6 Substrate-based Hydroponic Systems

6.1 Introduction

The main purpose of the substrate in hydroponic systems is to provide plant support, allowing roots to grow throughout the medium absorbing water and nutrients from the nutrient solution. The nutrient solution may be applied either to the surface of the substrate or through the base of the growing container via sub-irrigation or capillary action. Early substrate systems ran on the drain-to-waste principle, which meant the systems were simpler and less sensitive to nutrient solution composition or water salinity issues. With the concerns over water and fertilizer usage and environmental/disposal issues of draining nutrient solution to waste, collection and recirculation of the solution has become standard practice. This type of system consists of either large, shallow, media-filled beds or individual pots, slabs or containers, positioned in or above collection channels (Fig. 6.1). Drainage percentages are at least 10% or more where the solution is recycled after each irrigation and sterilization may be provided through the use of UV, filters, heat or slow sand filtration to prevent the accumulation and spread of root pathogens.

6.2 Properties of Hydroponic Substrates

Since the volume of soilless substrate is highly restricted as compared with soil cropping, the medium must be of a suitable physical structure to not only hold sufficient moisture between nutrient applications, but also drain freely, thus supplying the root system with essential oxygen, the level of which is dependent on the porosity of the substrate. Both air-filled porosity and water-holding capacity are dependent on the physical properties of a substrate, which in turn are affected by the shape and size of the constituent particles. Other important properties of substrates under hydroponic production are that they are free of weed seeds, salinity, contamination from pests and diseases, of a suitable pH for crop production and do not unduly influence the composition of the nutrient solution which is applied for plant growth. Soilless substrates also need to be biologically stable and not rapidly decompose, break down or fracture during the cropping period, particularly since the medium may be used for many successive crops. Inert substrates used in soilless culture typically have a low cation exchange capacity (CEC), thus do not play a role in plant nutrition which is controlled solely with the use of a well-formulated and balanced nutrient solution. Worldwide, a vast array of soilless media has been tested, developed, blended and manufactured for use under hydroponic production. The type of soilless substrate selected often depends on the materials available locally, as shipping bulky media long distances is costly. However, many substrates such as rockwool, perlite and coconut fibre (Fig. 6.2) gained acceptance rapidly and are now shipped worldwide to high-technology greenhouse and hydroponic growers in many different countries.

6.3 Open and Closed Soilless Systems

Soilless system nutrient management can be divided into two categories: those that allow the nutrient solution to drain to waste once it has passed through the root system, termed

DOI: 10.1079/9781789244830.0006

Fig. 6.1. Substrate system showing collection channels underneath troughs.

Fig. 6.2. Coconut fibre grow slab.

'open systems'; and those that recirculate the nutrient solution, termed 'closed systems'. Closed or recirculating systems are used in solution culture such as with NFT, DFT, float/raft systems, ebb and flow (flood and drain) and aeroponics, whereas hydroponic substrate systems may be open or closed depending on how the nutrient is managed. Open systems are more commonly used where the water may contain excess salts which prevent extended use or recirculating of the nutrient solution that can cause these to accumulate or where disease spread may become an issue. In open or 'drain-to-waste' systems, growers aim to minimize the volume of leachate and the associated loss of water and nutrients while at the same time providing sufficient nutrient solution to the crop. In closed systems, the nutrient drainage is collected from the base of the substrate and channelled back to a central reservoir where it often receives treatment such as filtration, sterilization, EC and pH adjustment before being reintroduced to the irrigation system (Fig. 6.3). Recirculation of the nutrient solution in closed systems is more cost-effective and poses less environmental risk; however, recirculation can spread certain root diseases and treatment with UV, ozone, heat or slow sand filtration is often used to control these issues. Recirculating systems also require a higher degree of control over the composition and balance of nutrient ions in the irrigation solution to ensure deficiencies do not occur over time and this is achieved with use of nutrient solution analysis and adjustment. Recirculating systems

Fig. 6.3. A closed cucumber production system where the nutrient solution is collected and recirculated.

require a high-quality water source which is low in excessive and unwanted salts such as sodium as these will accumulate through the recycling process, can lower yields and cause crop damage. Source water with a high content of unwanted salts can be treated with reverse osmosis (RO) to remove these contaminants and create pure water as a base for the hydroponic nutrient solution. If the water supply is of medium quality it is advisable to use 'semi-closed' systems where flushing out or periodically discarding the concentrated recirculating solution is carried out (Castilla, 2013).

6.4 Common Hydroponic Substrates

Soilless substrates utilized in hydroponic production fall into two main categories: those which are purely organic materials and those which are mineral substrates, the latter may include naturally occurring media such as gravel and sand, or artificially manufactured substrates such as perlite and rockwool. Organic materials used in hydroponic systems may be by-products of other industries such as sawdust, coconut fibre (coir), rice hulls, sugarcane bagasse, biochar, or other horticultural substrates such as peat and ground bark. Naturally occurring minerals such as scoria, pumice, sands and gravels are heavier, higher-density growing media, while manufactured substrates include artificially transformed minerals used to create mineral wool/rockwool, perlite, vermiculite and light expanded clay aggregates (LECA) or polyurethane foam, formed into a range of growing cubes and slabs. Under worldwide commercial production, the most commonly utilized soilless substrates are mineral wool, of which rockwool dominates, coconut fibre (coir) and perlite.

Hydroponic substrate-based systems used for crop production come in a diverse range of forms. Many are simply based on growing slabs of substrate (rockwool or coconut fibre) placed on a levelled floor, which allows the nutrient solution to drain away from underneath the plant. Grow slabs of rockwool or coco may also be contained within a rigid or plastic-film channel or support system or suspended up above floor height as in the 'hanging gutter system'. Loose substrates such as perlite, vermiculite, expanded clay, peat, sawdust, bark and others are placed inside growing bags, buckets, containers, trays, troughs or beds of a suitable volume for the crop to be grown. Drainage holes in the base of these containers allow nutrient solution to be channelled away after irrigation.

6.4.1 Stone wool (mineral wool, rockwool or glass wool)

Early substrate culture systems utilized naturally occurring media for plant support such as sand and gravel; however, by the 1970s Scandinavian and Dutch greenhouse growers were testing the use of stone wool, a man-made 'spun mineral wool' substrate that was originally produced for use as thermal insulation in the construction industry. Stone wool is manufactured by melting basaltic rock and spinning this molten mix into thin fibres which are then cooled by a stream of air. Grodan dominates the rockwool market worldwide and is the most common brand used by large and small hydroponic growers alike. Rockwool and other stone wool products developed for hydroponic cultivation are manufactured in a range of different products with varying degrees of density and water-holding capacity for different cropping uses. Stone wool of many brands is manufactured into a range of sizes from small propagation plugs for seeds to larger cubes for cuttings and fruiting vegetable transplants, as a wide range of slab sizes and as a granulated product.

Stone wool products are characterized by a moisture gradient within the substrate. At the base of the stone wool slab there is plentiful moisture, usually at media saturation levels, while in the upper layers of the slab, the roots are in drier conditions and hence have access to plenty of aeration and oxygen for root uptake and respiration. It is this moisture gradient from top to bottom of stone wool material that makes it a highly productive substrate for soilless production.

With tomatoes and similar crops, growers have the option of using the EC (strength of the nutrient solution) and moisture content of the stone wool/rockwool slab to help 'steer' the plants into either more vegetative or 'generative/reproductive' growth depending on what is required. Drying the slab back between irrigations and allowing the EC in the root zone to increase directs tomato plants into a more generative or reproductive state with less leaf growth and more assimilate being imported into the fruit. A higher level of moisture maintained in the stone wool/rockwool and a lower EC directs the plants towards more lush vegetative growth. Skilful growers use these techniques to direct their crop and control leaf, flower and fruit growth at different times and stone wool/rockwool is a substrate that allows this type of control via the root zone.

Stone wool/rockwool can be reused and commercial growers may grow many successive crops from rockwool slabs by steaming these after the plants have been removed and then replanting. Solarization is also possible, as is using chemical disinfectants, although the substrate must be rinsed well with water after using these. Commercial Grodan rockwool users have the option of the Grodan recycling service which picks up the used slabs and recycles them into new product. However, other growers may recycle the material by shredding it and reusing as a growing medium, as a component of potting mixes or incorporation into outside soils and gardens.

6.4.2 Coconut fibre (coir, palm peat, coco peat, coco)

Coco or coir is the outside layer of coconut husks (or mesocarp) which consists mainly of coarse fibres, but also finer material known as 'coir dust'. Harvested coconuts are first soaked in water, a process termed 'retting' which makes the fibre easier to remove. Usually the longer coarser fibres are removed for other uses while the coir pith then undergoes further processing and decomposition which makes it more suitable as a plant growth medium. Coir pith consists of mixture of shorter fibres and cork-like particles ranging in size from granules to fine dust.

'Coco fibre' is also the term often used to refer to the general-purpose grade of coco which is ideal for growing longer-term crops under hydroponic cultivation. Worldwide coco is used for soilless crops such as tomatoes, peppers, cucumber, melons, aubergines, ornamentals, cut flowers and many others because the structure of the coco does not break down over the time frame these longer-term crops are grown for. Thus, high rates of root-zone aeration and moisture retention are typical in both short- and long-term soilless crops and this results in high yields and good root health. Most coco fibre used in soilless systems has a water-holding capacity in the range 80–88% at container capacity and an air-filled porosity of 23–29% (Morgan, 2012).

Coco also comes in a range of different products – from small to large compressed 'bricks' to 'grow slabs' to pre-expanded, ready-to-use bagged product. Compressed bricks of coco fibre ensure the cost of shipment can be kept to a minimum; a typical 5 kg block of compressed coco can be expanded in water to over 65 litres of ready-to-use growing substrate. Pre-wrapped slabs of compressed coco can be less than 25 mm thick but when expanded with water within their plastic sleeve give a full-sized growing slab comparable in volume to rockwool (Fig. 6.4). The coco slabs only need be placed in position, slits cut in the plastic sleeve and water irrigated on – the coco expands and can be planted out with no further effort. The disadvantage of slabs is that they require a level surface to be placed upon so that drainage is even, and slabs only provide a relatively shallow depth of root volume compared with other bag- or container-based systems. Although coir fibre works well as a stand-alone medium, it can be blended with other substrates to improve the properties of the medium. Perlite can be mixed with coir fibre in a 50:50 mixture, which results in a medium that gives good support to the plants' roots and stems as well as holding more moisture than perlite alone.

6.4.3 Peat, bark and sawdust

Peat is used in many hydroponic systems and in seed-raising mixes mostly in Europe

Fig. 6.4. Grow slabs contain a substrate within a plastic sleeve.

where there are still reserves of good-quality peat available for use. The use of peat for soilless cultivation originated from the nursery industry where large volumes of peat-based potting media have been used for many decades for the production of container-grown plants. High-quality peat has good physical properties for soilless production; however, lower-quality peat can cause a number of problems if used in hydroponic systems as it can lose its structure and become waterlogged, resulting in root death. Peat is sometimes mixed with other substrates such as sand, pumice or media to 'open out' the structure and allow greater aeration and drainage in the mix.

Composted bark fines as a soilless substrate first came into use in the nursery industry in response to a decline in the availability and quality of peat resources. It was soon found that bark could also be utilized under hydroponic production and as a transplant-raising medium in soilless systems. To prepare a suitable substrate, bark of certain tree species such as *Pinus radiata* is composted with some form of nitrogen fertilizer to destroy any toxic substances or resinous materials and to prevent nitrogen drawdown once in use as a hydroponic substrate. If carried out correctly, the composting process also sterilizes the bark medium.

Fresh sawdust (i.e. uncomposted) of a medium to coarse grade is used as a short- to medium-term hydroponic substrate with reasonable water-holding capacity and aeration; however, problems arise with this medium when the sawdust starts to decompose and lose its physical structure. Once decomposition of the sawdust starts a number of problems can arise in the root zone, many of which the grower may not be aware of in the early stages. Growers using sawdust aim to produce one or two crops in this medium before it begins a process of rapid decomposition and needs to be replaced with fresh medium. Sawdust for hydroponic use needs to be free of toxins, plant resins and chemicals which are present in many tree species and in tanalized wood. *P. radiata* sawdust is the most commonly used in countries such as Australia and New Zealand, although other tree species are also suitable.

6.4.4 Perlite

Perlite is a siliceous material of volcanic origin which is heated to cause expansion of the particles to small, white kernels that are very light. The high processing temperature of this medium gives a sterile product which is often used for raising seedlings, particularly when combined with vermiculite, and for use in many types of hydroponic systems. Perlite is a free-draining medium that does not have the high water-retentive properties of many other substrates such as rockwool or vermiculite. It is essentially neutral with a pH of 6–7, but with no buffering capacity; unlike vermiculite, it has no CEC and contains no mineral nutrients. While this medium does not decay, the particle size does become smaller by fracturing as it is handled. Growers who handle perlite, particularly the finer grades, are required to wear either a respirator or dust musk to prevent inhaling the fine perlite dust particles or to wet down this substrate before filling growing containers or disposing of spent medium. Perlite is commonly used in the 'Dutch or bato bucket' system of soilless production that incorporates large rigid plastic growing containers with an interconnected drainage system which channels away the nutrient solution from the base of the bucket. Bato or Dutch bucket systems are typically used for larger fruiting plants such as tomato, capsicum and cucumber.

6.4.5 Pumice and scoria

Pumice and scoria (Fig. 6.5) are lightweight, siliceous, vesicular minerals of volcanic origin, characterized by high porosity and low bulk density. Pumice and scoria are generally free of pathogens and weed seeds and have a low CEC. The structure is stable and, being a natural product, can be used for many successive crops and disposed of with little environmental risk. Both substrates are available in a range of particle sizes from fine grades used in propagation to coarser grades which give a more rapid rate of drainage for long-term crop production.

Fig. 6.5. Scoria used as a hydroponic substrate.

6.4.6 Vermiculite

Vermiculite is a porous, sponge-like, kernel material produced by expanding certain minerals (mica) under high heat and it is thus sterile. Vermiculite is light in weight, with a high water-absorption capacity, holding up to five times its own weight in water, and a relatively high CEC – thus it holds nutrients in reserve and later releases them. Horticultural-grade vermiculite is available in a number of grades, with finer particle sizes used for seedling production and larger grades for hydroponic systems growing larger sized crops. Vermiculite is suited to hydroponic systems where the substrate is allowed to fully drain between nutrient applications, thus preventing waterlogging and allowing air to penetrate between the medium's granules.

6.4.7 Expanded clay

Expanded clay has a physical structure much like naturally occurring pumice or scoria and is produced by baking specially prepared clay balls or pebbles in ovens at 1200°C. The clay expands and the final product is porous, allowing good entry of both water and air. Expanded clay is known by many names and produced by a number of different manufacturers: pebbles or balls can range in size grades from 1 mm up to 16–18 mm. LECA is light expanded clay aggregate which is usually not formed into uniform round balls, but is of similar structure to expanded clay balls or pebbles. All types of expanded clay products are sterile after baking, inert and well suited to many hydroponic systems due to their free-draining nature and attractive appearance. Expanded clay, however, does not have a high moisture-holding capacity between nutrient applications and salt accumulation and drying out can be common problems in systems that are not managed well to prevent these from occurring.

6.4.8 Rice hulls

Rice hulls are a lesser known and utilized hydroponic substrate in most parts of the world; however, they have been proven to be effective for the production of a range of hydroponic crops including tomatoes and strawberries. As a by-product from the large rice production industry in many warmer regions of the world, rice hulls have the potential to be an inexpensive and effective medium for hydroponic production. Rice hull is a free-draining substrate, with a low to moderate water-holding capacity, a slow rate of decomposition and typically low levels of nutrients in the raw product. Rice hull media can be sterilized before use in hydroponic systems by the application of steam or through 'solarization' in climates where bright sunlight is consistent.

6.4.9 Sand and gravels

Sand and gravels of various particle sizes are one of the oldest soilless substrates utilized in hydroponics. Both have the advantage of being locally available and inexpensive in many regions of the world. The ideal sand particle size for use in hydroponic substrate systems is between 0.6 and 2.5 mm in diameter, rather than fine sand which can compact down when wet, excluding oxygen from the root zone. Sand and gravels used in hydroponic systems need to be inert and not release minerals into the nutrient solution, as well as free from contamination from soil, weed seeds, pests and disease, and salinity.

6.4.10 New substrates

Less widely used substrates in soilless production include polyurethane grow slabs, which are durable, light, inert and recyclable, but have a low water-retention capacity (Castilla, 2013); and a number of organic products such as composts, sphagnum moss, vermicasts and natural waste materials such as sugarcane bagasse from other industries. New substrate materials are continually being developed and assessed for hydroponic crop production. Much of the focus of this research is not only to improve crop performance and optimize plant growth, but also to improve sustainability, recycle organic materials and provide solutions to the waste generated by protected cultivation which is recognized as a major challenge (Urrestarazu *et al*., 2003). While research into the use of various composts and vermicasts as soilless substrates for crop production has been ongoing, new materials are continually being evaluated. Biochar is one such substrate that has undergone investigation as both a stand-alone substrate and in combination with other hydroponic media. Biochar, a charcoal-like material produced by heating biomass in the absence of oxygen, can be produced from a wide range of organic materials including greenhouse crop waste and has shown potential as a hydroponic substrate. Dunlop *et al*. (2015) found that biochar created from tomato crop green waste could be used subsequently as a substrate for soilless hydroponic tomato production, thus creating a closed-loop system. Other investigations have found biochar combined with various substrates resulted in a suitable hydroponic substrate for a wide range of applications. Awad *et al*. (2017) found that a blend of perlite and rice husk biochar produced a substrate which resulted in an increased yield of leafy vegetables compared with plants grown in perlite alone.

Other materials which have undergone investigation as new hydroponic substrates include sphagnum biomass formed into slabs, which proved to be a potential replacement for rockwool, while substrates based on sheep wool were less successful (Dannehl *et al*., 2015). The use of hemp (*Cannabis sativa*) and flax (*Linum usitatissimum*) bast fibre has also been assessed and while flax was unsuitable, hemp showed promise as a novel hydroponic substrate (Rossouw, 2016).

6.5 Substrates and Water-Holding Capacity

Many hydroponic substrates such as perlite, vermiculite, coconut fibre and others are available in a number of different grades, from fine, medium to coarse and mixed particle or fibre sizes. This allows growers to select different grades for propagation, smaller or larger plants, different hydroponic systems, longer-term crops and also for air-filled porosity and water-holding capacity. A good example of this is with horticultural coconut fibre used in hydroponic production. While orchids prefer a very coarse coco 'chip', using coco for propagation and germination of small seeds requires a much finer grade which will hold sufficient moisture as well as oxygen. While the high water-holding capacity of coir dust is required in some situations, it can create problems with oversaturation of the root zone, and grades of coco commonly used in grow slabs tend to consist of a mixture of longer coarse fibres or 'flakes' of coco, which keep the substrate open and aerated, and finer particles which hold more moisture. These grades of coco are ideal for longer-term hydroponic crops such as tomatoes, cucumbers, melons, peppers and cut flowers as the fibres assist in the prevention of the substrate 'packing down' over time. Other manufactured substrates such as stone wool, mineral wool or rockwool blocks/slabs also have a range of products with differences not only in overall moisture and air-filled porosity levels but also carefully calculated moisture gradients between the top and base. Many of these different products are aimed at different crops, growing climates and uses, and help provide the optimum levels of moisture in the root zone for different applications.

6.6 Substrates and Oversaturation

When nutrient solution is irrigated on to a substrate it displaces air in the open pores of the material; when draining subsequently occurs, more air is drawn down into the root system. If irrigation is too frequent the air-filled pores remain saturated and the plant has less access to the oxygen contained in air. Plants exhibit a strategy termed 'oxytropism' where roots will avoid growing into oxygen-deprived areas such as waterlogged soils, overwatered hydroponics substrates and stagnant nutrient solutions. This is most commonly seen inside the base of growing containers or slabs of substrate – areas devoid of any root growth, or small, thin brownish roots which have died back due to suffocation and oversaturation. If plants have been performing poorly observing root outgrowth into all areas of the substrate in the growing container or slab, particularly the base, will reveal if oversaturation has become a problem and prevented vigorous root growth. Other symptoms of root waterlogging include chlorosis (yellowing) or paleness of the new foliage, older leaves may also yellow and abscise, and flower and fruitlet drop become common. One of the more extreme symptoms of over-irrigation is epinasty where ethylene gas builds up within the plant causing the upper side of the leaf petiole cells to elongate whereas those on the lower side do not. The result is a severe bending downwards of the leaves which may be mistaken for wilting caused by a lack of moisture. Growers need to carefully check whether wilted plants are actually suffering from a lack of irrigation or epinasty due to waterlogging in the root zone.

Large amounts of algae may also grow on the surface of the medium if overwatering has been occurring. In seedling trays, high levels of moisture often lead to problems with 'damping off' caused by opportunist pathogens such as *Pythium* and *Rhizoctonia* that prey on young plants stressed by oversaturation and lack of oxygen. Cuttings and clones may suffer from stem rot and dieback as oversaturation cuts out much of the oxygen required for callus and root formation.

6.7 Matching Substrates to Crop Species

Some plant species are highly prone to problems with overwatering, while others are more tolerant. Strawberries are one common hydroponic plant that has no tolerance for a saturated substrate and many strawberry crop losses have resulted from overwatering the crown and the root rot that this causes (Fig. 6.6). Many cacti and succulents will also rot when over-irrigated and prefer a coarse and very free-draining substrate such as perlite or coarse sand. Other plants, more notably those that are grown under warm conditions, have large leaves and a rapid rate of growth and are better suited to highly moisture-retentive media that will hold sufficient water between irrigations. Cucumbers, tomatoes, squash and similar crops perform well in a medium that has a high water-holding capacity and also a good rate of air-filled porosity.

The rate of transpiration, temperature and humidity levels also play a role in substrate selection. Crops growing under warm, high-light, low-humidity conditions require frequent irrigation and benefit from a moisture-retentive medium which helps prevent drying out of the root zone and gives more of a safety buffer should failures with pumps or the power supply occur. Under cool conditions with slow growth and small plants, substrates which are highly free-draining and retain lower levels of moisture assist

Fig. 6.6. Hydroponic strawberries have little tolerance for oversaturated root zones, which can predispose the plants to crown and root rot pathogens.

with prevention of oversaturation under these conditions. These types of very free-draining, open substrates are also more forgiving of the application of higher levels of nutrient solution which may be needed, but at the same time not contributing to a water-soaked root zone when growth and transpiration rates are low.

6.8 Physical Properties of Soilless Substrates

The physical and chemical properties of a stand-alone medium for hydroponic production are an important component of crop performance. A growing medium is typically contained within the limited, fixed volume of a pot, container, trough, bed, grow bag or other system and must provide all of the oxygen and moisture requirements of the root system. The medium must also act as a physical support for plants, especially if these are large specimens grown over long periods (Carlile *et al*., 2015). Determination of the physical properties of growing media is carried out via a number of different analysis methods, these aim to measure variables such as water-holding capacity, air-filled porosity, and weight or bulk density which affects handling of the substrate. Chemical properties commonly determined include pH, CEC, salinity, specific ion contents, microbiology and potential contaminants.

6.8.1 Bulk density

Bulk density is related to the weight of a substrate and is defined as its dry mass per unit of volume (in a moist state), measured in g/cm^3 or kg/m^3 (Raviv *et al*., 2002). Most tests of bulk density are relatively simple to carry out: wet substrate is lightly packed or compressed under a given pressure into a container of a known volume, it is then dried down completely and weighed. Bulk density can vary considerably between different growing substrates and mixes; however, many producers of growing mixes seek media with a bulk density less than 300 kg/m^3 (Carlile *et al*., 2015). A low bulk density is often desirable in intensively grown greenhouse crops requiring a high air-filled porosity to meet the oxygen requirements of the root systems under frequent irrigation programmes.

6.8.2 Particle size distribution

The size and shape of substrate particles largely determine the air-filled porosity and water-holding capacity of a medium and vary considerably between different materials. Particle sizes in fine coconut fibre may range from 0.5 to 2 mm, while scoria, perlite and expanded clay can be several magnitudes larger. Peat may be screened into particle size grades ranging from 0–5 mm (fine) to 10–20 mm (coarse) or greater than 20 mm (very coarse). Substrates composed of one or more materials are often a blend of finer and coarser particle sizes, aimed to provide sufficient air-filled porosity but at the same time hold sufficient moisture between irrigations. Coarser materials such as perlite may be added to fine peat or coconut fibre to open out the structure of the growing medium, improving drainage and aeration where required. The particle size distribution of a specific medium is useful in estimating the hydraulic properties of the medium such as the water-retention characteristics and the hydraulic conductivity (Raviv *et al*., 2002). Growing substrates with larger particle sizes are generally more free-draining, highly aerated with a lower water-holding capacity than those with a higher percentage of small particles. These larger particle media require more frequent irrigation as less water is held in the substrate between waterings and are often utilized on crops that are sensitive to saturation of the root zone or require high levels of aeration around the root zone. Fine particle-sized substrates are suited to seed germination and seedling raising where there are no coarse particles to impede young root growth and sufficient moisture is held around germinating seeds.

6.8.3 Total porosity

Total porosity, or total pore space, is the combined volume of the aqueous and the gaseous phases of the medium (Wallach, 2008). The porosity of a growing medium is determined by the size, shape and arrangement of the particles and is expressed as a percentage of the total volume of the medium. Total porosity is an important variable as it can be further divided into the air-filled porosity and water-holding capacity which affect plant growth and root function. Most soilless substrates contain between 60 and 96% total pore space depending on particle size distribution. Total pore space includes those pores which are closed off and not accessible to water which tends to occur frequently in vascular materials such as pumice and scoria. 'Effective pore space' is a term which describes only those pores that can be saturated with water. Water is mainly held by the micropore space of a growth medium, while rapid drainage and air entry is facilitated by macropores (Drzal *et al*., 1999). Substrates with a good physical structure for plant growth tend to have an optimal distribution of large and small pores to meet the requirements for both high aeration and water-holding capacity.

6.8.4 Air-filled porosity

Air-filled porosity is defined as the volumetric percentage of the medium filled with air at the end of free (gravitational) drainage (Raviv *et al*., 2002). However the issue with air-filled porosity is that this value varies greatly with the height and shape of the container; for this reason, air-filled porosity is determined as the volumetric percentage occupied by air at a pressure head of 10 cm (or water suction of 1 kPa) (de Boodt and Verdonck, 1972). Most growing media have an air-filled porosity in the range 10–30% (Wallach, 2008), while highly aerated media such as those required for rooting cuttings have an air-filled porosity of greater than 20%. While air-filled porosity is a good indication of general oxygenation around the root system, problems can exist in the base of growing containers where a perched water table may form, thus excluding oxygen from this area. Growing container shape and size affect the moisture and air gradient from the top to the bottom of the container. Air content tends to decrease and moisture to increase from the top to base of growing beds and containers due to gravitational effects. Container geometry also influences air–water relationships within the medium, with air volume increasing by 25% and water volume decreasing by 13% in tapered pots compared with cylindrical types (Bilderback and Fonteno, 1987). Root systems, which respond to gravity, may also form a dense mat in the base of pots, beds or growing containers, which results in less than adequate root aeration despite the medium itself having suitable air-filled porosity.

6.8.5 Water-holding capacity or container capacity

The water-holding capacity or container capacity is dependent on the medium's particle size and container height: it is the portion of container pore space that retains water after drainage is complete. The water-holding capacity is comprised of both unavailable water, that which is not extractable by plants due to being held within very small pores or adsorbed on to particles, and available water, which is readily taken up by plant roots. To measure water-holding capacity, a container is filled with growing medium, fully saturated with water and then permitted to drain. Once draining is completed the damp medium is weighed, dried at 110°C until all moisture has been removed, then reweighed. The difference between the fresh and dry weights of the medium is the water-holding capacity. A water-holding capacity of 45–65% is considered optimum for most soilless growing media and container mixes. Substrates with a lower water-holding capacity require more frequent irrigation than those with a higher water-holding capacity.

While porosity, air space and water-holding capacity can be measured before a substrate is used for crop production, these variables can change over time, particularly with organic materials which are prone to decomposition. The structural stability of the growing medium is an important factor as microbial degradation and compaction or shrinkage can reduce aeration and increase moisture levels in substrates. Substrates and container medium components such as composts, wood fibre and sawdust are particularly prone to a loss in physical structure over time due to the breakdown of cellulose and other easily hydrolysable substances (Carlile *et al*., 2015).

6.9 Chemical Properties of Hydroponic Substrates

6.9.1 pH

The pH of a substrate is a measure of the level of acidity or alkalinity of the medium, which affects nutrient ion availability and uptake. The ideal pH in the root zone of most crops in a soilless medium is between 5.5 and 6.5. At high pH levels, the uptake of some trace elements such as iron and zinc and macroelements such as phosphate may be reduced, resulting in an induced deficiency. pH values can vary considerably between growing medium materials and may need amendment to obtain the correct values for optimum plant growth. Peat typically has a low pH in the range pH 3–4 depending on the degree of decomposition and peat-based substrates are amended with lime to adjust the pH as required. Dolomitic lime also provides calcium and magnesium and is applied at rates of 2 to 3 kg/m^3 for less decomposed (H2–H3) peat and 3 to 7 kg/m^3 for more decomposed peat (H4–H6) (Maher *et al*., 2008). Coconut fibre including coir dust, fines and chips generally has an acceptable pH within the range 5.5 to 6.5 and requires no pH adjustment. Pine and other bark, after the composting process, typically has a pH range of 5.0 to 6.5 and lime may be added as required to increase the pH in some composted bark substrates (Jackson *et al*., 2009).

6.9.2 Cation exchange capacity

The extent of cation adsorption by the surfaces within a growing medium is termed the 'cation exchange capacity' and may be expressed as meq/l, meq/100 g, meq/100 cm or mmol/kg; or, more commonly when referring to container mixes, CEC is related to volume unit in centimoles of charge per litre (cmol/l) or even as meq/pot. CEC refers to the medium's ability to hold and exchange mineral ions and varies considerably between soilless substrates. Growing media materials have electrical charges on the particle surfaces; negative charges contribute to the CEC and can bind positively charged ions (cations) to these sites. These cations can then be exchanged for another ion, releasing elements for plant uptake. The larger the number of negatively charged sites found on the substrate particles, the higher the CEC of the growing medium. A high CEC allows a soilless medium to hold nutrient ions in reserve and release these back later for plant growth, it therefore increases the buffering capacity or rate of change in fertility levels in the root zone. A high CEC can also buffer or resist changes in pH in a substrate; media with a high CEC require more lime to raise pH than those with a lower CEC. Soilless growing substrates can also have positively charged sites which attract negatively charged particles – this is referred to as the 'anion exchange capacity', which is far less significant than the CEC in a growing medium. While a moderate to high CEC value of 150–250 meq/l provides some good buffering capacity to a container or potting medium to pH changes and fertility, CEC is less of a concern in hydroponics or soilless crop production. Under hydroponic production a lower CEC is often preferable as plant nutrient requirements are fully met with frequent irrigations of nutrient solution containing all of the elements required for plant growth. Thus, a medium which retains high levels of ions, which are later released, can create imbalances in the nutrient solution surrounding the plant roots. Commonly utilized hydroponic substrates such as perlite and stone wool have low CEC values of 25–35 and 34 cmol/kg, respectively (Argo and Biernbaum, 1997; Dogan and Alkan, 2004). Materials with high CEC values include peat, with a CEC of between 150 and 250 cmol/kg, and composts, which can vary considerably in CEC depending on source materials and degree of decomposition (Carlile *et al*., 2015). Intermediate CEC values are found in other organic materials such as coconut fibre and composted pine bark. The CEC in some materials such as coconut fibre destined for use as a hydroponic medium can be adjusted before use with addition of solutions such as calcium nitrate which also help counter any nitrogen drawdown in this medium during the early stages of crop growth.

6.9.3 Specific ion contents, salinity and electrical conductivity

Salinity, which may include sodium as well as a number of other ions, can be an issue with certain materials used as soilless growing media. These are typically organic materials that can vary considerably with regard to EC, which is typically used to measure salinity levels. Some sources of coconut fibre can have high levels of sodium chloride (originating from coastal areas) as well as high levels of potassium present (50–200 mg/l) and require leaching or washing in water to remove these before use as a horticultural substrate.

6.9.4 Testing methods

While agricultural laboratories can carry out a full range of testing of soilless substrates, onsite testing by growers and manufacturers of growing mixes is a useful tool when evaluating media. The standard evaluation test for pH and EC (salinity) is the 1:1.5 medium/water extract. This involves mixing a representative sample of the growing medium with distilled water at a ratio of 1 to 1.5, stirring or shaking well, allowing to settle, filtering and then measuring the resulting pH and EC of the extract. The extract sample can then also be sent to a laboratory to analyse for specific ions to determine the fertility level of the substrate and for the presence of unwanted contaminants.

Conducting an onsite bioassay of new substrates is another rapid and inexpensive method of assessment of a hydroponic medium (Fig. 6.7). Since bioassay testing can also identify potential problems within a substrate that are not shown up by chemical physical analysis only (Kemppainen *et al.*, 2004), these types of evaluations play an important role in substrate quality assessment. A plant bioassay involves growing seedlings of a sensitive species such as cucumber, lettuce or tomato (Ortega *et al.*, 1996; Owen *et al.*, 2015) on a new substrate and comparing a number of growth variables against a standard or control substrate. Cucumber seedlings, which germinate rapidly, are a highly sensitive bioassay species and are commonly used for such assessments (Fig. 6.8). Common uses for bioassay tests are often with organic-based substrates such as peat, bark, sawdust, wood chips, coconut fibre, composts and similar materials, which may contain traces of phytotoxic compounds under certain circumstances (Ortega *et al.*, 1996). However, bioassays can be used for any substrate to compare the growth rate and plant performance to standard substrates. Once seedlings are grown for a limited period of time as part of the bioassay, they are assessed for variables such as germination count, coloration, height, leaf width, fresh and dry weight, root mass and overall appearance. Use of simple bioassays gives a close correspondence to actual growing conditions and should be part of the evaluation of new substrates.

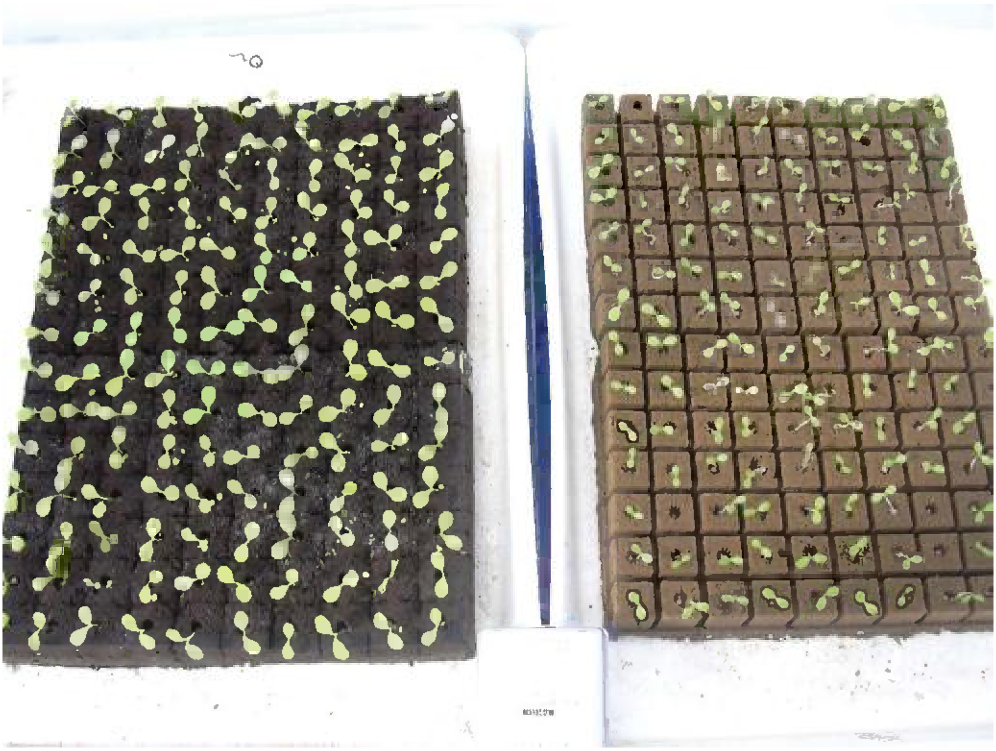

Fig. 6.7. Bioassays or growth comparison is an inexpensive way of assessing a hydroponic medium.

Fig. 6.8. Cucumber seedlings are a highly sensitive bioassay species.

6.10 Nutrient Delivery in Substrate Systems

6.10.1 Drip irrigation

Drip irrigation, also termed 'micro-irrigation', 'trickle irrigation' or 'low-volume irrigation', is an efficient method of supplying nutrient solution slowly and directly to the root zone.

Flexible drip systems incorporate the use of a wide range of emitters which operate at low pressure and allow adjustment of nutrient flow rates. Drip irrigation systems consist of either a pressurized water supply with nutrient injectors, or a central nutrient reservoir with a pump to provide low pressure to the system. Filtration is also commonly included to remove sediment and other material which may block components and emitters, and in recirculating drip systems a filter may also be included on the nutrient return system. Drip systems then feed nutrient solution through a main irrigation line or ring out to the cropping area which feeds smaller-diameter lateral pipes carrying the solution along the rows of plants. Small-diameter drip tubing (also termed 'microtubing' or 'spaghetti tubing') may then be installed into the length of lateral lines, these each have a dripper or emitter fixed to the end; this is then staked around the base of each plant to hold the dripper in position. These types of systems give maximum flexibility, with placement of the emitter allowing for differences in plant spacing to be easily accommodated.

Drippers or emitters control the flow of nutrient to the plant, come in a wide range of different options and are sized by the volume of nutrient solution they deliver (Fig. 6.9). Drippers are then further divided into pressure compensating and non-pressure compensating. Pressure-compensating drippers are more commonly used in large-scale commercial hydroponic systems as they are designed to discharge nutrient solution at a very uniform rate under a wide range of system pressures, so they deliver the same flow rate irrespective of pressure. These types of emitters are particularly useful in hydroponic systems as all drip emitters will start dispensing solution at the same time and prevent drainage of the solution after the irrigation has been switched off. Pressure-compensating emitters often incorporate a turbulent flow design which helps keep sediment and other particles in motion to help reduce clogging. One of the issues with pressure-compensating drippers is that they do not perform well on very low pressures such as with gravity-fed systems. Non-pressure-compensating drippers are the second type of emitter which also has applications for hydroponic systems. These emitters consist of two parts: a central body which is installed into the microtubing and a screw-on top which can be used to adjust the flow of nutrient. By winding the top further down on to the body of the emitter the flow of nutrient can be slowed and by winding this up, the flow is increased. This allows for emitters in the same system, under the same pressure, to deliver different rates of nutrient flow depending on what is required by individual plants.

The main issue encountered with drip irrigation is clogging of the emitters with salts, sediments or other material resulting

Fig. 6.9. Drip irrigation is an efficient method of nutrient delivery in substrate systems.

in uneven flow rates. High-quality water and prefiltration assists with some water supplies, particularly where sediment, sand or other organic matter might be present. Iron minerals in some water supplies are also a major contributor to blockages of irrigation equipment and are best removed before using to make up nutrient solutions. Drippers which are fully exposed to direct light can result in salt deposits accumulating and algae can also grow around emitter outlets causing blockages. In recirculating hydroponic systems where the solution drainage is redirected back to the nutrient tank for further irrigation, particles of growing substrate, pieces of root system and other organic material can all result in emitter blockages unless suitably sized filters are installed on the system. To avoid these issues resulting in plant growth problems, drippers should be regularly monitored while the irrigation is on to ensure all are working correctly. Blockages can often be cleared by tapping the dripper to loosen any sediment; accumulated salts can be removed by submerging the dripper in hot water for a few minutes to dissolve any deposits. Between crops, or at least once per year, drip irrigation systems can be cleaned with acid which removes not only salt deposits, but algae and bacteria as well.

6.10.2 Drip-irrigated systems – design and layout

Irrigation layout and design affect the distribution of nutrient solution to individual plants around the drip-irrigated system. One of the main issues in drip irrigation is differences in the volume of nutrient solution received by plants in different parts of the system. Some plants may end up underwatered while others are constantly too wet, and these issues become difficult to remedy once the irrigation system is in place. To achieve uniform and constant nutrient flow rates to all emitters in the system, a 'ring' or 'loop' layout can be installed. This consists of emitters placed into lateral irrigation pipes connected at both ends to a ring main system, which evens out the flow and pressure round an irrigation system. Each ring main is supplied by a main irrigation pipe directly from a pump or pressurized water supply (Fig. 6.10). This largely prevents the issue of plants furthest away from the pump receiving the lowest volume of nutrient solution at each irrigation.

Selecting irrigation pipe diameter and pump size is another aspect of hydroponic drip-irrigated system design which is often overlooked. A large-capacity pump will not compensate for irrigation pipes that are too small to carry the nutrient solution flow rate required. If the flow of nutrient appears too low from some emitters, it is often more effective to increase the diameter of the delivery pipes rather than invest in a more powerful pump. The type of irrigation emitters, the number of emitters and their flow rate determine the size of irrigation lateral pipe required in terms of flow rate and pressure needed.

Fig. 6.10. An irrigation design which evens out flow and pressure ensures equal volumes of nutrient solution are delivered to each plant.

6.10.3 Ebb and flow (flood and drain) nutrient delivery systems

In ebb and flow (flood and drain) systems, nutrient solution is pumped up into the base of the growing area where the plants are positioned in pots, beds, containers or troughs of soilless substrate. The nutrient solution ebbs for a given period of time, rewetting the growing medium from the base, before it is drained back to a reservoir tank below floor level. The ebb and flow process takes place several times per day depending on water and nutrient demands of the crop. Ebb and flow systems are more commonly used for potted plants and young nursery crops such as vegetable transplants being raised in rockwool propagation cubes. While allowing uniform delivery of nutrient to each plant, ebb and flow systems can have the disadvantage of pushing excess nutrient salts to the surface of the growing substrate particularly under conditions of high evaporative water loss.

6.10.4 Capillary watering systems

Capillary watering systems provide a continual shallow volume of nutrient solution around the base of the growing container, pot or slab of substrate, allowing the natural capillary action of the medium to draw up water into the root system area. The success of capillary systems depends very much on the natural structure of the growing medium and the ability of moisture to be 'wicked' up at sufficient rates to supply the plant. Capillary systems can cause problems with uneven moisture levels around the plant roots and salt build-up in the upper layers of the substrate.

6.10.5 Gravity-fed irrigation

Gravity-fed irrigation systems are another form of nutrient dispersal which rely on irrigation water flowing downwards to cropping areas under gravity rather than being pumped or manually moved. Rainwater collected from rooftops and stored in irrigation tanks may be used in gravity-fed systems in areas where no other source of mechanical water movement is available. Gravity-fed systems may also use pumps to fill reservoirs or tanks at a higher level, which then use gravity to irrigate crops as required on a low-pressure system of dispersal.

6.10.6 Nutrient dosing and injectors

There are two main methods of dosing nutrients into drip-irrigated substrate systems, these are 'batch feeding' and direct fertilizer injection. Batch feeding involves a mixing tank where the nutrient concentrates are dosed into water, EC and pH adjusted, and the working-strength nutrient solution is then pumped out into the irrigation system for application to the crop (Fig. 6.11). With direct injection, separate A and B stock solutions are injected directly into the water supply line, this system does not require a mixing tank (Fig. 6.12). The injection of the nutrient stock solution occurs via a pressure drop in the main supply line which draws the fertilizer concentrates into the flowing solution. The EC of the nutrient solution is controlled by the dilution rate which may vary from 1:50 to 1:200, with a 1:100 dilution rate being commonly used. Separate tanks of acid for pH control and other nutrient stock solutions such as calcium or potassium supplements may also be added to the injector system where required (Fig. 6.13).

6.11 Irrigation and Moisture Control in Substrates

Irrigation methods and frequency determine moisture and oxygen levels in the root zone, meaning that nutrient application rates and timing are often different for the same crop growing in substrates with different physical properties. This means that irrigation programmes need to be worked through by each grower based on their particular crop, system, substrate, climate and regular observations of moisture levels, rather than just following some predetermined irrigation settings. Between irrigations of nutrient solution, the soilless substrate must retain sufficient moisture for the roots to extract to maintain maximum growth rates, while excessive irrigation frequency and volumes must be avoided as these exclude essential air and oxygenation

Fig. 6.11. Batch feed nutrient tanks.

Fig. 6.12. Nutrient tanks and Dosatron injectors.

Fig. 6.13. Computerized nutrient injector system.

from the root zone and can lead to infection by root rot pathogens. Irrigation determination and scheduling in hydroponic substrates are more critical than in the field as the root-zone volume is severely limited and requires more frequent application of water. Irrigation determination in hydroponic systems may be based on grower observation of the moisture status of the substrate, measurement of the volume of leachate after each irrigation (nutrient solution draining from the base of the growing slabs or containers), with use of substrate moisture sensors, by weighing the substrate to determine when sufficient moisture loss has occurred to trigger subsequent irrigations or through measurement of incoming solar radiation and computer models which estimate crop transpiration based on this value.

6.11.1 Substrate moisture, growth balance and deficit irrigation

Plant growth for fruiting crops such as tomato, capsicum and cucumber is divided into two parts: 'vegetative' (leaves, stems) and 'generative' (buds, flowers, fruits). Many plants such as indeterminate tomatoes, capsicum and cucumbers have both vegetative and generative growth occurring at the same time, so the balance between these two is referred as 'growth balance'. A highly vegetative crop will have large, thin, soft leaves, minimal flowering, poor fruit set and may drop small fruitlets, or set fruit may end up undersized. Generative plants may look vigorous and healthy; however, much of the plant's energy goes into flower/fruit production with little vegetative growth to produce more shoots and foliage to support the developing fruit with a photoassimilate supply and continue crop development. One way of manipulating plant growth balance is with the use of moisture control, both via substrate selection and use of careful irrigation programming which controls the supply of nutrient solution. High levels of moisture in the root zone tend to have a vegetative effect on many crops so 'controlled deficit irrigation' is used on a wide range of crops, both hydroponic and those grown in soil, to help direct growth in a more productive or generative direction with controlled levels of stress. Deficit irrigation may include reducing the volume applied at each irrigation, allowing more time between irrigations, and allowing the medium to dry slightly overnight by restricting early-morning and evening irrigations. Along with restricting moisture levels via a reduction in nutrient application, growers can select substrates which are coarser, more free-draining with a higher air-filled porosity and lower water-holding capacity to help with controlling overly vegetative growth. This is a useful tool for certain crops or cultivars which are naturally vegetative and benefit from some growth control or those growing under environmental conditions which may favour vegetative over generative growth. For plants that may tend to be overly generative and set large numbers of fruit at the expense of foliage growth, use of a substrate that has a naturally higher water-holding capacity such as fine-grade coconut fibre is preferable for favouring vegetative growth.

Along with influencing growth balance, mild deficit irrigation can be used to help improve fruit quality, shelf-life and even volatile concentrations in some plants. Tomato fruit flavour is one such aspect that can be improved with restricting moisture in the root zone which has the effect of increasing the dry matter percentage of the fruit and reducing water content, thus giving more concentrated flavour and often improved keeping qualities as well. Mild deficit irrigation can also be used to 'harden off' transplants before they are planted out into a different environment to reduce stress and improve plant survival rates.

6.12 Microbial Populations in Substrates

Microflora develop rapidly after planting a crop in a hydroponic system and consume plant exudates, compounds in the nutrient solution and dead plant materials, with the composition of microbe species affected by environmental factors and the source of nutrients. Some of the microbe species may be pathogenic; however, these are generally outnumbered and outcompeted by populations of non-pathogenic organisms, unless conditions change which favour infection by disease-causing fungi or bacteria. In most hydroponic systems the species of beneficial resident microflora most commonly found are *Bacillus* spp., *Gliocladium* spp., *Trichoderma* spp. and *Pseudomonas* spp.

Studies into the effects of various species of beneficial bacteria have found a number of positive results on yield and quality of hydroponically grown fruits and vegetables (Sambo *et al*., 2019). Some studies have shown that growth-promoting rhizobacteria may provide a direct boost to plant growth by providing crops with fixed nitrogen, phytohormones, iron that has been sequestered by bacterial siderophores and soluble phosphate (Sambo *et al*., 2019). Other species may protect the plant from potentially highly damaging pathogens which would otherwise limit plant growth, quality and yields. *Bacillus amyloliquefaciens* has been shown to increase vitamin C content and water-use efficiency in tomatoes, while *Bacillus licheniformis* increased fruit diameter and weight of tomatoes and peppers and promoted higher yields (Garcia *et al*., 2004). A strain of *Pseudomonas* sp. (LSW25R) has been found to promote growth of hydroponic tomato crops and increase the uptake of calcium which in turn reduced blossom end rot of tomato fruit (Lee *et al*., 2010). In hydroponic strawberries, inoculation with plant-growth-promoting rhizobacteria (*Azospirillum brasilense*) resulted in a higher sweetness index and a greater concentration of flavonoids and flavonols in the fruit as well as increasing the concentration of micronutrients (iron) (Pii *et al*., 2017). In hydroponic tomato studies evaluating a number of different plant-growth-promoting rhizobacteria, it was found that a *Bacillus* sp. (strain 66/3) was effective in increasing tomato yield significantly – this increase in marketable yield was 37 and 18% compared with untreated control plants in autumn and spring crops, respectively (Kidoglu *et al*., 2009). Lee and Lee (2015) even state that the application of potential beneficial microorganisms could lead to an improvement in the nutraceutical properties of hydroponic crops. These effects of increased yield and improved compositional quality in hydroponic crops from microbial interactions are likely to have occurred via complex processes, some of which are still not fully understood. Some species of beneficial rhizospheric bacteria in particular are known to improve plant performance under stressful environments and thus improve yields either directly or indirectly.

The inoculation of hydroponic systems with specific plant-growth-promoting rhizobacteria using commercially available products is possible, however the species available are still somewhat limited. While naturally occurring beneficial microbes do typically self-inoculate into new hydroponic systems, this can be a slow process and species diversity may be limited. Well-established hydroponic systems tend to have a greater diversity of beneficial microbial species than newer systems. However, microbes can be introduced via a number of different methods. The plant-growth-promoting rhizobacteria commonly used in commercial inoculant products often include species of *Bacillus* and *Trichoderma* as these have been shown to have positive effects on a number of hydroponic crops. Such inoculant products are often designed to be added directly to the nutrient solution; however, some are in more widespread use as substrate inoculant incorporated into the growing medium before planting. If using inoculants, such as *Trichoderma*, it is simpler to establish beneficial microbes into a new substrate as little competition exists from microorganisms already present. However, if the substrate is relatively inert such as rockwool or other synthetic growing media, this is initially a difficult environment for microbial life to take hold. Once plants have established, carbon exudates from the roots and sloughed-off root material begin to provide organic substances for microbes to grow and population numbers then begin to build over time. Some microbial inoculants may also be applied as seed coatings and commercially obtained seed lots may be treated with inoculants aimed to improve germination and seedling establishment rates through a range of different processes including rot pathogen prevention and root growth promotion.

Alongside commercial mixes of inoculants, microbes may be introduced in other ways. The use of a 'slow sand filter' system for disease suppression and inoculation with beneficial microbes is one of the most effective ways of obtaining a diverse population of beneficial microflora. The sand filter system acts as a continuous source of inoculation with beneficial species and is particularly useful for solution culture systems where microbial life can be more limited than in substrate-based hydroponic systems. Other methods whereby beneficial microbial species may be introduced to a hydroponic system include the incorporation of composts and vermicasts, which naturally contain high levels of microbes. Where plant-growth-promoting rhizobacteria are being inoculated or actively encouraged, methods of nutrient sterilization should be avoided as these will not only destroy potential pathogens, but beneficial species as well.

Application of residual chemical agents such as chlorine to the nutrient solution should also be avoided as these can also negatively affect beneficial microbial life in the hydroponic substrate.

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