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A Suspended Net-Pot, Non-Circulating Hydroponic Method for Commercial Production of Leafy, Romaine, and Semi-Head Lettuce

B. A. Kratky
Department of Tropical Plant and Soil Sciences

This publication describes a system for growing leafy, semi-head, and romaine lettuce with a non-circulating hydroponic method. It is directed to the commercial grower, but it can be scaled to home-garden use. The entire crop of lettuce is grown with a single initial application of water and nutrients. Electricity and pumps are not needed. Polyethylene-lined tanks (5½ inches deep) are filled nearly to the top with nutrient solution. A cover with holes in it is placed over the tank. At transplanting time, individual net pots containing growing medium or grow-plugs and 1–3-week-old lettuce seedlings are placed into the holes. The lower ½ inch or so of each net pot is immersed in the nutrient solution. The entire growing medium in the containers moistens by capillary action, automatically providing the plants with water and nutrients. The nutrient solution level in the tank drops below the net pots within a few weeks, but by this time the roots have emerged from the net pots. The roots in the solution continue taking up water and nutrients, while roots between the net pot and the surface of the solution become “oxygen roots” and take up air from the humid air layer between the tank cover and the nutrient solution. The crop is harvested before the nutrient solution is exhausted. Then, the tank is cleaned and refilled with fresh nutrient solution and the process is repeated.

The additional production costs and complexities associated with aeration and circulation in many conventional hydroponic systems are totally avoided in this method. A diagram of the system is shown in Figure 1 (p. 2).

Various leafy vegetables may be grown on a commercial scale with this unique and efficient technique. However, the method is intended only for crops that require less than 2 gallons of water per plant for the entire growing season, from transplanting to harvest. Potential crops include leafy, romaine, and semi-head lettuces, cilantro, green onions, kai choy, pak choi, and watercress.

A prototype for this method was a simple hydroponic growing kit in which fertilizer and water were added to a 1-gallon plastic bottle to grow a single lettuce plant, with no additional attention needed until harvest (Kratky 2002). Other articles on the suspended-pot, non-circulating hydroponic method include Ako and Baker 2009; Kratky 1993, 1995, 1996, 2004, 2005, 2009; and Kratky et al. 2008.

Rain shelters

Rain shelters are required in rainy locations for the suspended-pot, non-circulating hydroponic method. Without shelters, rainfall enters the growing tanks and raises the liquid level. This causes roots that had been suspended in

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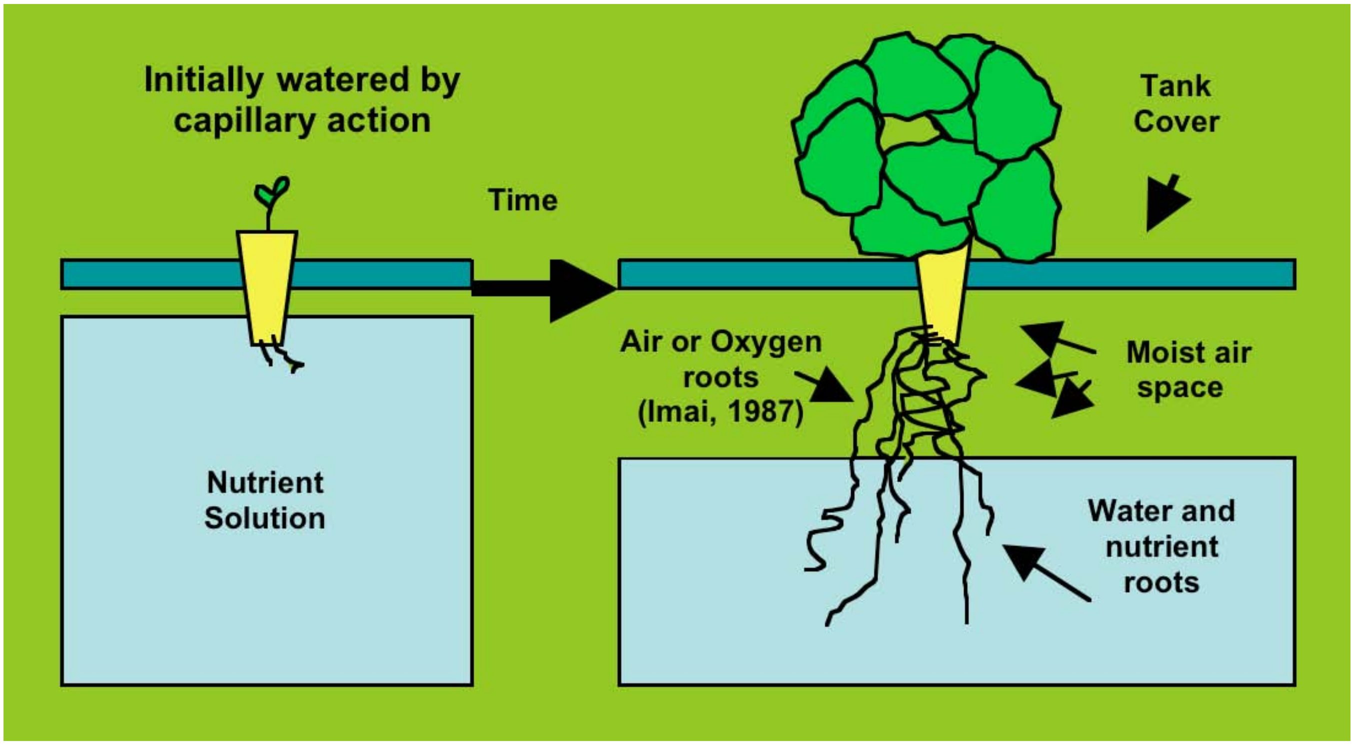

Figure 1. A model of a suspended-pot, non-circulating hydroponic system. Electricity, pumps, and wicks are not needed. All of the nutrient solution is applied prior to transplanting.

the moist air zone above the water to become submerged and starved for oxygen. Plants initially wilt and may suffer physiological damage or even "drown" and die.

Rain shelters generally consist of a structural frame covered with polyethylene film or rigid plastic panels, and possibly with screen on the sides and ends (Kratky 2006). Rain shelters do not contain active heating or cooling devices and do not need electrical power, but they usually include a water supply. Lumber and metal are the most common framing materials, but PVC pipe and locally available materials such as bamboo and guava stems have also been used as framing materials (Figure 2).

As with similar protective structures in the northeastern USA (Wells and Loy 1993), frequently referred to as "high tunnels," quonset-style, arched structures are the most common configurations, but gable and tent structures also are used. Rigid coverings such as fiberglass and polycarbonate are more expensive and durable than the UV-stabilized polyethylene films that are commonly used. Vendors of the various coverings gladly communicate advantages of their products with emphasis on cost, ease of covering a structure, lifetime of the covering, and plant responses to the light that passes through. In the case of plastic films, it is important to use only UV-stabilized films specifically manufactured for greenhouses and rain shelters, rather than construction-grade polyethylene, which will fail within 6 months of exposure to sunlight. Direct contact by some pesticides and wood preservatives may also adversely affect the lifespan of polyethylene films.

Polyethylene fits loosely when it covers gable or straight structural members, and it must be secured with battens to prevent flapping. However, polyethylene forms snugly to quonset and arched tunnel members when attached tightly at the ends and sides, and no battens are needed. In windy areas, hold-downs of rope or drip irrigation tape may be placed every 20 ft to prevent large waves from generating in the plastic. If arches are spaced too far apart, the polyethylene may sag if it has not been installed tightly, and water may pond on the relatively flat area at the top of the shelter. This may be remedied by placing light support members midway between the arches. Some designs employ a distinct peak at the top of the structure in an effort to minimize ponding. Structural

Figure 2. Polyethylene-covered rain shelters with frames (top to bottom) of bamboo (quonset and gable; Sunada Farm, Kainaliu), metal plus lumber (quonset; CTAHR Master Gardeners, Hilo), and lumber (gable with battens; CTAHR Volcano Research Station).

arches and other members that directly contact transparent plastic should be painted white, because this will prevent heat build-up and subsequent accelerated aging of the plastic covering.

The best time to cover a shelter with polyethylene film is on a warm, sunny day. Heat causes stretching of the film, and upon cooling, the polyethylene shrinks and assumes a tight fit similar to a drum membrane. Take caution on very hot days to avoid installing the film too tightly on the frame, because shrinkage occurring when the temperature cools can exert enough pressure to warp a metal frame or crack a wooden frame. To install the polyethylene, pull the film over the structure with several ropes attached to the edge of one side of the sheet. To prevent tearing of the plastic, wrap the film around a tennis ball or similar sphere and loop the rope under it with a slip knot. If the plastic hangs up on the purlins, push it up from underneath with a long pole. Pulling a new cover over a previously installed cover may seem easy, but then removing the old cover will be a problem, so this is not recommended. To allow for aeration and prevent heat build-up, the end walls and parts of the side walls are usually covered with screen rather than with polyethylene.

There are a variety of commercially available devices with which to attach the polyethylene to the structure, including plastic clips, metal extrusions, and “wiggle wire” inserted into a metal channel (Figure 3). To avoid wrinkling the polyethylene film, it is first attached to the top of the end arches. Next, it is attached on the sides starting from the middle of the structure and worked outward toward both ends; finally, the attachment to the lower parts of the end arches is completed.

Screens are recommended for the sides and ends of rain shelters to act as a windbreak and also to exclude large insects. Growers are confronted with the difficult choice of installing either a fine insect screen or a coarser 30% shade screen on the sides of a growing structure. A fine screen excludes more insects but restricts airflow and results in higher inside temperatures. There is more airflow through a 30% shade screen, and this will help to cool the structure, but in this case other insect control approaches need to be utilized for the smaller insects that may enter through this screen.

Options for orientation of a rain shelter are based on access to the structure, maximum light distribution, and prevailing wind direction. In a tropical climate, one opinion is that the structure should be oriented primarily to maximize exposure to the prevailing wind direction, because detrimental effects on crop production due to high temperatures overcome positive effects of the building’s orientation for optimum light interception. Lettuce grows best in cooler temperatures (60–70°F), which in Hawai‘i occur at upper elevations; high temperatures

Figure 3. Devices to attach polyethylene film to rain shelters.

can promote tip burning and bitter taste (Valenzuela et al. 1996). However, lettuce can tolerate temperatures in the 80s and low 90s, which are commonly encountered in rain shelters.

Solar radiation passing through a polyethylene roof is absorbed by inside surfaces and emitted as long-wave radiation, which does not pass back through the roof and is captured as heat. The maximum temperature in rain shelters typically occurs on a sunny day from noon to 2 p.m. For example, on Nov. 1, 1998 in Hilo, Hawai‘i, the sunlight energy received from 12:40 to 1:40 p.m. was calculated to be equal to 14.1 percent of the total sunlight energy for that day (Kratky 1999). Cooling by fans is effective but expensive. Fortunately, there are passive strategies for cooling rain shelter structures.

Shading will reduce incoming radiation, but it may decrease production or quality. However, 30–47 percent shading increased yields of ‘Green Mignonette’ lettuce, but 63 and 73 percent shading reduced yield and quality (Wolff and Coltman 1990a). Yields of two lettuce cultivars were increased in a spring planting with 30 percent shading, but shading reduced yields in a fall season (Wolff and Coltman 1990b). Shading may be provided by trees, situating a planting in the shadow of a hill, coating the roof with a shading compound, or covering the roof with a shade screen. A reflective shade screen would be better than a black shade screen, and it is preferred to place a shade screen outside of a structure rather than inside.

White surfaces within a rain shelter contribute to cooling it because they are very reflective and a significant

Figure 4. Top-vented (CTAHR Volcano Experiment Station) and upper-side-vented rain shelters (Mel Nishina, Hilo).

amount of the reflected radiation can pass back through the roof. For example, a white color equal to fresh snow reflects 80 percent of incident light (Lowry 1967), which is how people can become snow-blind. Growers can increase reflectivity by placing white fabric or film on walkways, cover the growing beds with white mulches, place white covers on hydroponic tanks, utilize white bags for bag culture, and coat trellis posts and structural members with reflective white paint.

Evapotranspiration cools the air and is related to the type and amount of foliage, the relative humidity of the air, and the water supply to the plants. A crop of lettuce was calculated to provide cooling by evapotranspiration equivalent to 27 percent of the incoming radiation during the hottest hour of the day (Kratky 1999). Even weeds growing in a rain shelter will provide some cooling by evapotranspiration proportional to their density. However, weeds should be removed from the rain shelter due to disease and pest concerns. Misting and fogging of the plants can also contribute to cooling. For example, misting accounted for cooling equivalent to 31 per cent of the incident radiation of a Hawai‘i rain shelter. However, misting or fogging too late in the day may contribute to plant diseases.

Air exchange is the most common method of cooling a rain shelter. In a Hawai‘i rain shelter, one air change per minute was required to maintain a temperature of 10°F above ambient temperature, but only a 0.4 air change per minute was needed if misting was done. A rain shelter 96 ft long that was half obstructed with crops required a 2.2 mph breeze to exchange the air every minute (Kratky 1999). The end screens can greatly impede airflow. Fine insect screens restrict more air movement than coarse screens and thus hinder cooling.

Reducing the length and width of the structure and increasing the height of screen on the sidewalls increases the perimeter-to-area ratio of the rain shelter, and this contributes to air exchange because the shelter can take better advantage of prevailing breezes. Although large, gutter-connected rain shelter complexes are less expensive per square foot to construct and also promote labor and other efficiencies, these larger structures can become too hot for lettuce production in warm environments. Tall structures are cooler for plants because hot air rises above the crop. Top-vented structures, including sawtooth designs, exhaust the warmest air from the structure (Figure 4), thus reducing the required air exchange rate. For example, air exhausting from the peak of the building removes 50 percent more BTUs per cubic foot than air exhausting at bench level. Maintaining a grassy space between rain shelters also contributes to cooling because air that passes over grass is cooled by evapotranspiration before entering the structure.

Small, individual rain shelters (Figure 5) confine insects and diseases to a particular structure rather than allowing their spread throughout a larger structure. A grower may find it affordable to schedule a fallow period following harvest in a small structure, and this can greatly reduce insect and disease problems. The entire crop can be harvested at one time, as opposed to having multiple crop stages in a larger structure, which may allow insects and diseases to spread from one crop to the next. Another disease and insect control strategy is to decrease the crop time in the rain shelter by transplanting

Figure 5. Lettuce growing in small rain shelters (Calvin Fukuhara, Kurtistown [left] and Glenn Sako, Hilo [right]).

seedlings. The cropping period in the rain shelter may be reduced by more than a third by transplanting compared to direct-seeding the crop.

Tanks

Hydroponic lettuce is grown in tanks filled with nutrient solution (water plus a complete hydroponic fertilizer) instead of in soil, as is common with conventional field production (Figure 6). The tanks are placed in plastic-covered rain shelters or greenhouses with screened ends and sidewalls to protect against rainfall and large flying insects. Tanks are filled with 1.5–2 gallons of nutrient solution per plant prior to planting. Thus a tank designed to grow 50 heads of lettuce should have a liquid capacity in the range of 75–100 gallons.

Common tank dimensions are 4 x 8 ft and 4 x 16 ft, but other dimensions may be used. Tanks should be level to within ¾ inch, but this becomes increasingly difficult to maintain as tank length increases. Most people are unable to reach lettuce plants located more than 3 ft away, which discourages the use of tanks wider than 6 ft.

A rectangular frame is constructed with 2 x 6 lumber by fastening either with 12 d nails or 2½-inch deck screws. A ½-inch or thicker plywood sheet is fastened to this frame and becomes the bottom of the tank. Lumber needed to build a 4 ft x 8 ft x 5½-inch high tank includes 2 x 6 lumber (2 lengths of 8 ft and 2 lengths of 45 inches) and a 4 x 8 ft sheet of plywood. Tanks should be constructed at a convenient working height (30–36 inches). A full 4 x 8 ft tank weighs more than 800 pounds. Tanks should be supported at least every 4 ft on stacked concrete blocks or have a well braced lumber frame.

There are less expensive tank construction alternatives. Recycled metal roofing can be used in place of plywood bottoms, but care must be taken to prevent sharp edges from cutting the plastic tank liner. A tank support structure from cross-braced, upright pallets may be constructed, and recycled metal roofing is then attached to this framework, making a tabletop (Figure 7). Lumber frames without the bottom plywood sheet may rest directly on the metal table top without any attachment. Similarly, lumber frames without the bottom plywood sheets may rest directly on level ground, but weed barrier fabric should be placed under the frame to cushion against rocks and prevent weeds from penetrating the plastic tank liner (Figure 7).

Tanks are lined with two layers of 6-mil black polyethylene sheeting (Figure 7). Clear greenhouse-grade polyethylene is also acceptable, but clear construction-grade polyethylene should be avoided because sunlight deteriorates exposed plastic not protected by the tank cover. It is easier to lay and fit the two layers consecutively rather than both at once. Polyethylene rolls are typically sold in 10- and 20-ft widths, but it is easier to work with the 10-ft width. When cutting the plastic, allow for several inches of overhang on the ends and sides. Lay the polyethylene loosely in the tank. Air pockets may develop if the plastic is fastened before water is added, and this often causes leaks. The plastic must be fitted snugly against the sides and bottom of the tank because unsupported plastic sheeting is prone to leak. Preliminary fitting is accomplished by using the side of one's hand with a slow-motion judo chop.

Figure 6. Hydroponic lettuce growing in tanks of non-circulating nutrient solution.

Figure 7. Left, a tank support structure from cross-braced, upright pallets with recycled metal roofing as a table top (Waite Farm, Mt. View). Center, a lumber frame rests directly on weed barrier fabric placed on a level surface. Right, tank is lined with two layers of 6-mil black polyethylene sheeting.

Then, add about 2 inches of water. The cool water causes the polyethylene to shrink and pull away from the sides of the tank. The polyethylene is then given a final fitting to the tank sides and bottom to ensure that it rests firmly against the lumber. Fold and trim the plastic at the ends of the tank. Neat folds are an acquired skill. Use a staple gun to fasten the polyethylene to the outside frame rather than to the top of the tank; stainless steel staples are preferred. If a tank leaks while a crop is growing, add a few handfuls of fine vermiculite to the tank. Rub the vermiculite between your hands to mill it to very fine particles. The vermiculite can plug small holes and retard the leak. To repair a leaking tank, a new sheet of plastic can be added over the two existing sheets after the crop is harvested.

The tank cover should be easily removable and fit loosely on top of the tank. Sheets of ½–1-inch thick expanded polystyrene (white beadboard, 2 lb/ft^3 density) or extruded polystyrene (Styrofoam™) are preferred because they are lightweight and it is easy to cut holes in them for the net pots. Individual sheets should be cut to 2 x 4 ft to facilitate handling (Figure 8). Larger sheets, such as 4 x 8 ft, are often broken while handling due to the fragility of the materials.

Plastic pots should be placed on the floor of the tank to provide additional support to the middle of the sheets. This prevents bowing or sagging of the polystyrene (Figure 9). Coating the top surface of the polystyrene with white latex paint will prolong its life.

Alternative options for tank cover materials include plywood and plastic. Thin plywood (¼ inch) or painted recycled wood wall paneling with 1 x 2 lumber reinforcements are preferred over thicker plywood because it is easier to cut holes for the net pots in thinner plywood. Several growers have successfully constructed tank covers by covering lumber frames with plastic weed barrier fabric; holes for the net pots are burned in the fabric with a hot pipe. A coat of white latex paint is recommended for plastic and plywood covers. This is especially true for dark-colored covers, which heat up in direct sunlight.

Planting density

The grower must determine the optimal planting density (the number of plants per square foot or the number of plants per tank.) Two common planting densities for lettuce are 1.5 and 1.9 plants per square foot, or 48 and 60 plants, respectively, per 4 x 8–ft tank. Densities greater than two plants per square foot for larger head cultivars grown to mature head stage will often result in crowding. Higher density plantings are usually done with smaller cultivars such as 'Lollo Rossa' or when plants are harvested at a younger stage. Growers are advised to compare several planting densities for their growing situation on a small scale before committing to a specific density for commercial-scale production. Parameters to consider include quality, weight, size, shape, diseases, and crowding.

Mark the cover sheets and use an electric drill with a 2-inch hole saw to cut holes at the layout marks (Figure 10). Preferably, holes are cut about ¾ of the way through from one side, and then the operation is completed from the other side of the sheet. This gives a better cut and prevents the plugs from sticking in the hole saw.

Equidistant plant spacing is preferred, but this is not always possible if 2 x 4–ft tank cover sheets are used. A suggested plant spacing for a density of 1.5 plants per square foot on a 2 x 4–ft tank cover sheet is to first mark three rows along the 24-inch side (located at 4, 12, and 20 inches) and then mark four plants per row on the 48-inch side (12 plants per sheet). The suggested layout of the first and third rows will be at the 4-, 16-, 28-, and 40-inch marks on the 48-inch side. The layout of the middle row will be at the 8-, 20-, 32-, and 44-inch marks (Figure 10).

A uniform spacing arrangement in the tank can be achieved in a 4-ft wide tank by alternating cover sheets so that the first sheet has the 4-inch mark of the first and third rows from one side of the tank and the adjacent sheet is flipped end-to-end with the 8-inch mark of the first and third rows on that same side of the tank (Figure 11).

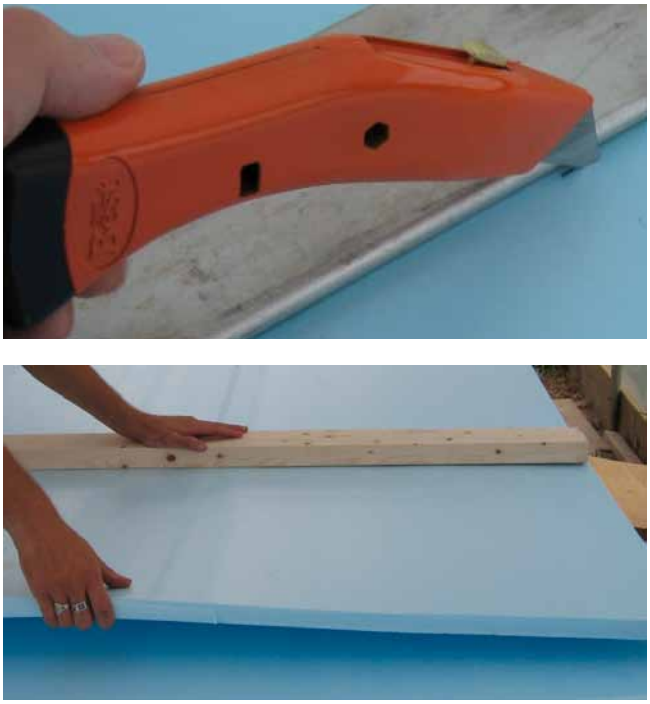

Figure 8. Cut a 4 x 8–ft extruded polystyrene sheet into 2 x 4–ft sheets. First, score the polystyrene about ¼ inch deep with a utility knife, then snap the sheet at the score line. Here, the sheet has been turned over so the score is on the bottom before pulling up on the edge.

For a density of 1.9 plants per square foot, there will be three rows of five plants, or 15 plants per 2 x 4–ft tank cover sheet. The suggested layout of the first and third rows will be at the 3-, 13-, 23-, 33-, and 43-inch marks of the 48-inch side. The layout of the middle row will be at the 5-, 15-, 25-, 35-, and 45-inch marks. Again, the adjacent sides of the sheets will be flipped end-to-end to provide a uniform spacing throughout the tank.

Water

Good water quality is required for the suspended net-pot, non-circulating hydroponic method. Water with high salinity should be avoided because salts concentrate as the nutrient solution is consumed by evaporation and transpiration, and plant growth may be adversely affected.

As the total amount of fertilizer salts in the nutrient solution increases, the osmotic effect increases, and it becomes more difficult for the plants to take up water. This is commonly referred to as a condition of high salinity,

Figure 9. A plastic pot placed on the floor of the tank provides additional support to the middle of the sheets, preventing bowing or sagging of the extruded polystyrene.

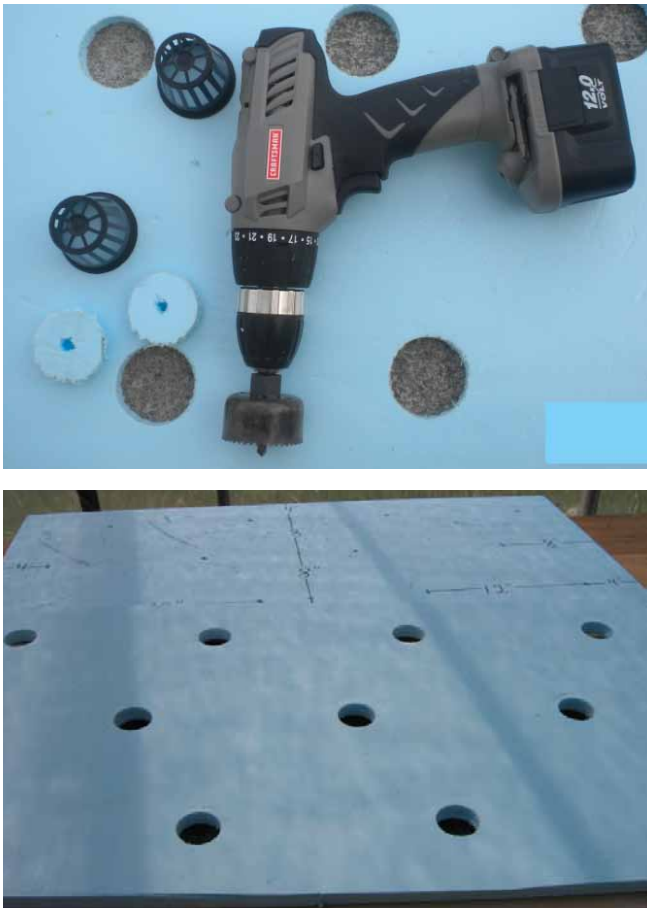

Figure 10. An electric drill with a 2-inch hole saw is used to cut holes in the top cover sheets at the layout marks. A template with a suggested plant spacing on a 2 x 4–ft tank cover sheet with a density of 1.5 plants per square foot is shown.

Figure 11. A uniform spacing arrangement is achieved by alternating the 2 x 4–ft tank cover sheets in an end-to-end fashion.

which can also cause complex physiological interactions that affect nutrient uptake, internal nutrient requirement, plant metabolism, and susceptibility to injury (Grattan and Grieve 1998). Also, toxic concentrations of ions in plants and other metabolic disturbances may occur with high salinity. Plants differ in sensitivity to salinity; e.g., lettuce is more sensitive to salt injury than beets, but less sensitive than beans (Maynard and Hochmuth 1997). Total fertilizer salts may be measured in milli-siemens (mS) with an electrical conductivity (EC) meter (Figure 12). The authors just cited defined the maximum salinity for lettuce without yield loss, based upon California soil culture, as 1.3 mS with a 13 percent yield decrease for each additional 1 mS. While the exact maximum optimum EC may vary with cultivar, environmental conditions, and season, growers should be wary of EC values over 2.0 mS and avoid EC values in excess of 3.0 mS. An effective way to correct a nutrient solution with high salinity is to dilute it with plain water.

Rainwater should be used if the municipal water source has high salinity. A good method to test water quality is to compare the growth of lettuce in 1-gallon bottles (Kratky 2002) of nutrient solution made with rainwater and municipal water. For example, municipal water in the Hilo area is generally very good and has an EC (electrical conductivity) of less than 0.1 mS, whereas some Kona municipal water may have an EC of 0.3 to 0.5 mS. Water with an initial EC of 0.5 mS from salt contaminants will concentrate to 2.0 mS when 75 per cent of the original nutrient solution has been lost by evaporation and transpiration.

The hydroponic system described here is extremely efficient with water use. Water use efficiencies of less than 3 gallons per pound of lettuce are common, and a water use efficiency as low as 1.3 gallons of water per pound of lettuce has been recorded (Kratky et al. 2008).

Fertilizer

Fertilizer nutrients from two stock solutions (concentrated fertilizer solutions) are added to tanks filled with 5 inches of water before the cover sheets are placed on the tank. For the sake of this discussion, Chem-Gro (Hydro-Gardens, Colorado Springs, CO) hydroponic lettuce formula fertilizer (8-15-36 + micronutrients), magnesium sulfate, and calcium nitrate are used to prepare the two stock solutions. Other hydroponic formulas are also acceptable, but stock solutions must be prepared based upon the manufacturer's instructions. Growers may also formulate their own fertilizer formulas.

Figure 12. Different models of electrical conductivity (EC) meters to measure total fertilizer salts in milli-siemens (mS).

The nutrient stock solutions (Figure 13) are made as follows:

Procure two good-quality plastic trash containers and place them on a firm foundation, such as a cement slab or thick plywood sheet. Make sure that there are no rocks under the containers, because they could crack the plastic and cause a leak. Label the first trash container as A and the second as B.

You will be filling both of the trash containers with exactly 25 gallons of water and making a 25-gallon mark on the container before removing about 5 gallons of water from each container, adding the fertilizer components, and topping them off with water to the 25-gallon mark.

To container A, add 25 lb of Chem-Gro 8-15-36 plus 15 lb of magnesium sulfate (epsom salts). To prepare smaller amounts of stock solution A, add l lb Chem-Gro 8-15-36 hydroponic fertilizer plus 0.6 lb (9.6 oz, 272 grams) of magnesium sulfate to each gallon of final solution.

To container B, add 25 lb of soluble-grade calcium nitrate. To prepare smaller amounts of stock solution B, add 1 lb of soluble-grade calcium nitrate to each gallon of final solution.

Some growers choose to add only the Chem-Gro 8-15-36 fertilizer in container A and to prepare a container C for magnesium sulfate.

Each stock solution should have its own measuring cup and stirring rod. Place a PVC pipe or similar stirring rod in each stock solution container and stir well before using. Place one plastic measuring cup in each stock solution. Concentrated stock solutions must be kept separate to prevent chemical reactions whereby precipitates are formed (e.g., calcium sulfate and calcium phosphate), which alters the soluble nutrient composition and causes fertilizer imbalances. Growers are advised to carry the solutions separately to the growing tanks. Stock solutions do not react when mixed in the dilute growing solution. Add the stock solutions uniformly to the growing tanks and stir lightly.

Stock solutions should be added in equal volumes to prepare a nutrient solution with an electrical conductivity (EC) of 1.5 mS. However, recommended electrical conductivities might range from as low as 1 mS during hot weather to as high as 2.5 mS in cool weather. Too much fertilizer causes salt injury, and too little fertilizer results in poor growth.

Grower experience is usually the final basis for determining the exact solution concentration. If one does not have an electrical conductivity meter, then ½ ounce (1 tablespoon) of stock solution A and ½ ounce (1 tablespoon) of stock solution B should be added to each gallon of water in the growing tank.

To calculate the capacity of a rectangular tank, first calculate the area:

Length x width = area

The inside dimensions of a 4 x 8 ft tank are 7.75 ft x 3.75 ft = 29.1 square ft.

1 inch of water depth on 1 square foot = 0.625 gal of water.

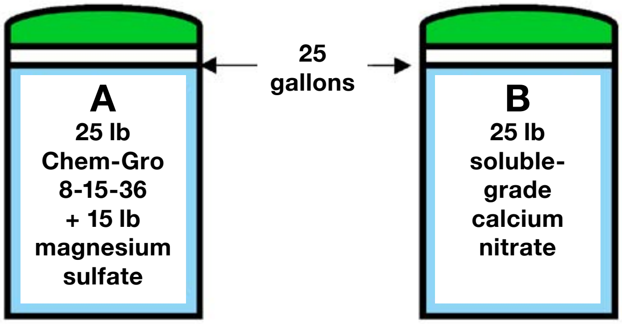

Figure 13. Nutrient stock solutions A and B.

1 inch of water in a 4 ft x 8 ft tank = 18.2 gallons.

5 inches of water in a 4 x 8 ft tank = 90.8 gallons.

At the ½ ounce/gallon rate of each stock solution, this would require 45 ounces of stock solution A and 45 ounces of stock solution B. At this application rate, one batch (25 gallons) of stock solutions should contain enough fertilizer to grow more than 70 tanks (4 x 8 ft) of lettuce.

If one has an EC meter and a measuring cup that measures in milliliters, the EC will rise approximately 0.1 mS for each 1 ml of stock A plus 1 ml of stock B that is added to 1 gal of water. Thus, adding 1500 ml of stock A and 1500 ml of stock B to 100 gal of water results in an EC of approximately 1.5 mS.

An EC meter measures electrical conductivity of all ions in solution, and it does not distinguish between individual ions. There can be a low level of an individual ion even if there is a high EC reading, and this can cause decreased yield or quality. Nevertheless, an EC meter is a very useful instrument when the grower applies a widely used commercial hydroponic lettuce fertilizer formulation. EC meters need periodic calibration. Inaccurate readings may occur with poorly mixed solutions. Higher readings are often found at the bottom of the tank. EC meters give higher readings when the nutrient solution temperature increases. For example, an EC reading of 1.28 mS at 68°F increases to 1.55 mS at 86°F. Some growers have noticed that EC readings were higher several days after the nutrient solution was prepared because the cold water that was added to the tanks caused an initially lower EC reading. EC readings of the nutrient solution tend to rise during hot weather, because plants selectively take up more water than nutrients to accommodate increased transpiration. This increases the concentration of total solutes and raises the EC of the nutrient solution. Conversely, during cool weather, plants selectively take up less water than nutrients, and the EC tends to decrease. As a result, growers generally add nutrient solution with a lower EC (1.2–1.5 mS) in hot weather and a higher EC 1.6–2.0 mS) in cool weather.

Ideally, tanks should be drained and refilled after each crop. However, some growers just "top off" the remaining solution with new nutrient solution, and they use EC readings to calculate the amount of additional stock solution to apply to the subsequent crop. As a general rule, tanks should be drained and refilled at least after every three crops, but sooner is better.

Other nutrients

Supplemental iron and silicon are not normally added to the nutrient solution in non-circulating hydroponic culture. However, a brief discussion of each is warranted.

Iron is normally applied to growing solutions at recommended rates via the commercial hydroponic fertilizer such as that in stock solution A. An iron concentration of 2–3 ppm should be maintained in the nutrient solution, but it can form complexes with other substances and become deficient (Jones 1997). Also, failure to properly mix the hydroponic fertilizer stock solution can result in an iron deficiency. Various iron chelates can be added to the nutrient solution (either to the calcium nitrate stock solution or directly to the growing solution); only 1 ounce of the active ingredient (elemental iron) will supply 1 ppm of iron to over 7000 gallons of nutrient solution.

Beneficial effects of silicon have been shown in many plants, and it is not present in most hydroponic solutions (Bugbee 2004). The recommended application rate is about 3 ppm of elemental silicon applied directly to the growing solution. If applied as liquid potassium silicate containing 7.8 per cent silicon, approximately ½ ounce of the commercial preparation added per 100 gallons of nutrient solution would result in the recommended silicon rate.

pH

The acidity or alkalinity of the nutrient solution is measured in pH units. If the nutrient solution is too acidic or alkaline, the crops will not grow well and may even die. Physiological processes are affected by nutrient solution with an abnormal pH (below 4.0 or above 7.0). For example, root growth and subsequent foliage growth was greatly retarded at a very acidic pH (below 4.0) on a Hawai'i hydroponic lettuce farm. Nutrient availability and uptake are affected by pH. Availabilities of manganese (Mn), copper (Cu), zinc (Zn), and iron (Fe) are decreased at a high pH, whereas availabilities of phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) are decreased at a low pH (Bugbee 2004).

Figure 14. Alternatives for measuring solution pH are a pH meter, a pH test kit, and pH indicator paper.

The recommended pH range is 5.5–6.5. Jones (1997) recommended a pH range of 6.0–6.5 and pointed out that plant growth may be affected below pH 5.0 or above pH 7.0. He also concluded that a pH range of 5.0–7.0 is less critical for flowing solution culture than for static solution culture. Bugbee (2004) recommended an optimum pH range of 5.5–5.8 and suggested that plants grow equally well between pH 4 and 7 if nutrients do not become limiting.

A pH meter is the most common way of measuring pH (Figure 14). All pH meters need periodic calibration, and pH electrodes tend to have a shorter life than EC meters. An inaccurate reading from a malfunctioning pH meter can wrongly direct a grower to alter the pH of the growing solution, with disastrous results. Inexpensive pH test kits with a pH range of 4.0–8.5 are also available and may be used alone or in addition to a pH meter. Several drops of indicator solution from the test kit are added to a test tube filled with nutrient solution, and upon color development, the pH is read from a color chart. The indicator liquid has a precision of 0.5 pH unit, and this is good enough for most growers and hobbyists. Growers may also use pH paper strips to monitor nutrient solution pH. The pH paper strips shown in Figure 14 have a pH range of 0–13 and a precision of 1 pH unit.

Field fertilizer formulations are not recommended for hydroponic applications because they typically have too high an ammonium nitrogen content. When the nitrate-to-ammonium ratio in the nutrient solution exceeds 9, pH tends to increase, but ratios below 8 cause pH to decrease (Jones 1997). Commercial hydroponic fertilizer formulations are usually blended to maintain pH values in the recommended pH range. However, nutrient solution pH may be affected by water quality, growing medium, the crop, and other factors. Acids and bases may be used to alter nutrient solution pH, but they are caustic. If the pH is too low, a simple method of raising pH is to place finely ground dolomite in fine netting, such as a nylon stocking, and immerse this in the tank until the pH adjusts upward, at which time the dolomite is removed. If the pH is too high, prepare a stock solution of 1 lb ammonium sulfate per 10 gallons of water and add ½ ounce of the stock solution per gallon of growing solution. The plant will utilize the ammonium nitrogen, and the solution pH will drop. Monitor the nutrient solution after several days and make necessary adjustments.

Growing seedlings

The first task in starting a crop is to select lettuce cultivars (varieties). Experience is the best guide in choosing a cultivar for a particular situation, season, and location. Beginning growers are advised to consult with a lettuce production guide such as Lettuce Production Guidelines for Hawai‘i (Valenzuela et al. 1996). It is useful to read cultivar descriptions in seed catalogs and order small quantities of seed such as garden packs of several cultivars each of leafy, oakleaf, semi-head and romaine lettuce, and also try both green and red cultivars. Cultivars may need to be changed with each season. For example, Manoa lettuce grows well in winter but gets severe tip burn during summer. Leafy cultivars tend to be more resistant to tip burn than semi-head and head lettuces. Both raw and pelleted seeds are available. Pelleted seeds resemble BBs and facilitate planting (Figure 15).

It is very important to produce high-quality seedlings. Lettuce seeds are “fragile” in the sense that they lose viability when exposed to warm temperatures and high humidity. This causes decreased germination and seedling vigor. A good seed source is important. If seed is ordered from a U.S. mainland source, it should be sent by air mail or priority mail.

Figure 15. Raw and pelleted lettuce seed. The original bulk seed batches remain in the refrigerator, while the smaller, working seed batches are transported in plastic bags from the refrigerator to the planting location and then back to the refrigerator.

If seed is purchased locally, give preference to seed stored under refrigeration or in an air-conditioned room. Do not leave seeds in a hot vehicle, in the greenhouse, or outdoors.

After procuring the seeds, date each batch. Then place the original seed batches in a sealable plastic container and store this in a refrigerator. These are the “mother batches” which remain in the refrigerator at all times except when filling bags or similar small containers with “working batch” seeds to be transported from the refrigerator to the planting location and then back to the refrigerator (Figure 15). Eventually, the seeds from the working batches lose viability, germinating poorly and producing weak seedlings. These should be discarded and replaced with seed from the mother batches. Eventually, the mother batches will also lose viability. The approximate life expectancy of lettuce seeds stored under favorable conditions is 6 years (Maynard and Hochmuth, 1997). However, it may be prudent to replace mother-batch seeds that are more than 3 years old.

Usually, lettuce is seeded into some type of growing plug with a pre-made dibble hole such as an Oasis® block, or into a multi-cell tray filled with growing medium. It is important to over-plant by about 20 percent to ensure that the best seedlings may be selected for transplanting into the growing tanks. Seeds may also be put directly into the net pots (tapered plastic containers with slits to allow root emergence) filled with growing medium that

Figure 16. Transplanting a lettuce seedling growing in an Oasis block and contained by a 2-inch net pot into an expanded polystyrene tank cover. Alternatively, net pots may also be filled with a peat-perlite growing medium.

are later moved to the growing tanks (Figure 16).

When growing medium is used, fine to medium grades of peat-perlite or peat-perlite-vermiculite media are commonly used. The growing medium should be moist and workable. Seedling trays and net pots are filled with growing medium and tapped slightly to settle the medium, but they should not be packed so tightly as to restrict air space. A small planting hole (¼ inch deep) is made in the medium of each cell or net pot with a pencil or dibble. Each net pot or cell is seeded with one or two seeds. Commercial vacuum seeders perform well, but they are expensive. Some growers fabricate a seeder in which pelleted seeds fill holes in a top sheet of plexiglass overlaying a bottom sheet of plexiglass that can be slid into a position in which the holes line up and the seeds fall into individual cells in a tray below; these devices can seed 100 or 200 cells at a time. However, most beginners struggle to seed by hand or with tweezers. This task can be simplified by making an "envelope seeder" (Figure 17). The top and right side of an ordinary envelope are trimmed with scissors. Either raw or pelleted seeds are placed in the envelope. The bottom crease forces seeds to line up in single file. A pencil or sharpened stick guides the seeds into the planting holes of the containers. A skilled worker can plant about 20 individual cells per minute with this method.

After planting, the seeds should be lightly misted with a spray mist bottle or a hose mist nozzle. Some growers cover the seeds lightly with additional fine growing medium or lightly close the planting holes, whereas other growers do not cover the seeds.

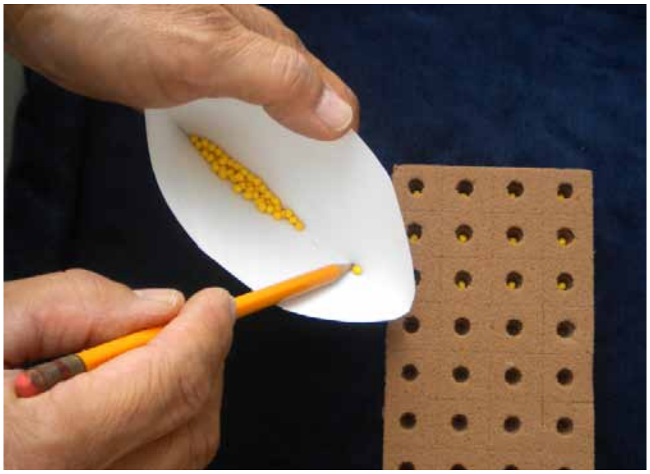

Figure 17. Planting pelleted lettuce seeds into Oasis blocks with an "envelope seeder."

Lettuce seeds may suffer thermodormancy damage when exposed to high temperatures, and this causes irregular or poor germination. Thermodormancy can occur at temperatures as low as 82°F (Borthwick and Robins 1928), and no germination was reported in lettuce seed stored at 95°F (Cantliffe et al. 1984). Therefore, freshly seeded trays should not be placed in a hot greenhouse immediately after seeding. Instead, the seeded trays should be covered with a 1-inch thick sheet of expanded polystyrene or a sheet of plywood for 24 hours and kept in a cool place, such as a garage. Another option is to stack the trays on top of each other and cover the top tray. This prevents the medium from drying out and insulates the trays from excessive heat. After 24 hours, remove the covers from the trays and place them on a bench that is misted at least twice daily. A good timetable is to seed at 5 p.m., cover the trays, then uncover them at 5 p.m. the next day and place them in the seedling house. This ensures at least 36 hours in a cool, moist environment, which helps initiation of the germination process. The newly germinated seedlings can tolerate the greenhouse temperatures. Forgetting to remove the cover from the trays will cause etiolation of the seedlings and damage them.

After 1–3 weeks in the seedling nursery, the seedlings may be transplanted into net pots, which are later moved to the growing tanks. The seedling greenhouse should be a separate structure from the production greenhouse(s). When seedlings are grown in the same structure with the production tanks, there is increased likelihood for transferring diseases and insects to the young seedlings.

It is not necessary to apply fertilizer to seedlings that are transplanted when they are only 1 week old, because there is adequate nutrition in the seed to support the very young seedling. For seedlings kept beyond 1 week before transplanting, fertilizer should be applied. The best option is to inject hydroponic fertilizer (at about ¼ the rate used in the production tanks) into the irrigation mist. Another option is to top-water with a sprayer or fine stream sprinkling can every 2 or 3 days with hydroponic fertilizer at a rate a quarter to half that used in the production tanks. Excessive fertilizer will cause the plants to become too lush and weak.

Transplanting and growing

Transplanting is preferred over direct seeding because when transplanting the grower can select the best plants. This makes it possible to regularly achieve a 100-percent stand in the growing tanks. Also, the time to maturity in the growing tanks is reduced compared to direct seeding, thus allowing more crops per year. Many growers choose to transplant 1–3-week-old seedlings into the growing tanks (Figure 18). When seedlings are growing in multi-celled trays, seedlings from individual cells are first transplanted into individual net pots, which are then placed in the tank cover openings. Depending upon the size of the cells, it may be necessary to add some extra growing medium to each net pot. When seedlings are grown in intact plugs, the empty net pots are first placed in the top-cover openings, and then the plugs are transplanted into the net pots. The plugs will not completely fill the net pots, but that is okay.

The lower portion (½–1 inch) of the net pots is initially immersed in nutrient solution. The growing medium in the net pot becomes moistened by capillary action, providing water to the seedlings. The nutrient solution level drops below the bottom of the net pots as the plants grow, and the solution is depleted by transpiration and evaporation. This creates an expanding moist air space beneath the tank cover, protecting the roots from drying out. At this point, direct capillary wetting of the growing medium is no longer possible, but the expanding root system readily absorbs water and nutrients from the tank. This system does not require wicks, pumps, aerators, electrical power, or mechanical devices. (These concepts are the subject of U.S. Patent 5,533,299, Kratky 1996).

Roots occupying the moist air space above the solution undergo vigorous lateral and branching growth and have been described as "oxygen roots" whose main function is aeration (Imai 1987). Roots extending into the nutrient solution have a limited elongation capability, because the oxygen content of the nutrient solution becomes progressively lower with depth, and they are considered to be "water and nutrient roots." The nutrient solution level may remain the same or be lowered, but it should not be raised, because submerging the oxygen roots will cause the plant to "drown." Thus, the growing tanks must be sheltered from rainfall and should be placed inside a greenhouse or rain shelter. Outdoor growing is only recommended for dry locations.

Nutrient solution consumption is very high in the later stage of the crop. If it appears that the tank will run out of nutrient solution before harvest, add about ½–1 inch of water or half-strength nutrient solution. If this occurs all year long, then consider switching to deeper tanks.

It is not unusual for slight wilting to occur at midday. Plants recover by late afternoon. Severe wilting often occurs on a very hot, sunny day immediately following an extended period of damp, overcast weather. Plants usually recover by nightfall, but they may have suffered some permanent damage. Partial shading with a 30–50 percent shade screen during the severe wilting period would be the best remedy, but this is not always possible.

The tank cover should not be lifted while the crop is growing, because roots may be torn and plant growth

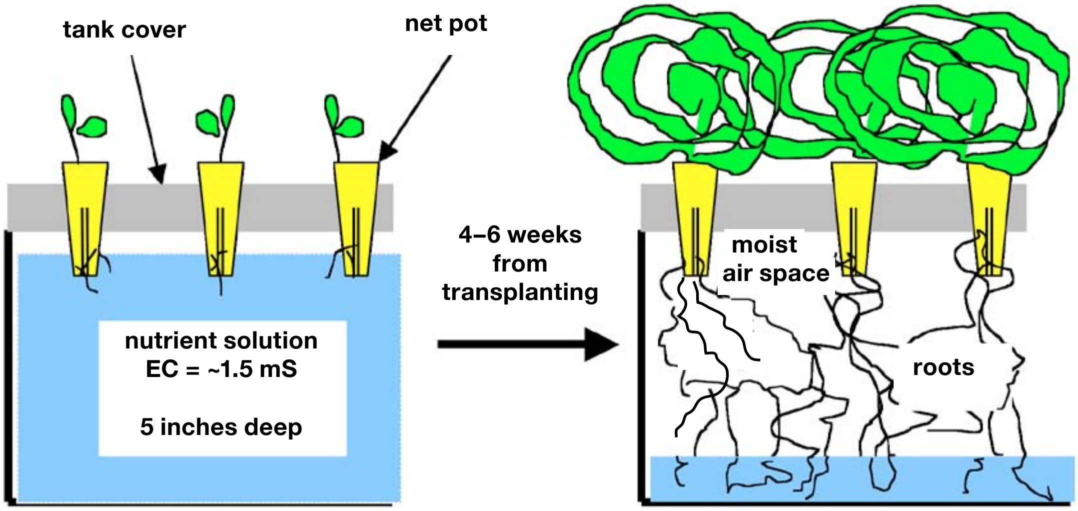

Figure 18. The lower portion (½–1 inch) of the net pots is initially immersed in nutrient solution. The entire growing medium in the net pot becomes moistened by capillary action, watering the seedlings. The nutrient solution level drops below the bottom of the net pots as the plants grow, and the solution is depleted by transpiration and evaporation. This creates an expanding moist air space.

will suffer.

Leafy or semi-head lettuce is ready for harvest about 4–6 weeks after transplanting, depending upon transplanting age, season (winter crops take longer than summer crops), and cultivar. The grower typically has multiple stages of lettuce growth, so it is possible to continuously supply a market. A new crop is transplanted within a few days of harvesting a mature crop. In fact, some growers harvest a mature crop and transplant a new crop in a tank on the same day. Thus, tank occupancy can be in the range of 300–365 days per year.

Harvesting

Early morning is the best time for harvesting. Hands must be washed well before harvesting, especially after a toilet visit. Lettuce is eaten raw, and the customer trusts that they are buying a clean and safe product.

Lettuce may be misted with municipal-grade water either before or after harvesting. Use a heavy-duty scissors or a knife to cut the lettuce (Figure 19); sanitize the tool beforehand. Leaves may be trimmed as necessary.

The lettuce may be placed in a plastic produce bag, a hard plastic container, or a box if taken to a restaurant. Sanitize hard plastic containers before use. Use new plastic bags, not reused ones. Use new cardboard boxes, particularly if the lettuce has not first been placed in plastic bags. Product labeling is suggested (Hollyer et al. 2009b).

After harvesting, the net pots should be cleaned. It may be easier to allow the roots to remain in the net pots and decay for 1–2 weeks, which will facilitate removal of plant debris and medium from the net pots. The net pots can be soaked in a 10-percent bleach solution, rinsed, and dried before reuse (Figure 20). The tank cover should be cleaned. Ideally, the remaining nutrient solution is siphoned from the tank and used to water some other plants growing in soil, because there are nutrients remaining in the solution. This solution should be dispersed over an area rather than dumped in one spot. Normally, the tank does not need to be rinsed with water. New nutrient solution is added to the tank, and the growing cycle is repeated.

Mosquitoes

Mosquitoes can breed in non-circulating nutrient solution and become both a health menace and a nuisance to workers. Following are some possible mosquito control methods.

Sides of the greenhouse can be screened to prevent mosquitoes access.

Figure 19. Harvesting lettuce.

Figure 20. After removing the remaining plant material and growing medium, the net pots may be soaked in a 10-percent bleach solution, rinsed, and dried before reuse (Waite Farm, Mt. View).

Window screen may be placed in the tank below the initial nutrient solution level. Roots will extend through the screen as the crop grows. When the nutrient solution level drops below the screen, newly hatched mosquitoes under the screen are trapped.

Fish that eat mosquito larvae may be placed in hydroponic tanks. When this is done, the tanks should be deeper than normal to ensure that at least several inches of nutrient solution remain in the tank at the end of the crop, or else the fish will die. Some fish cannot tolerate the salinity of the nutrient solution. It is recommended that several fish be placed in a bucket of nutrient solution for a few days to determine if they can tolerate the salinity.

Prentox® Pyronyl™ Crop Spray is currently registered for use with hydroponically-grown vegetables to control diptera larvae in the nutrient solution. Asian tiger mosquito larvae were killed within 36 hours by 1 ppm of the commercial formulation of Pyronyl (Furutani et al. 2005). It is difficult to measure the small quantities of Pyronyl needed to prepare a 1 ppm solution for small tanks of nutrient solution. In these cases, a 1% stock solution (10,000 ppm) of Pyronyl may be prepared by adding 10 ml of Pyronyl to 990 ml of water (1000 ml of stock solution.) Then, 3.8 ml of this stock solution are added to each 10 gal of nutrient solution (38 ml for 100 gal) and this becomes a 1 ppm Pyronyl concentration. Pyronyl could also be sprayed under the elevated tanks to control adult mosquitoes which frequently hide there.

Mosquito larvae in hydroponic tanks have also been controlled by *Bacillus thuringiensis israelensis* (Bti) toxins and methoprene (Furutani and Arita-Tsutsumi 2001a), but these materials reduced lettuce foliage weight and root growth. However, when a lower rate of Bti was applied in split applications 2 weeks apart, mosquito larvae and pupae were controlled and lettuce growth was not affected (Furutani and Arita-Tsutsumi 2001b). These results were experimental, and no Bti material is currently labeled for mosquito control in hydroponic lettuce.

Other considerations

Growers often harvest and replant a tank within 24 hours so there is little downtime for the tanks. However, a short fallow period between harvesting and replanting can be an effective method to decrease insect and disease pressure, especially if the whole greenhouse is harvested and fallowed. For this reason, the optimum greenhouse size is not larger than the area needed to produce one week's harvest. Smaller greenhouses or rain shelters are preferred over larger structures because larger structures become hotter than smaller structures.

The most common diseases affecting hydroponic lettuce in Hawai‘i are *Alternaria* spp., *Cercospora* spp., and *Oidium* spp. (powdery mildew). The most common insect problems are *Myzus persicae* (green peach aphids) and *Thrips nigropilosis* (Brian Bushe, personal communication, 2010). In addition, *Chrysodeixis eriosoma* (green garden looper) may become a problem if the greenhouse is not screened.

While the rain shelter cover and screened sides should eliminate the possibility of contamination of the crop by bird droppings, presence of slugs and snails in the production area, and rats in the vicinity, is of major concern because of the spread of rat lungworm infection, which causes human eosinophilic meningitis. Recent incidents in Hawai‘i of people contracting this serious disease from eating contaminated fresh produce (Hollyer et al. 2010) mean that growers should make every effort to ensure that slugs and snails cannot contact the lettuce crop and that rodents are eliminated from the area (Hollyer et al. 2009a).

The suspended-pot, non-circulating hydroponic growing method is not intended for production of long-term crops such as tomatoes and cucumbers, which require large quantities of water. Other non-circulating hydroponic methods for these crops have been described (Kratky et al. 1988, 2000, and 2005; Kratky 2003, 2004). Also, various other hydroponic growing methods for lettuce and other crops have been described (Resh 1991, Jones 1997).

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Note: Articles with author names in blue and preceded by an asterisk may be viewed via hyperlink in the pdf file of this document; click on the author name. If you are reading a printed copy, find the pdf file online at www.ctahr.hawaii.edu/oc/freepubs/VC-1.pdf.

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Disclaimer

Notice

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