SOILLESS CULTURE
of Greenhouse Vegetables

Almost all of the vegetables we find on grocery-store shelves are produced either directly or indirectly in open-field soil. However, soil itself isn't necessary for plant growth - only some of its constituents.

Field soil serves two basic purposes: it acts as a reservoir to retain nutrients and water, and it provides physical support for the plant through its root system. Artificial means can also provide these important requirements for plant growth with equal (and sometimes better) growth and yield results compared to field soil, although at substantially greater expense. Well-drained, pathogen-free field soil of uniform texture is the least-expensive medium for plant growth, but soil doesn't always occur in this perfect package. Some soils are poorly textured or shallow, and provide an unsatisfactory root environment because of limited aeration and slow drainage. Pathogenic organisms are a common problem in field soils. When adverse conditions are found in soil and reclamation is impractical, some form of soilless culture may be justified. This guide describes the materials used in soilless culture and discusses management practices in various soilless systems.

DEFINING SOILLESS CULTURE

Soilless culture is an artificial means of providing plants with support and a reservoir for nutrients and water. The simplest and oldest method for soilless culture is a vessel of water in which inorganic chemicals are dissolved to supply all of the nutrients that plants require. Often called *solution culture or water culture*, the method was originally termed *hydroponics* (i. e., "water working") by W. F. Gericke in the 1930s. Over the years, hydroponics has been used sporadically throughout the world as a commercial means of growing both food and ornamental plants. Today, it is used widely in research facilities as a technique for studying plant nutrition. Various modifications of pure-solution culture have occurred. Gravel or sand is sometimes used in soilless systems to provide plant support, and retain some nutrients and water. The retention of nutrients and water can be further improved through the use of spaghnum peat, vermiculite, or bark chips. These are the most commonly used materials, but others - such as rice hulls, bagasse (sugarcane refuse), sedge peat, and sawdust - are used sometimes as constituents in soilless mixes. Straw bales have been used as growing medium in England and Canada. Rockwool (porous stone fiber) is used in Europe, but there is little experience with it in this country.

Since the major constituent of the media in artificial growing systems may be solid or liquid, it is appropriate to use the term *soilless culture* in reference to this general type of growing system and reserve the term *hydroponics* for those in which water is the principal constituent. Soilless culture methods may thus be classified as either solid- or liquid-medium systems.

TYPES OF SOILLESS CULTURE

Liquid-medium systems are further differentiated from solid-medium systems by method of operation. Liquid systems are generally closed circuit with respect to nutrient-solution supply: the solution is recirculated from a supply reservoir either continuously or intermittently for a period of days or weeks. The two most common liquid systems in use today are *nutrient-flow technique* (NFT) and *gravel-bed culture*.

An NFT growing system consists of a series of narrow channels through which nutrient solution is recirculated from a supply tank. A plumbing system of plastic tubing and a submersible pump in the tank are basic components. The channels are generally constructed of opaque plastic film or plastic pipe (fig. 1); asphalt-coated wood or fiberglass also has been used. The basic characteristics of all NFT systems is the shallow depth of solution that is maintained in the channels. Flow is usually continuous, but some systems are operated intermittently by supplying solution a few minutes every hour. The purpose of intermittent flow is to assure adequate aeration of the root systems. This also reduces the energy required; but under rapid-growth conditions, plants could experience water stress if the flow period is too short or infrequent.

Therefore, intermittent-flow management seems better adapted to mild-temperature periods or to plantings during their early stages of development. Capillary matting is sometimes used in the bottom of NFT channels, principally to avoid the side-to-side meandering of the solution stream around young root systems, but it also acts as a reservoir by retaining nutrients and water during periods when flow ceases.

NFT channels are frequently designed for a single row of plants with a channel width of 6 to 8 inches (15 to 20 cm). Wider channels of 12 to 15 inches (30 to 38 cm) have been used to accommodate two rows of plants, but meandering of the shallow solution stream becomes a problem with greater width. To minimize this problem, small dams can be created at intervals down the channel by placing thin wooden sticks crossways in the stream, or by the use of capillary matting. The channels will need to be sloped 4 to 6 inches per 100 feet (10 to 15 cm per 30 in) to maintain gravity flow of the solution. Flow rate into the channels should be in the range of 1 to 2 quarts a minute (I to 2 liters a minute). Channel length should be limited to a maximum of 100 feet (30 in) in order to minimize increased solution temperature on bright days. The ideal solution temperature for tomatoes is 68^o to 77^oF (20^o to 25^oC). Temperatures of 59^o or 86^oF (15^o or $3O^oC$) have been shown to decrease growth and yield of tomatoes. Black plastic-film channels will cause solution temperature to increase on sunny days. During cloudy weather, it may be necessary to heat the solution to the desirable temperature. Solution temperatures in black plastic channels can be decreased by shading or painting the surfaces white or silver. Cooper (1979) provides greater detail on NFT management.

Gravel-bed culture utilizes a waterproof trough filled with pea gravel (or some other inert material of similar size), which is plumbed to a nutrient solution reservoir (fig. 2). Gravel particles retain very little water and nutrients, so the system must recirculate solution from the supply tank to the beds several times a day by means of a time clock and submersible pump. Some gravel systems are designed to be fed from the surface through perforated pipes, and drained at the base of the trough through a slitted drain line; others are both subirrigated and drained through a single pipe at the bottom of the bed. The advantage of the two-pipe system is that any root growth into the drain line will not interfere with the uniform distribution of nutrient solution to the bed. In either case, however, root growth will eventually clog the drain line and rotary cleaning equipment must be used to remove it.

Gravel-bed troughs are generally 24 to 36 inches (60 to 90 cm) in width and 8 inches (20 cm) deep. Pea gravel must be thoroughly washed before use to remove particles of soil or other material that might clog the drain line. Care should be used in selecting a gravel supply that is free from pathogenic organisms. Treatment of the gravel by steam sterilization or an appropriate fungicide is a wise practice when condition of the material is uncertain.

The nutrient-solution supply tank should be large enough to hold a volume of solution about twice that required to fill the beds; this provides a good margin of safety.

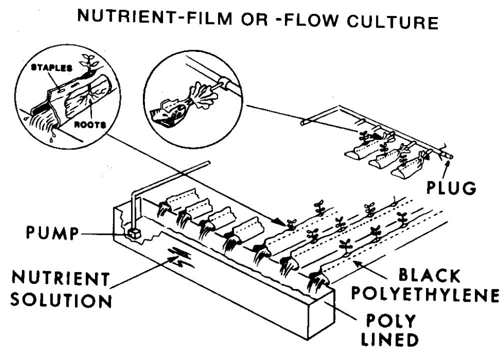

Figure 1. Nutrient-flow culture using plastic film to hold and feed plants through recirculation system.

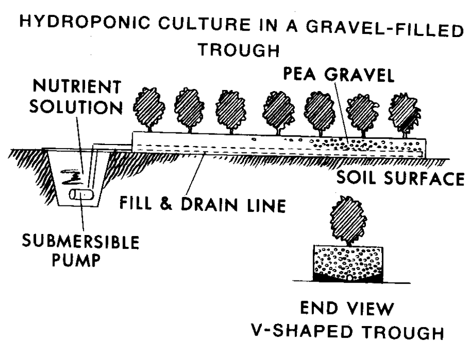

Figure 2. Hydroponic culture in a gravel-filled trough.

The plumbing-system lines and submersible pumps should have the capacity to fill the beds in about 15 minutes, and allow complete drainage in 30 to 45 minutes.

When managed properly, NFT and gravel-bed systems are capable of growing good crops, but there are some disadvantages that should be taken into consideration. The nutrient concentration of a recirculated nutrient solution is in a continuous state of change because plants are removing elements at different rates. Therefore, some means of monitoring and replenishing must be used to avoid deficiencies (and perhaps toxicities from excesses of some elements). This increases the cost of equipment and laboratory analysis. Recirculated systems are power dependent. If electrical energy is disrupted, there is little reservoir of water and nutrients to protect the plants from stress. Recirculation of the solution is an ideal means of spreading any pathogenic organism (such as water-mold fungi) that may be inadvertently introduced to the system. For these reasons, more management care, experience, and capital will be necessary for success with recirculated liquid-medium systems.

Solid-medium soilless culture may employ any one of many types of suitable media in various types of containers. Basic requirements are a material of uniform texture that drains well yet retains some nutrients and water, a container in which the material is confined, and a means of supplying nutrient solution. A well-drained sandy loam could be used as a growing medium, but a supply of very uniform soil in the volume required may be difficult to find, and the weight of soil is much greater than other types of material. Sand has been used in soilless systems in which the entire floor of a greenhouse is filled a foot or more in depth, but it is rarely used in container systems because of its weight. Where sand is used, particle-size distribution is an important consideration in order to maintain a good balance between drainage (aeration) and nutrient and water retention. Particle sizes should be in the range of 0.1 to 1.0 mm with an average of 0.25 to 0.50 mm.

Full-floor sand culture has been successful for vegetable culture in greenhouses and is considered a good means of providing plants with a uniform, well-drained rooting medium (fig. 3). Installation requires excavation of the greenhouse floor to the intended fill depth, and grading (about 4 inches per 100 feet [10 cm per 30 m]) for drainage. First, the graded area is covered with 10-mil plastic sheeting to prevent root penetration into the underlying soil. Then a system of drain tubes at the spacing of the plant rows is laid out on the plastic and connected to a common drain at the lower end of the house. Sand is then filled to the intended depth over the plastic sheeting and drain lines. Be careful to select sand according to its particle-size distribution, and its freedom from pathogens and constituents that might be toxic to the crop plants. Because of the permanent preparations for full-floor sand culture, it is recommended that sand intended for use in the system be given a growth test in containers before actually filling the greenhouse to determine if it meets the basic requirements.

Sand-culture systems for tomatoes or cucumbers are typically irrigated and fertilized by trickle irrigation. The nutrient solution should be supplied at each irrigation because of the relatively low nutrient retention of sand. Irrigation frequency will vary with the crop, its growth stage, and the temperature, but will range from two to several times a day. Depending upon plant size and temperature, tomato and cucumber plants will require in the range of 1/2 to 4 quarts (1/2 to 4 liters) per plant a day.

CONTAINER GROWING

Soilless culture in bags, pots, or troughs with a lightweight medium is the simplest, most economical, and easiest to manage of all soilless systems. The most common types of media used in containerized systems of soilless culture are peat-lite (Boodley and Sheldrake 1977), or a mixture of bark and wood chips. Container types range from long wooden troughs in which one or two rows of plants are grown, to polyethylene bags or rigid plastic pots containing one to three plants. Bag or pot systems using bark chips or peat-lite are in common use

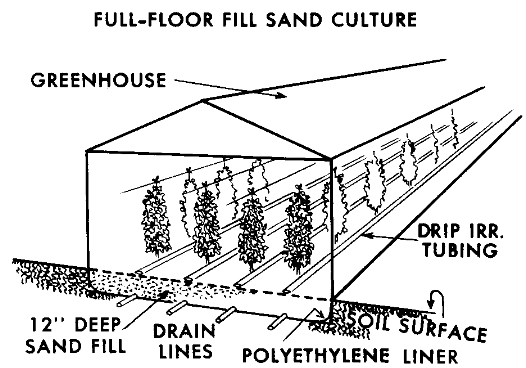

Figure 3. Full-floor sand culture.

throughout the United States and offer some major advantages over other types of soilless culture: (1) the medium materials have excellent retention qualities for nutrients and water; (2) containers of medium are readily moved in or out of the greenhouse whenever necessary or desirable; (3) they are lightweight and easily handled; (4) the medium is useful for several successive crops; (5) the containers are significantly less expensive and less time-consuming to install- and (6) in comparison with recirculated-hydroponic systems, the nutrient-solution system is less complicated and less expensive to manage. From a plant-nutrition standpoint, the latter advantage is of significant importance. In a recirculated system, the solution is continuously changing in its concentration and its nutrient balance because of differential plant uptake.

In the bag or pot system, the solution is not recirculated. Nutrient solution is supplied from a fertilizer proportioner or large supply tank to the surface of the medium in a sufficient quantity to wet the media. Any excess is drained away from the system through drain holes in the base of the containers. Thus, the concentration and balance of nutrients in solution fed to the plants is the same at each application. This eliminates the need to sample and analyze the solution periodically to determine the kind of necessary adjustments, and avoids the possibility of solution excesses or deficiencies.

In the *bag or pot system*, the volume of medium per container varies from about 1/2 cubic foot (14 liters) in vertical poly bags or pots to 2 cubic feet (56 liters) in lay-flat bags. In the vertical-bag system, 4-mil black poly bags with pre-punched drain holes at the bottom are common. One, or sometimes two, tomato or cucumber plants are grown in each bag (fig. 4). Lay-flat bags accommodate two or three plants (fig. 5). In either case, the bags are aligned in rows with spacing appropriate to the type of crop being grown. It is good practice to place vertical bags or pots on a narrow sheet of plastic film to prevent root contact or penetration into the underlying soil. Lay-flat bags, which have drainage slits (or overflow ports) cut along the sides an inch (2. 54 cm) or so above the base, would also benefit from a protective plastic sheet beneath them. Greater detail on lay-flat bag culture is provided by Bauerie (1984).

Figure 4. Cucumber plants in vertical poly bags.

Figure 5. Tomato plants in lay-flat bags.

Irrigation Systems

Nutrient solution is delivered to the containers by supply lines of black polyethylene tubing to spaghetti tubing, spray sticks, or ring drippers in the containers. Application devices have different wetting patterns and are available in different flow rates. The choice of application system is important in order to provide proper wetting of the medium at each irrigation. Texture and porosity of the growing medium, and the surface area to be wetted are important considerations in making the choice. Spaghetti tubing provides a point-source wetting pattern, which might be appropriate for fine-textured types of media and allows water to be conducted laterally with ease. In lay-flat bags, single spaghetti tubes at individual plant holes will provide good wetting of peat-lite media. In a vertical bag containing porous medium, a spray stick with a 90-degree spray pattern will do a good job of irrigation if it is located to wet the majority of the surface. Ring drippers are also a good choice for vertical bags although somewhat more expensive. When choosing an application system for bag or container culture, remember that the objective of irrigation is to distribute nutrient solution uniformly so that all of the medium is wet. Since a root system cannot function in dry medium, dry medium is wasted medium.

Growing Media

The growing medium used in container culture must have good nutrient- and water-holding characteristics, and provide good aeration to the root system. Light weight is another important consideration so that filled containers can be easily handled. Growing media should be free of pathogenic organisms and substances that are toxic to plants. The principal materials that meet these requirements are peat moss, bark, shavings, sawdust, vermiculite, bagasse, and rice hulls. Table 1 provides a summary comparison of the characteristics of these materials. Some should not be used alone, but have one or more characteristics that make them valuable constituents when used in a mixture. Bagasse is low in porosity and high in water-holding capacity, which would lead to poor aeration and drainage if used alone. Because rice hulls have low water-holding capacity and high pore space, plants would be vulnerable to water stress when rice hulls are used alone. Both vermiculite and sawdust are poor choices as sole constituents because their high water-holding capacities can lead to saturation and poor aeration if over-irrigated. Vermiculite particles also tend to collapse with time, resulting in compaction and volume loss. Sawdust (except for cypress and redwood) and bagasse have high carbon: nitrogen ratios (C:N ratios), and require extra nitrogen fertilizer to avoid the competitive demand for nitrogen between microorganisms and the plants. Bagasse, rice hulls, sawdust, and vermiculite possess useful characteristics when used in mixes with other materials in the range of 20 percent to 50 percent of the total volume. Because of their high C:N ratios, bagasse and most sawdust material should be limited to no more than 20 percent of the total volume of a mix.

Care should be used in the kind of wood material selected for soilless culture. Cedar, walnut, and eucalyptus may have components that are toxic to plants. Fresh redwood also affects the growth of some plants, but this effect becomes negligible with aging and leaching. The causes of toxicity from wood materials is not clearly understood, but probably varies with the type of plant being grown, and the type and age of wood being used. Wood materials are generally acidic and any toxicity from their use may be due to the effects of acidity on the availability of some nutrients to the plants. In redwood, the toxic component is transient because it decomposes or is leached away during composting. Materials such as pine sawdust decompose rapidly because of the high C:N ratio and, if supplemental nitrogen is not provided or is present in insufficient amount, the deficiency that develops may give the impression of toxicity. The barks of pine, fir, and redwood (and possibly others) can be safely used without growth-retarding effects, but cedar and walnut should be avoided. Sawdust and shavings of pine, fir, and redwood can make good, safe amendments when composted with nitrogen at 13 pounds per cubic yard (8 kg/m 3) for 2 to 3 months.

Mixes should not be made merely to take advantage of availability or low cost, but should consider the basic factors of weight, nutrient retention, water-holding capacity, pore space, and C:N ratio. Mixtures of spaghnum peat and horticultural vermiculite (peat-lite) have all of the required characteristics and make an excellent growing medium. Proprietary peat-lite mixes are available, or growers can prepare their own supply from the basic components (Boodley and Sheldrake

1977). Barks from pine, fir, cypress, and redwood have been used successfully as a growing medium for greenhouse cucumbers and tomatoes. Particle sizes of bark range generally from 1 to 10 mm in diameter; and the distribution of particle sizes in most mill-run material provides good aeration, and good water- and nutrient-holding characteristics. A bark medium can be used for several successive crops without a significant reduction in volume due to decomposition. A supply of bark with predominantly large particle sizes should be amended with a material such as sawdust, shavings, or bagasse in order to improve water-holding capacity.

TABLE 1. Physical and chemical characteristics of materials used in soilless culture.[1]

Material	Bulk density (weight)	Water holding capacity	Porosity	Cation exchange capacity	Decomposition rate (Carbon:Nitrogen)
bagasse	L[2]	H[2]	L	M[2]	H
sawdust	L	H	M	H	H
rice hulls	L	L	H	M	M–H
shavings	L	M	H	M	M–H
vermiculite	L	H	M	H	L
peat moss	L	H	H	H	M
bark	L	M	M	M	M
sand	H	L	M	L	L

[1]Adapted from R. T. Poole, C. A. Conover, and J. N. Joiner; *Foliage Plant Production* (Englewood Cliffs, NJ: Prentice Hall, 1981).

[2]Low	0.25 gm/cm³	20%	5%	10 meg/100 cm³	1:200
Medium	0.25–0.75	20–60%	5–30%	10–100	1:200–1:500
High	0.75	60%	30%	100	1:500

FERTILIZATION

In field culture, the clay fraction of soils can be expected to supply adequate amounts of at least some of the nutrients required by plants, especially the minor elements.

Fertilizer programs for soilless-culture systems must supply all nutrients required by the plants. Carbon, hydrogen, and oxygen are provided from water and carbon dioxide in the air. The grower will supply nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, boron, copper, zinc, manganese, molybdenum, and chlorine. Most medium materials contain small amounts of these elements; but they should not be considered in planning the fertilizer program because they are a small proportion of the requirement, or they may be in forms not readily available to plants.

Liquid-medium systems - such as NFT and gravelbed culture - use complete nutrient solutions prepared from soluble inorganic salts containing various elements. Proprietary mixes of all required elements are available, which are simply dissolved in water to prepare the nutrient solution. These mixes are available in various concentrations and ratios of elements. Nutrient solutions can also be prepared by the grower using readily available soluble salts. Many complete nutrient-solution formulas have been developed and used successfully. All contain the same elements and are generally prepared from the same compounds, although in somewhat different proportions. No one formula is necessarily the best for all plants, but all are capable of providing adequate nutrition. Special formulas are often recommended for a particular crop plant based upon research under the prevailing climatic and water quality conditions at a specific location. These formulas are soundly based for those conditions, but none should be construed as being the best universally under all conditions. They are good points of departure in developing a feeding program for the crop for which they are recommended, and may be well suited for use without alteration. Successful managers seek as much information as possible from reliable sources to develop a sound understanding of plant nutrition and inorganic chemistry before attempting to alter published formulas for their imagined or perceived needs.

Improper alteration of formulas can lead to serious adverse effects due to excesses or deficiencies. It is recommended that growers either utilize prepared nutrient mixes obtained from reliable manufacturers or, if preparing their own, follow recommended formulas carefully. Competent assistance should be sought before making changes. Solid-medium systems - such as bark or peat-lite- can be provided with nutrients by three methods: (1) entirely from a complete nutrient solution; (2) from a combination of premixing some elements in the medium and supplying others by liquid feed; or (3) premixing all elements in the medium. The complete nutrient-solution method is commonly used in sand culture and for various mixed media or bark. Nutrient solution is applied up to several times a day to maintain the medium in a moist (but not saturated) condition. This system requires either a supply tank for the nutrient solution or a ratio feeder or fertilizer proportioner that prepares solution upon demand from stock nutrient concentrates. For small greenhouses, the frequent chore of replenishing the solution supply in a tank may be more attractive than investment in a fertilizer proportioner. When using the supply-tank method for a recirculated growing system, the tank should be large enough to hold a volume of solution about twice that required to fill the system. This provides a safe margin of nutrient supply.

Nutrient-solution Formulas

Formulas for several nutrient solutions are given in the Appendix, along with methods of preparation. While they differ in concentrations of the elements, all have been used successfully by commercial growing operations, principally for the production of tomatoes. Formula I has been widely used in research greenhouses as a general nutrient solution for a wide range of plants, and is a good formula choice where more specific information is not known for a particular crop. It is possible that adjustments in concentrations of some elements (particularly nitrogen, phosphorus, or potassium) may be beneficial to the yield or quality of a given crop. Until research is clear on this, however, it is best to adhere to the basic formula.

The formulas in the Appendix list amounts of individual salts to be dissolved in 100 gallons (378 liters) of water.

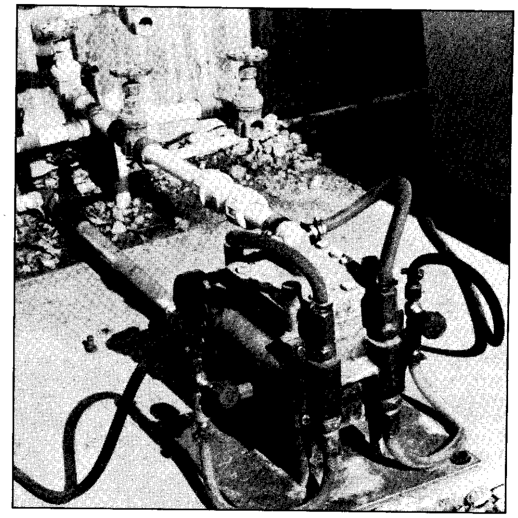

Figure 6. One type of fertilizer proportioner for nutrient-solution feeding.

This prepares the nutrient solution in the form to be supplied to plants from a storage tank. When a fertilizer proportioner is used, the amount of each salt must be adjusted to account for the dilution rate of the proportioner. By this method, liquid concentrates of the salts are prepared that will be diluted for the final nutrient solution as they are fed through the proportioner. For example (in formula 1), to calculate the amount of potassium nitrate to provide 50 gallons (190 liters) of concentrate to be used with a *200: 1* proportioner, divide 95 grams by 100 to obtain grams per gallon (or by 378 for grams per liter) in the final nutrient solution as shown, then multiply by 200 to obtain the amount in I gallon (or 1 liter) of concentrate, and finally multiply by 50 (or 190 liters) for the amount required for 50 gallons (190 liters) of concentrate. The amount of potassium nitrate required for 50 gallons (190 liters) of 200: 1 concentrate is 20.9 pounds or 9550 grams. When preparing concentrates for proportioners, two separate concentrates are required to avoid precipitates. One contains only calcium nitrate and the iron compound; all other ingredients are in the other concentrate. The concentrates are kept in separate tanks and must be used in conjunction with a twin-head proportioner. When activated, the proportioner draws equal volumes from each tank and mixes them with an appropriate amount of water to provide the dilute nutrient solution.

When using a proportioner, it is good practice to monitor its operation on a regular basis to be certain that solution of proper concentration of elements is being provided to the plants. This should be done in two ways. A water meter attached to the outlet side will record the volume of solution mixed for a particular period of time. The depletion of concentrate volume in each tank over the same period of time and the volume of solution supplied should be in the same ratio as the dilution ratio of the proportioner. Another check on the system is to compare periodically the total salt concentration of a physical dilution of both concentrates with water. As an example, mix 200 ml of water with I ml (using a 1-mi pipette for measurement) of each concentrate. Salt concentration can be determined by an analytical laboratory or by a portable battery-operated instrument that measures electrical conductivity (fig. 7). During preparation of the concentrates, measurements of the individual salts should be made very carefully so that the final solution will contain amounts of individual elements as intended in the formula. Mistakes can be made, however, and for this reason it may be wise to sample the final solution from the proportioner and have a complete analysis made in a laboratory on a periodic basis.

When premixing fertilizer materials with bark, or bark and sawdust, compounds that supply phosphorus, magnesium, calcium, sulfur, and all minor elements may be added to the growing medium prior to planting. A small amount of nitrogen may also be mixed with the medium I but most and sometimes all of this element is supplied in the irrigation water. Nitrogen is generally supplied in the nitrate form in the range of 100 to 200 ppm.[1] The ammonium form of nitrogen, if included, should not exceed 10 percent of the total nitrogen supplied. Potassium also is supplied routinely with nitrogen in the irrigation water at about 200 ppm. A nitrogen/potassium liquid-feed solution providing 150 ppm nitrogen and 2 10 ppm potassium can be prepared by mixing 0.45 pound (208 gm) potassium nitrate and 0.40 pound (182 gm) calcium nitrate in 100 gallons (378 liters) of water. To premix the other elements in the medium per cubic yard (or cubic meter), phosphorus can be supplied as superphosphate (0-20-0) at 2 pounds (1 kg), calcium and magnesium from dolomitic lime at 10 pounds (4.5 kg), and minor elements from trace element mixes such as FTE 503 or Esmigran at 5 ounces (15 5 gm). Additional iron may be added in diluted form at I ounce (28 gm) of 138 Fe.

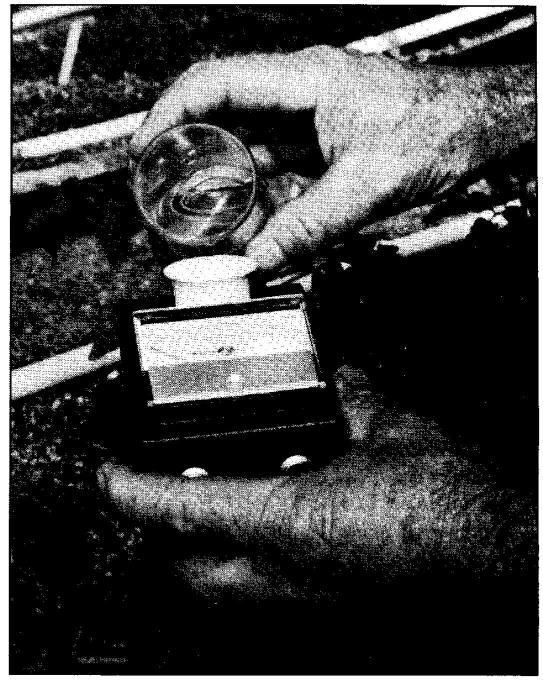

Figure 7. Portable meter for measuring electrical conductivity of nutrient solution.

The method of premixing all fertilizer materials in the medium before planting may include the use of slow-release nitrogen materials such as Mag-amp, Osmocote, isobutylidene diurea (IBDU), or sulfur-coated urea (SCU). This method is not commonly used but, when compared to the liquid-feed method, it is reported to produce equal or better yields of tomatoes (Sheldrake, Dallwyn, and Sangster 1971). The premix method offers important advantages by eliminating the need to prepare nutrient solutions, and the purchase and maintenance of a fertilizer proportioner. The potential disadvantage of slow-release fertilizers that supply all of the nitrogen and potassium is that they may not be able to release the elements at the proper rate to satisfy the plants' needs. While slow-release fertilizers are widely used in the ornamental plant industry, their success rate and cost-effectiveness on vegetables in soilless culture have not been adequately established. Until more information becomes available, it is suggested that their use be limited to medium amendments in proven fertilizer programs.

[1]ppm (parts per million) = mg per liter. Calculation example: to obtain 100 ppm N from potassium nitrate (14 percent N), 100 / 0. 14 = 715 mg potassium nitrate/liter = 0. 715 gm/liter = 2.79 gm potassium nitrate/gallon (1 gallon = 3.785 liters).

Analysis of Solution, Tissue, and Media

Knowledge of the nutritional status of all components of a soilless culture system is important for two reasons: (1) it is the only means of judging how successful management practices have been in attaining the objectives of the fertilizer program in terms of the availability of nutrients and the nutrient levels in the tissue; and (2) it helps diagnose the causes of any abnormal plant symptoms that may occur. The costs of this knowledge are a form of insurance toward success. Periodic laboratory analysis of the nutrient solution is imperative in recirculated hydroponic systems, especially if use of the solution is extended over a period of weeks. It is equally important in solid-medium systems in order to evaluate the operation of the fertilizer proportioner and the preparation of concentrates.

The nutrient solution in a recirculated hydroponic system-such as NFT or the gravel-bed method-may be used on either a short-use or extended-use basis. For short use, a fresh solution is prepared every week or every 2 weeks with periodic replenishment from concentrates. This system assumes that, during the short-use period, nutrient removal from the solution will not reach deficiency levels as long as some fresh concentrate is added every few days. This is a workable procedure and has been used with some success, but it is wasteful of some nutrients and, if the used solution is discarded on porous soils, it can be a source of groundwater pollution. The alternative is extended use of the solution for a period of several weeks or perhaps months. This method can also be successful but requires close periodic monitoring to avoid deficiencies or excesses of nutrient elements, either of which can have adverse effects on plant growth. Because the nutrient status of an extended-use solution is continually changing due to plant uptake, frequent analysis is necessary to maintain the solution close to the original concentration of elements. At a minimum, a complete analysis is warranted every 3 weeks with weekly analyses for nitrogen, potassium, and phosphorus. Daily determination of the total salt content will provide a useful estimate of the nutrient status of the solution although this cannot substitute for complete analysis (Johnson 1980).

The constantly changing nutrient status in recirculated solutions and necessity (and cost) for close control through solution analysis to avoid deficiencies and excesses of elements provide a logical justification for the preferred use of solid-medium systems in soilless culture. In solid-medium systems, plants are fed a uniformly balanced solution at each irrigation. Solution management problems are reduced to measuring precisely when preparing concentrates and monitoring the fertilizer proportioner to assure that it is in proper working order.

Tissue analysis is the best method to evaluate the nutritional status of the plants and the success of the fertilization program. Periodic sampling and analysis of leaf tissue during growth of the crop will provide information that can be used to make adjustments in fertilizer practices, as well as to help interpret any abnormal plant symptoms. Whole leaves, leaf petioles, or leaf blades are the plants parts normally used, although desirable levels for nutrients vary depending upon the part sampled, its location on the plant, and the analytical methods used. Desirable levels of nutrients have been reported for tomatoes, cucumbers, and a wide range of vegetables (Ward 197 3; Wittner and Honma 197 9; Lorenz and Tyler 198 3; and Johnson 1980). Growers who wish to include tissue analysis in their management program should seek assistance from their local county-extension agent or farm advisor in choosing an experienced agricultural analytical laboratory. The lab can help to outline procedures for sampling and the handling of samples, so that material provided to them is from the proper location on the plants, is representative of the growing area, and is in good condition upon arrival. Usually the youngest, fully expanded leaf should be sampled from randomly located plants throughout the area; this is generally the fourth or fifth leaf from the growing point. An adequate sample size is 30 leaves. A single sample will be adequate where plants are uniform in vigor and appearance. Abnormal plant growth should be sampled separately. Samples should be delivered as soon as possible, in a fresh condition to the laboratory.

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Appendix

Some useful formulas for complete nutrient solutions.[1]

Formula 1
(Johnson 1980)

	gms/100 gallons of water
potassium nitrate	95
monopotassium phosphate	54
magnesium sulfate	95
calcium nitrate	173
chelated iron (FeDTPA)	9
boric acid	0.5
manganese sulfate	0.3
zinc sulfate	0.04
copper sulfate	0.01
molybdic acid	0.005

	N	*P*	*K*	*Ca*	*Mg*	*S*	*Fe*	*B*	*Mn*	*Zn*	*Cu*	*Mo*
ppm	105	33	138	85	25	33	2.3	0.23	0.26	0.024	0.01	0.007

[1]When formula is to be used with a fertilizer proportioner, see procedure under section on Nutrient Solutions.

Formula 2
(Jensen, in Wittner and Honma 1979)

	gms/100 gallons of water
magnesium sulfate	187
monopotassium phosphate	103
potassium nitrate	77
calcium nitrate	189
chelated iron (FeDTPA)	9.6
boric acid	1.0
manganese chloride	0.9
cupric chloride	0.05
molybdic acid	0.02
zinc sulfate	0.15

	N	*P*	*K*	*Ca*	*Mg*	*S*	*Fe*	*B*	*Mn*	*Zn*	*Cu*	*Mo*
ppm	106	62	156	93	48	64	3.8	0.46	0.81	0.09	0.05	0.03

Formula 3
(Larsen 1973)

	gms/100 gallons of water
potassium nitrate	67
calcium nitrate	360
potassium magnesium sulfate	167
potassium sulfate	130
chelated iron (FeDTPA)	12
phosphoric acid (75%)	(40 ml)
manganese sulfate	1.5
boric acid	2.2
zinc sulfate	0.5
copper sulfate	0.5
molybdic acid	0.04

	N	*P*	*K*	*Ca*	*Mg*	*S*	*Fe*	*B*	*Mn*	*Zn*	*Cu*	*Mo*
ppm	172	41	300	180	48	158	3	1.0	1.3	0.3	0.3	0.07

Formula 4
(Cooper 1979)

	gms/100 gallons of water
potassium nitrate	221
magnesium sulfate	194
calcium nitrate	380
monopotassium phosphate	99
iron chelate (FeEDTA)	30
manganese sulfate	2.3
boric acid	0.6
copper sulfate	0.15
zinc sulfate	0.17
ammonium molybdate	0.14

	N	*P*	*K*	*Ca*	*Mg*	*S*	*Fe*	*B*	*Mn*	*Zn*	*Cu*	*Mo*
ppm	236	60	300	185	50	68	12	0.3	2.0	0.1	0.1	0.2

The author is Hunter Johnson, Jr., Extension Vegetable Specialist, Riverside.