Chapter 7

Plant Culture in Solid Media

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Introduction

Various natural or manufactured root-zone media supply water, oxygen and mineral nutrients and support for plants in growth chambers. Although liquid culture (discussed in Chapter 8) provides potentially better control of water and mineral supply, solid media are most often used because they demand significantly less maintenance or better fulfill experimental criteria. The nature of a medium's physical phase (matrix), especially those factors affecting soil water retention and aeration, ultimately determines its suitability for plants, although the container characteristics and irrigation method can also significantly influence growth. This chapter discusses selection, preparation, and use of solid media in growth chambers, including the choice of containers, and irrigation and fertilization methods.

Media

Fundamentals

A *solid medium* is a body of solid particles in which plant roots grow and from which they absorb water, oxygen and minerals. Solid medium in this context is functionally and edaphically analogous to *soil*. This encompasses a wide range of natural (soil, sand, gravel, peat, pumice, shale, etc.), modified natural (amended), or manufactured (vermiculite, calcined clay, Styrofoam, rubber, paper, etc.) media (Noland et al., 1992).

When a solid medium is used in growth chambers, it is usually held in small containers or pots. The container not only defines the root zone, it isolates the medium from the *earth* leaving the bottom (through drainage) as well as the top (growing surface) open to the atmosphere. The vertical distance between the surface and drainage is the *drainage depth*. Most container media have relatively shallow drainage. A perched water table always occurs at the drainage level after irrigation, i.e., the medium is saturated at the bottom, and water content decreases toward the top in a pattern determined by pore size distribution and total porosity (Spomer, 1974a; 1975b; 1980a; 1980b; 1990) (Fig.1). Most natural soils used in pots or other containers remain saturated throughout and, as a result, are poorly aerated and generally unsuitable for plant growth.

Container media have finite, small volumes, encompassing limited water and mineral reservoirs and constricted root growth spaces. Therefore, plant growth potential in a container is limited compared with that in ground beds (Spomer, 1975; 1981; Terman, 1974).

The combined effect of small size and shallow depth means container media retain too little water to maintain plant growth for more than a short time (small storage volume), yet they have excess water concentration (shallow depth) and poor aeration. This dilemma may be resolved through careful consideration and selection of container volume and depth, irrigation regime, and media composition. More frequent irrigation and fertilization compensates for the small volume; but it also aggravates the problem of poor aeration. Chamber size and experimental design or cultural requirements constrain the size and height of container. In most cases, physical amendment of natural soils or manufacture of special media (artificial soils, soilless media, growth media, manufactured soils) is required to ensure an adequate root-zone environment in growth chamber solid media cultures.

The most important factor determining medium physical suitability for plant growth is the nature of its pores; both total pore volume (porosity) and size distribution are important. Soil physical amendment or manufacture of artificial soils combines various natural and manufactured components in such a way as to guarantee adequate aeration through large aeration pores despite the perched water table (Spomer, 1974b; 1979; 1980a; 1980b; 1990). Most natural soils and fine-textured manufactured media contain predominantly small, *water retention* pores and will remain saturated after irrigation and drainage (Fig. 1). On the other hand, although also saturated at the bottom, a coarse or very coarse textured medium (2 mm dia., the size of horticultural grade perlite) contains predominantly large pores and will be nearly dry a short distance above the bottom shortly after irrigation even though no water evapotranspires from the container. A plant growing in fine-textured media likely will be adversely affected by poor aeration, and one in coarse textured media will be affected by a lack of water, especially if it is a young plant. A compromise between these two extremes is a medium that contains the maximum amount of water retention pores consistent with adequate aeration pores and is achieved in practice through soil amendment or component mixing. A mixed medium worse than any of the individual components, however, may result if they are mixed in the wrong

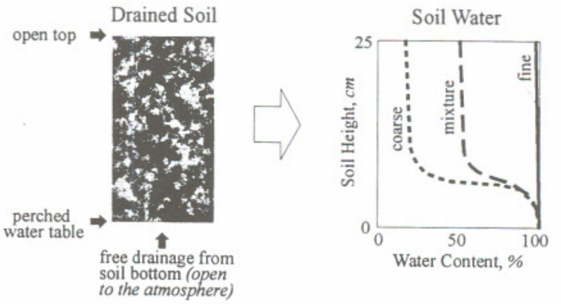

Figure 1. Effect of perched water table at bottom of drained container soil and media texture on media water distribution. All three media are saturated at the bottom, but the coarse media (coarse-textured sand) is dry at the top, whereas the fine media (silty clay loam) remains saturated throughout (poorly aerated). The mixture of coarse and fine achieves a compromise between the two soil types, resulting in a medium that is well aerated yet still wet at the top.

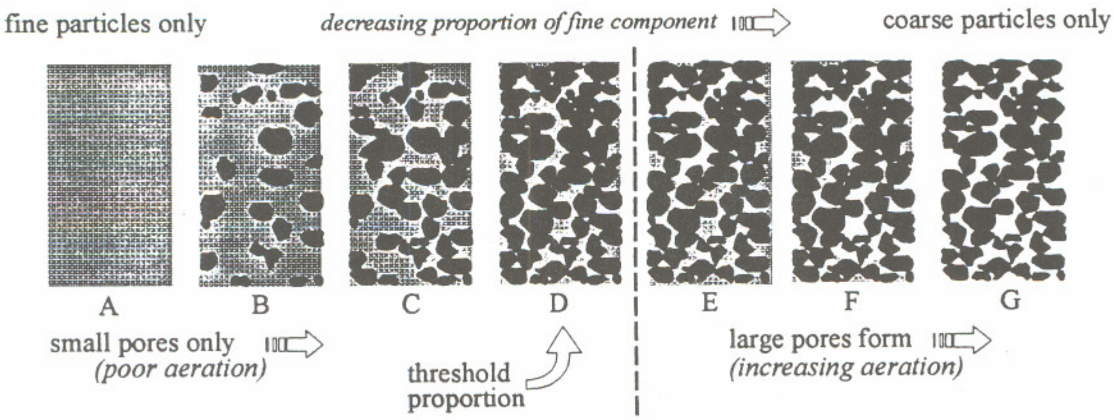

Figure 2. The effect of mixing coarse and fine media components on porosity, water retention, and aeration in drained containers.

proportions (Fig. 2). Insufficient coarse component (B, C, D) merely excludes soil volume without adding aeration pores, so total porosity actually decreases with no improvement in aeration. At the *threshold proportion* (D), the mixing volume is exactly full of coarse component, and aeration pores between the component particles are exactly full of soil. The threshold proportion, therefore, is determined by the coarse component's inter-particle porosity. Consequently, total porosity is at a minimum, and this is the worst possible medium in which to grow plants. As the coarse component *proportion* is increased above the threshold (E, F, G), aeration pores form, and aeration and total porosity both increase.

The same principle holds true in soilless container media in which one component's particle size is several times larger than the other's—for example, peat or ground bark or perlite *and* soil or fine sand or fine vermiculite mixtures. The coarse material must be sufficiently coarse to create aeration pores; otherwise, its pores will not drain regardless of the proportion used. Only coarse and very coarse textured (USDA textural grades) components produce aeration porosity in containers less than about 25 cm deep and only very coarse in containers less than 12 cm deep.

Materials

Soil. Natural soil or mixes containing natural soil are not generally recommended for growth chamber use unless *natural* soil is one of the experimental treatments or other requirements in the study. If it is used, it should be amended or used in sufficiently deep containers to ensure adequate aeration. Natural soil has many disadvantages for growth chamber use. It is neither physically nor chemically uniform, and results may not be reproducible from experiment to experiment. Natural soils also are often infested with seeds and pathogens. They are heavier than manufactured media, which may add stability but also may make them harder to use.

Peat is commonly used because it is light and has high water-holding capacity, although much of the water is absorbed internally by the particles and may not be available for plant use (Spomer, 1975a). The exchange capacity seems high when expressed in the traditional mass basis, but not when expressed on a volume basis. The most commonly used peat originates from sphagnum and is strongly acidic. The physical properties of peat can vary significantly from lot to lot or bag to bag. When different lots of peat are required for an experiment, they should be blended into a single batch to ensure uniform media among containers.

Vermiculite. This material is a mica, which has been expanded by heating to a very high temperature (therefore it is sterile after processing). Micas are potassium aluminum silicates with a variety of other cations. Even though it has high exchange capacity and good water-holding capacity, vermiculite alone will not sustain good plant growth. This may be due to an excess of unusual cations on the exchange sites. High amounts of lithium and barium have been found by the authors (Tibbitts) in seedlings growing in vermiculite. It is also strongly basic and, therefore, commonly mixed with peat to provide a reasonable pH. The particles crumble and otherwise break down physically with handling or use (expansion and contraction experienced during repeated wetting and drying). Its particle size distribution, therefore, tends to be inconsistent from lot to lot. When multiple lots are required for an experiment, they should be blended into a single batch as was suggested for peat. Very fine or mixtures of coarse- and fine-textured vermiculite should be avoided because they tend to be poorly aerated. Vermiculite sold for insulation is unsuitable for plant culture because it often contains materials highly toxic to plants.

Perlite is a very dense aluminum silicate formed when volcanic magma cools rapidly under pressure. It is processed for horticultural use by crushing and heating rapidly to 1000° C and thereby expands to many times its original volume to form white, lightweight particles containing a relatively narrow size distribution of sealed internal gas spaces (Noland et al., 1992). It is further crushed and graded and marketed as a chemically inert (pH 7.0-8.5), physically stable, 1 to 3 mm diameter particulate. Perlite has good exchange capacity but has little or no water holding capacity. It is also generally unsuitable as a plant growth medium by itself (Noland et al., 1992; Warren-Wilson and Tunney, 1965). It is commonly used in mixes with soil or peat or as a mulch on the soil surface to reduce algae accumulations. A similar mineral, pumice, is commonly used as a substitute for perlite without any processing other than crushing and sizing (Noland et al., 1992).

Arcillite is a baked (calcined) montmorillinite clay produced in sharp particles of 1 to 4 mm size and is sold as Turface. It has a high exchange capacity but, unlike vermiculite, does not expand when wetted. This material ranges from being strongly acidic to strongly basic, depending on the production lot. It can be used effectively for plant culture only if its pH is moderated by soaking the material in nutrient solution for 3 days, with the solution replaced daily. Arcillite is particularly useful for experiments in which plant roots must be recovered because roots do not penetrate the particles. A similar product, Hydrocorn, is commonly used as a substrate in hydroponic or ebb and flow systems. The most common form of Hydrocorn is large (10-15 mm diameter) rounded particles. Whichever product is used, it should be washed and sieved to remove fine particles before purchase or use.

Sand. Silica sand provides an inert, incompressible medium with little exchange capacity and low water-holding capacity. It is the heaviest material used for growth media. Other kinds of sand often influence media pH but can still be used when pH corrections are feasible. Sand is not generally recommended for growth chamber research except as a mixture component or when automatic irrigation with nutrient solution is used at very frequent intervals. Best results are obtained with sieved and washed sands.

Gravel is most commonly utilized with rapidly cycling nutrient watering systems. Its properties and use are analogous to sand.

Mixes

Mixtures of peat, vermiculite, and sometimes perlite or gravel, are usually more desirable for container culture than the individual materials alone. Both Cornell University and the University of California have published bulletins on preparation of mixes termed Cornell peat-lite and U.C. mixes, respectively (Boodley and Sheldrake, 1963; Baker, 1957). These and other mixes are commercially available. Most incorporate additives to balance pH and provide fertilizer to sustain plant growth. The ingredients should be blended in a rotary mixer, such as a small concrete mixer, for 10 to 15 minutes to ensure uniform distribution of components. Hand mixing should be accomplished by spreading the components on a large tarpaulin and turning the combination repeatedly. To ensure a homogenous mixture, the components should be moistened as they are blended. This also facilitates subsequent wetting in plant containers. Peat-lite mixtures should never be allowed to dry because they are extremely difficult to rewet.

The composition and preparation of a mix proposed by researchers at Cornell University are listed in Table 1 (Boodley and Sheldrake, 1963). If media are not homogenous, significant confounding of experimental treatments and results can occur. Thorough blending of the fertilizers with the media is essential, but this is difficult to accomplish because of the bulky character of peat and vermiculite. The entire quantity of mix for an experiment should be prepared in a single lot to eliminate inconsistency due to nonuniformity among different bales or bags of peat, vermiculite, or other components. The same procedure should be followed even when using commercially prepared mixes. All bags of mix should be blended into a single large lot before filling the containers. In addition to the physical inconsistency that commonly occurs among bags, the fertilizer is often incompletely blended into the mix, which often results in inconsistent nutrient supplies to plants among the different containers. To minimize this inconsistency, avoid purchasing mixes incorporating extra quantities of nutrient (i.e., Pro-mix). Thorough leaching of the mix before planting also reduces potential fertilizer toxicity.

As a general rule, manufactured media do not require sterilization if handled and stored cor-

Table 1. The composition and preparation of a container soil mix proposed by Boodley and Sheldrake (1963).

To make 1 yd³ yard (0.75 m³) of peat-lite mix	**Amount**
Sphagnum peat (fluffed*)	16.8 ft³ (0.48 m³)
No. 2 Horticultural grade vermiculite	16.8 ft³ (0.48 m³)
Water	12.5 gal (47.0 liters)
Dolomite lime	12.0 lb (5.6 kg)
4-10-10 NPK Fertilizer	7.0 lb (3.2 kg)
138 Fe iron chelate	1.2 oz (35.0 g)
or	
330 Fe iron chelate	0.75 oz (21.0 g)
Micronutrient concentrate	8.0 fl. oz (236.0 ml)
To make 1 liter of micronutrient concentrate	
Copper sulfate ($CuSO_4{\cdot}5H_2O$)	0.5 oz (14.0 g)
Zinc sulfate ($ZnSO_4{\cdot}7H_2O$)	0.2 oz (6.0 g)
Manganese sulfate ($MnSO_4{\cdot}H_2O$)	0.15 oz (4.0 g)
Boric acid (H_3BO_3)	0.5 oz (14.0 g)
Water: enough to make one liter of solution	

*1 ft³ baled peat equals approximately 1.5 ft³ *fluffed* peat. Mixed volume is less than the sum of the component volumes if components have dissimilar particle sizes. Peat resists wetting; add water slowly during mixing to ensure thorough initial wetting.

Various modifications of this mix used at other growth chamber facilities include (on a volume basis)—

North Carolina State University Phytotron, Raleigh, NC—50% gravel plus 50% commercial peat-vermiculite (1:1).

Duke Phytotron, Durham, NC—50% gravel (0.3 to 0.6 cm dia) plus 50% vermiculite.

Climate Lab in New Zealand—70% gravel (0.2 to 0.4 cm dia) plus 30% of a 1:1 blend of peat: and vermiculite.

University of Wisconsin Biotron, Madison, WI—1:1 commercial peat-vermiculite blend.

rectly. However, any mix containing natural soil should be sterilized. This is usually accomplished by pasteurizing the moistened media by heating it to about 82°C (180°F) with steam or an air-steam mixture for 30 minutes (Baker, 1957). Steam sterilization (pasteurization) of some soils can cause release of sufficient manganese to be toxic to plants. Again, leaching the medium before planting will minimize this problem.

Containers

Composition

Air circulation in growth chambers promotes evaporative water loss and concomitant soil drying and cooling. Containers for solid media, therefore, should be made from nonporous material to prevent direct water loss through the sides. Rigid polypropylene and polyethylene plastic pots are the most commonly used growth chamber containers. They should be sufficiently strong that the sides do not distort and disturb the medium and roots when the containers are moved.

Size

Container size is dictated by the amount of plant growth expected. The larger the container, the greater the growth potential (Spomer, 1981). The largest container consistent with experimental requirements should probably be used. One-liter containers (5-inch standard pots) are recommended for small plants, with larger containers used as needed. Potato growth was reduced in 20-liter (5 gal) containers compared with that in 40-liter containers—even before plants extended to the container edges (Wheeler and Tibbitts, 1987). The limited growing surface and volume in chambers usually dictates container size. Taller containers can sometimes be used in a given growing area to increase volume, but this also changes media water relations (Spomer, 1990).

Shape

Container shape is less critical than volume and overall height for most plants. Aeration and water content vary significantly with height in most container media (Spomer, 1975b). A medium in a tall container retains less water and has greater aeration than the same medium in a shorter container of identical volume.

Color

Although usually not very important, container color sometimes influences root growth and function. Darker colors absorb more radiation and may cause higher media temperatures than lighter colors, especially small pots containing lightweight media and those on the edges of the growing area. Use of white containers minimizes this effect; they should be sufficiently opaque, however, to limit light penetration of the root-growing area. In any case, all containers within an experiment should be the same color.

Drainage

Containers must have holes at the bottom to permit excess water to drain. A layer of inert, open-fiber matting over the drainage holes is recommended to restrict loss of fine-textured components (fine vermiculite, fine peat, natural soil, etc.). It should be very thin to avoid raising the perched water table. Glass wool often is used but may cause skin irritation during insertion. Greenhouse bench capillary watering mat material is a nonirritating alternative but is significantly thicker.

Watering

Because plant water status directly or indirectly affects every aspect of plant growth, ensuring optimum water availability is necessary in growth chamber experiments. The effects of watering practices often overwhelm the effects of experimental treatments. Such effects are more critical in controlled chambers than in the field because plants are usually growing in containers of limited size in which water status changes more rapidly and reaches greater extremes than in the field. Regulating medium water supply is fraught with difficulties because of the dynamic and complex nature of media-plant-atmosphere water relations. Therefore, the nature of the watering system is critically important in growth chamber studies to prevent inadvertent water stress. Several types of water delivery systems have been developed and subsequently refined for solid media culture. This section discusses the most commonly used watering systems.

Manual

Although inherently unreliable in many situations, manual watering of growth chamber plants is probably the most prevalent system. Only the most rudimentary equipment (a watering can or hose) is required, so manual watering systems are inexpensive. Another advantage is the ability to provide customized watering for different sized pots, plants, or drying conditions within a single chamber. Containers can also be moved or removed without changing watering tubes as would be required for most automatic systems. The main disadvantage is the potential for inconsistent frequency and amount of application. As automatic watering systems improve in efficiency, uniformity, and flexibility, the justification for manual watering in growth chambers decreases.

Automatic

Drip Irrigation. Automatic drip irrigation is the system of choice in most growth chamber applications. Water is supplied to individual containers through thin polyethylene (PE) microtubes from a larger pipe manifold. Standard or customized supplies are readily available from large garden and specialty watering system suppliers to satisfy most system requirements.

A linear relationship exists among time, pressure, drip tube length, and the volume of solution delivered: $Q = 16.2 + 116\ P \cdot T \cdot L^{-1}$, where Q = volume, ml; P = pressure, cm H_2O (cm $H_2O \cong 6.72 \times 10^{-5}$ lb in^{-2}) (any difference between manifold and tube outflow elevations must be accounted for); T = time, min; and L = tube length, cm. This equation applies for flow times greater than 0.5 minute, pressures ranging from 15 to 45 cm H_2O, and drip tube lengths of 30 to 90 cm. If all microtubes are the same length and their outflow levels are identical, supply rate is determined by manifold pressure and microtube diameter. The greater the pressure and larger the microtube diameter, the greater the supply rate. Larger diameters or higher pressures are used for larger containers to ensure uniform and thorough application. Sometimes multiple tubes are used for the same purpose (for containers greater than about 15 cm diameter).

The manifold water supply should be sufficient to maintain 15 to 30 cm H_2O pressure during irrigation. Uniform manifold pressure is essential for uniform application (Klueter et al., 1978). Simple U-tube manometer pressure gauges can be made from two vertical clear plastic or glass tubes (about 1 meter long) connected at the bottom with a flexible tube to form the U. One tube is open at the top and the other is connected to the manifold via a short piece of drip tubing. A gauge is inserted into each manifold at the center and ends, the water supply turned on, and the input supply valve adjusted until pressure reaches 30 cm (water level in open vertical tube 30 cm above the drip tube outflow level in the manifold). When all tubes are dripping at their steady rate, the pressure should be identical at any point on the manifold. Any deviation of more than 2 cm from the average compels manifold redesign. When uniform manifold pressure is achieved, all gauges except one can be removed. The remaining gauge is used for subsequent pressure measurements and adjustments. Flow rates from a number of different tubes should be measured to confirm uniform water supply (again, tubes must have identical lengths and outflow elevations). Plugs are available to fill holes left by removed microtubes.

Individual microtubes can be inserted into prepunched holes in a header of rigid polyvinyl chloride (PVC) or into bored and grommeted holes in flexible black PE pipe. PVC pipe often is preferred because it lies straighter. As long as manifold pressure remains uniform and constant, any number of tubes can be added or removed or opened or closed without affecting flow rate from the remaining tubes. In addition to being at the same elevation, the level of the outflow tubes should be slightly above that of the manifold to prevent drainage from the manifold when the water supply is off. Air subsequently trapped in the manifold from drainage or dissolution may block outflow tubes. Routine purging of the manifold is recommended to prevent flow problems. Microtubes should be held above the medium with a wire cage holder or inserted through a notch in a pot label to prevent the tube from being ejected from the pot or the medium from being eroded when water is turned on. Location above the media also prevents the flow of salts and light media components back into the tube when the water is turned off. The use of lead weights at the ends of the tubes is discouraged because they are a potential source of soil lead contamination.

Good filters on water and nutrient supply lines are necessary to reduce clogging of the tubes and nozzles. Frequent inspection of the system is still necessary to make certain that tubes are inserted in each pot and remain open and free of debris. On-Off tube, made from noncorrosive metal, can be manually closed when a pot is removed and opened when a pot is added. Extra tubes can also effectively be closed by inserting round toothpicks into their ends.

Water and nutrients should be supplied uniformly to the roots without salt buildup. The flow rate should be adequate to easily wet the entire medium cross section within a reasonable time without disturbing the surface. Sufficient flow time should also be allowed to ensure thorough leaching of accumulated salts. This is achieved through a combination of outflow device and flow rate, duration, and frequency.

Solution can be provided through simple single or multiple tubes, spray sticks, or ring drippers. These devices provide a variety of wetting patterns and flow rates. Tubing provides a point source wetting pattern, which might be adequate for fine but not coarse media. Spray sticks or ring drippers disperse the flow across a broad surface and are, therefore, better for coarse media. Irrigation frequency can be determined by a time clock schedule or from direct measurements of the media water content. Balances under selected containers can be used as switches to turn on the irrigation system whenever the soil reaches a selected level of dryness. The balances must be adjusted periodically to account for the weight of plant growth. Soil sensors, such as gypsum blocks, are also sometimes feasible for irrigation control in natural soils. They are not useful in manufactured soils because of the vast difference in sensor block and soil water retention characteristics. In each case, after the system is triggered on, it runs for a predetermined period before shutting off to ensure thorough wetting of the medium. In some cases, the sensor also turns the system off after the medium reaches a selected degree of wetness, although this may not provide sufficient leaching. The disadvantage with weighing or other triggering systems is that nonuniform air movement and radiant energy distribution usually cause different rates of drying of containers in different chamber locations. Differences in plant size also cause different rates of water use. Unless each plant is on its own balance or has its own sensor, water supply is not uniform throughout.

Media texture, porosity, and surface area also are important considerations in choosing an application method. Berry et al. (1981) irrigated lettuce plants in a 1:1 peat-vermiculite mix with an automatic watering system every 4 hr for 21 days with 50 ml of nutrient solution and from day 22 to 28 with 100 ml per pot. At least 25 ml of drainage was provided with this volume, thus assuring a relatively constant water content in the medium at close to field capacity as well as uniform nutrient concentration.

In conclusion, the main disadvantages of drip irrigation systems are high initial setup expense and reduced flexibility. Advantages include automatic control, rapid and simultaneous water application to all containers within a treatment, high uniformity, minimal soil disturbance, dry foliage, high consistency, and greater container isolation, which reduces disease spread and increases treatment discrimination. Maintaining these advantages, however, usually mandates a high level of attention.

Subirrigation culture is used widely in greenhouse plant nutrition studies but less commonly in growth chambers. This technique differs from other solid medium systems in that the irrigation water is applied to the medium from the bottom through wet porous mats or by raising a water table around the containers. Watertight as well as conventional benches, trays, and pots can be used for subirrigation systems. Substrate used in these systems is usually very coarse and relatively inert, such as sand, gravel, coarse vermiculite, and peat-vermiculite mixtures. The ideal substrate provides good root support, rapid and uniform water distribution, and adequate water retention between irrigations. Occasionally less coarse media are used such as a mixture of fine and coarse textured quartz sand (Maynard et al., 1970), which provides a good balance between water holding capacity and aeration.

Major problems that may occur with use of these systems include nutrient imbalance, disease infestation, and disruption of environmental control. As nutrient analysis methodology has improved, mineral nutrition has become less problematic. The spread of disease is facilitated by a common source of water supply and is especially significant in recirculating systems. Preventive sanitary procedures are mandatory to reduce occurrence of this problem. The large surface area of trays when a subirrigation system is used can compromise growth chamber environmental control by seriously disrupting the airflow (especially in vertical air flow chambers).

Pumped systems supply nutrient solution by pumping it up through the substrate 1 to 4 times daily with gravel, or less frequently, with finer media, depending on the crop and its growth stage as well as on cultural and ambient environmental conditions. When sand culture is used, entry and exit tubes may extend into a glass wool trap that prevents sand from being carried out with the drainage (Maynard, 1970). A typical, fully automatic subirrigation distribution system (Stanwood et al., 1974) consists of a submersible pump in a lower storage reservoir, lifting solution into an upper reservoir through opaque plastic tubing. Pumping is controlled by a remote mechanical or solid state timer or computer. Flow into the upper reservoir should be greater than the upper reservoir drain outflow, but less than drain plus standpipe outflow. Solution level must be maintained long enough to thoroughly subirrigate the container medium. When pumping stops, excess solution drains to the lower reservoir. Other subirrigation systems are detailed in a book on hydroponic systems by Resh (1989).

Solution often is stored in a polyethylene, glass, or stainless steel reservoir between flushes and is renewed as required to maintain pH, conductivity, and nutrient levels. Two tanks, one above the other, often are used to independently supply nutrient solution and water into the distribution system. Commercially available proportioning injectors can be used. As water flows through the injector, concentrated nutrient solution is automatically added in standard ratios from 1:100 to 1:1000. The accuracy of the nutrient solution proportioner should be checked frequently.

The *ebb and flow pump system* is often used for individual plant containers, usually with the containers placed directly on plastic trays. The tray should be ribbed or the containers should have lips or feet on their bottoms to raise them at least 0.5 cm above the tray surface. This ensures water movement into and drainage out of the containers and prevents them from standing in water retained by the trays. A 7-10 cm siphon is used to permit filling the tray to that depth with water, ensuring thorough wetting of the medium before draining (flushing).

Capillary mat systems supply subirrigation water through a wetted mat supporting the containers. Water moves into the medium through capillary action. Unlike containers used for other subirrigation and conventional systems, each container's drainage holes must be flat on the bottom to ensure direct media contact with the mat. The mats are usually manufactured from reprocessed cloth or synthetic fibrous material and thus are often of variable composition and provide a nonuniform water supply across their surfaces. Newspaper has also been used successfully as a mat (Larson and Widmer, 1978) but is probably not appropriate for research applications. Capillary mat systems are constructed by laying a 2 mil polyethylene film (black is preferred because it reduces algae growth) on a flat, plastic-covered surface. The surface must be flat and level to ensure uniform moisture distribution. Drip or spaghetti tubes uniformly distributed across the mat surface are often used to ensure uniform water application (Widmer, 1984). Water not held by the mat drains away. Hand watering two to three times a day can also be used. Containers should be thoroughly watered when placed on the bench to ensure capillary contact. Advantages of capillary mat watering include simplicity, low installation cost, and flexibility (plant density and container size may be varied without altering irrigation equipment). Potential problems include excess soluble salt or algae buildup on the mat, container, and media surfaces; excess media water content (if the wrong medium is used); media and mat insect infestation; and rapid disease spread.

Nutrition

Proper nutrition is required if plants maintained in controlled environmental chambers are to be grown in a predictable way. Even when it is not the objective of a study, nutrition can influence the final result (Gauch, 1972). Deficiencies and toxicities of one or more of the essential elements can and do occur. Moreover, an excess of one element can trigger a deficiency of another element. Some common problems are buildup of salts in leaves when transpiration rates are high and accumulation of excess manganese when pH levels are decreased or with excess water in the soil. The smaller the container, the more likely nutritional problems will occur.

Many factors affect the absorption and utilization of nutrients, including secondary or tertiary effects of applied treatments. For example, if the root medium temperature drops below 15°C, the phosphate availability decreases rapidly. In low-temperature experiments, additional phosphate must be provided to maintain a favorable plant phosphate status. The nutrients required by a plant also are a function of growth rate. If plant growth is slowed by low temperature, light, or carbon dioxide, then less nutrients are required. Conversely, if these growth conditions become more favorable, amount and frequency of nutrient application should be increased.

Required Nutrients

Plant physiologists generally consider 16 elements essential for the normal growth and development of higher plants (Arnon and Stout, 1939). Of these, carbon is the only one normally absorbed from the atmosphere by the shoots. The rest are generally absorbed by the roots from the root-zone media. Two, hydrogen and oxygen, come from water. Six, the cations potassium, calcium, and magnesium plus the anions phosphorus, nitrogen, and sulfur, are called macronutrients because they are found in relatively large concentrations in plant tissues. The remainder, iron, chlorine, boron, manganese, zinc, copper, and molybdenum, are called micronutrients because their concentration in plant tissues is much lower than the macronutrients. Other elements required for plant growth include sodium, essential for halophytes, and cobalt, required for symbiotic fixation of nitrogen by legumes. Silicon provides a structural benefit to certain plants, particularly monocots.

Terminology

Moles (mol), parts per million (ppm), percentage, and equivalents (eq) are the units commonly used to quantify elemental concentration. Mole m^{-3} is the base SI unit for concentration and is recommended for reporting. The major nutrients in solutions are commonly reported in mmol l^{-1} and minor nutrients as µmol l^{-1}. Ppm, as mass per mass or volume, is commonly used for the micronutrients because they occur in much smaller concentrations than characterized by percentage (1% = 10,000 ppm).

Equivalents are based on chemical reactivity. A substance's eqivalent weight is its atomic or molecular weight divided by its valence or charge. For example, potassium's equivalent weight, 40, is equal to its atomic weight because it has a valence of one. That of calcium, 20, is one-half of its atomic weight, 40, because it has a valence of two. Solutions made on an equivalent basis have the same chemical reactivity because with the same number of equivalents, they have the same number of chemical units to participate in chemical reactions. A convenient unit for expressing cation and anion concentrations in culture solutions is milliequivalent (meq = 0.001 eq). To convert meq to ppm, multiply by the equivalent weight or divide to convert ppm to meq.

More specific terminology is used to describe nitrogen form. Nitrate-nitrogen (NO_3^+-N) refers to the amount of nitrogen present in the nitrate form and ammoniacal-nitrogen (NH_4^+-N) in ammonical form.

Commercial-grade chemicals or fertilizers can often be substituted for reagent-grade chemicals at a substantial savings, even in small experiments. The percentage of the primary nutrients, nitrogen, phosphorus, and potassium, in commercial fertilizers is given by three numbers representing their respective percentage (e.g., 10-8-6, NPK). Nitrogen is given in elemental terms (N), whereas phosphorus and potassium represent oxides (P_2O_5 and K_2O). Table 2 gives the conversions for P and K in commercial fertilizers to elemental amounts.

Table 2. Conversion of the oxide-elemental forms of phosphorus and potassium.

Conversion to Element:	P_2O_5 x 0.44 = P K_2O x 0.83 = K
Conversion to Oxide:	P x 2.29 = P_2O_5 K x 1.20 = K_2O

Formulations

A complete formulation of all required nutrients commonly utilized for regular watering of plants growing in growth chambers in the aforementioned materials and mixes is shown in Table 3. It is essentially the same formulation as recommended for general use in hydroponic systems. It is necessary to prepare the two stock concentrates in separate containers to avoid precipitating the calcium and iron phosphates. The concentrate is diluted for application to plants by adding equal volumes of the two stock concentrates to 200 volumes of water (200:1 water:stock dilution). Ten liters of nutrient solution is prepared by filling a 10-liter container three-quarters full of water, adding 50 ml of each stock solution, then adding water until the total volume equals 10 liters. This solution is about one-half the strength of Hoagland's original solution (Hoagland and Arnon, 1950).

Stock solutions can be made in large batches and stored successfully for 2 or 3 months in cool, dark conditions (i.e., in a refrigerator in opaque or brown containers). Holding tanks should be plastic, fiberglass, or plastic-lined and should also be opaque or covered with opaque material to prevent algae growth. The approximate concentrations of elements in the diluted solution are shown in Table 4. The electrical conductivity of this solution will be about 1 dS (1 millimho cm^{-2}).

Although developed for tomatoes, this solution satisfies the nutrient requirements of many other species. Slight changes in composition of this solution may improve the growth of some plants depending on the species and type of re-

Table 3. Nutrient solution formulation.

Stock Concentrate 1	
Potassium nitrate (KNO_3)	50.55 g l^{-1}
Potassium di-hydrogen phosphate (KH_2PO_4)	27.22 g l^{-1}
Magnesium sulfate ($MgSO_4 \cdot 7H_2O$)	49.30 g l^{-1}
Sodium chloride (NaCl)	5.85 g l^{-1}
Micronutrient concentrate	100.00 ml l^{-1}
Make up to one liter with water and mix thoroughly to dissolve salts.	
Micronutrient Concentrate	
Boric acid (H_3BO_3)	2.850 g l^{-1}
Manganese sulfate ($MnSO_4 \cdot H_2O$)	1.538 g l^{-1}
Zinc sulfate ($ZnSO_4 \cdot 7H_20$)	0.219 g l^{-1}
Copper sulfate ($CuSO_4 \cdot 5H_20$)	0.078 g l^{-1}
Molybdic acid (MoO_3) (85%)	0.020 g l^{-1}
Add water to make one liter and mix thoroughly to dissolve all salts.	
Stock Concentrate 2	
Calcium nitrate ($Ca(NO_3)_2 \cdot 4H_2O$)	118.08 g l^{-1}
Sequestrene 330 Fe*	5.00 g l^{-1}
Make a slurry of the iron chelate in a small amount of water before adding to the calcium nitrate concentrate.	

*Other iron chelates will work (Jacobson, 1951): Sequestrene 138 Fe at 8.3 g l^{-1} or NaFe EDTA at 4.2 g l^{-1}.

Table 4. Approximate concentration of nutrients in final solution (200:1 dilution of stock concentrates).

	N	P	K	Na	Ca	Mg	S	Cl
Element weight	14.01	30.97	39.10	22.99	40.08	24.31	32.06	35.45
ppm	105.0	31.0	136.8	11.0	100.0	24.0	32.0	17.7
$meq \cdot l^{-1}$	7.5	1.0	3.5	0.5	5.0	2.0	2.0	0.5
$\mu mol \cdot l^{-1}$	7.5	1.0	3.5	0.5	2.5	1.0	1.0	0.5

	Fe	B	Mn	Zn	Cu	Mo
Element weight	55.85	10.81	54.94	65.38	63.55	95.94
ppm	02.5	0.25	0.25	0.02	0.01	0.005
$\mu mol \cdot l^{-1}$	44.8	23.1	4.6	0.38	0.16	0.052

Table 5. Conversion factors for modifying nutrient solutions. (Multiply by these factors for conversion).

Nutrient	Molecular weight	Elemental weight	ppm to mmol	mmol to ppm	meq to mmol	mmol to meq	ppm to meq	meq to ppm
Potassium nitrate								
KNO_3	101.11							
K		39.10	0.025	39.10	1.0	1.0	0.025	39.10
N		14.01	0.071	14.00	1.0	1.0	0.071	14.01
Potassium di-hydrogen phosphate								
KH_2PO_4	136.09							
K		39.10	0.025	39.10	1.0	1.0	0.025	39.10
P		30.97	0.032	30.97	1.0	1.0	0.032	30.97
Magnesium sulfate								
$MgSO_4 \cdot 7H_2O$	246.48							
Mg		24.31	0.041	24.31	0.5	2.0	0.082	12.16
S		32.06	0.031	32.06	0.5	2.0	0.062	16.03
Sodium chloride								
NaCl	58.44							
Na		22.99	0.043	22.99	1.0	1.0	0.043	22.99
Cl		35.45	0.028	35.45	1.0	1.0	0.028	35.45
Calcium nitrate*								
$Ca(NO_3)_2 \cdot 4H_2O$	236.15							
Ca		40.08	0.025	40.08	0.5	2.0	0.050	20.04
N		14.01	0.071	14.01	1.0	1.0	0.071	14.01
Boric acid								
H_3BO_3	61.83							
B		10.81	0.093	10.81		(Not relevant)		
Manganous sulfate								
$MnSO_4 \cdot 7H_2O$	169.01							
Mn		54.94	0.018	54.94		(Not relevant)		
Zinc sulfate								
$ZnSO_4 \cdot 7H_2O$	287.54							
Zn		65.38	0.015	65.38		(Not relevant)		
Copper sulfate								
$CuSO_4 \cdot 5H_2O$	249.68							
Cu		63.55	0.016	63.55		(Not relevant)		
Molybdic Acid								
MoO_3 (85%)	143.94							
Mo		95.94	0.010	95.94		(Not relevant)		

*For each mole of calcium nitrate there are two moles of nitrate or nitrogen.

sponse desired (whether shoot, root, fruit, flower, or some other aspect of growth or yield is being encouraged). If corn and certain other monocots are grown in this solution, the amount of added iron should be increased 2 to 4 times. Conversion factors for salts utilized in this formulation are shown in Table 5.

Literature Cited

Arnon, D.I., and P.R. Stout. 1939. The essentiality of certain elements in minute quantity for plants with special reference to copper. Plant Physiol. 14:371-375.

Baker, K.F. 1957. The U.C. System for Producing Healthy Container-Grown Plants. Univ. Calif. Agric. Exp. Stn. Manual 23. 332 pages.

Ball, V. 1986. "I like ebb and flow." Grower Talks (Feb.):34-39.

Berry, W.L., T.T. Krizek, D.P. Ormrod, J.C. McFarlane, R.W. Langhans, and T.W. Tibbitts. 1981. Variation in elemental content of lettuce grown under baseline conditions in five controlled-environment facilities. J. Amer. Soc. Hort. Sci. 106:661-666.

Boodley, J.W., and R.W. Sheldrake. 1963. Artificial soils for commercial plant growing. New York State College of Agriculture, Cornell University, Agric. Ext. Bull. 1104.

Davis, R.D., P.H.T. Beckett, and E. Wollan. 1978. Critical levels of twenty potentially toxic elements in young spring barley. Plant Soil 49:395-408.

Dolar, S.G., and D.R. Kenney. 1971. A self-watering system for growing plants in potted soils. Agron. J. 63:334-336.

Gauch, C.H. 1972. Inorganic Plant Nutrition. Dowden, Hutchinson and Ross, Stroudsburg, Penn.

Guevarra, A.B., Y. Kutamura, A.S. Whitney, and K.G. Cassman. 1980. A low-cost system for circulating nutrient solutions in pot studies. Crop Sci. 20:110-112.

Hoagland, D.R. and D.I. Arnon. 1950. The water-culture method for growing plants without soil. Calif. Agric. Exp. Stn. Cir. 337. Davis, CA.

Jacobson, L. 1951. Maintenance of iron supply in nutrient solutions by a single addition of ferric potassium ethylenediamine tetra-acetate. Plant Physiol. 26:411-413.

Klueter, H.H., W.A. Bailey, W.A. Dungey, D.T. Krizek, and G. Gurdge. 1978. Watering Systems. In: R.W. Langhans (ed.), A Growth Chamber Manual. Comstock Publishing, Ithaca, NY.

Larson, R.A., and R.E. Widmer. 1978. Mat watering: a progress report. Minn. St. Flor. Bull. (Apr):7. St. Paul, MN.

Maynard, D.B., A.V. Barker, and H.F. Vernell. 1970. A semiautomatic sand culture system for greenhouse plant nutrition research. Agron. J. 62:304-306.

Moody, J., and R. Lindstrom. 1977. Selection and cleaning of plastic containers for storage of trace element samples. Anal. Chem. 49:2264-2267.

Noland, D.A., L.A. Spomer, and D.J. Williams. 1992. Evaluation of pumice as a perlite substitute for container soil physical amendment. Commun. Soil Sci. Plant Anal. 23(13 & 14):1533-1547.

Resh, Howard M. 1989. Hydroponic Food Production, 4th Edition, Woodbridge Press Pub. Co., Santa Barbara, CA.

Roberts, F.J. 1959. The magnesium supplying power of glazed porcelain pots. J. Aust. Inst. Agric. Sci. 25:299.

Smith, R.C. 1987. Automated watering methods save time and money. Greenhouse Manager. (April):36-46.

Spomer, L.A. 1974a. Two classroom exercises demonstrating the pattern of container soil water retention. HortScience 9:152-153.

Spomer, L.A. 1974b. Optimizing container soil amendment: The "threshold proportion" and prediction of porosity. HortScience 9(6):532-533.

Spomer, L.A. 1975a. Availability of water absorbed by hardwood bark soil amendment. Agron. J. 67(4):589-590.

Spomer, L.A. 1975b. Small soil containers as experimental tools: Soil water relations. Commun. Soil Sci. Plant Anal. 6:121-26.

Spomer, L.A. 1979. Three simple demonstrations of the physical effects of soil amendment. HortScience 14:75-77.

Spomer, L.A. 1980a. Prediction and control of porosity and water retention in sand-soil mixtures for drained turf sites. Agron. J. 72:361-362.

Spomer, L.A. 1980b. Graphical prediction of porosity and water retention in sand-soil mixtures for drained turf sites. Can. J. Soil Sci. 60:787-791.

Spomer, L.A. 1981. The effect of container soil volume on plant growth. HortSci. 17:680-681.

Spomer, L.A. 1990. Evaluating 'drainage' in container and other shallow-drained horticultural soils. Commun. Soil Sci. Plant Anal. 21(3&4):221-235.

Stanwood, P.C., J.C. Phillips, and D.O. Chilcote. 1974. Fully automatic subirrigation system for glasshouse and growth chamber use. Crop Sci. 14:773-774.

Terman, G.L. 1974. Nutritional aspects of container culture. Commun. Soil Sci. Plant Anal. 5(2):115-121.

Warren-Wilson, J., and J. Tunney. 1965. Defects of perlite as a medium for plant growth. Aust. J. Exp. Agric. Anim. Husb. 5:137-40.

Wheeler, R.M., and T.W. Tibbitts. 1987. Utilization of potatoes for life support systems in space. III. Productivity at successive harvest dates under 12-h and 24-h photoperiods. Potato J. 64:311-320.

Widmer, R.E. 1984. Capillary mat watering. Minn. St. Flor. Bul. 33:2. St. Paul, MN.