Manual on quality seed potato production using aeroponics

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Tackling the food crisis in Eastern and Central Africa with the Humble potato: Enhanced productivity and uptake through the 3G revolution

VÍCTOR OTAZÚ

2010

INTERNATIONAL POTATO CENTER

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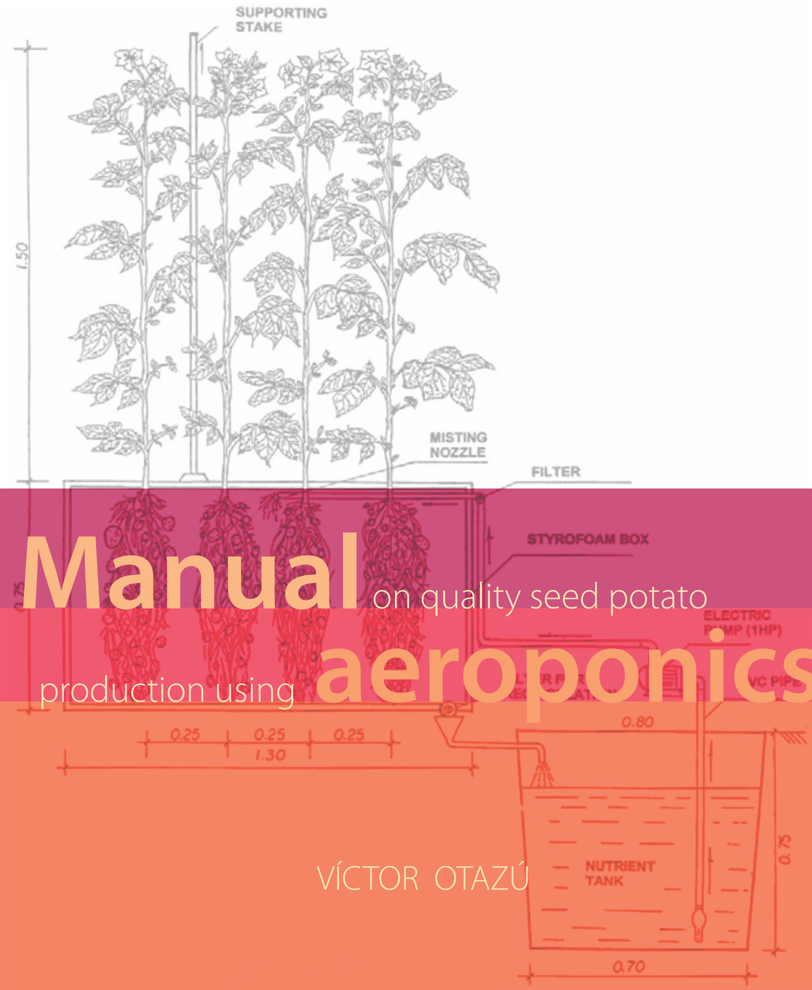

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MAIN ELEVATION
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TRANSVERSAL CUT

INTRODUCTION

Most potato growers in developing countries do not use quality seed, because of high costs and lack of access. As a result, there is a high need for cost-effective methods to produce quality seed that can be accessed by small farmers at affordable cost.

The purpose of this manual is to facilitate the diffusion of aeroponics for quality seed potato production in developing countries to improve access and lower costs. Aeroponics is a soilless method for producing pre basic potato seed (Figures 1-3). The method can produce higher yields (up to 10-times higher), more quickly, and at lesser cost than conventional growing methods.

The conventional way of producing quality pre basic potato seed is to multiply clean in vitro material in the greenhouse. This method usually produces yields of 5 to 10 minitubers per plant. The conventional method uses a sterile substrate made of soil and a mixture of various components. In modern agriculture, methyl bromide has been used as the soil disinfectant of choice, because of its low cost and ability to efficiently eliminate arthropods, nematodes, pathogens and weeds, without altering other soil characteristics. However, methyl bromide was discovered to significantly affect the atmosphere's ozone layer and is now banned in agricultural activities. The International Potato Center evaluated alternative methods (e.g., steam heat, solarization, metham sodium, and chloropicrin) and found steam sterilization to be most reliable. However, it is significantly more expensive compared to methyl bromide due to equipment and fuel costs.

Aeroponics offers the potential to improve production and reduce costs compared to conventional methods or to the other soilless method of hydroponics (growth in water). Aeroponics effectively exploits the vertical space of the greenhouse and air-humidity balance to optimize the development of roots, tubers, and foliage.

Commercial production of potato seed using aeroponics is already progressing in Korea and China. In the Central Andean Region of South America, the technology has been used successfully since 2006. At the Huancayo, Peru facility of the International Potato Center, yields of more than 100 minitubers/plants have been obtained using relatively simple materials. Current efforts are underway to incorporate aeroponics into potato seed systems of some Sub Saharan African countries.

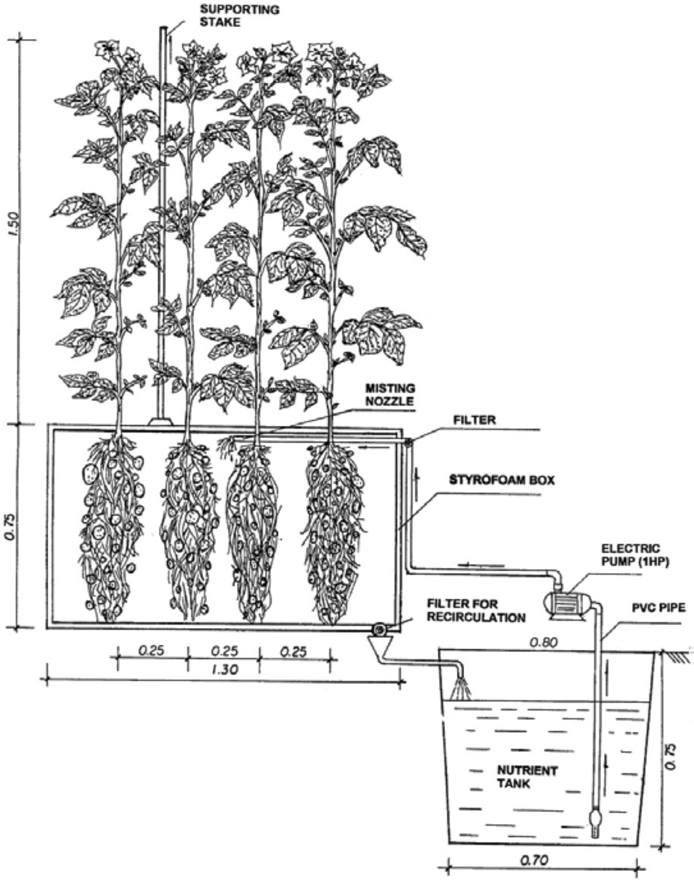


Figure 1 An aeroponic system for quality seed potato production

Figure 2 Foliage development of Peruvian potato cultivars grown in aeroponic conditions at CIP Huancayo Station, Peru.

Figure 3 Tuber development of Peruvian cv "Canchan" grown in aeroponic conditions at CIP Huancayo Station, Peru.

What we know and what remains to be known in aeroponics:

Aeroponics was first used for vegetable production. It is a relatively new technique, especially for seed potato production. Initial tests provide us with the following information:

- Potato seed production can be increased dramatically in the greenhouse.
- Potato cultivars (cvs) respond differently to aeroponics. Tuberosum type cvs tend to produce less than cvs with andigena genes. This is also observed when grown in substrate.
- Aeroponic production is particularly sensitive to climate.
- Sequential harvests are needed.
- Vegetative period of plants is increased in 1 to 2 months.
- Aeroponic seed yields the same as conventional seed in the field.
- Initial investment can be recovered rapidly.
- Bacteria inoculation to nutrient solution seems promising in increasing seed production using aeroponics. This is under current investigation at CIP.

- Aeroponics can significantly increase income or reduce the production costs of quality potato seed to make it more accessible to growers.
- Non-conventional energy sources (solar, wind) seem promising for aeroponics.

Optimization of seed potato production by aeroponics is still possible. The following factors need to be studied to this end:

- New cultivars need to be tested. Artificial conditions such as extra lights can be easily supplied in the greenhouse for cultivars grown in different latitudes.
- Different cultivars may require different optimum nutrient solution. Optimum concentration of nutrient solution needs to be identified.
- Nutrients available in each location need to be tested. Unknown mixtures may cause toxicities.
- Plant spacing for each cultivar remains to be determined. Andigena cvs may need more spacing than Tuberosum cvs.
- *In vitro* plants have proved to yield well in aeroponics. We also need to determine and compare other plant materials such as cuttings and tuber sprouts.
- Best production season needs to be determined for each location according to weather and field production season.
- Conventional methods of pest/disease control are not applicable to aeroponics. New methods need to be developed for aeroponics.

There are also some limitations, constraints or disadvantages of the technology:

- The technology is energy-dependent. Prolonged power failures can cause a total loss in the production cycle.
- Personnel need specialized training.
- As happens with new technologies, many issues need to be answered through research.
- Some materials/equipment may not be readily available in some countries.
- Any root pathogen will readily spread and contaminate all boxes.
- Aeroponics does not perform well in warm environments, unless it is implemented with expensive cooling equipment, which will significantly increase production costs.

FACTORS TO CONSIDER BEFORE GETTING INTO AEROPONICS

The greenhouse

A normal greenhouse structure should provide us with a safe environment for potato production, with a minimum investment for climatic control. This will allow us to keep our production costs as low as possible. This environment should protect our plants from pests and adverse climatic factors.

Basic elements

Conventional greenhouse infrastructures for seed potato production are usually too low. In aeroponics we want to exploit the vertical space of the greenhouse. Both root system and foliage usually grow longer in aeroponics than in substrate. Furthermore, the climatic limiting factor in the greenhouse is most commonly heat. Greenhouses with lower roofs are normally warmer than those with higher roofs. The orientation of the greenhouse is also an important factor in avoiding heat during the day. Normally, greenhouses with east-west orientation are cooler than those with north-south orientation. Screenhouses without a roof have proved to be inadequate for aeroponics. The tops (roof) of the screen may concentrate dust and fungal spores which, with the rain, may wash the spores into the aeroponic boxes, eventually contaminating all plants. The ground assigned for greenhouse construction should be properly leveled and should be free of surrounding trees, buildings and crops, especially potatoes and related solanaceous crops. Water and electricity should be accessible.

Materials and construction

Materials for greenhouse construction are available in most places. Lumber, cement, anti-aphid net and roofing material is mostly used. Of these, the roofing material is most critical in terms of price and duration. Plastic is the cheapest and can last up to three years depending on the quality. For a greenhouse of 15 m x 5 m a plastic roof can cost from US$100 - 200. Fiber glass and polycarbonate sheets last longer (10 - 15 years) but they are significantly more expensive. The same greenhouse may need around US$1500 - 2000 with these materials. If plastic is used, the wood infrastructure should not have sharp surfaces that may break the plastic by the action of strong winds. Anti-aphid nets usually last around 10 years. The floor needs a 3" thick layer of gravel or ballast. This layer will isolate the ground soil and avoid weeds and other soil borne pests. Cement flooring is expensive and during sunny days it absorbs and reflects too much heat. The inclusion of a head house or pre-chamber should be considered in the construction plans.

The roof needs to be covered by a shading net in order to lower the solar heat in the greenhouse. There are many types of shading nets with different percentages of solar luminosity transmission. Roof and doors need to be properly sealed in order to avoid insect entrance. A stapler gun is a very useful tool for fixing the roof and lateral net. Greenhouse height should be 2.5 m or higher. For warm places a 3 m high greenhouse should be considered. The following diagrams and pictures should be of help in constructing a greenhouse for seed potato production (Figures 4-9).

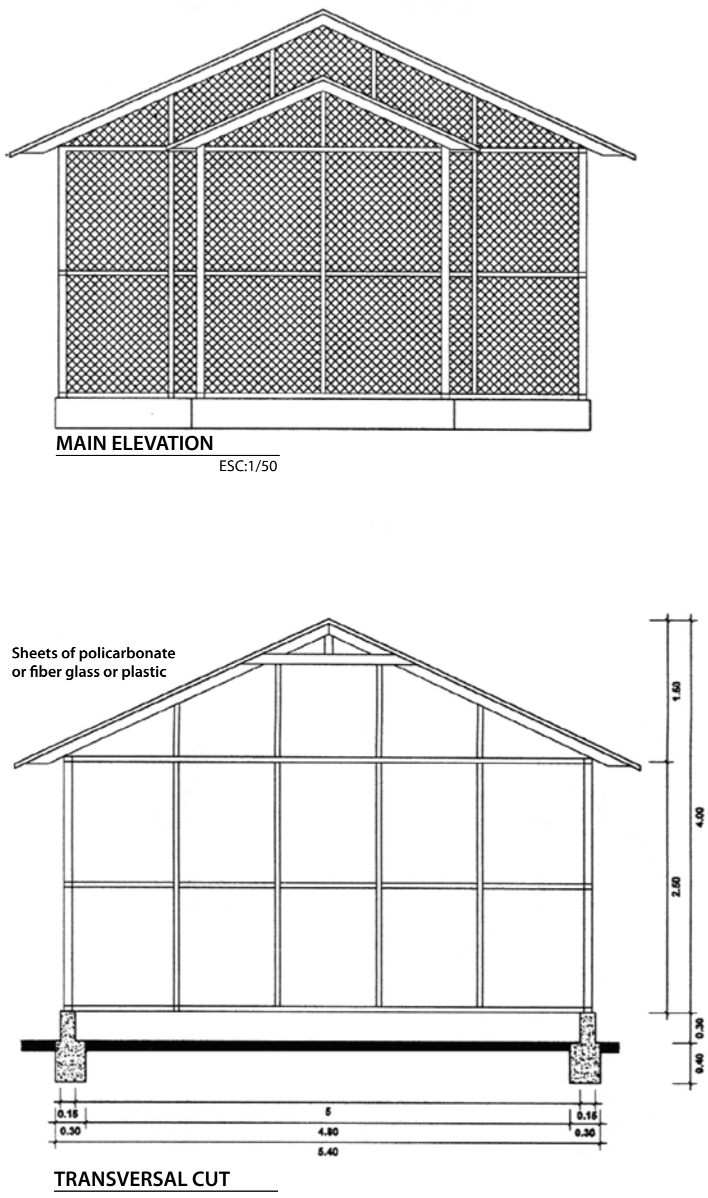
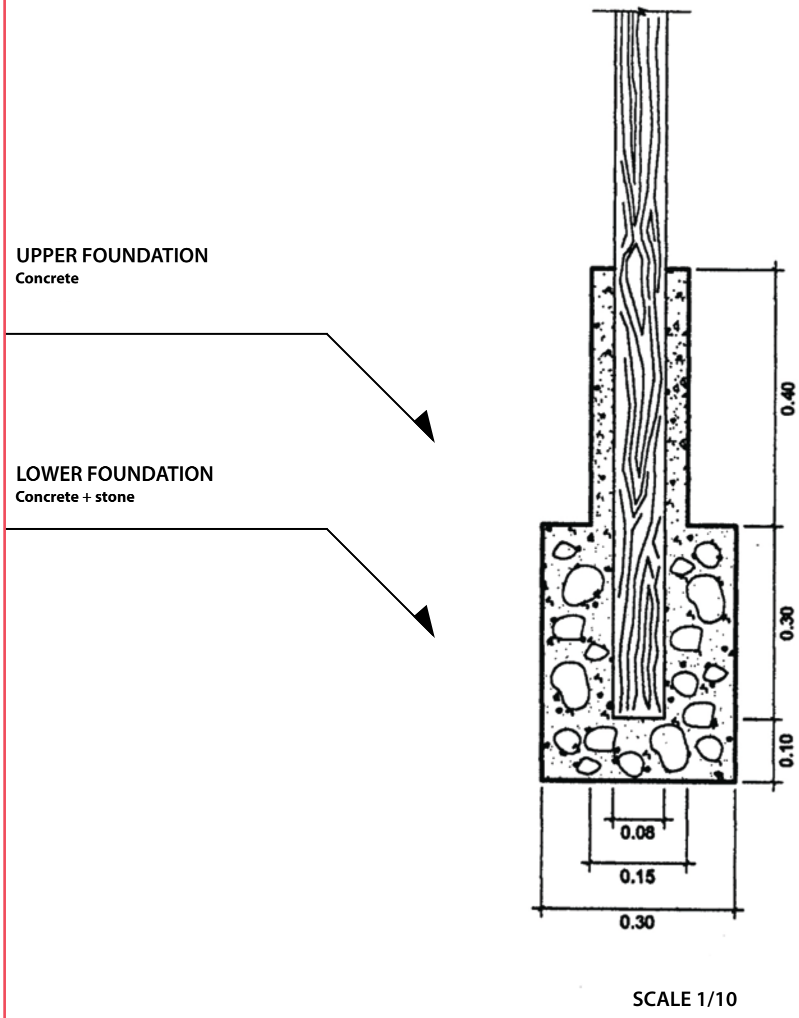


Figure 4 Front view and transversal cut of a regular greenhouse with lateral net and polycarbonate or fiber glass roof.

Figure 5 Anchoring of a typical wood column 3 m long and 4" x 4". Note the detail of lower foundation with cement concrete that should be at ground level and the upper foundation above it.



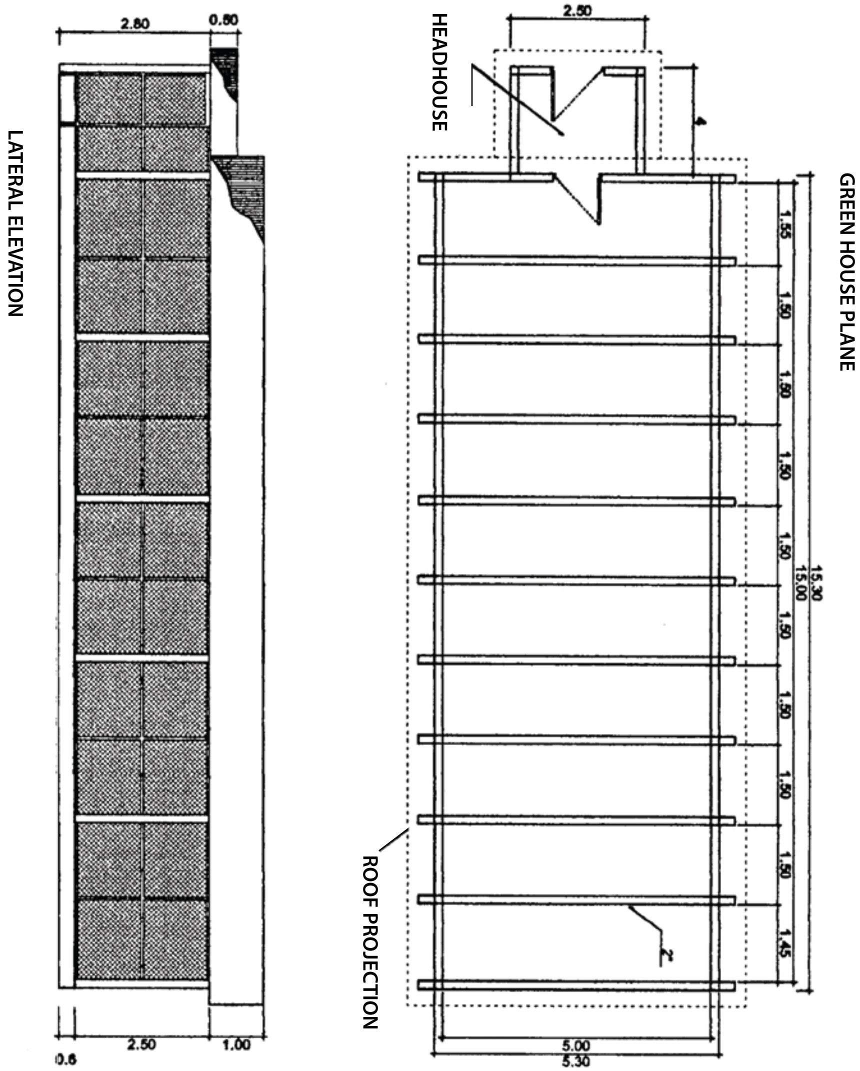


Figure 6 Lateral elevation and upper view of a 15 m x 5 m greenhouse including a head house.

Figure 7 Wood structure distribution and ground level foundation. A 15 m x 5 m greenhouse. Front view.

Figure 8 Greenhouse with upper foundation and polycarbonate roof. Rear view.

Figure 9 Finished greenhouse with plastic roof and head house.

Greenhouse management and sanitation practices

Conventional potato seed production in the greenhouse requires strict sanitation measures in order to avoid contamination. In aeroponics, these measures should be of even higher standards. Assuming that the entire greenhouse is properly sealed, no insects should be allowed inside. The greenhouse operator should be adequately trained. The pre chamber or head house is an important component of the greenhouse. Unnecessary entrances to the greenhouse should be avoided. Visitors should remain outside. The operator should not be in a crop field before entering the greenhouse. When entering, the head house door should open first and the main door must be closed. Never open both doors at the same time. The pre chamber should have a lavatory with tap water and the following materials: 2 - 3 clean coats, a bottle containing liquid soap, a bottle containing Na (sodium) (or Ca [calcium]) hypochlorite solution 2 percent (bleach), and paper toweling. Also, a tray containing calcium oxide (lime) dust should be placed at the entrance. A cloth mat dipped in a concentrated solution of copper sulfate or quaternary ammonia (benzalkonium chloride, and other synonyms) can do the same job. Sulfur powder can also be used. Placing the shoes on this tray eliminates shoe contamination with mites and soil borne spores. If no plants are to be touched, hands should be washed with soap and water. If plants are to be handled, disinfectant and soap should be used. Disposable gloves may be used when many plants are to be handled. Disinfectant should be used after handling each plant. The operator should always use a clean coat, which should always remain in the pre chamber. This procedure diminishes the chances of carrying into the greenhouse insects that may impregnate clothing. The following note should be hung in the pre chamber or head house:

SANITATION RULES

Never open both doors at the same time.

Place your shoes in the dust/mat tray before entering.

If no plants are going to be touched, wash your hands with soap.

If plants are to be handled, wash your hands with Na hypochlorite.

Always wear a coat inside.

No foods allowed.

Na hypochlorite is usually sold in stores as bleach in 3 - 5 percent concentration. A solution of 0.1 percent is used for seed tuber disinfection. This usually kills most superficial bacteria. Calcium hypochlorite comes as a white powder that can be dissolved in water. Both are used in potable water treatment. Both solutions are decomposed by light, so if plastic bottles are used in the greenhouse, they need to be covered by aluminum foil. Ca hypochlorite at 2 percent is needed to eliminate virus. This is particularly relevant if we need to make cuttings, in which case knives either flamed or dipped in Ca hypochlorite mixed with liquid soap should be used. Absolute ethanol diluted to 70 percent is also efficient for hand disinfection.

Hanging yellow traps at two or three points in the greenhouse not only helps to control insects but is also useful for detecting their presence. If traps are attracting many insects, this suggests that somewhere within the greenhouse is a space that is not properly sealed, or else that the operator has been careless. Anti-aphid nets are insect-proof, but not spore-proof. Spores of *Phytophthora, Oidium* and other pathogens can go through the net inside the greenhouse and, if climatic conditions are favorable, disease will develop. In this case fungicides will need to be used. Try to use only 50 percent of the dose recommended for regular plants. It is strongly advised to always observe the rules for safe use of pesticides. Protection equipment should always be used. A conveniently sized ladder may be needed for handling aeroponic plants. Never mix pesticides with the nutrient solution, unless previous tests have shown this to be safe.

There should be a maximum-minimum thermometer inside the greenhouse. The operator should monitor and record daily temperatures. Night temperatures lower than 4°C are too cold for aeroponic plants. Day temperatures higher than 30°C are too warm. When tuberization begins, it is desirable to have maximum night temperatures of 10 - 15°C and day temperatures around 20°C. We can lower temperatures using shading nets (Figures 10, 11). There are many types of shading nets on the market (Figure 12). Black shading net that cuts light entrance by 50 percent is commonly used because of its price and availability. It is also important to monitor the temperature of nutrient solution. When nutrient solution temperature is too high (over 20°C), it helps to place blocks of ice covered in plastic bags into the nutrient solution tank.

Figure 10 Shading net (50 percent) covering the plastic roof. Besides shading, it also protects the plastic roof from strong winds.

Figure 11 Greenhouse with opaque fiber glass sheets. The same shading net, but installed differently. It allows for better luminosity and a cooler environment inside.

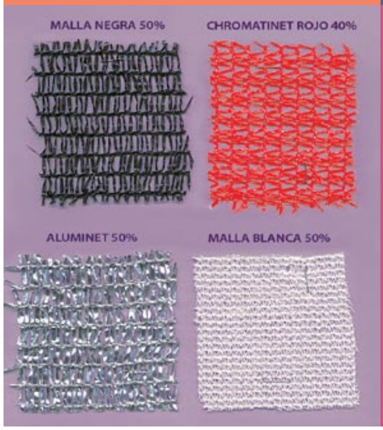


Figure 12 Some types of shading nets generally available.

Water source

This is also an important factor to observe. Usually, potable water is treated with chlorine. Chlorine and sodium are elements that increase significantly the electric conductivity of water. When potable water is used to irrigate plants grown in regular substrate, chlorine is usually harmless because it combines with organic compounds to form chlorides which are not harmful to the plants. In hydroponics and aeroponics, chlorine is readily available to the plants and can be harmful if present in concentrations over two parts per million (ppm). The root tips will be burned. The indicator that measures the amount of salts in water is electric conductivity (EC). The greater the salt content, the greater the EC and vice versa. The EC is expressed in miliSiemens per centimeter (mS/cm), deciSiemens per meter (dS/m) or milimhos per centimeter (mmhos/cm). Water to be used in aeroponics should have a low EC, not exceeding one mS/cm. Water pH is also a useful indicator. Water sources with a pH of over eight are questionable for aeroponics. It is useful to have a water chemical analysis, even if EC and pH measures fall into acceptable levels.

The other problem we may have to face is water biological contamination. Water from deep wells is usually not contaminated. Water from superficial wells, especially near urban areas, is likely to be contaminated with coliform bacteria, including Pectobacterium. Water from suspicious sources should have a microbiological analysis. Special filters can minimize this risk. If available, water should be filtered before going into the nutrient tank. Boiling is also another alternative if no other is available.

The plant material

Optimum plant material should be used for aeroponics. *In vitro* plants are preferred because of sanitary reasons. However, they need to be handled with proper care by experienced technicians. These plants should be the appropriate age and size and should go through a thorough acclimatization period before going into the greenhouse. Sometimes, in order to lower costs, plants are sold in plastic bags, with smaller area and little media to develop well in *in vitro* conditions. These plants will take longer to develop a good root system. Very old and yellowish plants are not suitable for aeroponics. Other plant materials, such as rooted cuttings and tuber sprouts, should be clean and disease free. The presence of any kind of symptom should be sufficient reason to discard the whole batch of plants. This should be noticeable when transplanting into the boxes. The underground part of the tissue coming from the sand trays should be completely clean and sand free. Before placing into aeroponics, plants should be managed in a clean greenhouse environment.

Handling *in vitro* plants

When we obtain *in vitro* plants in test tubes or in magenta boxes, they should be placed immediately in to an environment with lights. During transportation they are usually packed in such a way that they are not exposed to light for many days. The laboratory environment is different to the greenhouse environment. Therefore, plants should be acclimatized for two to three days in the greenhouse before transplanting in sand trays. They can also be transplanted directly into the aeroponic boxes. However, in our experience, a considerable number of plants die because they do not have enough root tissue to absorb water and nutrients. The other advantage of rooting previously in sand is that we can select uniformly grown plants and discard smaller or anomalous plants. Sand should be obtained from an uncontaminated source. River sand is usually contaminated with chemicals. True potato seed of any family is a good indicator of contamination. Trials with sand from different sources should be conducted to identify the most reliable source. Sand should be washed several times with running tap water before sterilization. If there is no facility for steam sterilization, after washing the sand can be boiled with water or can be washed again with boiling water several times. Most pathogens are eliminated with heat after half an hour at 70ºC. Soil substrate that is sterilized at higher temperatures can release toxic manganese to plants. Sand does not present this problem. After sterilization, sand is placed in plastic trays, 5 - 7 cm deep. If no plastic trays are available, crates lined with plastic sheets can be used. These crates can be utilized later for storage. The sand should be humid enough to enable holes to be made at regular intervals for transplanting. One day prior to transplanting, test tubes or magenta boxes should be opened to expose plants to greenhouse relative humidity. At this time it is important to avoid direct sunlight. During the first five to seven days plants should be watered with nutrient solution diluted 1:1 with water. After this period, they should be watered with full strength nutrient solution. Depending on the environment in the greenhouse, only the necessary amount of watering is required, as we do not want to expose plants to unnecessary stress. Under watering or over watering should be avoided. Direct sunlight should be avoided during the first days after transplanting. After 15 - 20 days, plants should have formed enough root system and should be ready for transplanting into aeroponics.

Handling tuber sprouts

Pre basic tuberlets (that have never been exposed to field conditions) with vigorous sprouts should be planted at regular intervals in sand trays in a similar way as explained for *in vitro* plants. Tuberlets harvested from aeroponic culture should be preferred. These plants only require clean water for watering since emerging plants will depend on the mother tuber for nourishment. Depending on the cultivar and weather conditions, after two to three weeks plants should have formed small stems and enough root system for transplanting into aeroponics. Depending on the apical dominance of seed, usually more than one stem per tuber is obtained. Mother tubers should be discarded.

Handling stem cuttings

If we are provided with clean mother plants, after two to three weeks of planting we should cut off the apical tip of each plant to induce branching. A sterile surgical knife should be used each time. Cuttings from young branches should be obtained for rooting in sand boxes prepared in a similar way, as previously explained. Dipping the cuttings into a rooting hormone solution or powder just before placing each cutting into the sand will facilitate the rooting process. Old cuttings should be avoided. Watering during the first week is carried out using water only, until some root system is formed; after that it is done in the same way as *in vitro* plants. When they have enough root system place them into aeroponics. Old cuttings will not form many tubers in aeroponics. Aseptic conditions should be observed at all times during these procedures.

DESIGN AND MATERIALS USED IN AEROPONICS

Box distribution and design

If there is already a greenhouse facility, the box distribution should be done in such a way to optimize the greenhouse space. Boxes can be distributed lengthwise (Figure 13) or widthwise (Figure 14). In the first distribution pattern we can fit 994 plants in 80 m^2 with a space efficiency of 63%, or 12.4 plants/ m^2 of greenhouse space, assuming we use a density of 20 plants/m^2. With the second distribution we can get 1480 plants in 162 m^2 with a space efficiency of 50.9%, or 9.1 plants/m^2, using the same density as in the previous case. However, in the first distribution pattern, lateral boxes have only one side window, which could be of concern to the operator at harvest time. The second pattern involves having windows at each side, thus making harvesting simpler. The other consideration we have to analyze before making a decision on design and distribution of boxes is the availability of materials. The most expensive item in the construction of boxes is the Styrofoam sheets. These come in different sizes, depending on the location, and in some countries are not easily available. The width of boxes will have to be adjusted to the size of the available sheets. Sizes usually available are 3.0 m x 1.5 m and 1.2 m x 2.4 m. The larger size is more convenient because it can be used more efficiently in terms of plant distribution in each box. Figures 15 and 16 show plant distribution in two boxes of different widths. The type of nebulizers (fog makers) to be selected should also be considered. Most nebulizers reach efficiently a 50 cm radius, so a 1.0 m wide box with a central feeding pipe is convenient. A 1.5 m wide box will require two feeding pipes (Figure 16).

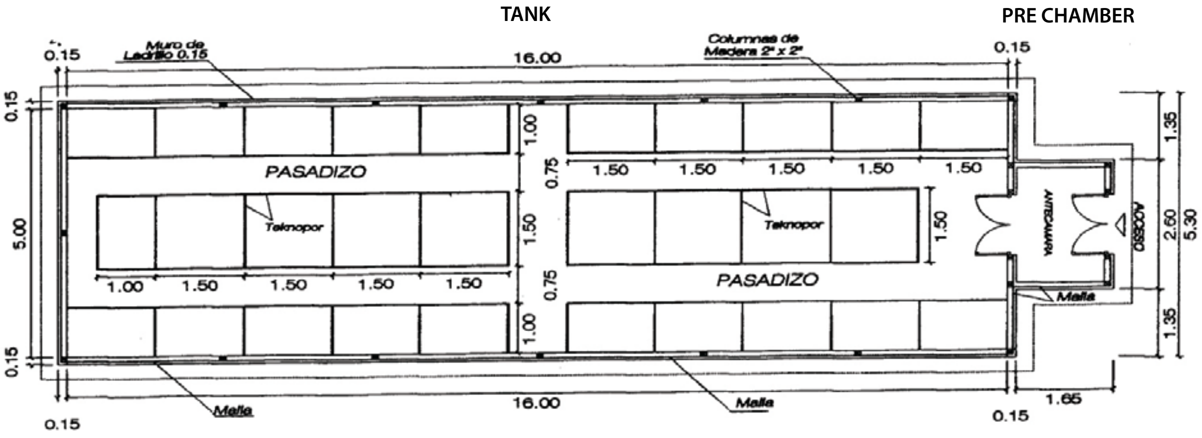


Figure 13 Box distribution for an aeroponic facility in a 16 m x 5 m greenhouse. CIP, Huancayo.

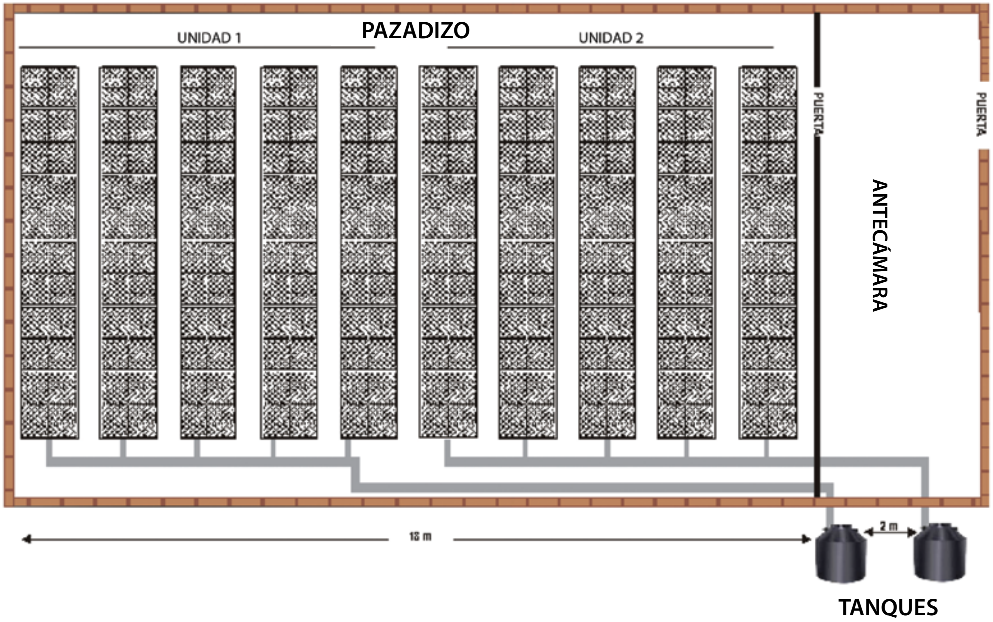
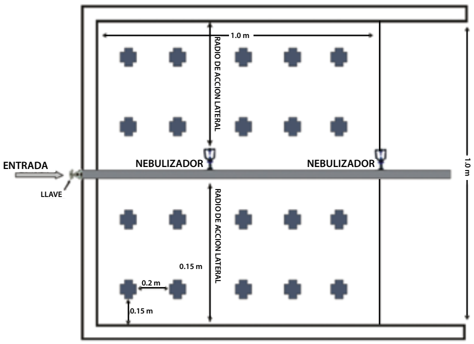


Figure 14 A different box distribution in an 18 m x 9 m greenhouse. GTIL. Nairobi .



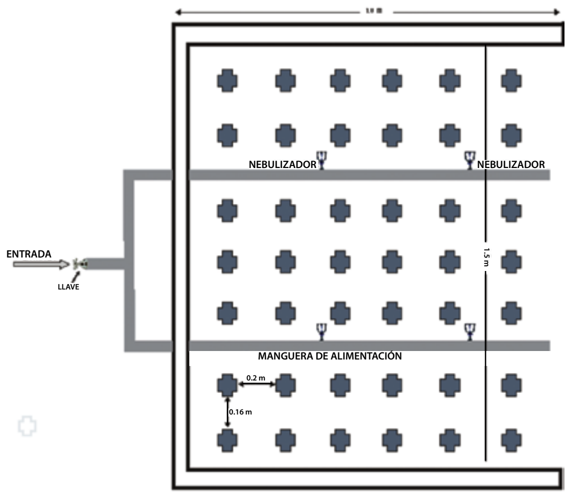


Figure 15 (Left) A plant distribution pattern with a 1 m wide (or 1.2 m) wide box. The feeding pipe should be placed in the middle.

Figure 16 (Right) A plant distribution pattern with a 1.5 m box. Even with 6 plants (recommended for cvs with Andigena genes) we will get a more efficient use of aeroponic space.

Materials

Aeroponic boxes need to have proper insulation, so that temperature variation in the greenhouse will not affect root development of plants. Boxes also need to have the necessary firmness and solidity. With this in mind, availability of materials and cost has also to be considered. For construction of boxes we may consider various options. The frame of the box can be made of wood or metal. Wood is cheaper and always available. To fill the frame we want to use an insulating material that can also provide mechanical support to the structure. Styrofoam is best, but compressed cardboard (ceiling board) or compressed sawdust can also work if we provide necessary protection against humidity. All this filling material needs to be covered with plastic, which is widely available. A plastic welder (Figure 17) is a useful tool for plastic lining. With this tool we can eliminate unnecessary wrinkles and seal leaks. Table 1 presents a list of materials used in aeroponics with reference prices in Peru.

Figure 17 A plastic welder, useful for inside box lining

Table 1. Supplies and equipment needed for one aeroponic module (16 m x 5 m greenhouse)

Item	Unit	Quantity	Price reference/unit in Peru. US $
Tank and plumbing supplies			
Plastic tank (500-600 lt)	ea	2	90
Galvanized (or pvc) nipples 1”	ea	4	1
PVC elbow union 1”	ea	6	1
PVC elbow union 3/4”	ea	10	1
PVC elbow union 2”	ea	4	1.5
PVC universal union 1”	ea	4	2
Tee union pvc, 1”	ea	2	1
Tee union pvc, 3/4”	ea	6	1
Bushing adapter pvc, slipxmale thread	ea	16	1
Thick pvc pipe, 3m long, 1”	ea	1	7
Thick pvc pipe, 3m long, 3/4”	ea	1	6
Reduction union, pvc,slip, 1” to 3/4”	ea	4	1
Sewage pipe pvc, 3m long, 2”	ea	1	5

Valve, pvc ¾ x 16mm	ea	8	1.55
Polyethylene black pipe 16mm (5/8")	m	70	0.18
Teflon tape	ea	8	1.5
Shut off valve, ball type (metal) 1"	ea	2	4.5
Shut off valve, ball type (metal) 1" (metal) 3/4"	ea	10	4.5
Check valves 1"	ea	2	3
Spin clean filter 1"	ea	2	24.45
Naandan nebulizers	ea	93	2.44
Boxes			
Lumber for frame and floor, 2" x 2" x 10'	ea	280	3.1
Lumber for tops 2" x3/8" x 10	ea	30	2.8
Styrofoam sheets 2" thick, 2.40 x 1.20m	ea	61	8.5
Black plastic, 3m wide	m	100	1.5
White plastic, 3m wide	m	50	1.5
Vinyl duct tape	ea	3	6.1
Heavy duty adhesive tape	ea	5	2
Silicone glue	tube	10	3.36
Nails, 3"	kg	10	1.5
Nails, 4"	kg	4	1.5
Electric equipment and supplies			
Electric pump 0.5 HP(+hydropneumatic)	ea	2	370
Electric generator (for power failure)	ea	1	500
Timer, for 15 min calibration	ea	2	50
Electricity cable, Nº. 12	m	50	35
Electro magnetic starter with thermal relee	ea	1	72
Disconnecting switch	ea	2	20
pH meter	ea	1	180
EC meter	ea		180
Nutrients	kg	10	20.0
Sulfuric or phosphoric acid	lt	0.5	10.0

Construction of boxes

The height of boxes must be from 80 cm to 1 m, depending on the cultivars to be grown. Boxes must have 0.5 m x 0.3 m side windows every other meter, so that the operator can get access to the root system at harvest times. A carpenter should be able to build these structures (Figures 18, 19). When the system is operating, the liquid left over from nebulization should return to the nutrient tank by gravity. For this purpose the boxes should have a slope. A slope of 30 cm for 7 m long boxes (4%) is adequate. The top Styrofoam cover should have holes for fixing plantlets (Figure 21). These holes need to be lined with plastic or with pieces of pvc (Figures 21, 22). An adequate fit is obtained when we make ½" holes and line with ¾" pvc pipe. This should be done according to the distancing required. For narrow boxes, four rows of holes 25 cm apart have proved to be adequate for most potato cultivars (20 plants/m^2). A convenient size of top cover is 1.20 m x 1.20 m. These were used at the aeroponic facilities at Kabale (Uganda) and Ruhengeri (Rwanda).

The inside lining of boxes requires black plastic (Figure 20) as we want to avoid any admittance of light to the root system of the plants. The internal bottom (floor) should be lined with thick plastic to avoid nutrient leaking. The external top lining can be made with transparent or white plastic to allow less heat concentration and greater luminosity for the plants. The internal lining of the top covers should also be created using thin black plastic (Figure 22).

The same thin black plastic should be used for covering the windows as double curtains. The internal curtain prevents the nebulized nutrient solution from escaping the box. The external curtain prevents light entering the box. When we use thick plastic for window coverage, it may harm the root system or cause minituber droppings on the occasions when we want to open the windows for harvesting or during inspection purposes. The 16 mm pipe must run through the central top of narrow boxes with nebulizers every 60 - 65 cm. The top covering should fit exactly over the rest of the structure. The transversal bars should hold the distribution pipe (Figure 20). These bars will be exposed to the nutrient solution. Therefore it is good if this is made of aluminum, as this material does not corrode. However it can be expensive and can be replaced with wood or cheaper metal (iron) properly protected from corrosion. The wider boxes have two central pipes. Having two tanks and two pumps per module allows us to have separate feeding systems for *in vitro* plants and for any other plant material. This also facilitates the planning of experiments with the module. The pumps and tanks must be located at the external lateral locations of the greenhouse. One pump feeds half of the boxes and the other the remaining half. All boxes must have a slope towards the tank. This slope allows the excess nutrient solution to return to the tanks by gravity. To this end the tanks should be installed below ground level so that the lower part of each box is always above the upper portion of the tanks. The following figures illustrate the construction process of aeroponic boxes.

Figure 18 An aeroponic module in construction in Njuli, Blantyre-Malawi. Wood frame for aeroponic boxes. The upper bars are made of expensive aluminum. They can be replaced by plastic-lined wood or other inexpensive metal.

Figure 19 Wood frame filled with styrofoam panels.

Figure 20 One aeroponic box lined internally with thick plastic. Note how the central feeding pipe is fixed for nebulizers.

Figure 21 Part of a box showing how the central pipe should be placed under the styrofoam top. Note also the distribution of the wells for the plants.

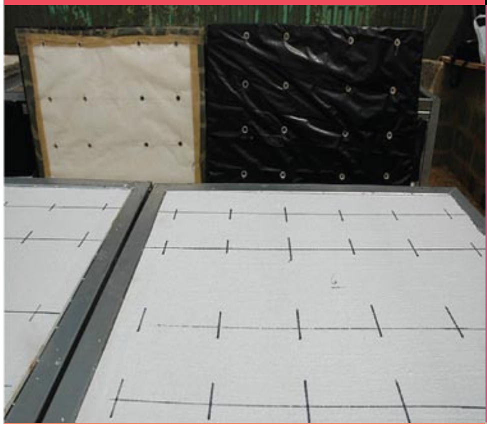


Figure 22 Lining of internal and external box cover. Notice also lining of holes with pieces of pvc.

Figure 23 Aeroponic boxes lined with plastic in a commercial operation. Huancayo, Peru.

Electricity and plumbing installation

Electricity connection should be independent for the module. A stand-by electricity generator should be ready at all times in case general power fails. In places where power failures are frequent, a good generator with an automatic start up system should be considered. Plants should not be without power for more than one hour, especially during warm periods of the day. PVC bushings, unions and pipes can be found in any hardware store. The input of a skilled electrician and plumber is important at this stage. Any leak from the boxes or pipes should be immediately repaired. It is useful to have two external ball type valves. One of them shuts off the nutrient solution entrance into the boxes. The other is open only when we want to change the nutrient solution. It flushes unwanted liquid out, until the tank is empty. This arrangement also helps when priming the pump before it gets started. The drainage opening should be located at the lowest end of each box and should be adequately sealed (Figure 25). A spare pump should be available for replacement, in case of operating pump malfunction, although this situation seldom occurs. Tank, pump and pipe installations can be observed in the following figures (Figures 24, 25, 26, 27).

Figure 24 External tank and pump installation. The purpose of the dark blue ball type valve above the pump is to flush out nutrient solution from the tank. The general valve (next to the black filter) needs to be closed. Aeroponic module in NJuli-Malawi.

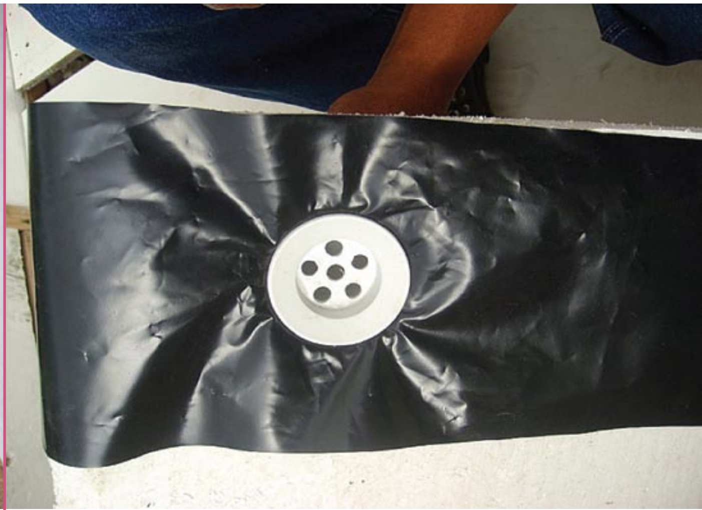


Figure 25 Detail of the draining attachment at the bottom of box. A lavatory water trap is used to fit the plastic layer sheet and the sewage pipe connected to the tank.

Timers and other components

Timers exist that can be calibrated every 10 seconds. These digital timers are not readily available and are expensive. Furthermore, they require a complicated program process that may be altered by frequent power failures. At Huancayo we have used timers that can be manually calibrated every 15 minutes. In areas where no technical support is available, these timers should be considered. Farran and Mingo-Castell (2006) used timers calibrated so that the system can work for 10 seconds every 20 minutes. During cool nights it is only necessary to activate the system for 15 minutes every hour. During the day we need 15 min. after every 15 min. of inactive period. There are many kinds of nebulizers. These are usually sold in irrigation or greenhouse equipment stores. The prices per unit are usually low, so it is convenient to buy one of each kind, test them and then buy the number needed with the type that works best. If there is not an automatic change-over switch when power fails, it is necessary to have an efficient emergency system to activate the generator, especially during weekends. This is crucial in places with an unreliable electricity service.

Figure 26 Feeding pipe installation with independent valves.

Figure 27 Feeding pipe installation for wide boxes (double).

Nutrient solution

Sources of nutrients

Each crop has an optimum nutritional requirement. Each potato cultivar may require a different nutrient solution. This also depends on the water chemical quality and the nutrients used for nutrient solution preparation. When we add nutrients to water, the EC goes up. In general we should have an EC not higher than 2.0 MiliSiemens per cm (mS/cm) if we want to avoid phytotoxicity problems. In hydroponics and aeroponics, sources of nutrients are common fertilizers that can be found on the market. A list of different nutrients is displayed in Table 2. We should not use fertilizers containing sodium (Na) or chlorine (Cl). There are some fertilizers that increase EC more than others. Nitrogen (N) and potassium fertilizers are good contributors to EC. There are also fertilizers that contribute to a higher or lesser degree to alkalinity or acidity. It is useful to have this information. Among acidic fertilizers are: ammonium phosphate, ammonium sulfate, urea, and ammonium nitrate. Among alkaline fertilizers are: calcium phosphate, potassium carbonate, potassium phosphate, and potassium nitrate. Plants need macronutrients: Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), and micronutrients: Iron (Fe), Sulfur (S), Manganese (Mn), Copper (Cu), Zinc (Zn), Boron (B), Molybdenum (Mo) for normal growth. These elements should be dissolved in water so that plants can absorb them through their root system.

Table 2. Salts and minerals used as nutrient sources for hydroponics and aeroponics

MACRONUTRIENTS

Salt or fertilizer	Formulae	Molecular weight	Nutrient	Concentration (%)
Potassium nitrate	KNO_3	101	K	13.0
			NO_3	13.0
Calcium nitrate	$Ca(NO_3)_2.4H_20$	236	Ca	17.0
			$N0_3$	12.0
Magnesium nitrate	$Mg(NO_3)_2.6H_20$	256	Mg	9.5
			NO_3	11.0
Ammonium phosphate	$NH_4H_2PO_4$	115	NO_4	12.0
			P	27.0
Ammonium sulfate	$(NH_4)_2SO_4$	132	$N\text{-}NH_4$	21.0
			S	24.0
Ammonium nitrate	NH_4NO_3	80	NO_3	16.5
			NO_4	16.5
Potassium phosphate	KH_2PO_4	136	K	29.0
			P	23.0
Potassium chloride	KCl	75	K	52.0

Potassium sulfate	K_2SO_4	174	K S	41.0 17.0
Magnesium sulfate	$MgSO_4.7H_20$	247	Mg S	10.0 13.0
		MICRONUTRIENTS		
Fe sulfate	$FeSO_4$	153	Fe	20.0
FeEDTA (Disolvine)	Fe-EDTA	430	Fe	13.0
FeEDTA (Arbore Fe)			Fe	4.0
FeEDDHA (Ferrilene)			Fe	6.0
Boric acid	H_3BO_3		B	17.0
Borax	$Na_2B_40_7.10H_20$	381	B	11.0
Cu sulfate	$CuSO_4$	161	Cu S	13.0 12.0
MnEDTA	Mn-EDTA	366	Mn	15.0
Zinc sulfate	$ZnSO_4$	161	Zn	22.0 S 22.0
Zinc chloride	$ZnCl_2$	136	Zn	45.0
Molibdic acid	$H_2Mo0_4.H_20$	180	Mo	66.0

Only fertilizers previously tested should be used in aeroponics. Not all fertilizers are always available at all locations. The following nutrient solutions were used previously for aeroponic seed potato production (Table 3):

Table 3. Nutrient solutions used for aeroponic seed potato production

Farran *et al.*		**Otazu *et al.***	
Nutrient	**Concentration**	**Nutrient**	**Concentration**
KNO_3	0.4 me/l	KNO_3	5.40 me/l
$Ca(NO_3)_2$	3.1 me/l	NH_4NO_3	4.40 me/l
NH_4NO_3	4.4 me/l	Ca superphosphate	2.60 me/l
KH_2PO_4	4.4 me/l	$MgSO_4$	1.00 me/l
$MgSO_4$	1.5 me/l	Fe(EDTA-Fe 6%)	8 ppm
		B (boric acid)	1 ppm
		Micro (Fetrilon*)	12 ppm
pH 5.7		pH 6.5	

*Fetrilon combi is a commercial foliar micronutrient powder that has the following formulation: 9% MgO, 3% S, 4% Fe, 4% Mn, 1.5% Cu, 1.5% Zn, 0.5% B, and 0.1% Mo.

How to calculate nutrient concentration

Macronutrient concentration is usually expressed as milimoles/liter or miliequivalents/liter (me/l). It is also expressed as grams/liter (g/l) or as a percentage of N, P_20_5 and K20. Micronutrient concentration is expressed as milligrams/liter (mg/l), or the same amount in parts per million (ppm). It is useful to understand certain chemical terms (mols, equivalents) for nutrient preparation. The molecular weight is the sum of the atomic weight in grams of the atoms that are part of the chemical formula of the compound. The equivalent number is obtained by dividing the weight of the compound in grams by its equivalent weight. The equivalent weight is calculated by dividing the molecular weight by its valence. One miliequivalent is 1/1000 of one equivalent. Using information in Table 2 we can calculate the equivalent weight of Ca nitrate (118), ammonium nitrate (80), potassium phosphate (136.1) and potassium sulfate (87.2). This can also be expressed in g/l (Table 4):

Table 4. Fertilizer concentration expressed in two types of measurement

Fertilizer	**Formulae**	**me/l**	**g/l**
K nitrate	**KNO_3**	**1**	**0.101**
NH_4 nitrate	NH_4NO_3	1	0.080
K sulfate	K_2SO_4	1	0.087
Mg sulfate	$MgSO_4$	1	0.247
K phosphate	KH_2PO_4	1	0.136
Ca triple superphosphate	$Ca(H_2PO_4)_2$	1	0.117

Water analysis helps to adjust nutrients if we want to be more precise. Most water sources contain enough boron (B). Plants require minute quantities of this element. If water is completely lacking B, then we can buy boric acid from any pharmacy (sold to treat feet fungi), dissolve 0.1 g in 1 liter of water and mix it with 100 l of nutrient solution. For 400 l we need 0.4 g. In our formulation, Fetrilon combi already contains some B. Water analysis not only is useful to determine its chemical quality but also to adjust precisely its nutrient components. Cadhia describes the following example to prepare a Hoagland solution with a certain water source (Table 5):

Table 5. Water composition, ideal solution and adjustment for a proper Hoagland solution preparation, milimoles/l. (Adapted from Cadhia)

	NO^{3-}	**$H2PO^{4-}$**	**$SO4^{2-}$**	**HCO^{3-}**	**Cl^-**	**$NH4^+$**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**Na^+**
Water	-	-	1.0	3.5	1.0	-	-	2.0	2.0	1.5
Hoagland solution	14.0	1.0	4.0	-	-	1.0	6.0	8.0	4.0	-
Adjustment	-	-	+3	-3*	-	-	-	+6	+2	-

*Equivalent to adding 3.0 me H^+ (acid). , Five me/l of $HCO3^-$ is left as buffering source for other acids.

Nutrient preparation

If we want to prepare a nutrient solution for 400 l the following table will help:

Table 4. Nutrients required for a potato aeroponic module of 400 l.

Nutrient	Concentration(me/l)	g/l	g/400 l
K Nitrate	5.40	0.54	216
NH4 Nitrate*	4.40	0.35	140
Ca triple superphosphate	2.60	0.28	112
Mg Sulfate	1.00	0.24	96
Fetrilon combi	12 ppm	0.012	4.8
Iron quelate (6%), optional	9 ppp	0.009	3.6

* To be reduced in concentration by half when tuberization initiates (around two months after transplant)

All nutrients are easily dissolved in water, except Ca superphosphate. Nutrients must be dissolved separately in small amounts of water until completely dissolved. Sometimes previous filtration may be required in order to eliminate impurities before placing into the nutrient tank. For Ca superphosphate we must place the granules in a piece of anti-aphid net, wet it in a bucket of water and with one hand try to crush and squeeze until the granules disappear. Next, we must wait until the solution settles down, then transfer the clear supernatant, discarding impurities at the bottom. The other option is to filter the solution, but this takes longer. If new nutrient sources are to be used, they need to be tested beforehand. In particular, other micronutrient sources may not mix well with other nutrients, thus causing phytotoxicity to plants. Initially, for the first few days, prepare only for 100 l and add water to make up 200 l (50% strength). After the second week the solution must be full strength and the final volume 400 l. Appearance of any toxicity symptom in leaves will indicate that the nutrient solution is not compatible with plants and should be changed immediately. It is also convenient to check the pH of water and nutrient solution. An optimum pH allows for a maximum nutrient availability for the plants. If the pH of the nutrient solution is higher than 7.3 we can lower it with a diluted solution of sulfuric acid or phosphoric acid to achieve a slightly acidic pH (6.8).

Alternative methods

The Peruvian Agrarian University, La Molina, sells commercially concentrated stock nutrient solutions. At CIP these nutrients were used for hydroponics, but they can also be used for aeroponics. Preparation of these nutrients is described:

Concentrated stock solutions are prepared for macronutrients (solution A) and for micronutrients (solution B). They are kept in separate bottles until a final solution is made.

Stock solution A

- In a plastic container soak, in enough water (500 ml), 180g of Ca superphosphate for 24 hours.
- With a pestle and mortar crush all granules until most of it is dissolved. Discard insoluble inert material. The final volume will be 5 l.
- In a separate container add 550 g of K nitrate to 3 l of water. It should dissolve rapidly.
- To the same container add 350 g of ammonium nitrate and dissolve it.
- Mix together the solutions from both containers and adjust the final volume to 5 l. Keep this solution in an opaque plastic bottle as solution A.

Stock solution B

- Prepare micronutrients in 1 l of distilled water: In about 300 ml of water add the following components: 1.0g of Cu sulfate, 1.7g of Zn sulfate, 0.2g of NH_4 molibdate, 3g of boric acid and 5.0g of Mn sulfate (in that order). Make up the final volume to 1 l with distilled water. Keep this solution in a clean bottle.
- In 1 l of water dissolve 220 g of Mg sulfate.
- To this solution add 400 ml of micronutrient solution and mix well.
- Add 17g of Fe-EDTA quelate (6% Fe).
- Add enough water to make up the final volume to 2 lt. This is solution B.

Final preparation:

Before mixing both solutions, shake both bottles well. For the final concentration mix 5 ml of solution A with 2 ml of solution B for every liter of nutrient solution. For 100 l of nutrient solution we should mix 500 ml of solution A with 200 ml of solution B, and so on.

Calcium Nitrate

In some countries ammonium nitrate is not available, so we need to have an alternative nutrient solution. In Mauritius the following nutrient solution is used for aeroponics: Prepare a stock solution as follows: In 10 liters of water weigh and mix:

Nutrient	g
Calcium nitrate ($Ca(NO_3)_2.4H_20$	118
Potassium phosphate (KH_2P0_4)	68
Potassium nitrate (KNO_3)	252
Magnesium sulfate ($MgS0_4$)	246
Fe EDTA	11.7
Boron	0.7

Manganese chloride ($MnCl_2$)	1.5
Zinc sulfate ($ZnS0_4$)	0.3
Copper sulfate ($CuS0_4$)	0.1
Molibdenum (Mo)	0.1

For 1 l of preparation add 20 ml of stock solution (2%)
For 100 l add 2 l of stock solution, etc.

Plant and nutrient handling

When plants are ready for transplanting into aeroponics, they should be carefully extracted from the sand trays. Big forceps are useful for this. A soft brush is helpful to clean off the sand remaining on the roots. In addition, a water hand sprayer or a picet is useful for washing off the sand. A piece of thin sponge is wrapped around the neck of the plant and fitted to each hole into the Styrofoam box. With a pair of forceps we proceed to push the sponge and plant down until the root system is exposed to the nutrient fog. After transplanting we may need to cover each hole with a piece of thin black plastic (light blockers) to avoid any light entering the box. When transplantation is finished, we should look for light leaks into the boxes and check that the roots are fully exposed to the nutrient fog. We also need to prepare the supporting system. Initially, transplanted plants will be able to support themselves for two to three weeks. After this period, they will grow quickly and will need a supporting system, such as stakes or wire (Figures 28, 29), or supporting nets (Figure 30). Agricultural twine is the cheapest material that can be used for this purpose. After a month or so, lower leaves need to be removed with a dissecting blade following strict aseptic measures. If stolons start to form in the upper part of the root system, plants need to be lowered for better stolon formation. Some cultivars tend to form superficial stolons and they may be formed in the sponge within the pvc pipe. If we do not push the stem down until the sponge is below the styrofoam top, one or more tubers may develop in the pvc pipe, pressing and strangling the stem and eventually killing the plant. The process of lowering the stems is important and is the equivalent to hilling up in the field. When we finish this process, the stems will be free and without a supporting mechanism. Therefore plants should be properly tied to stakes, or other supporting devices such as supporting nets. It is also important at this stage to avoid light leaks into the boxes. A second light blocker made of thick plastic may be helpful. A sample of leaves should be obtained for ELISA tests to see if there is any virus contamination. Nutrient solution needs to be checked regularly. CE and pH are useful indicators. CE should not exceed 2.0mS/cm. Similarly, pH should not exceed 7.3. Diluted phosphoric acid can be used to lower pH to a slightly acidic pH (6.5 - 6.8). Each month the nutrient solution needs to be changed. This can be done with the pump turned on while monitoring the two valves (Figure 24). Close the general valve (light blue) and open the dark blue valve to eliminate unwanted nutrient solution. Later on, when plants develop abundant foliage, nutrient consumption is increased. If there is

Figure 27 Plants may need different types of supporting systems. Stakes, wire or twine can be used. Some cvs develop abundant foliage.

Figure 28 A wire supporting system used in aeroponics in Malawi.

Figure 29 Nylon supporting net used at GTIL-Nairobi.

an unusual consumption of nutrients, it means that there is a leak in the plastic lining somewhere. A filter fixed at the end of the draining pipe into the tank is useful for retaining root pieces or other solids that may come off the system (glue, plastic, etc.). A piece of anti-aphid net wrapped around the pipe works well to retain impurities. The black filter needs regular maintenance and cleaning (every month).

When the season is over, a general cleaning and disinfection operation should be performed in tanks, boxes, pipes, and nebulizers. Salts usually tend to accumulate in filters and nebulizers. A weak acid like acetic acid or a diluted concentration of sulfuric acid is efficient in removing salts. A 50 l preparation of 2 percent Ca or Na hypochlorite should be run through the system with the pump on for 15 minutes, followed by two to three runs of water as a rinse.

Harvesting and storage

After two months of transplanting, early cultivars start to produce minitubers. We can start harvesting tubers that weigh around 8 g or more (Figure 31). We should open the external curtain first, and then very carefully the internal curtain, to avoid damage to the root system of the plants. Harvests should be planned for early mornings when temperatures are still cool. Timers can be stopped for half an hour at a time. We can plan harvests every 10 to 14 days thereafter. Harvesting aeroponically grown minitubers is different than conventionally grown minitubers. The basic difference is the sequential harvests in aeroponic plants. In the conventional system there is only one final harvest. Depending on the cultivar, with aeroponics we have many harvests, up to 10 or more. Every time we harvest we should treat the seed with a 0.1 percent Na hypochlorite solution, followed by one or two water rinses. This is performed only as a precautionary measure to avoid bacterial contamination. If we have followed strict sanitation rules during the season, we should not have sanitary problems and we should not treat our seed with other pesticides. Next, seeds should be allowed to cure in a dry and clean environment for two to three weeks before placing them into cold storage or a diffused light store. Before this, we should grade and separate our seed according to size (Figure 32). Small tubers (less than 5 g) should preferably be kept in cold stores. If we want to use diffused light stores we should provide additional protection for our storage crates, covering them with pieces of anti-aphid net (Figure 32).

One major disadvantage of sequential harvests is that when the season is over we end up with a non-uniform seed lot regarding sprouting. Tubers harvested during the first months of harvest will sprout first; the ones harvested last will sprout later. This will also cause irregular emergence after planting. Although this irregularity does not seem to affect yield, it can partially be corrected by storing the first harvested tubers in cold stores, then, a month before the season is over, by placing all of them in a diffused light storage. Very small sized minitubers (1 g - 2 g) can be used in conventional seed multiplication (pots or beds).

Figure 31 Aeroponic minitubers recently harvested, cultivar Canchan, Peru.

Figure 32 Three sizes of minitubers (cultivars Cruza and Canchan) (left). Crates covered with anti-aphid net in a diffused light storage (right).

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APPENDIX

TECHNICAL TERMS USED IN AEROPONICS

Anti-aphid net: A net usually made of polyethylene, nylon or acrylic material that does not allow aphid entrance into the greenhouse. Also called "insect proof net". It comes in rolls of different widths.

Aseptic: Clean. Implies avoiding contamination of any kind.

Ballast: Pieces of broken stone of different grades used for concrete mixtures or greenhouse floors.

Bleach: A solution of 3 - 6 percent of Na hypochlorite (Na0Cl) commonly used as a whitener and disinfectant.

Bleaching powder: Calcium hypochlorite.

Box: A light-proof container that houses the root system of plants in aeroponics.

Ceiling board: Cardboard compressed material, used as ceiling panel.

Cultivar: A potato variety (cv).

Difused light store: A room with indirect solar light used for storing seed potatoes.

Elbow union: A plumbing union that can be made of metal or PVC in an L shape.

Electric conductivity (EC): Estimates the total dissolved salts or total amount of dissolved ions in water.

Head house: Pre chamber. Important infrastructure of a greenhouse at the entrance used to avoid insects.

***In vitro* plants:** Plants produced in the laboratory under *in vitro* conditions. They come in tubes or magentas.

Light blockers: Pieces of black plastic covering holes in aeroponic transplants to avoid light entrance into boxes.

Macronutrients: Essential elements needed in relatively large amounts for plant growth. Generally N, P, K, and Ca, Mg are considered as macronutrients.

Micronutrients: Essential elements required for plant growth but in very minor quantities. They include: S, Mn, B, Cu, Fe, Cl, Co, Mo, Zn.

Nebulizers: Also called micro jets. They are fog-making nozzles.

Nipple: A short piece of tube that serves for connecting pipes.

Nutrient solution: A solution with balanced fertilizers that plants use for their nutrition.

pH : Degree of alkalinity or acidity of a solution.

Plastic: Polyethylene material that comes in different compositions and thicknesses for greenhouse roofs, box lining and other uses.

Polycarbonate: A rigid type of plastic that comes as corrugated sheets that are used for greenhouse roofs.

Pre basic seed: Potato seed produced in the greenhouse in disease-free conditions. It usually originates from clean *in vitro* plantlets.

Priming: Removal of air inside pump casing by flooding with water. It is required before starting the pump.

PVC: Polyvinylchloride. Material widely used for plumbing components such as pipes and unions.

Quaternary ammonium: Active ingredient in disinfectants and sanitizers. It has many synonyms. Benzalkonium chloride is one of the best known.

Reduction union: A union (PVC or metal) that connects pipes with lesser diameter.

Shading net: A net used to provide shade and lower internal greenhouse temperature.

Slab: Concrete structure used to anchor permanently any equipment, such as a pump.

Slope: The inclination that boxes should have to allow excess nutrient solution to flow towards the tank by gravity.

Styrofoam: White insulating material that comes in 3.0 m x 1.5 m or 2.40 m x 1.20 m panels and in different thicknesses.

Supporting net: A net made of twine, nylon or wire, used to tie and support foliage of aeroponic plants.

Timer: Electrical device that automatically controls pump operation.

Valve: Device that controls (shuts off or opens) fluid circulation in a pipe.

Trouble shooting chart: main problems/solutions that may occur in aeroponics

General problem/symptom	Probable cause	Solution
Yellowish *in vitro* plants.	Plants maintained in the dark for a long time.	Place plants under lights for some time before transplanting.
Elongated growth pattern of *in vitro* plants in sand trays.	Too warm greenhouse, not enough lights.	Monitor temperature before installing shading net.
Most plants in aeroponics are wilting.	Not enough pressure. Foot valve of pump clogged. Filters clogged.	Clean foot valve. Remove and clean filters.
Some plants in boxes wilting.	Adjacent nebulizer clogged.	Clean (change) nebulizer.
Plant wilting even with enough fogging.	Mechanical damage somewhere in the stem of plant.	Remove plant. Replace it if possible.
Tank becomes empty unusually soon.	Nutrient solution is leaking somewhere. Drainage opening clogged.	Spot the leak, fix it. Clean drainage opening.
Plants start showing symptoms of leaf burns.	Deficient preparation of nutrient solution. Inadequate source of water. Greenhouse too hot.	Remove and change nutrient solution/water. Cool down nutrient solution in tank.
Plants with foliar symptoms.	Pathologic. *Phytophthora, Oidium* are most frequent pathogens.	Identify pathogen. Apply product at half recommended rate.
Nutrient solution with pH too high (more than 7.4).	Source of nutrients/water too alkaline.	Lower pH with diluted acid to pH in range of 6 to 7.
Nutrient solution with pH too low (around 5).	Weak (old) nutrient solution.	Prepare a fresh nutrient solution.
Nutrient solution with a high EC (more than 2 mS/cm).	Source of nutrients/water too alkaline.	Identify which component is alkaline. Add water to lower EC.
Measurements of pH or EC not consistent.	Equipment not properly calibrated.	Calibrate equipment.

INTERNATIONAL POTATO CENTER

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