

Chapter 8

Plant Culture in Hydroponics

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CONTENTS

Introduction
Types of Systems
Static
Flowing
Individual Containers
Nutrient Film Technique (NFT)
Intermittent Subirrigation
Root Misting
Membrane
Nutrition
Formulations
Mixing
Concentration Control
pH Control
Desirable Range
Monitoring
Adjustment
Oxygen Level
Water Purification
Contaminant Control
Removal of Organic Compounds
System Components
Algae Control
Microorganism Control
Literature Cited

Growing plants in nutrient solution culture is a widely adopted concept. Solution culture systems can easily be adapted to a tremendous variety of treatments and studies because they allow for consistent and immediate control of the root-zone environment. A system for supplying nutrient solutions to plant roots should be able to maintain adequate aeration in the root zone, provide solution at a known rate and concentration of nutrients, and maintain the integrity of different nutrient treatments. Some type of inert matrix often is used with hydroponic systems to support plants and aerate their root system. If the matrix is not inert and has a significant cation exchange capacity, readers should refer to the preceding chapter on solid media. Several variations of hydroponic culture may be used for growth chamber research. These include static solution culture, flowing solutions, and misting systems.

TYPES OF SYSTEMS

STATIC

Static or standing solution systems are commonly used for experiments involving large numbers of nutrient treatments because multiple treatments can be costly to establish when flowing solution cultures are used. Thus plant responses to different amounts of nutrients in solution, or hormones applied to roots or shoots, are often studied in static culture systems. Static cultures, however, do not provide a constant concentration of nutrients because nutrient concentrations decline with time as the plant uses the nutrients. With static systems, it is difficult to provide identical aeration rates, pH, electrical conductivity, and nutrient levels in each cul-

ture vessel, especially as plants become large in relation to the culture vessel. Suitable vessels for static systems include polyethylene beakers (Rietveld, 1982), pots, glass jars, and containers lined with black polyethylene film (Rousos and Harrison, 1986). It is important that containers be opaque to prevent algal growth, that they do not possess any inorganic elements or organic compounds that could be phytotoxic, and that they are not permeable or absorptive. For example, new polyvinyl chloride (PVC) pipe at times contains organic compounds on its surface that can be toxic to plant roots. Fortunately, if the PVC is regularly exposed to moisture or submerged in water, the phytotoxicity diminishes within a few months.

In nonflowing aerated systems, solution may drain back through the air lines if the air supply is stopped. If air lines are installed in the bottom of the culture vessel, check valves should be installed. If air lines are installed through the top of the vessel, siphoning can be prevented by making a small hole in the inlet tube above the solution (Hershey and Merritt, 1986). A num-

ber of containers can be aerated equally from one high-pressure manifold. A manifold can be constructed with a large diameter latex rubber tube fitted with No. 26 hypodermic needles. The latex rubber tube connected to a filtered air supply becomes a manifold for providing a uniform air supply, monitored through the hypodermic needles to each individual container by way of a plastic tube and a length of glass tubing inserted into the solution. The inside diameter of this glass tubing should exceed 5 mm to limit nutrient precipitation at the end of the tube, which eventually would restrict the air supply. The flow of air should be sufficient to cause rapid circulation of the nutrient solution. Do not use rubber tubing in direct contact with the nutrient solution because organic compounds can leach out and provide a carbon source for the proliferation of microorganisms.

Effective aeration can also be achieved by using an aquarium airstone at the end of an air line in each container; many aquarium airstones, however, contain CuSO_4 at levels that can be toxic to plants.

FLOWING

Flowing solution culture systems can provide a consistent nutrient environment for roots (Asher, 1981; Edwards and Asher, 1974). They are highly amenable to automatic control (Jenner and Starkey, 1980) but are subject to rapid plant desiccation if the flow of solution stops for any reason. Thus frequent attention is required, and alarm systems should be installed, if possible, to inform operators of failures in the system.

Individual containers: Several types of flowing solution cultures are available for individual containers (Hewitt, 1966). One system uses air-lift perfusion to continuously recirculate nutrient solution to individual containers (Guevarra et al., 1980). Solution from the base of the container flows through a glass tube into a short

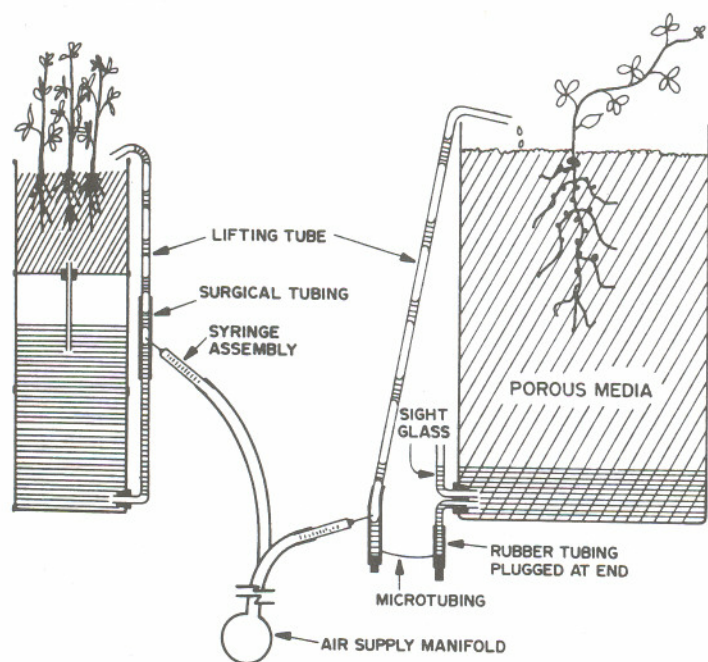


Figure 1. A schematic diagram of the airlift perfusion circulation system. (Guevarra et al. 1980).

section of rubber tube, which is plugged at the opposite end by a glass rod (Fig. 1). A short piece of polyethylene microtubing is inserted into the rubber tube and serves to regulate the flow of solution into the rubber tube at the base of the lifting tube (the longer the tubing, the less the flow). Air is then introduced into this tubing at a point below the level of solution in the pot.

A system for maintenance of a constant solution level has been described by Callahan and Engel (1986). Solution is moved from a reservoir to a distributor tank through a siphon delivery system. Essentially, the system is "closed" between the reservoir and distributor tank; the level of solution in the distributor tank is controlled by raising or lowering an air inlet tube in the airtight reservoir by the principle of a Mariotte's bottle (Fig. 2). The distributor tank then feeds the plant containers with a siphoning tube. A siphon drain tube, supported through a hole in the rubber-stopped lid of the plant containers, is used to maintain slow, continuous drainage. The siphoning drain must have a larger diameter and a lower flow rate than the siphoning feed. The nutrient solution reservoir volume must equal or exceed the volume of all the plant containers to allow uniform initial filling of each plant jar.

Another container system feeding 20 polyethylene containers from a common, recirculating nutrient solution is described by Tibbitts et al. (1978). As water is lost by evapotranspiration, the system automatically replenishes solution at a set rate to minimize changes in H^+ and nutrient ion concentrations. Nutrient solution (22 liters total) is aerated by continuously recirculating the solution through each plant container (solution drains through a tube in the middle of each container) and back into a 2-liter common PVC reservoir at a rate of at least 200 ml min^{-1} . The level of solution in the reservoir is controlled by a styrofoam float valve, which actuates a so-

lenoid valve to provide solution from a reserve nutrient solution carboy when the solution level is too low. A small pinhole in the supply tubes to each plant container prevents siphoning of solution from the plant containers if the pump should fail. The system automatically replenishes fresh nutrient solution at $5 \text{ liters day}^{-1}$ by dripping solution from the reservoir out a small diameter polyethylene tube. The length, diameter, and height of the tube relative to the pots control the drip rate and thus the solution replacement rate.

Nutrient Film Technique (NFT): The basic principle of NFT (Cooper, 1979; Graves, 1983) is that of recirculating a shallow stream (approx-

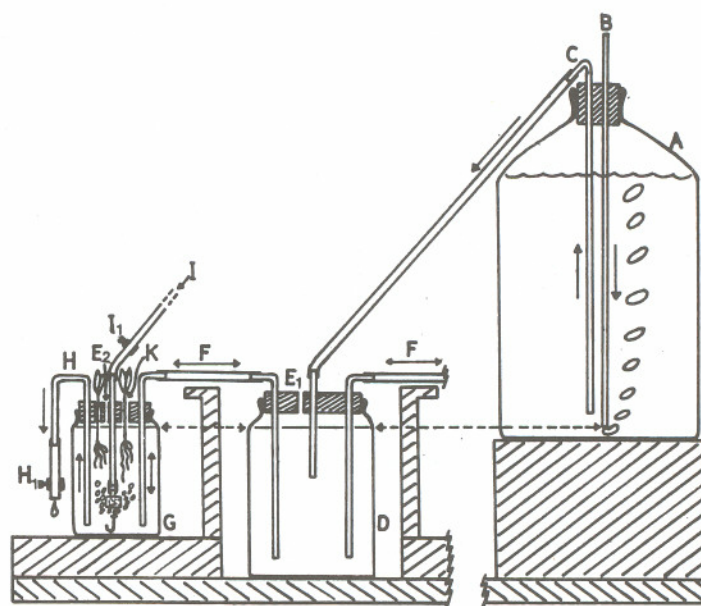


Figure 2. Side view of a single continuous flow nutrient solution renewal system showing only one of twelve plant culture jars (drawing not to scale).

- A=continuous flow nutrient solution reservoir. A rubber stopper in the top forms an airtight seal.
- B=Air inlet tube controls the head of solution flow into the distributor jar (D).
- C=Siphon delivery tube from reservoir (A) to distributor jar (D).
- D=Distributor jar for supporting several smaller plant culture jars (G).
- E₁, E₂=Open air holes in distributor jar (D) and plant culture jars (G).
- F=Siphon connector tubes between distributor jar (D) and plant culture jars (G).
- G= Plant culture jars.
- H=Siphon drain tube, and regulating screw clamp (H₁).
- I=Air induction system for forced aeration, and regulating screw clamp (I₁).
- J=Aquarium-type airstone for aerating the solution.
- K=Three 15-mm diam. holes in the rubber stopper of the plant culture jars (G) for mounting plants.

mately 3 mm deep) of nutrient solution over the roots to provide water, nutrients, and aeration. Plants are usually grown in a parallel series of sloping troughs made of polyethylene vinyl or other inert material. Solution is recirculated continuously or intermittently (Graves and Hurd, 1983) by a pump from a reservoir to the upper end of the troughs and flows through the plant roots until it reaches a catchment pipe that returns the solution by gravity to the reservoir below the trough level. The slope of troughs should be no less than 1%. Slightly steeper slopes (2 to 5%) are desirable to avoid stagnant areas along the trough (Spensley et al., 1978). The flow rate should be no less than 2 liters/min, but this will vary with the size and number of plants in each trough (Jenner and Starkey, 1980). The troughs should be covered to exclude light and provide a high relative humidity in the root zone.

Plants can be germinated in a seedling starter tray and then transplanted to NFT trays. The plants can be supported by polyurethane plugs inserted into holes in the rigid plastic cover or by small slits in the polyethylene film. Seedlings are sometimes germinated and grown in cubes of rockwool or compressed peat, which can be set in the bottom of the troughs to provide support for the seedlings.

INTERMITTENT SUBIRRIGATION

A common type of intermittent subirrigation culture uses a waterproof container filled with pea gravel, coarse sand, or other nonphytotoxic material plumbed to a nutrient solution reservoir. (See solid media chapter for discussion of particle size.) Because the solid matrix retains relatively little water and nutrients, the solution must be circulated from the supply tank to the beds several times per day. Several subirrigation systems are detailed by Resh (1989).

The media must be thoroughly washed before use; this will remove particles of soil or other

material that might clog the drain line. Between crops, the media can be treated by steam sterilization and/or an appropriate fungicide.

ROOT MISTING

In this application of closed system hydroponics, plant roots are suspended in midair in a misting box. Plants are supported through holes in a panel cover made of expanded polystyrene, PVC, or other material. The growing box is sealed to maintain a high RH and to keep out light to prevent algal growth. A misting system is used to spray nutrient solution on the plant roots continuously or for a few seconds every 2-3 minutes, depending on the application. Some systems recirculate the nutrient solution, whereas others discharge the solution to waste. Details of an effective misting system are provided by Gibony (1980). Centrifugal atomizers are often used instead of spray nozzles to keep nozzles clear of nutrient salts and provide long-term, continuous, fine misting.

A modified version of the root mist system has been developed by Soffer and Levinger (1980). They used narrow troughs (20 cm wide with a depth of 10 cm) with spray nozzles spaced at equal intervals that sprayed water onto the roots. The solution runs down the slanted troughs into a catchment tank and is recirculated through the system.

MEMBRANE

Membrane systems have been developed to deliver nutrients and water to plant roots under microgravity (e.g., space flight) conditions while still containing the nutrient solution within the system. These systems use a concept proposed by Wright and Bausch (1988) and further developed by Dreschel and Sager (1988), Koontz et al. (1990), and Tibbitts et al. (1995) for controlling nutrient solution supply by using the capillary properties of microporous, hydrophilic

membranes or tubes. Because of the capillary properties of the systems, the nutrient solution will not flow through the membrane or tubes when the solution is maintained at a small negative pressure relative to the atmosphere, commonly in the range of -0.5 to -1.0 kPa.

A number of plant species have been grown in the porous membrane systems with yields comparable to those obtained in the field. Trials with wheat indicated that plants grow better with a negative water potential of -0.5 kPa than at -0.8 or -3.0 kPa (Berry et al., 1992).

NUTRITION

Much of the information on nutrition in hydroponic systems is similar to that detailed in the chapter "Plant Culture in Solid Media." The use of recirculating systems, however, and the lack of media to buffer pH changes, requires more precise monitoring and control of the nutrient solution.

FORMULATIONS

Formulations are detailed in the preceding chapter, "Plant Culture in Solid Medium."

Hydroponic systems provide an opportunity to study individual nutrient deficiencies, which are difficult to study in soil culture. Tables 1 and

2 give formulas for making solutions deficient in each macronutrient. If nutrient stress or deficiency symptoms are desired on larger and/or more mature plants, it is desirable to grow them for a period of time in a complete nutrient solution before changing to a deficient or nutrient-limiting solution. Seeds germinated on truly deficient nutrient solutions will not grow beyond the seedling stage (typically 4 or 5 days), thus only very small plants showing very acute deficiency symptoms will be obtained. This is especially so for small-seeded plants and for deficiency studies of the macronutrients.

MIXING

Mixing procedures are detailed in the preceding chapter, "Plant Culture in Solid Media."

CONCENTRATION CONTROL

When nutrients are recirculated in a hydroponic system, each nutrient must be maintained at the desired concentration. Concentrations will change as plants take up nutrients and as water is lost from the system through transpiration and evaporation. Solution concentration changes that occur during growth are difficult to predict because of the difficulty of calculating or measuring transpiration rates and uptake of each

Table 1. Composition of deficient nutrient solutions

	Complete solution (m mol/L)	Deficient solution (m mol/L)					
		N	P	K	Ca	Mg	SO ₄
Cations							
Na	0.5	0.5	0.5	0.5	0.5	0.5	0.5
K	4	4	4	0	8	4	4
Mg	1	1	1	1	1.5	0	1
Ca	2.5	2.5	2.5	4.5	0	3.5	2.5
Anions							
NO ₃	7	0	7	8	7	7	7
PO ₄	1	2	0	1	1	1	2
SO ₄	1.5	2.5	2	1	1.5	1.5	0
Cl	0.5	4.5	0.5	0.5	0.5	0.5	2.5

Note: Micronutrients in mg/liter are 0.25 B, 0.25 Mn, 0.025 Zn, 0.01 Cu, 0.005 Mo, and 2.5 Fe as the EDTA complex. All solutions are designed to have the same total salt concentration.

Table 2. Preparation of nutrient solutions deficient in one of the essential macronutrients

Stock solution	Complete solution (ml/L)	Deficient solutions (ml/L)						Molecular weight
		N	P	K	Ca	Mg	SO ₄	
1M Ca (NO ₃) ₂ ·4H ₂ O	2.5	0	2.5	4	0	3.5	2.5	236.16
1M KNO ₃	2	0	2	0	7	0	2	101.10
0.5M K ₂ SO ₄	1	3	2	0	0	3	0	174.26
1M MgSO ₄ ·7H ₂ O	1	1	1	1	1.5	0	0	246.48
1M KH ₂ PO ₄	1	1	0	0	1	1	2	136.09
1M NaCl	0.5	0.5	0.5	0.5	0.5	0.5	0.5	58.45
Iron*	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
Micronutrients**	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
0.05M Ca (H ₂ PO ₄) ₂ ·H ₂ O	0	10	0	10	0	0	0	252.07
1M CaCl ₂	0	2	0	0	0	0	0	110.99
1M MgCl ₂	0	0	0	0	0	0	1	95.23

*330 Fe concentrate at 50g/L. Store in refrigerator.

**Micronutrients in ,g/liter in the final solution are 0.25 B, 0.25 Mn, 0.025 Zn, 0.01 Cu, .005 Mo, and 2.5 Fe s the EDTA complex. See page 109 for formulation.

nutrient by the plant as it develops and matures.

Desired nutrient concentrations can be maintained by continuously leaking a significant quantity of solution from the recirculating system. Thus, the solution is replenished with the desired concentration of nutrients, which can be changed as the plant goes through different phases of growth. The leakage rate can be determined by monitoring solution electrical conductivity(EC). As plants enlarge, this leakage rate should be increased.

Nutrient concentrations can be adjusted either manually or automatically after measurements of the EC. It is common to prepare two stock solutions, one containing calcium nitrate and iron and the other containing all the required chemicals, to prevent precipitation of calcium phosphate. Whenever the conductivity changes more than desired from the original, the appropriate amounts of both the concentrates are added until the reference EC level is restored. The reference EC level is approximately 1 dS m⁻¹ for hydroponic formulations, similar to half-strength Hoagland's solution. Under average growth chamber conditions, during vegetative growth the amount of concentrate required will be close to the amount necessary to make the

make-up water similar to the original half-strength Hoagland's solution. This amount of concentrate will vary slightly, however, depending on environmental conditions and plant species. When the plants are subjected to high vapor pressure deficits and are transpiring rapidly, they will require less nutrients per liter of make-up water than when transpiring slowly. The amount of nutrient required is more closely associated with growth than with transpiration.

The electrical conductivity of the solution gives a measure of total salt concentration (Richards, 1954), but it does not provide information about individual elements and is nearly unaffected by the levels of micronutrients in solution. Because the fertilizer concentrates are not matched to the nutrients utilized by the crop, eventually the composition of the nutrient solution will change, with some nutrients accumulating and others becoming depleted. Maintaining accurate control of nutrients in solution requires periodic chemical analysis. The timing of the analysis depends on the degree of control desired and the rate of biomass accumulation.

Significant amounts of micronutrients found can be as contaminants in macronutrient salts and the supply water. They also can be released

from the plumbing and system containers, including the gravel and sand used for plant support. Choose only inert material, such as quartz sand, and wash it thoroughly before using. For micro-nutrient deficiency studies, an additional wash in 1.2M HCl followed by a number of distilled water rinses (3 to 5) is recommended.

In hydroponics, because of the limited nutrient-buffering capacity of the system and the ability to make rapid changes, it is necessary to carefully monitor the system. Two aspects of nutrition need to be considered: the supply of nutrients from the nutrient delivery system and the plant nutrient response. The plant response, or nutrient status, is usually determined by elemental analysis of the most recently matured leaves. Tissue analysis determines whether changes are needed, and solution analysis provides information as to what changes are needed and to what degree. For most common crop plants, critical levels for most nutrients have been determined (Chapman, 1966; Jones et al., 1991). The American Society of Agronomy has a publication describing the most common analytical methods for tissue and soil (Page et al., 1983).

pH CONTROL

In hydroponic culture, pH changes with the uptake of excess amounts of either cations or anions relative to one another. For example, if the plant takes in nitrate anions, the solution pH tends to become more basic. If the plant takes in potassium cations, the solution pH tends to become more acidic. Because the pH buffering capacity of hydroponic systems is relatively low, the pH tends to change rapidly and can reach levels that will limit the availability of a number of essential nutrients. In acidic solutions (low pH), manganese and aluminum are solubilized and are readily available, and in very acidic solutions ($\text{pH} < 5$), they may become toxic. In basic solutions ($\text{pH} > 6.5$), the avail-

ability of many of the trace elements decreases (Zn, Cu, and Fe); thus, as the pH increases, larger and larger amounts of these elements are required to maintain availability. As a general rule, problems will develop when more than a third of the solution nutrients are absorbed by the plants. Thus, pH control is a necessity in hydroponic solutions that are not renewed frequently.

DESIRABLE RANGE

The pH range of 5.5 to 6.5 is optimal for the availability of nutrients from most nutrient solutions for most species, but species differ significantly and several can grow well outside of this range (Islam et al., 1980). The pH requirements for species commonly grown in growth chambers is provided in Appendix A.

MONITORING

In hydroponic systems, pH is constantly changing as the plant grows. Changes in pH of less than 0.1 pH unit are not significant in most hydroponic experiments. The pH should be monitored with a pH electrode made of glass (unless there is danger of breakage). Inexpensive pH meters, even the pocket-sized pH meters with glass electrodes, are adequate for most hydroponic experiments. However, all pH meters require periodic calibration against pH buffers. This calibration should be undertaken every time the meter is turned on. In nutrient systems, electrodes left in the solution for a period of time can become covered with a biofilm that will affect its readings; thus, electrodes should be cleaned on a routine basis. It is difficult to obtain precise pH measurements with pH papers in complex and dynamic systems such as hydroponics, for the pH determined by pH-sensitive paper is affected by the composition of the nutrient solution and the light quality in which it is read.

ADJUSTMENT

The pH of individual containers is usually controlled with additions of either acid or base. Rapid plant growth can result in rapid pH changes, and some method of buffering pH is desirable. Unfortunately, all buffering compounds used to stabilize pH have disadvantages when used at high concentrations. Inorganic buffers (borate, phosphate) can be phytotoxic when used at the levels necessary to provide adequate buffering capacity. Solid carbonate salts can stabilize pH, but at the relatively high pH characteristic of carbonate salts, nutrient absorption will be affected. Ion exchange resins are effective buffers, but they also will absorb nutrient elements from solution and buffer them. The organic buffer MES (2-N morpholino ethanesulfonic acid) is effective at concentrations above 1 mM (Bugbee and Salisbury, 1985), but in some plant species this concentration of MES affects the uptake of other elements (Miyasaka et al., 1988). The MES buffer seems to be the buffer of choice when necessary, but it is still very expensive and less than ideal.

Because of the limitations of buffers, pH is controlled preferably with automatic pH controllers. An automatic pH controller monitors pH and controls either a pump or a solenoid valve that adds a pH control solution to the bulk solution. Acids or bases are typically used for pH

control. Table 3 provides information for dilution of common acids and bases. Nitric acid is preferable to hydrochloric or sulfuric acid because it helps to maintain the nitrogen concentration in solution. For the same reason, potassium or calcium hydroxide is preferable to sodium hydroxide. Calcium hydroxide is difficult to use because it is only slightly soluble in water, and solutions must either be very dilute or be agitated to maintain the calcium hydroxide in suspension.

Because the direction of pH change in the nutrient solution is strongly influenced by the form of nitrogen used, it usually is not necessary to use both acid and base if only one form of nitrogen is used in the nutrient solution. If ammonium is the predominant form of nitrogen absorbed, a base is necessary to keep pH up, whereas if nitrate is the predominant form absorbed, an acid is necessary to keep the pH down. As plants absorb anions (NO_3^- , H_2PO_4^- , SO_4^{2-} , and Cl^-) from the solution, they maintain charge balance by excreting hydroxyl anions. Conversely, as cations (K, Ca, Mg, NH_4^+ , and Na) are absorbed, hydrogen ions are excreted into solution.

It has been proposed that the pH of hydroponic solutions can be partly controlled by the nitrate/ammonium ratio in the solution (Trelease and Trelease, 1935). This procedure

Table 3. Composition of concentrated reagent acids and hydride solutions

	HCl	HNO_3	HClO_4	H_2SO_4
Molecular wt.	32.46	63.01	100.46	98.08
Specific gravity of conc. reagent*	1.19	1.42	1.67	1.84
Strength (w/w) of conc. reagent (%)	37.2	70.4	70.5	96.0
Molarity of conc. Reagent	12.1	15.9	11.7	18.0
ml conc. reagent per liter for a one molar solution	82.5	63.0	85.5	55.5
	H_3PO_4	NH_4OH	NaOH	KOH
Molecular wt.	98.00	35.05	39.99	56.10
Specific gravity of conc. reagent*	1.70	0.90	1.54	1.46
Strength (w/w) of conc. reagent (%)	85.5	57.6	50.5	45.0
Molarity of conc. reagent	14.8	14.8	19.4	11.7
ml conc. reagent per liter for a one molar solution	67.5	67.5	51.4	85.5

*Approximate.

suggests that a stable pH would result if similar rates of ammonium and nitrate uptake could be maintained. This sounds straightforward, but most plants absorb ammonium preferentially over nitrate. The problem is to continuously renew low levels of ammonium in solution. A partial answer is to add ammonium with the pH control solution. When the pH increases to the set level, the controller opens a solenoid that adds a pH control solution with both nitric acid and ammonium nitrate. The nitric acid quickly reduces the pH in a localized area around the electrode, and the solenoid closes. The ammonium added to the solution results in the plant producing additional acid as the ammonium is absorbed. Plants then absorb the nitrate, and the pH increases, causing the pH controller to open the solenoid and repeat the cycle. This method of pH control supplies both forms of nitrogen to the plants, which is reported to increase nitrogen uptake and improve plant growth (Trelease and Trelase, 1935).

OXYGEN LEVEL

For rapid growth, the rooting medium must supply sufficient O_2 for root respiration. Roots require water in their surrounding environment, but water is an effective barrier to the rapid diffusion of gases. For example, O_2 moves 12,000 times more slowly through water than through air under a given set of environmental conditions (Burg and Burg, 1965). In nutrient culture systems, the more deeply the roots are submerged, the greater is the barrier to gas movement between roots and the aerial environment, unless the solution is aerated. The O_2 content of water saturated with O_2 depends upon temperature, barometric pressure, and, to a limited extent, salt concentration. The amount of roots that plants are producing, the nutrient flow rate, and the microbial population determine the amount of O_2 required for good root growth. At a tem-

perature of 20 °C at sea level, pure water contains 9.62 mg L⁻¹ of O_2 . Increasing temperatures increase the roots' respiration rate, and with each 10° rise in temperature, the demand for O_2 is doubled (Jackson, 1980). The required O_2 content of solutions has also been found to be species dependent, with mature cucumbers removing more O_2 from solution than mature tomatoes (Gislerod and Kempton, 1983). Anaerobic root conditions (low O_2) can result in wilting, epinastic curvature of leaves, leaf chlorosis, slow extension growth of leaves and stems, slow rates of dry matter production, and many other physiological growth-limiting responses. In many instances, concentrations between $1/2$ and $3/4$ of that found in saturated water can reduce growth and affect morphology of plants (Bertani and Branbilla, 1983). Jackson et al. (1984) found that addition of inorganic, open-structured materials such as rockwool or perlite to peat or peat-sand composts reduced the risks of aeration stress. Low solution flow rates ($< 2 \text{ L min}^{-1}$) also can result in dramatically falling O_2 concentrations in NFT systems (Maher, 1977). Edwards and Asher (1974) in reviewing research with nutrient systems, found that flow rates of most systems were not adequate to maintain uniform O_2 concentrations throughout the system. Because differences in the size of the boundary layer are a function of flow rate, the minimum concentration of O_2 required in bulk solution depends heavily on solution flow rate.

WATER PURIFICATION

Use purified water in the preparation of all hydroponic solutions. Tap water is not recommended for preparation of nutrient solutions because of the high likelihood of contaminants (such as boron) or high salt concentrations that could adversely influence plant growth. When water softeners are used to replace the Ca and Mg with sodium, salt damage likely will result.

Indeed, it is highly recommended that softened water never be used for horticultural purposes. Water should be purified by distillation, deionization, or reverse osmosis.

CONTAMINANT CONTROL

REMOVAL OF ORGANIC COMPOUNDS

Organic compounds can be removed with a charcoal filter, but it is difficult to quantify organic compounds in water, and knowledge of their effect on plant growth is inadequate. Therefore, most hydroponic studies have been conducted without filtering or monitoring organic compounds in solution. Charcoal has a high affinity for high-molecular-weight, hydrophobic compounds. It is particularly effective when used with ion exchange resins (which remove charged, hydrophilic compounds).

If the charcoal filter is put in line after the deionization columns or tanks, it will be exposed to relatively pure water and thus will have a longer life than if it is placed before the ion exchange resins. Different brands of charcoal filters vary widely in both their removal efficiency and their lifetime.

SYSTEM COMPONENTS

All pipework and ancillary fittings (valves, connectors, etc.) should be made of plastic. Metal fittings, such as brass and copper, will contribute significant and potentially toxic amounts of zinc and copper to the solution. Stainless steel or plastic-bodied pumps of the self-priming type should be used in hydroponic systems.

Some additives in flexible PVC, particularly plasticizers such as dibutyl phthalate (DBP), are phytotoxic (BAHPA, 1979). Rigid PVC, acrylonitrile butadiene styrene, or Alkathene piping is preferable for usage. Vapors of DBP also were found in glazing strips, aluminized plastic liners, flexible plastic pots, and thermocouple wire (Hardwick et al., 1984). The concen-

tration of DBP vapor in air from glazing strips was sufficient to significantly inhibit growth of cabbage in a greenhouse.

Epoxy resins used in paints and sealants release toxins upon drying and, therefore, often require a curing time of months (Tibbitts et al., 1977). They should be avoided when possible. Conventionally used sealants, such as apiezon grease, paraffin, Vaseline, lanolin, and vacuum grease, all produce hydrocarbons that may have phytotoxic effects (Bassi and Spencer, 1979). Silicone sealant (such as that by Dow Corning) produces only low quantities of hydrocarbons, but the release of acetic acid during curing makes it unsuitable for use around stems. Some forms of silicone sealant, however, use water rather than acetic acid for curing. Cellulose water-based Polyfilla (FMC of Canada Ltd., Burlington, Ontario) was found to be quite suitable as a sealant.

ALGAE CONTROL

Many surfaces can be infiltrated by algae, including glass, plastic, benches, walls and floors of the growth chamber, mats, surfaces of the root-zone medium, and even surfaces of the plants. Infestation can damage the surface, serve as a breeding ground for pathogens, interfere with the transmission of light, and impede access of plant roots to water and nutrients.

Good housekeeping is the best method of controlling algae. For example, surfaces should be kept dry, and black plastic overlays should be used under the plants to limit light. Nutrient stock solutions should be kept in the dark and cool to reduce growth of algae. Sanitation of reused plastic system components and benches will reduce algal populations after a crop is removed from the chamber. Typical sanitizers include chlorine bleach solution, quaternary ammonium chloride salts, cryptocidal soaps, and phenolic materials. The major problem with these materials is that they do not leave a pro-

tective residue, nor will they remove particulate material. Copper sulfate has been used underneath benches to control algal growth, but copper toxicity occurs in plants at very low concentrations in the nutrient solution, >0.5 ppm (Powell, 1986; Berry, 1978).

MICROORGANISM CONTROL

Sterile root-zone environments are extremely difficult to achieve and are required only for very specialized research. It is critical, however, to minimize plant pathogens in the root-zone. Sub-micron filtration (0.2 to 0.4 μm pore size) effectively removes microorganisms when used as the final filter in a water purification system, although filter elements must be replaced frequently to maintain system efficiency (Schwartzkopf et al., 1987). Some bacteria have the ability to grow through the pores in the filter, thus limiting the effective use of filtration to short periods of time.

If proper sanitation procedures are used, most recirculating hydroponic systems will not be limited by root-infecting plant pathogens. Many sanitized systems, however, have become infected with pathogens, possibly because of inadequate sanitation or low plant tolerance due to other environmental stresses (Csinos and Hendrix, 1978).

Organisms commonly encountered in hydroponic solutions are the wilts caused by *Fusarium* and *Verticillium*, and species of *Pythium* and *Phytophthora*, which destroy all but the main roots. These can cause serious problems when injury starts because there are no effective fungicides cleared for use in hydroponics. A chemical, metalaxyl, has been highly effective for control of *Pythium* on vegetable crops growing in recirculating hydroponic conditions, but it is not registered for this use. Root death of tomatoes by *Pythium* infestation was overcome by heating nutrient solutions to 20-22°C (Davies, 1980).

Using ultraviolet (UV) radiation is one way to counteract infection. A combination of UV lamps with a minimum energy output of 25 mW $\text{cm}^{-2} \text{sec}^{-1}$ and a solution flow rate of 2.2 L min^{-1} through the purifiers reduced counts of bacterial plant pathogens to less than 5% of that attained with no irradiation control (Ewart and Chrimes, 1980). Buyanovsky et al. (1981) showed that a 4-hr exposure was sufficient to remove 90% of solution bacterial populations. Ultraviolet-treated water specifically controlled root rot of spinach caused by *Pythium aphanidermatum* (Bates and Stanghellini, 1984). Ultraviolet irradiation does cause an iron chlorosis due to destruction of iron chelate (Daughtrey and Schippers, 1980). This problem can be eliminated by regular additions of iron to the nutrient solution (Schwartzkopf et al., 1987).

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