Lataster et al., 1993): plastic film, with or without integrated drain pipe, U-shaped polypropylene troughs, V-profiles and PVC profiles, metal troughs (Fig. 5.14).

One of the least expensive closed systems consists of a plastic bag or film wrapped around a substrate slab with collection pockets on one side. Often a drain pipe is laid into the channel along the length of the row to keep the drainage channel open.

Plastic sheeting material consisting of polypropylene or polyethylene, 1–2 mm thick, delivered in rolls, can be used to create a system of drainage troughs. These are typically 15–25 cm wide and have vertical edges 5 cm high. The bottom can be flat or V-shaped. The system requires careful levelling and compaction of the ground to prevent depressions where water can stagnate. Recirculation of the nutrient solution to the water treatment unit is easy because special fittings interconnect the troughs and the main pipeline.

Troughs have also been made of polyvinyl chloride (PVC), but such systems are much less flexible. This material is brought in its final shape from the factory and, consequently, cannot be delivered in roll form to the greenhouse for production of the trough on the spot. Lengths of 6–12 m have to be assembled at the greenhouse into the desired configuration. There is a risk of breakage.

Metal troughs can also be created either through shaping on-site off of large rolls (with a machine) or from preshaped trough segments. While expense may be a deciding factor as to whether plastic of metal needs to be used, it is important to note that some subsoil may not have adequate support for a plastic system, so that the stronger metal systems are needed so as to prevent breakage and reduce sagging.

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One consideration when selecting a material for drainage troughs is the need to disinfect the troughs between crops. If steam or hot water is applied to a trough made of thin plastic, then the trough is likely to deform. Solarization of these materials is possible, but temperatures must reach at least 70°C, and this is obviously dependent on the prevailing weather conditions. PVC has the added disadvantage that burning during disposal releases chlorine into the atmosphere and is therefore prohibited in many countries, while polyethylene and polypropylene can be burned completely without introducing too much pollution.

A system consisting of both a metal trough and a plastic film may be needed in situations where the structure of the soil of the ground is such that it results in sagging of a production system installed directly on the ground. Coated metal troughs are available in many widths and shapes (Formflex, 2005, Fig. 5.15) and can be placed directly on the ground or above the ground and even as movable systems (as described below). A metal trough system is typically more expensive than a plastic trough, but it is less susceptible to settling and sinking of the ground, and may be more durable, lasting more than 10 years.

5.3.1.3 Vertical Systems

Vertical systems are ones where some plants are on the ground while others are stacked in rows vertically. Such systems have been tested for crops with small plants like strawberry and lettuce with limited results (Fig. 5.16). The nutrient solution is

FIGURE 5.15 Suspended troughs for uniform water contents of the substrate and drainage of the nutrient solution (see also Plate 14).

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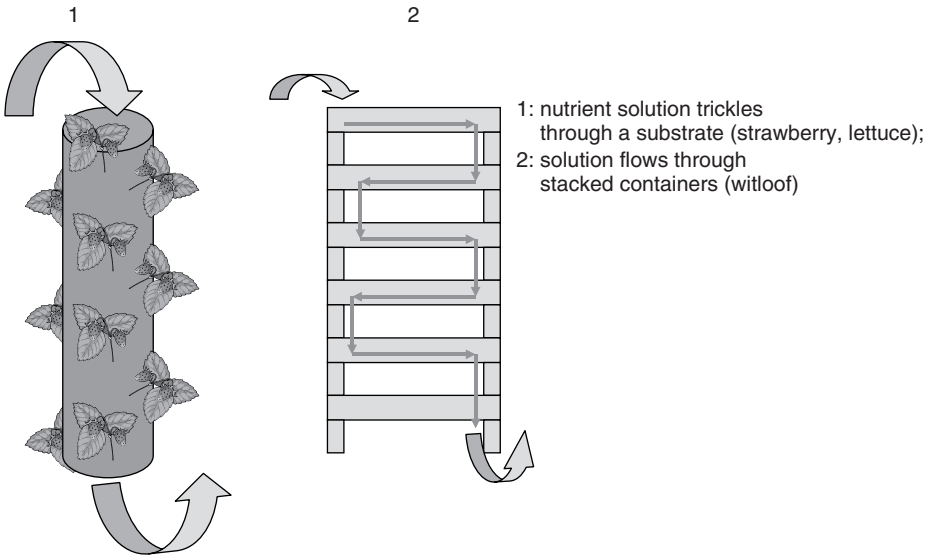

FIGURE 5.16 Vertical systems.

applied at the top and drips through a bag filled with substrate (Massantini, 1977). Drain water is collected at the bottom. Similar systems are in use as aeroponics or as stacked containers (Liu, et al. 2005) or containers fixed to a pillar (Vincenzoni, 1982). The main reason for using such an approach is to make optimal use of available space in an attempt to maximize the yield per square meter. However, the available light intensity is distributed over more plants making less light available to those at the bottom than those at the top. The consequences of this on year-round cropping should not be neglected: if harvesting of all plants begins at the moment the upper ones are ready, then the top layer crop is of good quality, but the yield from the lower layers decreases; if, on the other hand, replanting is only begun after the bottom plant is ready, each layer will yield a high-quality crop, but it will take longer before all plants are harvested and the system can be replanted.

Vertical systems are not widely used commercially. A similar approach to seek increases in yield per square meter greenhouse area using A-frames is described below.

Vertical systems for production of Belgian Endive (*Chicorium endivia* L. witloof, Fig. 5.17) is feasible despite this problem (Van Kruistum, 1997). Plants are placed in containers outside the growing area where they are grown to until they reach a specified size. These are later installed in 4–8 tiers of containers of 100×120 cm. Nutrient solution can flow through the containers in a zigzag pattern from top to bottom; the solution is then recycled. The plants are watered, kept at a temperature of approximately 22°C and are protected from light. White heads of Belgian Endive can be harvested after a forcing period of 3–4 weeks. A similar approach has been tried for asparagus (Van Os and Simonse, 1988).

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FIGURE 5.17 Belgian endive in stacked 120 × 120 cm containers (see also Plate 15).

5.3.1.4 Crops in Beds

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Several flower crops, such as chrysanthemums, carnation, freesia (*Freesia* spp.) or alstroemeria (*Alstroemeria aurantiaca* L.), are grown in beds at a density of 20–60 plants per square meter (Fig. 5.18).

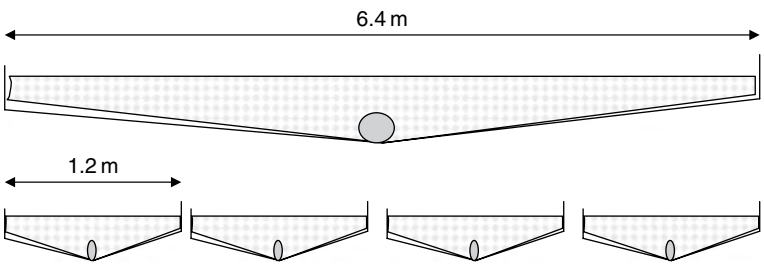

FIGURE 5.18 Systems for crops in beds.

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In this case, row systems as described above with slabs or substrates in bags are not used because the return on investment is not adequate to support such a system for these crops.

Polypropylene liner and substrate

The most widely used system for crops grown in beds consists of a 110–140 cm wide bed, with a 1–1.5 mm thick polypropylene liner between the subsoil and a layer of 5–10 cm of granulated substrate. Sidewalls are needed when the system is above the subsoil. If the aisles are raised, they can serve as sidewalls. A drainage pipe is laid at the lowest point of a bed. Depending on the type of crop, either heating or cooling pipes can be embedded. This system is especially useful for crops such as bulbs, tubers and rootstocks [lily (*Lilium longiflorum* Thunb.), freesia and alstroemeria] which have to be removed entirely between cropping cycles.

Polystyrene panels

Sometimes crops like lettuce or chrysanthemums are grown in beds without substrate, but with an NFT or aeroponic system (Ikeda, 1985; Ruijs et al., 1990a,b; Ito, 1994; Both et al., 1999; Kratky, 2005; Both, 2005). In this case, plugs are firmly secured by means of a sponge substrate (polyurethane foam) in polystyrene panels. Sprinklers moisten the roots from below (aeroponics, Figs. 5.2 and 5.4) or there is a thin (NFT, < 2 cm) or thick (deep flow technique, DFT; 5–10 cm) water layer.

Plant plane hydroponics

The 'Plant Plane Hydroponic' (PPH) system (Schröder, 1994) consists of a polyethylene or polypropylene liner below a layer of fleece material (plastic or cellulose), covered by a second liner to prevent evaporation and algae growth. The whole system is placed on a slight slope within the width of the bed of about 0.2 per cent. Water flows down the slope through the fleece to a drainage line in the centre or at the side of the bed. In large installations, the uniformity of the slope is very important and, consequently, subsidence of the ground beneath can be a problem.

Eco-organic soilless system

It is also worth mentioning a cheap soilless bed production system developed for Chinese growers (Jiang, et al. 2004). In a traditional Chinese solar lean-to greenhouse, AU9
beds of 48 cm wide, 15 cm high and 5–7 m long are walled with bricks and lined with a 0.1 mm polyethylene liner. The beds are filled with locally available substrates (rice husks, sunflower or maize stems, coal cinder, sawdust, sand). Solid chicken manure is an essential part of the substrate which means there is no need for liquid fertilizers and the plants receive only plain water.

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Span wide

Beds have also been installed with much greater widths than those mentioned above. Ruijs et al. (1990b) described a system for chrysanthemums, with a 0.5–1.5 mm polypropylene film below a 10 cm soil layer. In the middle of the span, at the lowest point, there is a drain pipe to collect the drain water. In practice, a thicker layer of soil proved necessary because a thin layer stayed too wet. Fair results were achieved by Bleijaert et al. (2004) when cultivating lettuce and cucumber in a 40 cm soil layer lying upon a plastic liner. Watering should be adapted to the substrate, which should be rather coarse. The system is not widely used on a commercial basis because the investment required is too high compared to the profit potential, particularly as far as leaf vegetables are concerned. Many times growers avoid wide beds as it makes pest management difficult since it is impossible for workers to inspect the plants in the centre of the bed. Wide beds are only feasible where all plants are harvested at the same time.

Concrete floor

One variant of the wide bed approach incorporates a flooded concrete floor (Fig. 5.5) or sprinkler irrigation. This type of system is used mainly for labour-extensive pot and bedding plants, raising young plants for fruiting vegetables and rooting cuttings in crates (60×40 cm). The concrete floor sometimes has embedded heating tubes. The floor is divided into watering sections; irrigation water enters the section and through gutters which are also used for drainage. The floor has a slope of 0.2–0.4 per cent to facilitate drainage. If sections are too wide or if the slope is too steep, the difference in water height becomes too great to realize a uniform water level for all containers on the floor. The depth of water during irrigation can be as much as 5 cm. Containers placed on an ebb and flow floor must have a special edge at the bottom to facilitate drainage. This type of growing system is especially suited to highly mechanized methods where containers are placed or collected with specialized machines (automaton/robotics). The expected lifetime of a concrete floor is the same as for a greenhouse (around 15 years). It should be considered that removing the concrete floor is just as costly as its original construction, and it is therefore hard to conclude whether the use of such a floor is economically feasible.

A floor should be designed with flexibility in mind. Birch (1979) designed a concrete floor system with a 10 cm trough-profile for year-round lettuce production. Transport equipment was incorporated into the design. Unfortunately, such a system excludes the possibility of changing to any other crop, forcing the grower to achieve the payback on the investment without any opportunities for changing the cropping system over the years.

5.3.2 ABOVE-GROUND PRODUCTION SYSTEMS

It has also been found that elevating the production system above the ground can have significant benefits due to better air circulation around the plants, reducing the incidence of plant diseases. Some plants also benefit from improved control over the

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temperature of the root zone. Another reason for elevating crops above ground level is to improve working conditions in the greenhouse by allowing workers to reach the plants or fruits to be harvested more easily. Raised systems can be either fixed or movable and are used for crops such as pot plants, strawberry, lettuce, rose, tomato, pepper, cucumber and gerbera. As with production systems which are placed on the ground, crops can be in single rows or in beds. Above-ground beds are typically called 'benches' and represent the majority of container-grown flowering potted plant production.

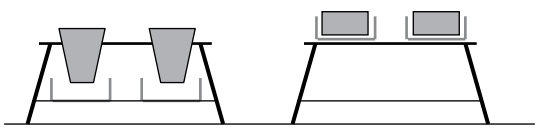
5.3.2.1 Single Rows

Racks constructed of metal or wood are installed on stone blocks or risers made of metal or treated lumber, so as to form a single or double row of container-grown plants from which harvests are taken on an ongoing basis. The root zone can either be formed by a set of pots or by elongated pans or troughs. Examples of crops which have been grown in such systems are roses, gerbera and strawberry (Fig. 5.19) and various other crops are being tested by growers. The racks are placed on the ground or secured partially in the ground depending on degree to which the ground is able to support the system without subsiding.

One example of this type of system consists of 15–25 cm diameter containers placed in a metal rack, where a trough is placed just below the containers to carry away drainage water (Worm, 2005). This trough can be made of polypropylene, PVC or coated metal. The system can be tailor-made on site by the grower.

Another example uses long trays (100–133 cm long, 15–20 cm wide and 7.5–10 cm high) to hold bags or slabs. Each tray is supported by a rack at the point where two trays meet (every 100–133 cm). More sophisticated systems consist of an aluminum frame into which containers are hung. Two frames are placed upon a rack, the height of which can be adjusted.

Outdoor crops can be grown in a one-row system, where the supporting frame is rigidly placed in the subsoil. Special accessories are also available to fit a rain shelter over the one-row system.



1: fixed racks for containers (gerbera, strawberry)
2: troughs or long-shaped containers on racks

FIGURE 5.19 Systems above the ground.

5.3.2.2 Suspended Troughs

Some systems have also been developed where the entire production system is suspended from the greenhouse frame by steel cables (Fig. 5.15). In this situation, there

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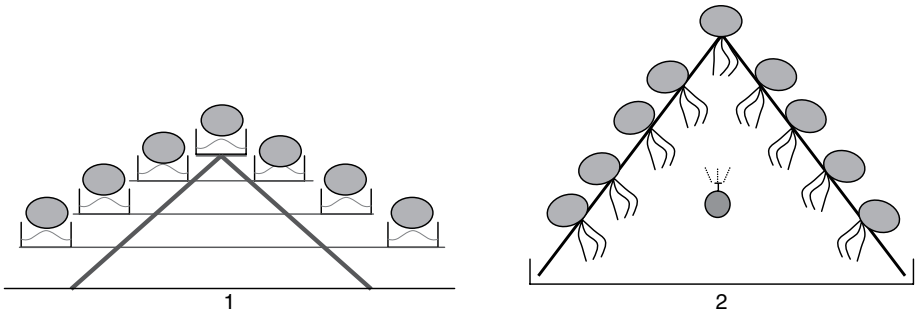
is no need for racks to support the system from below. Clearly such an installation is only feasible if the greenhouse is engineered to support this significant extra weight. Cables attached to the structural supports of the greenhouse at 2.5–4 m intervals are installed so as to give the suspended rows a smooth slope of 0.2–0.5 per cent. Troughs of various cross-sectional shapes are available for such application. A commonly used design is called 'the plateau trough' (10–30 cm wide) where slabs or bags lie on an almost flat plateau, with small channels (4.5 cm) on both sides (about 10 cm lower) for drainage water collection. The height difference is especially useful for avoiding root growth in the drain water gutter, thus minimizing the risk of dispersal of pathogens among plants in the row.

5.3.2.3 A-frames

The use of A-frames or arches to increase the efficiency of space utilization has been investigated. Morgan (1985) described the principle for a trough system with 12 tiers; Leoni et al. (1994) described the use of an A-frame for the growth of tomato and lettuce with aeroponic watering (Fig. 5.20). Morgan's system was 240 cm wide at its base, 40 cm wide at the top and 230 cm high. It accommodated 12 troughs with an NFT system for lettuce, and was designed for a 3.2 m span of greenhouse space. This configuration doubled the cropping surface (up to 40 lettuce plants per square meter) with 8–9 crops annually (Morgan, 1985). The system of Leoni et al. consisted of two polystyrene panels of 100 cm wide. The two panels formed a triangular A-frame shape with 120 cm at its base. The system included two A-frames in a 3.2 m span.

In such A-frame systems, the lower tiers of plants receive less light than the higher ones resulting in lower productivity for the lower plants. In the format of the system by Leoni et al., there is also a risk that plants will grow in a crooked shape of the lettuce head.



1: troughs with NFT system
2: polystyrene paels with aeroponics

FIGURE 5.20 Archway or panel system to increase the utilization of space.

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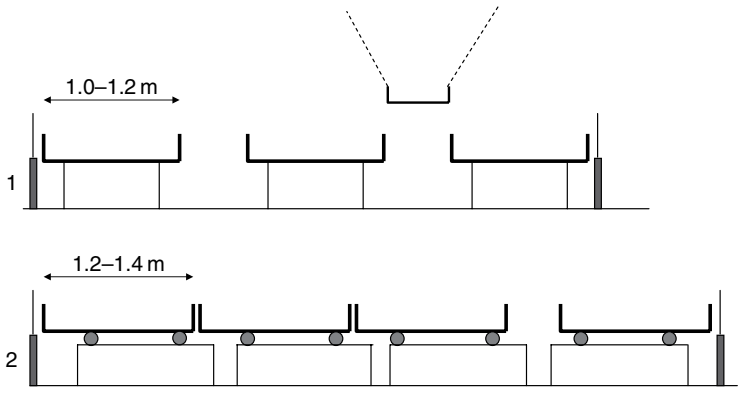

1: fixed benches in 3.2 m span, including a movable one hanging on chains
2: rolling benches in a 6.4 m span with one movable aisle

FIGURE 5.21 Fixed and rolling benches.

5.3.2.4 Benches

Benches are generally used to hold a large number of plants side by side so as to minimize the aisle space in the production area. The bench width is dictated by the distance that workers can reach into the crop to manipulate the plants. Benches can consist of fixed (Fig. 5.21), rolling benches or movable benches. Fixed benches cannot move and always have the same position in the greenhouse. They are mostly used for the cultivation of pot plants where aisles are needed for crop maintenance. Space utilization is relatively low (65–75 per cent).

Rolling benches are made of lighter-weight reinforced materials installed so that they sit on two long metal pipes which extend the full length of the bench. Cranks on the ends of the pipe allow the entire bench to be rolled side-to-side. The distance that a bench can roll is governed carefully with stops to prevent the bench from rolling off its supports. In such systems, only one aisle is needed for all the benches since every bench can be rolled so that the utilization of space is increased to 85–93 per cent.

Another step in the development of rolling benches was the introduction of aluminum benches, with water-tight plastic liner.

There has also been a trend towards wider benches, some as wide as 1.5 m. This, however, appears to be too wide for rolling benches with labour-intensive crops. For ergonomic reasons, a bench width of less than 1.4 m is recommended, because the reach of an average Northern-European worker is about 65–70 cm. If workers are of a shorter average height, then the width of the bench would need to be decreased.

Movable benches

Movable bench systems were developed in regions where labour and land costs are high, for use with plants that require a lot of manipulation (spacing). Special transport

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FIGURE 5.22 Movable benches can be transported out of the greenhouse bay to another place. Mostly the pipe-rail system is used; sometimes a lifter to get a quicker transport of an incidental bench (see also Plate 16).

systems are designed to allow an entire tray of plants to be moved at one time by rolling it to a different location on this transport system (Fig. 5.22). This allows the plants to be easily moved in large batches to the worker, instead of having the workers spend time going near the plants. Such systems also allow for minimization (sometimes elimination) of aisle space.

Movable benches are manufactured to standard sizes with length of 3, 4 or 6 m. The width of the bench varies between 120 and 150 cm. This results in a greenhouse space utilization of about 90–95 per cent. Many such movable benches are also equipped with a water tight bottom (PVC) or liner so that irrigation can take place via ebb and flow or capillary mats.

The concept of bringing the plants to the workers is also currently being tested for cut-flower production. For rose and gerbera, labour-intensive crops with a daily harvest from the same each plant, transporting the single rows of plants from the greenhouse to a separate harvesting area is being tested (Van Weel, 2005; Van Henten et al., 2005; Van Tuijl et al., 2005; Fig. 5.23). When set up in this way, all the plants in the row can be reached easily for maintenance or harvesting. Two problems have yet to be overcome with this type of system: one is the development of an optimal drip irrigation systems that can easily (and in an automated fashion) be disconnected and reconnected; this is a technical challenge that can probably be overcome. The other problem is related to the frequency with which such small rows of plants need to be

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FIGURE 5.23 Movable row system for rose (see also Plate 17).

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moved and the rate at which they can be transported. The rows need to be transported at an interval of 4–8 h. Rows in one span come to the main path, where maintenance or harvesting takes place; it then returns to is normal location via a separate aisle. Managing the cycles of harvests for each plant is difficult.

Individual plant

In intensive greenhouse production, plants in crops are being treated in an ever more individualized fashion. In the case of rolling benches, the smallest movable unit is the 1.5 m wide bench with its whole span length of 20–50 m. In case of transporting benches, the smallest movable unit is the bench of 1.5 m by 3–8 m. In case of the movable troughs, the smallest movable unit is one row of plants with a size of 0.8 by 3–8 m. Ultimately, it may happen that individual plants will be moved and treated individually.

The 'Walking Plant System' offers the most individualized treatment (Formflex, 2005; Fig. 5.24). After potting up in pots, they are placed on a movable belt. A machine places the plants onto a movable belt in the bottom of a trough. This system is programmed by the grower to place the plants into a certain row at a particular spacing. Other machines are used to space the plants within the trough by using one automaton or machine to pull the plants out of the trough and place them onto a main transport belt; a second automaton sets the plants into a trough at a specified spacing.

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FIGURE 5.24 Walking plant: an individual approach.

5.4 EXAMPLES OF SPECIFIC SOILLESS CROP PRODUCTION SYSTEMS

The list of soilless growing systems is continually expanding. Many different crops have been tried and a considerable number of them have been adopted by growers. In this section, a variety of such production systems will be described and some advantages and disadvantages will be discussed (Table 5.1).

5.4.1 FRUITING VEGETABLES

One of the largest segments of soilless production is the production of fruiting vegetables in greenhouses. These crops group generally have long cropping period (4–12 months), 1–3 plantings per year, 2–5 plants per square meter, rows separated by 0.8–1.2 m and within the row a plant distance of about 0.3–0.6 m.

Along the length of the row, substrate slabs (stone wool) or bags are laid in different types of trough systems or directly on the ground. Plants are propagated in the same

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TABLE 5.1 Overview of Crop Groups

No	Group name	Crops
1	Fruiting vegetables	Tomato (truss, cherry, beef, round), sweet pepper, cucumber, melon, aubergine, courgette, French beans, hot pepper
2	Single-harvest leaf vegetables	Butterhead lettuce, iceberg lettuce, kohlrabi, endive, Chinese cabbage, other salads
3	Single-harvest vegetables, drilling	Radish, spinach, (medicinal) herbs
4	Other vegetable crops	Strawberry, witloof, asparagus
5	Cut flowers	Rose, carnation, gypsophila, bouvardia
6	Single-harvest cut flowers	Chrysanthemum, aster, lisianthus
7	Flowering bulb, tuber and rootstocks	Freesia, amaryllis, alstroemeria, lily, tulip, iris, hyacinth
8	Other cut-flower crops	Anthurium, gerbera, cymbidium
9	Flowering potted plants	Cyclamen, begonia, saintpaulia, pot chrysanthemum, fuchsia, kalanchoe
10	Foliage potted plants	Ficus, dracaena, monstera, schefflera, ferns

substrate to ensure the correct rate of drainage when planted on the slab or in the bag. Drip irrigation is used to fertigate the plants. Nearly all fruiting vegetable crops in the United States, Canada and Europe are grown in this type of system. There are few other types of systems such as NFT (Cooper, 1979) or ebb and flow. This is mainly because of the potential for the dispersal of soil-borne pathogens via the recirculated water, the enormous quantity of circulating nutrient solution and, in places, the relatively poor water quality which can lead to sodium accumulation.

Currently in the Netherlands, all new greenhouses are installed with a suspended trough system, developed for tomato, cucumber and sweet pepper (Fig. 5.12). The big crop advantage is the uniform water content of the substrate and, after a few weeks, the uniform height at which the fruits hang to be harvested and, consequently, more efficient use of labour.

Movable systems per row have been tested (Van Os et al., 1993). In this design, the plants move in the length of the row, hanging on a rail, they return via the next row at 0.8 m distance. Continuous moving damages the leaves extensively because they rub against each other. Irrigation is carried out in one place along the path of travel. Further developments are focusing on making the plants movable so as to travel to stations where harvesting can occur. Here, one unit consists of two rows of plants, trained to a high wire system; the unit moves along one bay at a time, until it reaches the harvesting point at the main path. Here harvesting takes place while the unit moves sideways. After harvesting the unit moves into the next bay. Watering takes place via drip irrigation, but connection to and disconnection from the main water pipe line is optimized. A mobile system should not be considered if the utilization of space

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cannot be increased or a saving on labour input cannot be realized, since the system is very expensive in terms of both the initial investment required and the annual running costs; maintenance costs are also expected to be high. For sweet pepper, a much slower growing crop, a system of movable containers is under development in which utilization of space in the beginning of the crop is of importance. Here the walking-plant-system is being used (Formflex, 2005; see Sect. 5.3.2.4, Fig. 5.24).

5.4.2 SINGLE-HARVEST LEAF VEGETABLES

Many leafy vegetables are grown to size and then harvested when each plant has reached some specified size. Row spacing is generally 10–30 cm depending on plant size, with similar distances between plants along the length of the row. For these mostly short-term (4–12 weeks) crops, it is generally not feasible to use drip irrigation nor substrate slabs or bags. Most systems used are based on troughs with NFT or beds with DFT or aeroponics.

In the United Kingdom in the 1970s, commercial hydroponic lettuces production (2 ha) was set up using 10 cm wide concrete troughs (Birch, 1979). In the Netherlands in the 1980s, a commercial system (Van Os and Kuiken, 1984) was introduced to facilitate the seasonal switch between lettuce and tomato to address the issue that economic feasibility is generally related to competition with field-grown vegetables where such systems are profitable during the winter, but not during the summer. Seven troughs of 25 cm with two rows of lettuce per trough in winter are combined with only four troughs with slabs for tomato in summer. However, Dutch growers who invested in soilless tomato systems and butterhead lettuce have disappeared from the greenhouse market. Many other systems were developed for research or on a semi-commercial level (Ikeda, 1985; Morgan, 1985; Panel, 1988; Ruijs et al., 1990a; Benoit AU12 and Ceustermans, 1994; Ito, 1994; Leoni, et al. 1994). In north-western Europe, lettuce is not widely grown in soilless systems because market prices are often too low to compensate for the high annual costs.

On a large commercial scale, the movable gully system of Hortiplan, based on a Swedish design (Hortiplan, 2005), appears to be economically feasible. However, the level of investment required is also high. It is a system in which troughs are spaced during cropping; planting and harvesting take place at the same side of the greenhouse. AU13 Another spacing system was developed in the United States by Both et al. (1999) and Both (2005) where lettuce is produced on floating panels or floating rafts. The panels have a fixed planting density and various densities are used throughout the year. A similar large-scale system is in use in Canada for year-round production of lettuce and herbs. In Australia and the United States, variants of trough systems are in use, which are more suitable for small-scale production. Special systems have been developed for special crops such as lamb's lettuce (Benoit and Ceustermans, 1989a), cabbage (Anderson, 2004) and medicinal herbs (Dorais et al., 2001). Other crops use systems developed for butterhead lettuce with some adaptations, but these systems are only economically viable under certain special circumstances.

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The archway concept for lettuce production (Sect. 5.3.2.3) has progressed no further than use as a research tool. The practical problem of growing differences within one panel reduces the economic feasibility of the system. Lettuce is often used as a pilot crop in plant factories. In a plant factory, mostly of Japanese or Korean origin, lettuce plants are placed in a huge growing chamber with artificial lighting from which sunlight is excluded. Benches with a water buffer and without substrate are moved to a central place to be harvested. However, economic feasibility proved poor.

5.4.3 SINGLE-HARVEST SOWN VEGETABLES

Crops such as radish or spinach are grown in soil in a system covering the entire area in rows 5–15 cm apart from each other and a spacing of 2–5 cm within the rows. For soilless systems, this means that the entire greenhouse area has to be covered with substrate, which is generally not economical. Alternately, a NFT or DFT system has to be used. In this case, a separate system must first be used to germinate the seeds, grow the seedlings and then transplant them into the soilless system where they will grow to maturity. Both et al. (1996), Ikeda et al. (1995) and Maruo et al. (2001) describe such a system for spinach. In Japan, spinach is commercially grown in soilless systems, while in north-western Europe, economic feasibility is too low because of competition from outside production. Ruijs et al. (1990a) also describe several systems for radish, but here again it appears that economic feasibility is poor.

5.4.4 OTHER SPECIALITY CROPS

5.4.4.1 Strawberry

Problems associated with soil-based production of strawberry – such as the low utilization of space, loss of yield through diseases, and limited potential for crop rotation – have prompted growers to seek soilless cultivation methods. In the 1980s, growers tried to increase the utilization of space by putting plants in large containers (25 cm diameter buckets) so that the ripening fruit were hanging along the container, resulting in less botrytis and easier harvesting. In a movable suspended trough system, every second trough was hanging near the top of the greenhouse creating a path to pick the lower troughs, hanging at easy picking height (Van Os, 1986). This system proved too expensive and was replaced by a system where the containers were mounted higher in the greenhouse without any aisle space. Here the fruit was hanging above the harvesters, making the harvesting of fruit uncomfortable. Many other systems have been tested for strawberry production such as a vertical wall with plant holes to collect solar heat for the night; archway concepts; DFT systems with floating panels; vertical bags filled with substrate. Nowadays, many growers use a system of metal, plastic or polystyrene troughs with a special profile into which bags or slabs can be laid. The strawberries to be harvested hang at eye level. A cheaper alternative is the use of containers filled with peat or coir, mostly placed in round pipes at a similar height. The 20 cm diameter white PVC pipe is a drain water collector and a container support at the same time. In tunnels and shelters, strawberries are also grown in a soilless

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FIGURE 5.25 Strawberry in suspended troughs: optimized utilization of space (see also Plate 18).

system. These systems are less sophisticated but work well technically. Containers are often placed at a height of between 50 and 100 cm to make harvesting easier and prevent the hanging fruits coming into contact with the wet soil. Alternatively, metal troughs are placed at a height of 1.30 m, into which substrate bags are laid; the crop is watered via drip irrigation (Fig. 5.25).

Belgium endive (witloof)

In France, Belgium and The Netherlands, Belgian Endive (witloof) is an important hydroponically grown crop. The first stage of cultivation takes place in the open field where a root is grown from seed. Before winter, the roots are lifted and stored. Over the course of the winter, the roots are taken in batches and forced in dark temperature-controlled chambers, where around eight containers are placed on top of each other. A 3–5 cm water layer flows from the upper to the lower container over the roots. After about three weeks, a yellow-white head can be cut from the roots (Fig. 5.17). This has become a year-round forcing method which has completely replaced soil forcing.

5.4.4.2 Asparagus

In a similar system to that used for witloof, asparagus plants can be forced for white spears (van Os and Simonse, 1988). Growers became aware that asparagus plants could also produce spears under temperature-controlled conditions during the winter, but no way has been found to exploit this commercially. The supply season was considerably extended by the use of greenhouses, soil heating and other planting methods (ridges of 1 m high).

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5.4.5 CUT FLOWERS

One type of cut-flower production involves the use of the same plant for several months or years with daily harvests. The crop stays in the same substrate at a spacing that is dictated by harvesting needs. Crops such as rose are grown in single or double rows, while crops such as carnation, alstroemeria and bouvardia were grown in wider beds of 1.30–1.45 m. A granulated or preformed slab substrate is used. The feasibility of producing cut flowers in soilless production is linked to the profitability of the crop. Carnation, for instance, has proved uneconomical in soilless production in northern Europe and North America and was abandoned while they are still grown in tuff beds in Israel. Roses production in these regions also changed dramatically with nearly all rose production in these areas now being in soilless production. The change to soilless cultivation resulted in an increase of the production level and fewer diseased or dead plants. This was the main reason why the change to soilless systems for roses happened so rapidly. In other parts of the world, soil dispersion due to continuous application of monovalent ions (K^+ and NH_4^+) was another cause for shifting to soilless culture. Later, rose bushes were placed in single rows with a stone wool slab or a bag with granulated substrate. This made the system cheaper, as less substrate per square meter was needed. The introduction of the bent cane system in rose production became feasible when production was shifted to above-ground systems and this approach has become standard practice to control the quality of rose cut flowers. The introduction of the movable trough may be seen as a system for the future (Van Weel, 2005). The trough is at a slight incline to collect the drain water, and watering takes place by drip irrigation. Connecting the rigid water network to the movable drip irrigation system was a problem for a long time but has been solved (Van Zaal, 2005). During harvesting and crop maintenance, the troughs are disconnected from the watering system and pushed to the main path to perform the necessary tasks. After that, the trough moves sideways over a conveyor belt and into the following span. Each rotating unit consists of two spans 12–16 m wide and 50–100 m long. The advantages of the mobile trough system are the reduced labour requirements (the plants come to the worker), and the improvement of the quality of the labour (the roses to be harvested can be seen better; the worker does not need to reach to the middle of a bed). For the future, this mobile trough system can be used for a stage-related rose production giving each stage its own optimized climate conditions and leading to a synchronized crop. For this, the whole greenhouse area will be divided into three sections: one for sprouting of the buds to a stem length of about 5 cm; a second for the growth to a visible flower bud; and a third for development into a harvestable flower. In the last stage, all flowers must be harvested at one time. After harvesting, the bent branches are still on the plant and allow the plant to sprout again. First experiments are under way and look promising (Van Weel, 2005). The main problem to address has been the deviation in the harvesting time between the plants; over a course of six weeks, the harvesting period has been reduced from 14 to 5 days within one group of plants. The challenge is to reduce the harvesting period even more, if it can be done in one day, mechanical harvesting becomes possible. In addition to this, each individual plant must be of a similar perfect quality to flower at exactly the same time as the adjacent plant. After

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harvesting, the plants move to another section in the greenhouse to obtain an optimal climate to sprout.

Anthurium, gerbera and cymbidium cut-flowers can also be produced in a soilless production using containers, slabs or bags. For cymbidium as cut flower and several other orchids, the substrate is only needed for physical support. A large container filled with substrate is sufficient.

Over the course of a number of years, Anthurium grows into a large plant. A heavy substrate, such as clay or lava granules, is often chosen to fill large containers. Sometimes containers are placed in a bed of an ebb and flow system, otherwise drip irrigation is used. Less frequently, beds filled with granules (Fig. 5.18) are used; in this case, too much substrate is needed to fill the bed, and the plant needs support in height to avoid falling by imbalances.

Gerbera flower production is currently entirely done in soilless production, frequently in containers, but also in bags and slabs (Worm, 2005) which are placed in racks or in long-shaped containers filled with substrate. These rack systems are designed to have the plant at a height suitable for easy harvesting. As most flowers are pulled from the plant, it is important that the plant is fixed well in the substrate. Mobile trough systems are under development, similar to those used for rose (Van Tuijl et al., 2005), which involve harvesting in a central place.

5.4.5.1 Single-harvest Cut Flowers

Crops such as chrysanthemum, lisianthus and aster are grown from cuttings or plugs in beds 1.0–1.2 m wide and at a density of 30–70 plants per square meter with the expectation that all flowers will be ready for harvest at the same time so that the entire bed can be harvested at once. This means that the total area of the greenhouse is covered with plants, so the introduction of a soilless system means that the whole greenhouse area must be covered with substrate, which is economically unattractive. In the 1980s, NFT systems were introduced for research purposes (Van Os, 1980; Morgan, 1985). Flat-bottomed troughs 3–5 cm wider than the stem or the rooting medium block appear to work best. In that case, the flowing nutrient solution easily finds its way past the plants and blocks, even if the root mat grows to fill the entire trough at later stages. In the 1990s, several studies were undertaken to investigate if commercial chrysanthemum production is feasible in soilless culture (Ruijs et al., 1990b; Lataster et al., 1993). Production in soilless systems resulted in only a small increase in yield, while investment and running costs are much higher, resulting in reduced economic feasibility. Systems using beds filled with substrate, aeroponics or movable benches appear more expensive than NFT, and even NFT is no more financially viable than soil growing (Ruijs et al., 1990b). In 2004, a new NFT system was developed using troughs: the plants are gradually spaced further and further apart during the long-day period; by the short-day period, they have reached their final spacing distance. Optimum light, temperature and nutrient solutions are supplied during all the stages of growth (Van Henten et al. 2005; Van Os, 2006). Calculations made clear that up to 30 per cent extra yield per square meter is possible, which must be used to pay the system costs.

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5.4.5.2 Flowering Bulbs and Tubers

Flowering bulbs, tubers and rootstocks must be discussed in two separate groups: those which are grown in beds to produce flowers; and those which are first grown in open fields to a marketable bulb size to be forced in soilless production during winter and spring. These production systems are also single-harvest systems with the planted plant material being replaced after harvest.

Freesia, amaryllis, alstroemeria, lily

Freesia and some varieties of alstroemeria need root cooling to obtain a perfect year-round crop. These crops need a granulated or loose substrate to facilitate the planting and digging of the bulbs and tubers. Rolling benches (four benches of 1.45 m per 6.4 m span) appear to be the most economical soilless system to use (Hendrix and Ruijs, 1992), followed by 60 × 40 cm trays/boxes placed upon a plastic liner in which a drain pipe has been laid (Fig. 5.18). In both systems, combined heating/cooling pipes are used, while watering takes place by drip irrigation. The increase in the utilization of space leads to an improvement in efficiency. Alstroemeria is currently being tested in a commercial greenhouse in which 1.2 m beds are used, made of a plastic film and filled with a loose substrate.

Tulip, iris, hyacinth

In The Netherlands, around 2 billion tulip bulbs are produced per year in open fields. A small fraction of these bulbs are not exported but forced hydroponically for cut flowers. Here, a forcing method is employed that uses clear water, relying on the fact that the bulbs already contain the nutrients they need to grow. This fraction represents an area of around 500 ha. The main problem is keeping the bulbs in the correct position, with their tip pointing upwards, and preventing the stem from dropping during the growth. After many years of trial and error, two systems are currently in use: (1) containers with an aluminium device (90 × 120 cm, like those used in witloof forcing) with holes in which to place the bulbs and to allow them root into the water layer beneath the device; (2) bulbs are impaled on pins in the base of the case to keep them in the right position (Armstrong, 2002a). With either method, the vernalized bulbs are placed in the greenhouse at a temperature between 16 and 21°C. Water is added via in-line drip irrigation. This approach saves on labour and avoids the expense of a substrate. Similar systems are being developed for forcing hyacinths (Armstrong, 2002b). Recent experiences show that the best results are achieved with the NFT and ebb and flow systems. Stagnant water decreases yield, probably because of the low quantity of dissolved oxygen.

5.4.6 POTTED PLANTS

Flowering potted plants are relatively labour-intensive compared with cut-flower production and are grown on benches (orchids, cyclamen, begonia, saintpaulia, pot chrysanthemum, fuchsia, kalanchoe and a host of others (Fig. 5.22). Many are forced to flower on particular dates (e.g. holidays), requiring manipulation and grading.

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Green foliage plants typically have less labour input and are not scheduled as precisely. They are grown to reach a particular size, rather than a stage of flowering. A wide range of production systems are in use, ranging from gravel beds and concrete floors to fixed or moving benches or trays. Potted plant lends itself to extensive automation since the plants are individually grown.

5.4.6.1 Flowering Potted Plants

Introducing movable benches is the first step to the automation of the potted plant production process. The increased utilization of space translates into an increase in yield, which is generally enough to achieve a return on the investment. High labour input and increasing labour costs are driving investment in automation. Movable trays and benches allow work to be performed in a central location: the plants come to the worker rather than the worker going to the plants. Labour conditions can be improved in the work area and the less-favourable working conditions in the greenhouse are avoided. Nearly all facets of potted plant production lend themselves to automation so that it can be expected that ultimately all tasks from the filling of pots to planting, grading and packing of the plants can be automated. All this automation comes at a price; consequently it is not suitable for all types of potted plants. Generally flowering pot plants require the most labour so that it is the cultivation of these plants where the greatest savings can be derived from automated system.

Potted flowering orchids, such a phalenopsis, are also grown with such a system and this type of automation is being used by several growers. This crop takes a relatively long time to produce and benefits from various movements of plants through various temperature regimes and pot spacing as the plants grow.

Another automation system that is seeing continued development is the process of colour automated grading. Saintpaulia (African Violet) is grown in production systems in Europe, where the plants pass through an image analysis system which identifies how much colour the plant is showing. This can be used to assess whether the plant is ready to be marketed, and in conjunction with spacing machines can be used to sort plant onto several trays depending on how far from harvest each plant is. The various trays are transported to differently controlled greenhouse compartments to adjust the rate of development and force the plants to be ready on desired target dates. Similar image analysis systems are feasible for many other high-value potted flowering plant crops.

5.4.6.2 Foliage Plants and Outdoor Container Production

Large foliage plants (Ficus species, Monstera, Dracaena species, palms, ferns) spend longer periods in the greenhouse without little need for maintenance except for watering and fertilizing. For this type of plants, movable systems are often too expensive and the plants are also bigger, which make transporting more difficult. Here, the process of collecting and placing of larger containers has been automated. If watering takes place by ebb and flow upon a concrete floor, special adaptations to the pot and floor need to be made.

The outdoor production of container plants is comparable with the foliage plants mentioned above. The growing period is relatively long, while labour input per plant

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is lower than that for other potted plant production. Overhead sprinkler irrigation is generally used on gravel beds covered with a weed barrier (Bailey et al., 1999). Robotic automation is also being tested for outdoor nursery crops with considerable success. Such equipment includes automated pot filling, transplanting, placement of plants onto carts and spacing of plants into bed using robotic fork-lifts.

5.5 DISCUSSION AND CONCLUSION

Irrigation and fertigation systems, along with all the technology related to them, are undergoing continual innovative transformations leading to widespread use of automation and new developments in many areas. Irrigation approaches, in particular, have undergone considerable changes. Irrigation emitters improved with the introduction of pressure-compensated emitters, for both drip and sprinkler irrigation. In areas where water is becoming more expensive and where pollution due to excess fertigation is being regulated, sprinkler irrigation is being replaced by drip irrigation with more precise emitters and control strategies. Improvements in filtration equipment are responsible for major advancements in soilless production technology.

There is a small niche for NFT in crops such as chrysanthemums and lettuce in narrow troughs. DFT is in use to avoid excessive increase of the temperature of the recirculating nutrient solution and where control options are minimal. Ebb and flow is mainly in use for pot plants on benches or concrete floors. Aeroponics is rarely used on a commercial basis but could see more widespread use if the technological hurdle of lack of buffering can be resolved. Good production is possible with all these methods, but each method requires a different strategy to achieve optimal growth conditions and economic viability.

In the 1980s, the first soilless systems were open or run-to-waste systems. The excess of nutrient solution flows into the soil or to surface or groundwater was polluting the environment. Research projects showed that savings in water consumption and a decrease in the eutrophication of surface water by greenhouse crop production could be accomplished through recirculation of irrigation water (Van den Boogaard et al., 2003; Lecomte et al., 2004). In many countries and states this has led policy makers to force growers to switch to closed systems which involved reusing the nutrient solution. The basic logic behind this approach is well understood by growers: it saves water and fertilizers. But the resulting systems are much more expensive and need to incorporate the disinfection of the solution. Again, this is technically feasible, but not economically viable unless all competing growers are forced to adopt the same expenses. With a substantial increase in government regulation in Europe and North America since 2000, many growers are now seeing the need to modify their systems into closed or semi-closed systems to avoid fines. At the same time, this area is developing rapidly as new components and technologies related to recirculation are coming on the market. Researchers are also now developing information that helps this field evolve. Stanghellini et al. (2003) calculated the water-use efficiency of tomato grown in a closed climatized greenhouse to be 15–25 l of fresh water for one kilogram

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of tomato, as compared to 25–40 l for a soil-grown, non-climatized greenhouse and 40–60 l for outdoor production. The variation between 15 and 25 l water per kilogram is accounted for by the difference between an open soilless system (25 l) and a closed system (15 l) in a climatized greenhouse. This means that greenhouse production in dryer or hotter climates may be able to use less high-quality water, compared to outdoor production, but also that still more water (and expensive fertilizers) can be saved if a closed soilless system is used rather than an open system.

The commercial acceptance of soilless-grown crops in the 1980s and early 1990s raised expectation that many more crops would soon change over to soilless systems. Indeed, when one looks at all the systems developed for various crops, there are few technical limits to soilless cultivation: any crop can be grown perfectly well in soilless systems. However, to date not all crops have been changed over to soilless systems apparently, in many cases, due to the large economic investment. The required investment and annual costs in particular are too high. Insufficient increases in yield and quality are realized, while the price per unit of production area is declining. Those crops where the transition was made where commercial soilless systems is now the norm achieved this because of at least two of the following benefits to the grower: an increase in production at the same plant density, an increase of the utilization of space, or a lower planting density. Upon transition from soil- to soilless-production crops such as tomato, cucumber and sweet pepper, that are characterized by a relatively low plant density (2–5 plants per square meter), showed an increase in yield. When grown in soil, these crops were subject to many soil-borne diseases which could not be eliminated. At the same time, they changed from a rather low-quality water supply to an excellent quality rainwater supply. All of this has led to increased production. Almost all of these crops grown in The Netherlands now use a soilless system and are the major crops grown in soilless systems in other countries too.

On the other hand, leaf vegetables are grown in the ground at many plants per square meter (about 10–20), completely covering the ground. Changing to a soilless system results in relatively little increase in yield compared to soil production. The utilization of space can only be increased in some special cases. In such systems, increases in productivity would have to be realized through more-rapid accumulation of biomass, through shorter intervals between harvests. Consequently, soilless systems for these crops are feasible where this increase in production per unit greenhouse space per unit time is adequate to compensate for the large investment that is required. The costs in such systems may be due to the need for the entire greenhouse area to be covered with substrate or due to the need for an extensive and expensive NFT or DFT system. At the same time, competition from open-field production or from other countries is keeping the prices low, limiting the extent to which growers can recoup investment cost. Similar results can be seen in floriculture. Crops such as chrysanthemum, freesia and alstroemeria have been widely tried in soilless systems. The technical system and the cultivation method are not the problem, but the fact remains that for a commercial grower, there is no reason to change if his crop has a high plant density and there is insufficient improvement in yield or in the utilization of greenhouse space. With rose and gerbera, on the other hand, the plant density is low and the utilization of

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space increases in a soilless system; consequently, it is financially beneficial for the grower to change to a soilless system. Additionally, these crops suffer from soil-borne diseases, which can be avoided in soilless cultivation and, consequently, direct yield also increases.

Fertigation control involves precise control over the various fertilizer ions that are needed for plant nutrition. In the past, this has been done mostly by controlling the stock solutions and precise combination into irrigation solution. With the advent of recirculation, this has become more difficult since augmentation of nutrients to blended irrigation water requires knowledge of concentrations of the various ions. Currently many growers collect run-off in large storage basins and then test this water for available nutrients. This water is then used by blending with fresh water at a known rate and injecting fertilizers at a modified rate to achieve the desired recipes. While ISE can theoretically be used to dynamically monitor recirculating water, this technology is not yet stable and thus not feasible. Further research and development are needed to improve this.

Mathematical models which describe plant nutrition-related phenomena are widely used in research (Heinen, 1997; Gieling et al., 1998b,c) and can also be adapted for use in fertigation management through implementation in computer-controlled systems. Such models can replace direct measurements with predictions based on models (Le Bot et al., 1998). In some cases, this has been shown to be successful, but more research is needed.

Alternately if ion-specific electrodes can be developed to be as stable as current in-line pH and EC sensors, then such model-based ion concentration predictions may not be needed. Ion-specific measuring principles promise much greater degree of accuracy in the supply of nutrients to the plants than is possible with existing methods. The ratio of the uptake by the plant of various ions, and also the uptake-rate itself, may change over time, due to variations in the plant's needs. Using ion-specific control allows faster compensation for these fluctuations by adjusting the ion content of the incoming water and opens the possibility for feedback on the actual uptake of these ions (Gieling, 2001; Gieling et al., 2005). One of the biggest advantages would be the fact that water could be recycled dynamically rather than first accumulating batches.

Application of this innovative control technology would ultimately include the following:

- ion-specific monitoring of the nutrient solution in a closed growing system;
- monitoring of plant-related variables like photosynthesis, leaf area index (LAI), water uptake, leachate flow;
- control of fertigation based on feedback on the ion content of the drainage water;
- prediction of the uptake of water and nutrients using a model-based soft sensor or observer;
- decision-support systems for feed-forward control of the diurnal nutrient supply, using a plant-substrate model;
- use of a plant-substrate model in optimal model-based control of water and nutrient supply.

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The idea of controlling the supply of water and nutrient ions by means of feedback measurements is the subject of considerable research and development into new control technologies. Such controllers have been shown to operate consistent with expectations (van Straten et al., 2006). This and other research projects exemplify the role that model-based optimal control currently plays and will play in future issues related to systems engineering and automatic control of plants in protected cultivation (Tap et al., 1993; Van Henten, 1994; Van Henten and Bontsema, 1996; Van Henten et al., 1997).

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