

LIQUID CULTURE HYDROPONIC
SYSTEM OPERATION

12

Neil Mattson¹ and J. Heinrich Lieth²¹*Horticulture Section, School of Integrative Plant Science, Cornell University, Ithaca, NY, United States*²*Department of Plant Sciences, University of California, Davis, CA, United States*

Growing plants in “liquid culture” or “water culture,” without the use of any solid substrates, has been around for decades. The key in this type of plant production is that the water has nutrients and oxygen dissolved in the water at levels that lead to high rates of plant growth. The roots of the plants are grown within this solution.

Initially, water culture was used to better understand the role of soil in plant growth. In 1699, John Woodward published an experiment with spearmint, whereby plants grown in water containing a soil extract had much greater growth than plants growing in distilled water. [von Liebig \(1840\)](#) promoted the concept that soil was not necessarily required for plant growth but that it contributed mineral elements necessary for plant growth, specifically potassium, phosphate, and ammonium. During the intervening decades, several scientists employed the water culture method to determine the necessity of various mineral elements in plant growth which led to the development of various nutrient solution recipes. One of these early recipes was proposed by Johannes Sachs in 1860 and contained potassium nitrate, calcium phosphate, magnesium sulfate, calcium sulfate, sodium chloride, and iron sulfate ([Hoagland and Arnon, 1950](#)). Nutrient solution recipes were further refined as scientists became aware of additional elements essential for plant growth.

The term “hydroponics” was coined by [Gericke \(1937\)](#) to mean water culture without employing any substrate. Over time the term hydroponics has evolved to encompass a broader meaning to include any of the soilless culture methods where the nutrient solution moves past the roots of the plants either continuously or many times per day regardless of whether there are solids in the root zone, as long as the substrates do not restrict the flow of the nutrient solution. Some sort of substrate may well provide stability to the plant and to provide an inert matrix which may provide some benefits such as providing air porosity or increased water retention. In addition to including systems where the roots are within a substrate matrix, systems where relatively small amounts of water are continuously or frequently move to the roots within a volume that includes mostly air, and without any substrates at all, are also considered hydroponic systems.

Strictly speaking, however, hydroponics is the practice of growing plants in nutrient solutions where the roots are exposed to nutrients in a dynamic manner. Any nutrient molecule dissolved in the water has an opportunity to interact with a root surface many times in a short time, perhaps

even as a continuous flow. Furthermore, such nutrients are the only source of nutrients. This is in contrast with conventional potted plant production in organic substrate where the organic matter contributes to the nutrients which the plant takes up. Also in conventional potted plant production, irrigation is provided only when a considerable amount of the water has been taken up by the plants. Such conventional irrigation practices place water into the root zone less often than with hydroponic systems. Between irrigation events, the transport of nutrients from the root zone to the root surface is accomplished through diffusion along the concentration gradient set up by the root taking up nutrients. Ion transport from roots to shoots then occurs both passively (through the transpiration stream as plants take up water) and actively (through channels and pumps which can allow for uptake against a concentration gradient).

In hydroponics, water flows through the root zone during irrigation events. During such movement of water, the nutrient molecules dissolved in this water move at speeds that are several orders of magnitude greater than the diffusion processes. This type of movement is termed “bulk flow.” A key facet of all hydroponic systems is that bulk flow is used much more extensively to move nutrients and as such the root surfaces are exposed to more nutrient molecules at greater rates. Furthermore, these rates are so much larger that typical hydroponic nutrient solutions can be much more dilute than conventional irrigation nutrient solutions yet still give the plant as much or more opportunity to take up nutrients. Such low concentrations of nutrient solutions, as measured by lower electrical conductivity (EC) level (less salinity), can be very beneficial to plant growth as described in Chapter 6, Nutrition of Substrate-Grown Plants.

Prior to the advent of hydroponic plant production, fertilizers were provided to the root zone of plants through a combination of organic materials, nonsoluble substrates, slowly dissolving fertilizer products as well as ionic formulations where the fertilizers were salts which dissolved to provide the nutrients which the plant needs. Invariably such salts included some anions or cations which were not particularly useful to the plant or which the plant needs only in smaller amounts (e.g., Na^+ , Cl^-). When organic compounds are used to provide nutrients, microbes are generally depended on to release the nutrients. By the mid-1930s [Gericke \(1937\)](#) reported that agricultural crops (vegetables and flowers) had been produced for market employing hydroponic techniques. The publication of Hoagland’s nutrient formulation ([Hoagland and Arnon, 1938](#) and revised in [Hoagland and Arnon, 1950](#)) led to increased commercial plant production using hydroponics either in true solution culture or with an inert substrate such as gravel or sand.

One logical conclusion that might be drawn from the above is that one could simply increase the concentrations of desired nutrient ions in the nutrient solution and to thus make the bulk flow less of an imperative. When one tries to increase the nutrient load in a nutrient solution above certain levels, the result is less growth by the plants. This is due to the fact that total salinity has an effect on the osmotic potential. Thus there is a maximum concentration for the total nutrient load and once this maximum is exceeded, the plant experiences reductions in growth. So there is a trade-off between more nutrient availability and negative effect due to salinity. The latter can be measured with EC. A general guide in soilless culture has been to avoid EC levels above 3 dS/m but this is only a general guide, as the threshold EC value is species and cultivar dependent and is affected by the environmental conditions.

Over time, several types of liquid culture systems have been used commercially. The earliest systems we identify today as “Deep Flow” or “Deep Water Culture” are basically a relatively large vessel filled with nutrient solution with the roots dispersed freely in this liquid ([Fig. 12.1](#)).

**FIGURE 12.1**

Deep water culture.

It is well known that oxygen has to be forced into this water and that without it, plants would suffer from “water logging” which is basically oxygen starvation. To avoid oxygen depletion, air is introduced at a rate required to maintain the appropriate level of dissolved oxygen (normally, around 8 ppm). Water can also pick up oxygen from the surface as long as there is adequate head space above the water and oxygen can freely diffuse into this head space. As such, the concept of aeration is a key feature of hydroponics and can be accomplished with either bubbling with an air/aquarium pump, by causing the nutrient solution to be splashed or frequently moved to the surface with a water pump, or use of a pump with a Venturi air intake to aerate the return water. Commercially, some deep flow systems also inject oxygen from a tank, which can allow for supersaturated dissolved oxygen (Goto et al., 1996), but more often is used as alternative to mechanical pumping and to ensure adequate dissolved oxygen in large commercial installations.

One facet to liquid culture systems is that it is important to minimize the amount of nutrient solution that is exposed directly to light. Growth of algae in the system will proliferate if light is not restricted since the nutrient solution is just as optimal for algae as the crops being grown. It is unavoidable that some algal growth will be present in nearly all systems. The antagonistic effect of algae is twofold: (1) the algae take nutrients and dissolved oxygen that are destined for the crop and thus compete with the crop and (2) the proliferating cells will cause unattractive sludge and perhaps clog components in the system, such as filters and drip emitters. There is an entire industry that uses the algae as the crop for energy, biomass, etc.; in that domain, the nutrient solution containing algae is exposed explicitly to high light and dissolved oxygen to maximize their production.

The other reason why light is avoided is because blue and ultraviolet light degrades chelating molecules which can then lead to iron/micronutrient deficiency (Albano and Miller, 2001).

12.1 TYPES OF HYDROPONIC SYSTEMS

Many hydroponic systems are described with technical detail in Chapter 13, Technical Equipment in Soilless Production Systems. So here we define terms for later use in this chapter where the discussion focuses on crops and operations. As such, specifics about system design are handled in Chapter 13, Technical Equipment in Soilless Production Systems. It is relevant that the popularity of hydroponics is increasing steadily as both commercial and noncommercial (hobby; home-use) installations are increasing. This has resulted in hydroponics supply stores springing up in many communities, even in small towns. This itself is encouraging further expansion of the market because the technical elements (fertilizers, pumps, systems) are easy to obtain.

Deep Flow systems, as mentioned above, involve a relatively large body of water in which the roots are suspended (Fig. 12.1). The plant is held above the water surface and all fertilizer nutrients are dissolved in the water. These types of systems can range in size from buckets to ponds. Generally commercial installations are aerated with both air pumps (or by injecting oxygen from tanks) and water pumps. Water movement is important to ensure proper mixing/replenishment of nutrients and dissolved oxygen. The flow rate and water movement are customized by the grower, increasing either if oxygen becomes deficient or the plant shows signs of nutrient deficiency.

One type of implementation, sometime referred to as a “raceway,” has the vessel consisting of a long trough where water is pumped in at one end and allowed to flow to the other end where the pump intake is located. The system is level so that the motion of the water is imposed by the pump.

Deep Flow systems can have the plants mounted by holders that hold the plants above the water and only the roots and end of the stems are in the water. Another approach is to mount the plants on floats (often insulation boards) which have adequate buoyancy to keep the crown of the plant above water at all times. This is also sometimes referred to as a “raft/pond” system.

Nutrient film technique (NFT) uses an approach whereby roots are suspended in a trough whereby a thin layer of nutrient solution is continually recirculated. The NFT system was developed beginning in the late 1960s by Cooper (1975). Since only a thin film of water is used at a time, the system has less water during operation than deep water systems. However, that does not mean that it uses less water. Water use is a function of transpiration of the plant and that could easily be the same for all hydroponic systems.

NFT systems (Fig. 12.2) consist of long white channels with holes in the top side for mounting the plants. The plants grow through these holes while the roots stay in the channel where the relative humidity is 100% and the layer of water is flowing from one end to the other using the force of gravity. A slope of 1%–4% is typically maintained from the end of the channel where water flows in, to the drain end so as to obtain adequate water flow and drainage. The drainage water is captured and reused directly to prevent the NFT root film from drying out.



FIGURE 12.2

NFT system. *NFT*, Nutrient film technique.

Aeroponics involves spraying the nutrient solution onto the roots by pushing the nutrient solution through misters either continuously or many times per hour within the root zone. The root zone is primarily air and the roots, the water quantity is similar to NFT in that only the floor of the root zone is wet and it is constantly draining back into a reservoir. The water is filtered as part of the continual reuse, so as to avoid clogging the misters in the root zone.

“Aerohydroponics” was developed as the Ein Gedi system (Fig. 12.3) in the 1980s (Soffer, 1986; Soffer et al., 1991). It is a hybrid between Deep Flow and Aeroponics. It was commercialized by General Hydroponics and, as such, accounts for a very large installed base in the United States and Europe, mostly in the hands of urban growers. As with Deep Flow there is a relatively large amount of nutrient solution in the root zone, and as with aeroponics, there is a relatively large amount of head space above the nutrient solution which is continually misted onto the roots. Here some roots are suspended in humid air and other roots are suspended in the reservoir. The frequent misting is responsible for saturated dissolved oxygen concentration of the nutrient solution so that both nutrient and oxygen availability are maximized. The original Ein Gedi system also had a speed control for the spraying so that it was possible to fine-tune the oxygen concentration and even control it down to near zero oxygen for research purposes (Soffer et al., 1991). While this system consisted of a large round tub equipped with spinner for creating the mist, another version consisted of a long channel with holes in the top to accommodate a plant.

The above hydroponic systems often use small amounts of substrate to anchor the plant into the system as well as for early development of seedlings/cuttings prior to transplanting into the system. Inorganic substrates such as rockwool or phenolic foam (e.g., oasis) are most frequently used; however, it is possible to get excellent plant production results with some organic substrates as long as the organic substrate is slow to decompose. The decomposition process releases nutrients and changes the substrate physical properties. Coconut coir, peat, and various organic/inorganic mixes



FIGURE 12.3

Ein Gedi aeroponic system seen with banana tree growing within it. Note spinner motor (black) on top with control for rate of aeration.

have been used successfully and many growers prefer using organic media rather than inorganic media in such systems. When used in these solution culture hydroponic systems, these organic substrates may be glued together or held by a wrapper to avoid the components being lost into the solution which can clog pumps and emitters.

The selection of which system to use for a given application often relates more to logistical considerations than to differences in plant performance between the different systems. Some of the practical considerations include installation and maintenance cost, labor efficiency and automation, ability to respace plants (more common in deep flow vs NFT) to improve space efficiency, and ability to control root zone conditions. For example, deep water ponds are often 20–30 cm in water height. This large volume of water reduces fluctuations in temperature, dissolved oxygen, pH, and nutrition as compared with NFT which typically utilizes a much smaller volume of water in the reservoir. As stated earlier, actual water consumption of the two systems is typically similar, depending primarily on plant transpiration. Because of the large surface area between channels and the aerial environment and the relatively smaller volume reservoir, solution temperature is more difficult to control for NFT as compared to deep flow systems. [Thompson et al. \(1998\)](#) reported that control of solution temperature to 24°C for lettuce

(*Lactuca sativa*) “Ostinata” in deep flow allowed for acceptable lettuce production under otherwise unacceptably high air temperatures (31/26°C day/night). Ikeda et al. (1994) grew several spinach varieties in deep flow and NFT. Interestingly they found greater yield in deep flow during the winter but with NFT during the summer. When comparing deep flow to NFT for basil (*Ocimum basilicum*), Walters and Currey (2015) found only subtle differences in yield between the two systems when water temperature, aerial environment, and nutrient solution were held similar.

12.2 WATER QUALITY

In closed hydroponic systems, such as deep flow, NFT, and aeroponics, the irrigation water is captured and reused whereas in open systems it is not. EC of source water should ideally be less than 0.25 dS/m for closed systems. Many hydroponic growers have found it necessary to filter source water and perhaps use reverse osmosis to remove some solutes so that it is pure enough for closed hydroponic systems. It is relevant that any solute in the water can only leave the root zone by either entering the plants or by having some of the nutrient solution discarded. These solutes consist of whatever is dissolved in the source water (e.g., calcium carbonate, etc.) and fertilizers put there by the manager. Water that evaporates from the nutrient solution does not carry these solutes out, leading to a gradual concentration buildup. Furthermore, then plants take up water and nutrients somewhat independently, and especially take up more water in response to a need to cool the foliage through evapotranspiration. All this points to the need for nutrient solutions to be as light in these solutes as possible.

The way to counter salt buildup in closed systems is to blend in fresh water with little or no solutes, or, if this is not possible, then purposely drain off and discard some proportion of the nutrient solution and replace this with fresh water. In open systems the buildup of salts can be managed by applying excess water to leach out soluble salts. Therefore, source water EC can be higher than in closed systems; ideally less than 1.0 dS/m. The issue of the effects and management of EC in opened and closed systems is further discussed in Chapter 10, Water and Nutrient Management and Crops Response to Nutrient Solution Recycling in Soilless Growing Systems in Greenhouses.

12.3 CONTROLLING THE NUTRIENTS IN HYDROPONIC SYSTEMS

Perhaps the most difficult facet of operating a hydroponic system is to manage, over days and weeks, the many nutrients which the plants needs to take up through the roots. The key facet of hydroponics is to capture all leachate and to reuse it as much as possible by pumping the water through a process system (filtration, disinfestation, injection of nutrients, etc.). The technical and scientific details of this are covered in Chapter 10, Water and Nutrient Management and Crops Response to Nutrient Solution Recycling in Soilless Growing Systems in Greenhouses. Theoretically, if we can have a system where the injected nutrients are in perfect balance with what

the plants take out of the nutrient solution, then we can avoid discharging water from the system and the only water lost is through transpiration. While this is easy to consider, it is not at all easy to do, particularly if the environment around the plant is changing, thus affecting transpiration and growth differently in relation to the targeted growth.

The key problem is that there are many nutrients and the plants use each at different rates, at different times (see Chapter 6: Nutrition of Substrate-Grown Plants). To provide exactly what the plant needs requires a method for predicting this for the particular plants. Models can be used but most are not as yet adequately accurate to account for all the possibilities.

Ideally we would have a sensor for every nutrient that is dissolved in the water (N, P, K, Fe, Ca, etc.) as well as the compounds which are undesirable (e.g., sodium) so as to be able to identify whether any one of these is insufficient (i.e., causing deficiency in the plant) or in excess (causing toxicity), preferably as a continuous variable with sensor systems at adequate resolution to allow for anticipation of undesirable conditions.

Achieving better control is indeed possible by obtaining more accurate measures of each nutrient in the nutrient solution. Many such in-line sensors exist but these are fairly expensive and may need frequent calibration and replacement so that growers generally seek a simpler, less expensive solution. It is also possible for growers to use in-house ion-specific probes or test kits to periodically measure many of the nutrients of interest (e.g., CleanGrow technology). This can still be time consuming and expensive, and accuracy depends again on frequent calibration. Another approach is to periodically send nutrient reservoir samples to analytical labs. However, the turn-around time tends to be slow and the expense is significant. Nevertheless, commercial producers using deep flow ponds often send nutrient solution for analysis every week or two and use the results to adjust the pond solution over time.

Ultimately, because exact nutrition composition is difficult to monitor, EC, a measure of total salinity (both fertilizer and nonfertilizer ions) is more practical for day-to-day monitoring and adjustment. While EC values do not tell us the nutrient composition, they give an indication as to the salinity and therefore provide some information as to the relative strength of the nutrient solution. Typically, EC is monitored not only to ensure there is adequate fertility but also to make sure salinity is below the level where it affects the growth of the plant through osmotic pressure. EC targets vary by crop but are often in the range of 1.0–2.5 dS/m from the fertilizer plus the EC contribution from the water source. A low EC indicates that not enough fertilizer is being supplied to meet plant needs. It is relevant that this approach to control is only possible through the use of nutrient solutions which contain ionic fertilizers. This makes it possible to use the measurement of salinity to account for changes in the nutrient solution. Urea is generally not used in recirculated hydroponics, in part for this reason, and partly due to potential for phytotoxicity.

Beyond EC, it is important to closely monitor and adjust nutrient solution pH. In some hydroponic systems, pH can swing more than one pH unit in the course of a day as the plants selectively remove certain ions during active growth. As such, production management may require testing more frequently than daily. Generally, the more water is in the system, the slower the pH fluctuations. When the principle source of nitrogen is nitrate, its consumption by the plant results in rising pH, while nitrogen consumed as ammonium tends to lower the pH. As such, growers may try to balance the ratio of these two N sources so as to achieve a stable pH. The exact ratio required to

achieve stable pH is not readily predictable as it depends upon several factors: plant's differential uptake of nitrogen form over another, the rate that ammonium is converted to nitrate through nitrification (a process which also decreases pH), and the relative buffering of the water source due to its alkalinity. A study with hydroponic cut flower roses in which ammonium:nitrate:urea ratio was adjusted as the sole method of pH control in a high alkalinity water source found that in winter 25:75:0 resulted in optimum growth, while in summer 12:88:0, 25:75:0, or 0:50:50 resulted in optimum growth (Bar-Yosef et al., 2009). Despite the use of different N forms, pH was still very difficult to manage in the experiment. Adjusting N form is an efficient tool for hydroponic growers; however acids (such as nitric, muriatic, or sulfuric acid) or bases (such as potassium hydroxide) are also used to adjust pH.

In commercial facilities, pH and EC are monitored and adjusted at least daily. If done manually, common practice is to measure and adjust 1–3 times daily.

The minimum set of sensors that a professional grower must use is two: one for pH, resolving to 0.1 dS/m over the range from 3 to 8 dS/m with targets between pH of 5 and 7 and another for EC over the range from 0 to 5 with most measurements falling between 0.1 dS/m and 3 dS/m. The wider range for the meters is needed to be able to detect when the nutrient solution is very far from optimal. At such times an accurate measurement is needed to allow calculating blending percentages with either clear water or nutrient solution. In-line pH and EC sensors are commercially practical and so these attributes may be measured continuously and used to inject fertilizer stock solution or acid/base (e.g., Bluelab controllers).

While the control via pH and EC can achieve excellent results, there will invariably come a point where an existing nutrient solution cannot be used anymore as indicated by the measurements. This may be due to nutrient imbalances, buildup of unwanted ions (e.g., Na, Cl), or lack of knowledge as to the nutrient composition. Ultimately the solution may need to be discarded (in part or wholly) and be replaced with a fresh solution where the exact concentrations of each nutrient are known and optimized.

12.3.1 PREPARING NUTRIENT SOLUTIONS

Plants require 14 essential elements that must be supplied in the root zone including the macronutrients (required in relatively large quantities) of nitrogen, phosphorus, potassium, sulfur, calcium, and magnesium; and the micronutrients (needed in smaller amounts) of iron, manganese, zinc, boron, copper, molybdenum, chloride, and nickel (Chapter 6: Nutrition of Substrate-Grown Plants). All of these nutrients must be supplied by either the hydroponic nutrient solution, the substrate, or the water source. Many hydroponic fertilizers provide 12 of the essential elements but don't specifically provide chloride and nickel as they are available in sufficient quantities as impurities with the fertilizer. For fruiting crops, chloride (or saline conditions/elevated EC) is sometimes provided at high concentrations to increase flavor/soluble solids but at the expense of crop yield as in the case of tomato (Pascale et al., 2001).

Numerous recipes exist for preparing nutrient solutions of hydroponic crops (Resh, 2001; Sonneveld and Voogt, 2009). Because many factors influence plant nutrient uptake (genotype, crop growth stage, weather), the selection of a nutrient solution recipe (i.e., target values for macro- and micronutrients) is not an absolute science but refined over time based on empirical observations.

That is, a nutrient recipe is initially selected based on past experience or from conversations with a crop consultant or cooperative extension educator. Then this recipe is refined over time based on periodic tissue and nutrient solution analyses. A couple of different strategies are typically used when preparing hydroponic nutrient solutions: (1) Small and hobby growers often prefer to purchase preformulated fertilizers with fertilizer salts already preblended. In this case typically 1–3 liquid concentrates or powdered solids are mixed together to prepare a complete nutrient solution. (2) Medium-to-large commercial growers often prepare their own fertilizer solutions on site using bulk ingredients (i.e., individual fertilizer salts, concentrated liquid stock solutions, etc.). This then uses precise quantities of raw fertilizer materials to be dissolved into stock tanks dosed into source water to create the desired nutrient solution. Details of such systems and their operation are described in Chapter 13, Technical Equipment in Soilless Production Systems. The first approach requires less background knowledge and labor; however, it is typically more expensive and does not allow much flexibility with adjusting the composition of the nutrient solution over time. The latter approach is cheaper when large quantities are used and allow greater flexibility to adjust individual fertilizer salts if particular elements are used by the plant in different quantities than the original target values.

When fertilizer ingredients are purchased for hydroponic use, it is important that they are “greenhouse/solution grade” not “field grade,” they have less impurities, and also they do not have waxy coatings. For example, field grade calcium nitrate has a greasy coating around the prills so that the fertilizer which is hygroscopic does not absorb too much water from the air. However, such a coating is undesirable for dissolving into stock tanks for greenhouse use. It is possible to obtain premade dry or liquid nutrient solution concentrates from various vendors. Regarding strategy no. 1 (using premade preparations), these are formulated to group various fertilizer nutrients together in such a way that (1) the various chemicals do not react with each other, (2) are completely soluble, (3) every nutrient stays in solution until it is used. For small/hobby growers, hydroponics shops sell an array of products from various manufacturers, and some are series that some measured amount is taken from each concentrate and stirred into a fixed amount of water. Generally there are two-part solutions and three-part solutions. With the three-part solutions, the grower can also make some adjustments during the phases of crop development (e.g., adjusting nitrogen during the crop cycle).

Most commercial hydroponic growers prepare nutrients in concentrated stock tanks and then dilute these either manually or with a fertilizer injector to prepare them at the final desired concentration with the deep flow pond or NFT reservoir. When preparing concentrated stock tanks, which are often at 100–200 times greater concentration than the nutrient solution target concentration, it is important to be aware of the solubility limits for each specific fertilizer salt at room temperature. If a fertilizer salt is not fully soluble in water, a precipitate will form, which means that a fraction of the fertilizer is not available. Also, such precipitate can clog fertilizer injectors and hydroponic drip lines. In addition, when multiple fertilizer salts are combined in the same stock tanks, one must be aware of compatibility. Some fertilizer salts are incompatibility meaning they rapidly combine to form an insoluble salt. The most common incompatibility issue is that calcium is incompatible with sulfates and phosphates. Compatibility of common fertilizer salts is presented in [Table 12.1](#)

The various issues with fertilizer compatibility dictate that several concentrated stock tanks (2, 3, or more) are used. Growers who need to be able to deliver many varied recipes to crops at

Table 12.1 Compatibility of Common Fertilizer Salts Used in Concentrated Stock Tanks for Fertigation

	Urea	Ammonium Nitrate	Ammonium Sulfate	Calcium Nitrate	Potassium Nitrate	Potassium Chloride	Potassium Sulfate	Ammonium Phosphate	Fe, Zn, Cu, Mn Sulfate	Fe, Zn, Cu, Mn Chelate	Magnesium Sulfate	Phosphoric Acid	Sulfuric Acid	Nitric Acid
Urea	C													
Ammonium nitrate	C	C												
Ammonium sulfate	C	C	C											
Calcium nitrate	C	C	I	C										
Potassium nitrate	C	C	C	C	C									
Potassium chloride	C	C	C	C	C	C								
Potassium sulfate	C	C	R	I	C	R	C							
Ammonium phosphate	C	C	C	I	C	C	C	C						
Fe, Zn, Cu, Mn sulfate	C	C	C	I	C	C	R	I	C					
Fe, Zn, Cu, Mn chelate	C	C	C	R	C	C	C	R	C	C				
Magnesium sulfate	C	C	C	I	C	C	R	I	C	C	C			
Phosphoric acid	C	C	C	I	C	C	C	C	C	R	C	C		
Sulfuric acid	C	C	C	I	C	C	R	C	C	C	C	C	C	
Nitric acid	C	C	C	C	C	C	C	C	C	I	C	C	C	C

C, Compatible; I, incompatible; R, reduced solubility.

Adapted from Smart Fertilizer Management <https://www.smart-fertilizer.com/articles/fertilizer-solubility>.

various stages of growth may have each of the fertilizers that is used in largest quantity in a separate stock tank. The most common approach is to consider the use of two tanks and then increase the number of stock tanks depending on the need. In this approach the two tanks are identified as A and B tanks, with the A tank holding most of the nitrogen fertilizer.

The following identifies a common strategy for using three stock tanks whereby stock tank A is used for calcium nitrate and other compatible salts; tank B is used for sulfates, phosphates, and other compatible salts; and tank C is used for either an acid or base to adjust pH (Adapted from Resh, 2011):

- Tank A
 - Calcium nitrate
 - Half of the potassium nitrate
 - Iron chelate
- Tank B
 - Half potassium nitrate
 - Potassium sulfate
 - Monopotassium phosphate
 - Magnesium sulfate
 - All other micronutrients
 - Monoammonium phosphate
 - Ammonium nitrate
- Tank C
 - Acid, used to drive down pH (or base if very pure waters, acidic N source)
 - Sulfuric/Phosphoric
 - Nitric

This strategy can also be implemented with two tanks (A and B) if the tendency for pH adjustment tends to be very similar week after week. In that case, sulfuric and phosphoric acids would be included in the B tank, while other acids, such as the nitric acid, would be included in the A tank.

This, however, takes away direct control over pH. This might not be a big issue for some growers, but having the ability to control pH in hydroponic production is very important for most growers.

There may also be reason to increase the number of stock tanks and injectors. For example, some growers find that they prefer to have better control over calcium to cope with instances of leaf margin burn, blossom end rot of fruits, or similar calcium disorders.

12.4 NUTRIENT SOLUTION RECIPES FOR LEAFY GREENS AND HERBS

In this section we present two nutrient solution recipes for growing leafy greens and herbs that have been successfully used for many years by the Cornell University Controlled Environment Agriculture group in deep flow and NFT. These examples are for 1000 L of dilute fertilizer

solution. If using stock tanks (i.e., a $100\times$ concentration), then the quantities are the amount to use per 10 L in a $100\times$ concentrated stock tank. The Tank A and Tank B components *Must* be prepared separately so a precipitate does not form.

The first is an approach that uses 750 g of calcium nitrate (15.5-0-0) per 10 L of stock solution in one stock tank. In the second stock tank, 750 g of preblended semicomplete hydroponic fertilizer with analysis of 5-12-26 (“Hydroponic,” J.R. Peters Inc., Allentown, NJ) is dissolved in each 10 L of water.

The second approach uses individual fertilizer salts to create a modified Sonneveld’s solution for leafy greens as described by [Mattson and Peters \(2014\)](#). Note that the items marked with an asterisk (*) must be weighed out with an analytical balance to achieve the desired accuracy:

- Tank A
 - 486 g $\text{Ca}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$
 - 38.0 g NH_4NO_3
 - 442 g KNO_3
 - *10.0 g 10% iron-DTPA
 - Sprint 330 or Sequestrene 330
- Tank B
 - 136.1 g KH_2PO_4
 - 245.9 g $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$
 - *0.777 g $\text{MnSO}_4 \cdot \text{H}_2\text{O}$
 - *0.930 g H_3BO_3
 - *0.061 g $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$
 - *0.573 g $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$
 - *0.092 g $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$

These two nutrient solution recipes result in final nutrient composition as follows:

	Calcium Nitrate + Hydroponic Base (5-12-26)	Modified Sonneveld’s Solution
Macronutrients (mM)		
Nitrogen (N)	10.7	10.7
Phosphorus (P)	1.3	1.0
Potassium (K)	4.1	5.4
Calcium (Ca)	3.5	2.3
Magnesium (Mg)	1.9	1.0
Micronutrients (μM)		
Iron (Fe)	41.2	17.9
Manganese (Mn)	6.9	4.6
Zinc (Zn)	1.7	2.0
Boron (B)	35.2	14.8
Copper (Cu)	1.8	0.4
Molydenum (Mo)	0.8	0.3

The above recipes can be adjusted to suit specific crops. It is relevant that in the above the primary target is to grow leaf materials along with a small amount of stem and roots. Clearly the two recipes are not identical in what is delivered to the plant, this demonstrates that many nutrient solution recipes can be used fairly effectively; however the grower may adjust over time as indicated by laboratory analysis.

These two approaches are presented since many practitioners will begin hydroponic production with off-the-shelf solutions (such as approach 1 above) and begin to make adjustments with further experience, ultimately ending up with an approach similar to no. 2. The most common facet of this experience is a notion that premixed fertilizers are more expensive relative to ones that must be mixed from the raw materials.

It is also relevant to understand how the nutrient solution recipes have evolved in the hands of firms marketing fertilizers. Many target some particular crop for growers that share a particular set of conditions (climate, water sources, substrate mixes, etc.). Most notable in any set of these conditions is that it can be expected that the pH of the nutrient solution will range between some specific minimum and maximum and that the source water or blending of water will result in buffering capacity which will cause the root zone to be at some pH level fairly frequently. This pH level affects nutrient availability just as much as that actual amount of nutrient present in the solution. For hydroponic systems the range of 5.5–6.0 is fairly commonly used so that nutrient concentrations in recipes assume this range.

Growers who find their pH fairly different from the midpoint of this range will need to account for the reduced micronutrient availability by supplying some nutrients at a greater rate; nutrients which are more available at such pH levels would need to be reduced in the nutrient solution. Clearly this is not feasible with off-the-shelf fertilizers so that pH control must be practiced to keep pH stable (within ± 0.2 range) and at a level that works well.

As part of pH control it is important to know where fluctuations come from. The most dominant factor shifting pH is the nitrogen form. Nitrate taken up by plants results in increasing the pH while ammonium use reduces the pH. So, it makes sense to use both nitrate and ammonium in such a way that the pH changes very little or not at all.

12.5 NUTRIENT SOLUTION RECIPES FOR FRUITING CROPS

With crops where the target is flowers or fruit, or even tubers or roots such as carrots, the recipes need to be different from those for growing primary leaf material. Providing fertilizer nutrients can be viewed simplistically as providing the building blocks of the biomass. The proportion of N, P, and K, and other nutrients in flowers and fruits, is very different from the leaves; so it makes sense that adjustments are needed in rates of each.

At the same time, once enough of any one nutrient is available, the plant can easily cope with some excess, as long as the total salinity stays low. This provides some flexibility to the practitioner since it is not imperative to get every nutrient concentration perfect.

When fruiting and flowering plants are young, they can initially be provided fertilizer in the same approach as the leafy-greens recipe above. As the plants grow, the proportion of N in relation to Ca and K needs to be changed during the production period, and the timing needs to be commensurate with observations of flowers, fruit, or tubers.

Below is an example of a fertilizer solution adjusted according to crop stage (from the University of Arizona CEA Center, [Mattson and Peters, 2014](#)).

Macronutrients (mM)			
NO ₃ -N	6.4	8.6	13.6
NH ₄ -N	0.0	0.0	0.0
P	1.5	1.5	1.5
K	3.7	9.0	9.0
Ca	3.6	4.0	5.0
Mg	2.5	2.5	2.5
S	3.6	3.6	3.6
Cl	2.5	2.5	2.5
Micronutrients (μM)			
Fe (DTPA/EDTA)	35.8	35.8	35.8
Mn	10.0	10.0	10.0
Zn	5.0	5.0	5.0
Cu	0.79	0.79	0.79
B	31.5	31.5	31.5
Mo	0.52	0.52	0.52

As above we can take two approaches to getting a recipe that works well. As before one strategy is to buy off-the-shelf fertilizers from a store marketing specifically hydroponics fertilizer. These products come with “feed charts” (i.e., labeled rates) that identify roughly how much of each purchased stock solution to dissolve in water to create a nutrient solution. For flowering and fruiting plants, these feed charts will be subdivided into the various growth phases of the crops. As above, the firms have taken the task of separating the stock nutrients into parts which are compatible (not forming precipitates in the bottle) and also providing enough flexibility to allow growers to easily make adjustments as the crop grows.

For tomatoes (and other fruiting crops) we present two approaches for developing the Stage 3 (multi-crop) recipe. A simple approach for 1000 L of dilute fertilizer solution (or 10 L of 100 × concentrated stock solution) is to use 950 g of calcium nitrate (15.5-0-0) dissolved in water in one stock tank. In the second stock 10 L tank uses 950 g of preblended semicomplete hydroponic fertilizer with analysis of 5-12-26 (“Hydroponic”, J.R. Peters Inc., Allentown, NJ).

The second approach uses individual fertilizer salts to create the Stage 3 (multi-crop recipe) as used by the University of Arizona CEA Center ([Kroggel and Kubota, 2018](#)). Note that the items marked with asterisk must be weighted out with an analytical balance to achieve the desired accuracy.

- Tank A
 - 919 g $\text{Ca}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$
 - 403 g KNO_3
 - *20.0 g 10% iron-DTPA (Sprint 330 or Sequestrene 330)
- Tank B
 - 171.4 g KH_2PO_4
 - 486.9 g $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$
 - 303.0 g K_2SO_4
 - *1.693 g $\text{MnSO}_4 \cdot \text{H}_2\text{O}$
 - *1.600 g H_3BO_3
 - *0.127 g $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$
 - *1.450 g $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$
 - *0.195 g $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$

These two nutrient solution recipes result in final nutrient composition as follows:

	Calcium Nitrate + Hydroponic Base (5-12-26)	University of Arizona, CEAC Recipe
Macronutrients (mM)		
Nitrogen (N)	13.6	13.5
Phosphorus (P)	1.6	1.3
Potassium (K)	5.2	8.7
Calcium (Ca)	4.4	4.3
Magnesium (Mg)	2.5	2.0
Micronutrients (μM)		
Iron (Fe)	51.1	35.8
Manganese (Mn)	8.7	10.0
Zinc (Zn)	2.14	5.05
Boron (B)	44.4	25.9
Copper (Cu)	2.20	0.79
Molybdenum (Mo)	1.04	0.52

12.6 DAY-TO-DAY MANAGEMENT

It is relevant that hydroponic plant production involves daily, perhaps even hourly, changes within the system. Changes over a 2-day span can easily be very detrimental. The best advice is to inspect everything twice per day for anomalies. The most obvious of things the grower must attend to is the total amount of water that the plants are exposed to every day. Every reservoir needs to be inspected daily to verify that it holds enough resource until the next inspection. An injector stuck in open position can drain an entire stock tank and apply the resulting salty solution to the plants.

It cannot be taken for granted that all hydroponic systems are totally dependent on electricity. Power failures create huge problems. Failure to aerate for 20–30 minutes in a deep flow system can result in all plants wilting (depends on reservoir size). Aeroponic or NFT systems without power for 30 minutes will likely result in dead plants. For many systems the critical duration may well be much shorter.

Growers should have working pH and EC meters and be using each at least once per day. Data should be recorded so that trends can be observed. As a general guideline, the pH for hydroponic crops should be maintained at 5.5–6.0 and the EC at 1.4–2.0 dS/m (for leafy greens) and 2.0–2.6 for fruiting crops. Any changes in the system should be recorded as part of the data collection. Each pH and EC meter will have specifications that identify how often to calibrate this test equipment. It is imperative that a standard calibration practice be implemented by the grower. Every time a problem occurs, then test equipment should be recalibrated to assure that the error is not an artifact.

Another element of the system is the fact that oxygen is explicitly managed. As such any aeration equipment should be inspected with each crop inspection. It is common that air hoses have come out. Less common is that air pumps are failing, but this too is possible. Where air pumps are bubbling into nutrient solution, each such instance should be inspected to assure it is happening and that the air hose is not dangling above the water level. Many times scanning the crop and seeing a few plants wilting is due to inadequate aeration so that the wilted plants are sitting in stagnant water, deprived of oxygen.

An important facet of crop production is to have an eye on the target: selling the plant/crop for profit. This means that there will be key stages of crop development and this will include the first date on which the product can be shipped and the last day on which it might be marketable. During any routine inspection, the grower should check the crop production charts to verify that the crop is on track for the marketing objective. If the fertilizer injection, humidity control, pH, EC, etc. are suboptimal, then the product will be delayed or damaged. It is important to spot signs of this as early as possible so as to mitigate any damage.

12.7 OTHER ADJUNCTS

Since we recommend starting with stock solutions from stores, we must also provide a bit of advice about the many adjuncts that can be purchased. Are these needed? Most often the answer is “no.” Can they do harm? Generally not, as long as they are used according to the label. Some plants may well have a greater requirement for some nutrient (e.g., silicon) than is typically present in most nutrient solutions, but this is rare and so crop specific that a practitioner can find out whether a product is likely to be of some benefit or not (further discussion on silicon in Chapter 6: Nutrition of Substrate-Grown Plants). A grower who does not have high-quality fresh water available will need to be very judicious with inclusion of compounds that might have some elusive effect because anything added to the nutrient solution may well build up and handicap the grower in prolonged use of the irrigation water.

In this discussion we have not included the use of plant growth regulators (PGRs). Some adjuncts or amendments include PGRs and these should only be used with a full understanding of what these materials will do to the plants and what consequence might be on the final marketed horticultural product. If a material does not disclose its constituent materials, then it should not be used.

12.8 ORGANIC HYDROPONICS

With the continued growth of hydroponic plant production, there is considerable interest in being able to certify the resulting products as “organic.” This is, however, problematic with the above approach since there are items in each of the fertilizer recipes which are synthetic rather than mined or derived from plant or soils. In each country where foods in stores are marketed as “certified organic,” this means that the producer has been inspected and found to be using only materials and methods which are on a list of approved “organic” materials. Furthermore, the crop cannot have been produced with any material that is not on the list. The most basic requirement in this domain has been the requirement that crops be grown in soil and that soil health and sustainability is of paramount consideration. Thus “soilless” culture would appear to be a clear violation. Mineral wool or synthetic foams are not allowed. However, there are substrates which are obviously organic or could be certified as such. So that it may be technically possible to overcome some of the hurdles to getting certification. Plastic mulches are allowed and there may well be some latitude where some new materials could be placed on the list. Where plastic vessels are not allowed, these could be replaced with ceramics (at greater expense, of course). The most relevant omission from the “organic certified” list is calcium nitrate, a mainstay in all hydroponic systems. Without it, the fertilization approaches described above get very complicated and frustrated. Sodium nitrate (a mined product) is technically usable but in recirculated hydroponics, the sodium builds up very quickly to unacceptable levels. Many other fertilizers derived from plant or animal products tend to be much more expensive per amount of fertilizer and also typically include particles which clog emitters and filters.

As such there are commercial operations which claim to be practicing organic hydroponic production. These generally do not recirculate their irrigation water, instead growing with approved products in a flow-through approach using substrates derived from plants (peat, coir, sawdust, etc.). These are not hydroponic systems as defined in this book.

REFERENCES

- Albano, J.P., Miller, W.B., 2001. Photodegradation of FeDTPA in nutrient solutions. I. Effects of irradiance, wavelength, and temperature. *HortScience* 36, 313–316.
- Bar-Yosef, B., Mattson, N.S., Lieth, H.J., 2009. Effects of $\text{NH}_4\text{:NO}_3\text{:urea}$ ratio on cut roses yield, leaf nutrients content and proton efflux by roots in closed hydroponic system. *Sci. Hortic. (Amsterdam)* 122 (4), 610–619.
- Cooper, A.J., 1975. Crop production in recirculating nutrient solution. *Sci. Hortic. (Amsterdam)* 3 (3), 251–258.
- Gericke, W.F., 1937. Hydroponics—crop production in liquid culture media. *Science* 85 (2198), 177–178.
- Goto, E., Both, A.J., Albright, L.D., Langhans, R.W., Leed, A.R., 1996. Effect of dissolved oxygen concentration on lettuce growth in floating hydroponics. *Acta Hortic.* 440, 205–210.
- Hoagland, D.R., Arnon, D.I., 1938. Growing Plants Without Soil by the Water-Culture Method. In: Circular. California Agricultural Experiment Station. 39 p.
- Hoagland, D.R., Arnon, D.I., 1950. The Water-Culture Method for Growing Plants Without Soil. In: Circular. California Agricultural Experiment Station, vol. 347, second ed. 32 p.
- Ikeda, H., Wada, T., Mirin, T., Okabe, K., Tazuke, A., Furukawa, H., 1994. Year-round production of spinach by NFT and DFT in the greenhouse. *Acta Hortic.* 396, 257–264.

- Kroggel, M. and Kubota, C. 2018. Hydroponic nutrient solution for optimized greenhouse tomato production. The Ohio State University Agriculture and Natural Resources Factsheet HYG-1437. 7p.
- Mattson, N., Peters C., January 16–19, 2014. A recipe for hydroponic success. Inside Grower.
- Pascale, S.D., Maggio, A., Fogliano, V., Ambrosino, P., Ritieni, A., 2001. Irrigation with saline water improves carotenoids content and antioxidant activity of tomato. *J. Hortic. Sci. Biotechnol.* 76 (4), 447–453.
- Resh, H.M., 2001. *Hydroponic Food Production: A Definitive Guide of Soilless Food-Growing Methods*, sixth ed., Woodbridge Press, p. 567.
- Soffer, H., 1986. A device for growing plants aero-hydroponically: the E.G.S. (Ein Gedi System) miniunit. *Soilless Cult.* 2, 45–52.
- Soffer, H., Burger, D.W., Lieth, J.H., 1991. Plant growth and development of Chrysanthemum and Ficus in aero-hydroponics: response to low dissolved oxygen concentrations. *Sci. Hort.* 45, 287–294.
- Sonneveld, C., Voogt, W., 2009. *Plant Nutrition of Greenhouse Crops*. Springer Verlag, p. 431.
- Thompson, H.C., Langhans, R.W., Both, A.J., Albright, L.D., 1998. Shoot and root temperature effects on lettuce growth in a floating hydroponic system. *J. Am. Soc. Hortic. Sci.* 123, 361–364.
- von Liebig, J., 1840. *Die organische Chemie in ihrer Anwendung auf Agricultur und Physiologie (Organic Chemistry in Its Applications to Agriculture and Physiology)*. Friedrich Vieweg und Sohn Publ. Co., Braunschweig, Germany.
- Walters, K.J., Currey, C.J., 2015. Hydroponic greenhouse basil production: comparing systems and cultivars. *HortTechnology* 25 (5), 645–650.