HYDROPONIC CULTURE FOR THE TROPICS: OPPORTUNITIES AND ALTERNATIVES

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ABSTRACT

Hydroponics is perhaps the most intensive method of crop production in today's agricultural industry. It uses advanced technology, is highly productive, and is often capital-intensive. Since regulating the aerial and root environment is a major concern in such agricultural systems, production takes place inside enclosures that give control of air and root temperature, light, water, plant nutrition and protect against adverse climatic conditions. While most greenhouse horticultural crops are grown in soil, the last 12 years has produced an avalanche of reports in hydroponics. There are many types of hydroponic systems as well as many designs of greenhouse structures and methods of control of the environment therein. Not every system may be cost effective in any location. The future growth of hydroponics depends greatly on the development of systems of production competitive in cost with systems of open field agriculture.

INTRODUCTION

Hydroponic culture is possibly the most intensive method of crop production in today's agricultural industry. In combination with greenhouses or protective covers, it uses advanced technology and is capital intensive. It is highly productive, conservative of water and land, and protective of the environment.

There has been increasing interest in the use of hydroponic or soilless techniques for producing greenhouse horticultural crops. While most vegetable crops are grown in soil, the last twelve years has produced an avalanche of reports in hydroponics. The future growth of hydroponics depends greatly on the development of systems of production which are competitive in costs with systems of open field agriculture.

While the techniques of hydroponic culture in the tropics can be quite similar to those used in temperate regions, greenhouse structures and the level of control of the environment may be very different. This paper will discuss these differences, along with the advantages and constraints of hydroponic culture in the tropics.

HYDROPONIC CULTURE

Definition

Hydroponics is a technology for growing plants in nutrient solutions (water and fertilizers), with or without the use of an artificial medium (e.g. sand, gravel, vermiculite, rockwool, peat moss, sawdust) to provide mechanical support. Liquid hydroponic systems have no other supporting medium for the plant roots; aggregate systems have a solid medium of support. Hydroponic systems are further categorized as open (i.e., once the nutrient solution is delivered to the plant roots, it is not reused) or closed (i.e., surplus solution is recovered, replenished, and recycled).

Some regional growers, agencies, and publications persist in confining the definition of 'hydroponic' to refer to liquid systems only. This exclusion of aggregate hydroponics serves to blur statistical data, and may lead to an underestimation of the extent of the technology and its economic implications.

Virtually all hydroponic systems in temperate regions of the world are enclosed in greenhouse-type structures in order to provide temperature control, to reduce evaporative water loss, to give better control of diseases and pests, and to protect hydroponic crops against the elements of weather, such as wind and rain. This last reason why hydroponic systems are used in greenhouses is especially valid in tropical regions, where wind and rain may do considerable damage to crops. However, in the tropics the sides of a greenhouse structure are often left open for natural ventilation, while if pest infestations threaten to occur, the sides can be covered with screens.

While hydroponics and controlled environmental agriculture (CEA) are not synonymous, CEA usually accompanies hydroponics, and they share many of the same potentials and problems. Although hydroponics is widely used to grow flowers, foliage and bedding plants, and certain high-value food crops, this paper will focus mainly on vegetable crops.

Attributes

The principle advantages of hydroponic CEA include high-density planting, maximum crop yield, crop production where no suitable soil exists, freedom from the constraints of ambient temperatures and seasonality, more efficient use of water and fertilizers, minimal use of land area, and suitability for mechanized production and disease control. A major advantage of hydroponics, as compared with culture of plants in soil, is the isolation of the crop from the underlying soil which may have problems associated with disease, salinity, or poor structure and drainage. The costly and time-consuming tasks of soil sterilization and cultivation are unnecessary in hydroponic systems, and a rapid turnover of crops is readily achieved.

In the tropics, the incidence and control of disease and pest infestations are a major concern. Most temperate regions have climatic changes, such as cold winters, to break the life cycle of many pests. In the tropics, the life cycle of diseases and pests is hardly slowed in the course of the seasons, and they are a year-round threat. Unfortunately, less is known about many of the diseases that occur in the tropics than those common in temperate regions. A comparison of three major food crops grown in the tropics and temperate regions of the world indicates that the number of diseases is much greater in the tropics, as shown in Table 1.

The control over soilborne diseases and pests given by hydroponics can be a considerable advantage. The principal disadvantage of hydroponics, relative to conventional open-field agriculture, is the high cost of capital and energy inputs, especially if the structure is artificially heated and evaporatively cooled by fan and pad systems. Such systems of environmental control are not always needed in the tropics. A high degree of competence in plant science and engineering skills are required for successful operation. Because of its significantly higher costs, successful applications of hydroponic technology are limited to crops of high economic value in specific regions and often at specific times of the year, when comparable open-field crops are not readily available.

Table 1. Number of Crop Diseases

Crop	Temperate	Tropical
Rice	54	500-600
Corn	85	125
Beans	52	250-280

Source: Wittwer 1981

With CEA, capital costs are several orders of magnitude higher than those for open-field crops, and the types of food crops feasible for hydroponics are severely limited by potential economic return. Agronomic crops are totally inappropriate. A decade ago, it was calculated that the highest market prices ever paid would have to increase by a factor of five for hydroponic agronomy to cover the cost. Since then, CEA costs have more than doubled, while crop commodity prices have remained constant. Indeed, in the United States there is usually a surplus of open-field agronomic crops, and a significant percentage of the available cropland is deliberately left idle. Repeated pricing studies have shown that only high-quality, garden type vegetables — tomato, cucumber, and specialty lettuce — can cover costs or give a return in hydroponic systems. These are, in fact, the principal (and virtually only) hydroponic CEA food crops grown today in the United States; in Europe and Japan, these vegetables along with eggplant, pepper, melon, strawberry and herbs are grown commercially in hydroponic systems.

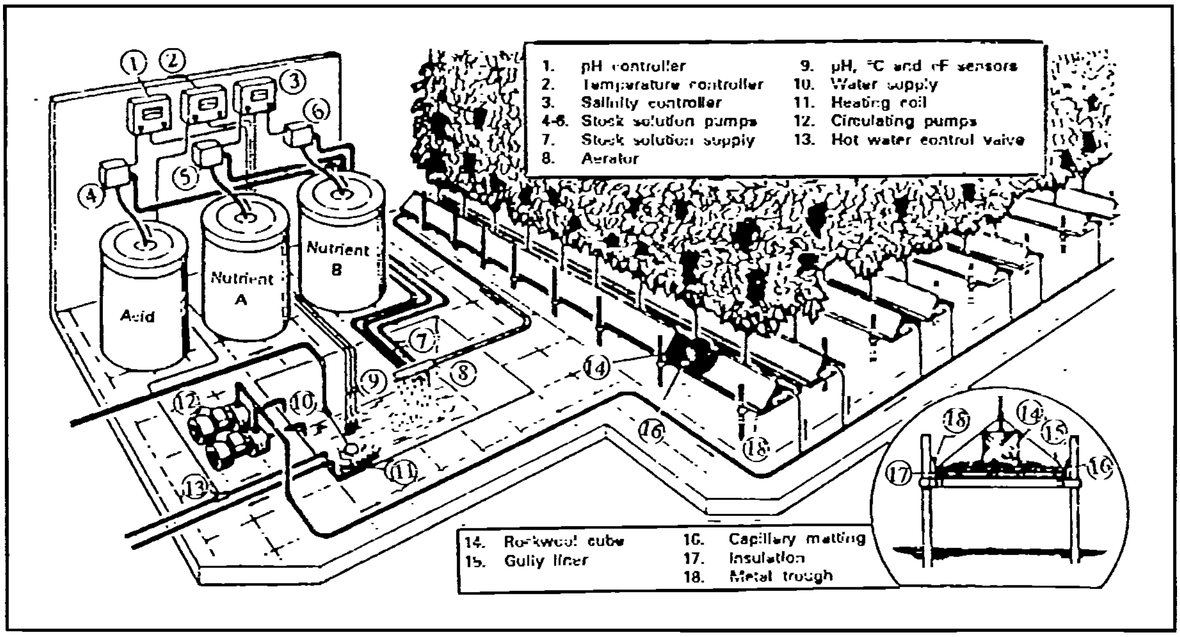

Fig. 1. Main features of a nutrient film hydroponic system (Graves 1983)

GROWING SYSTEMS

Liquid (Nonaggregate) Hydroponic Systems

Liquid systems are, by their nature, closed systems in which the plant roots are exposed to the nutrient solution, without any type of growing medium, and the solution is reused.

Nutrient Film Technique (NFT)

The nutrient film technique was developed during the late 1960s by Dr. Allan Cooper at the Glasshouse Crops Research Institute in Littlehampton, England (Windsor *et al.* 1979); a number of subsequent refinements have been developed at the same institution (Graves 1983). Together with the modified systems to which it has given rise, NFT appears to be the most rapidly evolving type of liquid hydroponic system today.

In a nutrient film system, a thin film of nutrient solution flows through the plastic lined channels which contain the plant roots. The walls of the channels are flexible to permit them being drawn together around the base of each plant to exclude light and prevent evaporation. The main features of a nutrient film system are illustrated in Fig. 1.

Nutrient solution is pumped to the higher end of each channel and flows by gravity past the plant roots to catchment pipes and a sump. The solution is monitored for replenishment of salts and water before it is recycled. Capillary material in the channel prevents young plants from drying out, and the roots soon grow into a tangled mat.

A principle advantage of this system in comparison with others is that a greatly reduced volume of nutrient solution is required, which may be easily heated during winter months to obtain optimum temperatures for root growth or cooled during hot summers in arid or tropical regions to avoid the bolting of lettuce and other undesirable plant responses. Reduced volumes are also easier to work with, if treatment of the nutrient solution is required for disease control. A complete description on the design and operation of a NFT system is published in *Horticultural Reviews* (Vol. 7, pp. 1-44). In addition to this article, the following are important points for the design of NFT systems for the tropics.

The maximum length of the channels should not be greater that 15-20 m. In a level greenhouse, longer runs could restrict the height available for plant growth, since the slope of the channel usually has a drop of 1 in 50 to 1 in 75. Longer runs and/or channels, with less slope, may accentuate problems of poor solution aeration.

To assure good aeration, the nutrient solution may be introduced into channels at two or three points along their length. The flow of nutrient solution into each channel should be 2-3 liters per minute, depending on the oxygen content of the solution. The temperature of the nutrient should not go above 30°C. Temperatures greater than this will adversely affect the amount of dissolved oxygen in the solution. There should be approximately 5 ppm or more of dissolved oxygen, especially in the nutrient solution which flows over the root mat in the channel.

In tropical regions, it is important to have the channels colored white in order to mitigate the problems of heat build-up from direct sunlight. Normally, a white-on-black plastic is used for the channels. High air temperatures are common in the tropics. A NFT system may permit economical cooling of plant roots, avoiding the more expensive cooling of the entire greenhouse inside air temperature.

In research conducted by Jensen (1985), it was found that root temperatures of lettuce must not exceed much more than 20°C, especially when air temperatures are 32-35°C or above, due to the problem of bolting (formation of the seed stalk). It was found that cooling the nutrient solution dramatically reduced bolting (Fig. 2) as well as lessening the incidence of the fungus *Pythium aphanidermatum*, which also affects the establishment and yield of hydroponic tomato and cucumber crops.

In 1983, the capital cost of an NFT growing system was estimated to cost $81,000/ha (not including the cost of construction labor and the greenhouse enclosing the system), with an annual operating cost of $22,000/ha (Van Os 1983) for replacement of plastic troughs and other items. NFT is not as popular as it was ten years ago, due to the high installation cost and the introduction of rockwool.

Floating Hydroponics

In 1976, a method for growing a number of heads of lettuce or other leafy vegetables on a floating raft of expanded plastic was developed independently by Jensen (1980) in Arizona and Massantini (1976) in Italy. Large-scale production facilities are now common and are quite popular in Japan (Jensen 1989). In the Caribbean, lettuce production has been made possible by using this system of hydroponics while cooling the nutrient solution, to stop the bolting of lettuce.

The production system consists of horizontal, rectangular-shaped tanks lined with plastic. Those developed by Jensen (1985) measured 4 m x 70 m, and were 30 cm deep. The nutrient solution was monitored, replenished, recirculated, and aerated. Rectangular tanks have two distinct advantages: the

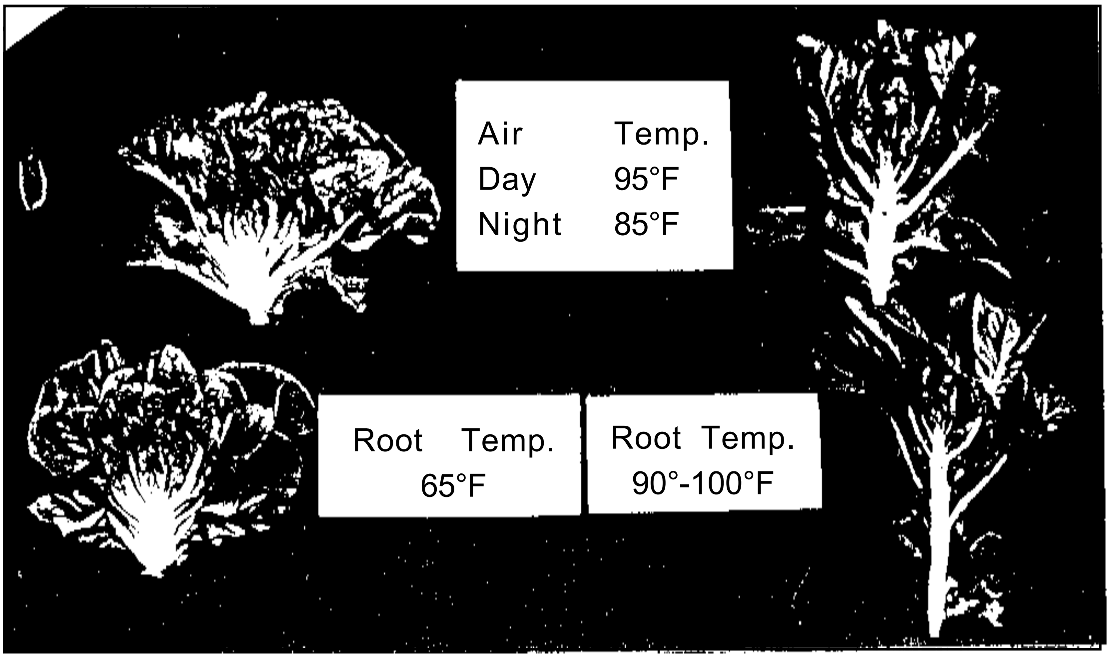

Fig. 2 Cooling of nutrient solution to 18°C (65°F) from 32-35°C (90-100°F) dramatically reduced bolting, when air temperatures at night were 29°C (85°F) and at day 35°C (95°F)

nutrient pools are frictionless conveyor belts for planting and harvesting movable floats, and the plants are spread in a single horizontal plane so that interception of sunlight per plant is maximal. In the Arizona trials, four commercial cultivars of lettuce were grown in the floats: short-day leafy type ('Waldmann's Green') and three cultivars of summer butterhead ('Ostinata', 'Salina', and 'Summer Bibb'). In comparing these cultivars to similar types, they exhibit the best tolerance to bolting, tip-burn, and bitterness, common physiological disorders in warmer climates such as the tropics.

Two- to three-week-old seedlings were transplanted into holes in the 2.5 cm thick plastic (polystyrene) floats in staggered rows with approximately 300 cm^2/plant. (The original concept was to plant more heads with narrower spacings and subsequently transfer them in mid-growth to floats with fewer holes and wider spacings. This concept was modeled but not executed). With the high level of solar radiation in Arizona, the period from transplanting to harvest was four to six weeks. As a crop of several floats was harvested from one end of a tank, new floats with transplants were introduced at the other end. Long lines of floats on which lettuce were growing moved easily with the touch of a finger.

Growth rates of all cultivars correlated positively with levels of available light, and did so up to the highest levels measured, although radiation levels in the Arizona desert are two to three times those of more temperate climates (Glenn 1983). This finding was surprising, in that open-field lettuce is saturated by relatively low levels of light, and growth is inhibited as radiation increases. Additionally, greenhouse lettuce in other regions is usually regarded as a cool-season crop. A further finding was that crops grown during autumn, when daylight hours are decreasing, used available light two to three times more efficiently than winter or spring crops.

The reason for the latter effect is that daytime air temperatures also correlated positively with growth; therefore, fall crops grown under higher temperatures were more efficient than spring crops. (However, during the summer monsoon season when evaporative cooling systems are ineffective, a combination of high temperature and high light levels caused lettuce to bolt. Several experiments were conducted to chill the nutrient solution, which reduced bolting). The best predictor of lettuce growth in the prototype system was the product of daytime temperature and the log of radiation (Glenn 1983).

Together with the operation and modification of the production system, packaging and marketing experiments were conducted. Packaging individual heads in air-sealed plastic bags extended shelf-life to as long as three weeks, and provided protection during transportation. This procedure has also been found to be effective in Norway (Lawson 1982). Sealing the heads in a CO_2 atmosphere had no apparent beneficial effect. The lettuce was also sealed with the roots intact, as researchers at General Mills (Mermelstein 1980) had reported that this permitted plants to stay alive and unwilted for a longer period. This procedure has also been used by ICI in England (Shakesshaft 1981). In the Arizona experiments, however, leaving the roots on did not appear to increase shelf-life, was three times more expensive to prepare and pack, increased product volume and weight for transportation, and was not particularly popular with wholesalers or retailers.

The economics of such a production system in the United States is not favorable, due to the year-around production of lettuce in the open field at a lower cost of production. However, in many tropical regions where local production does not occur during the warmer months of the year, such production systems using root cooling certainly deserve consideration.

Aeroponics

In an unusual application of closed system hydroponics, plants are grown in holes in panels of expanded polystyrene or other material with the plant roots suspended in midair beneath the panel and enclosed in a spraying box (Fig. 3). The box is sealed so that the roots are in darkness (to inhibit algal growth) and in saturation humidity. A misting system sprays the nutrient solution over the roots periodically. The system is normally turned on for only a few seconds every 2-3 minutes. This is sufficient to keep roots moist and the nutrient solution aerated. Systems were developed by Jensen in Arizona for lettuce, spinach, and even tomato, although tomato production was judged not to be economically viable (Jensen and Collins 1985). In fact, there are no known large-scale commercial aeroponic operations in the United States, although several small companies sell systems for home use.

The A-frame aeroponic system developed in Arizona for low, leafy crops may be feasible for commercial food production. Inside a CEA structure, these frames are oriented with the inclined slope facing east-west. The expanded plastic panels are a standard size (1.2 m x 2.4 m), mounted lengthwise, and spread 1.2 m at the base to form an end view equilateral triangle. The A-frame rests on a panel-sized watertight box, 25 cm deep, which contains the nutrient solution and misting equipment (Jensen and Collins 1985). Young transplants in small cubes of growing medium are inserted into holes in the panels, which are spaced at intervals of 18 cm. The roots are suspended in the enclosed air space and misted with nutrient solution as described above.

An apparent disadvantage of such a system is uneven growth, the result of variations in light intensity on the inclined crops. An advantage of this technique for CEA lettuce or spinach production is that twice as many plants may be accommodated per unit of floor area as in other systems; i.e., as with vine crops, the cubic volume of the greenhouse is better utilized. Unlike the small test systems described here, larger plantings could utilize A-frames more than 30 m in length, sitting on top of a simple, sloped trough that collects and drains the nutrient solution to a central sump. Furthermore, greenhouses could be designed with much lower roofs (Fig. 3).

Another potential commercial application of aeroponics, in addition to the production of leafy vegetables in locations with extreme restrictions in area and/or weight, would be the rooting of foliage plant cuttings. Such a system of rooting works well with regard to the control of foliage diseases, if export regulations for cuttings require that no soil be on the roots at the time of shipping. While heavy shading is required over the cuttings at the time of rooting, no overhead misting is required. This greatly reduces the problems of fungus diseases and the leaching of nutrients from the cuttings.

Aggregate Hydroponic Systems

In aggregate hydroponic systems, a solid, inert medium provides support for the plants. As in liquid systems, the nutrient solution is delivered directly to the plant roots. Aggregate systems may similarly be either open or closed, depending on whether, once delivered, surplus amounts of the solution are recovered and reused. Open systems do not recycle the nutrient solution. Closed systems do.

A. Open Systems

In most open hydroponic systems, excess nutrient solution is recovered. However, the surplus is not recycled to the plants, but is disposed of in evaporation ponds or used to irrigate adjacent landscape plantings or windbreaks. Because the nutrient solution is not recycled, such open systems are less sensitive to the composition of the medium used or to the salinity of the water. This, in turn, has given rise to experimentation with a wide range of growing media and development of lower-cost designs for containing them. In addition to wide growing beds in which a sand medium is spread across the entire greenhouse floor, growers also use troughs, trenches, bags, and slabs of porous horticultural grade rockwool.

Fertilizers may be fed into the proportioners (Fig. 4 Plan A) or may be mixed with the irrigation water in a large tank or sump (Fig. 4 Plan B). Irrigation is usually programmed through a time clock, and in larger installations, solenoid valves are used to allow only one section of a greenhouse to be irrigated at a time. This permits the use of smaller sized mechanical systems.

Trough or Trench Culture

Some open aggregate systems involve relatively narrow growing beds, either as above-ground troughs or below-ground trenches, whichever are more economical to construct at a given site. In both cases, the beds of growing media are separate from the rest of the greenhouse floor and confined within waterproof materials. For ease of description, this will henceforth be called trough culture.

Concrete used to be a common construction material for permanent trough installations (it may be covered with an inert paint or epoxy resin). Fiberglass, or plyboard covered with fiberglass, is also used. To reduce costs, polyethylene film at least 0.01 cm thick is now widely used. The film, usually in double layers to avoid leakage (pinholes in either layer will seldom match up), is placed on top of a sand base and is supported by planks, cables, or concrete blocks.

The size and shape of the growing bed are dictated by labor needs rather than by engineering or biological constraints. Vine crops such as tomato are usually grown in troughs only wide enough for two rows of plants, for ease in pruning, training, and harvesting. Low-growing plants are raised in somewhat broader beds, but are still narrow enough for a worker to be able to reach the middle of the bed. Bed depth varies with the type of growing media, but about 25 cm is a typical minimum. Shallower beds of 12-15 cm are not uncommon, but irrigation pratices will then require more attention. Length of the bed is limited only by the capability of the irrigation system, which must deliver uniform amounts of nutrient solution to each plant, and by the need for lateral walkways for work access. A typical bed

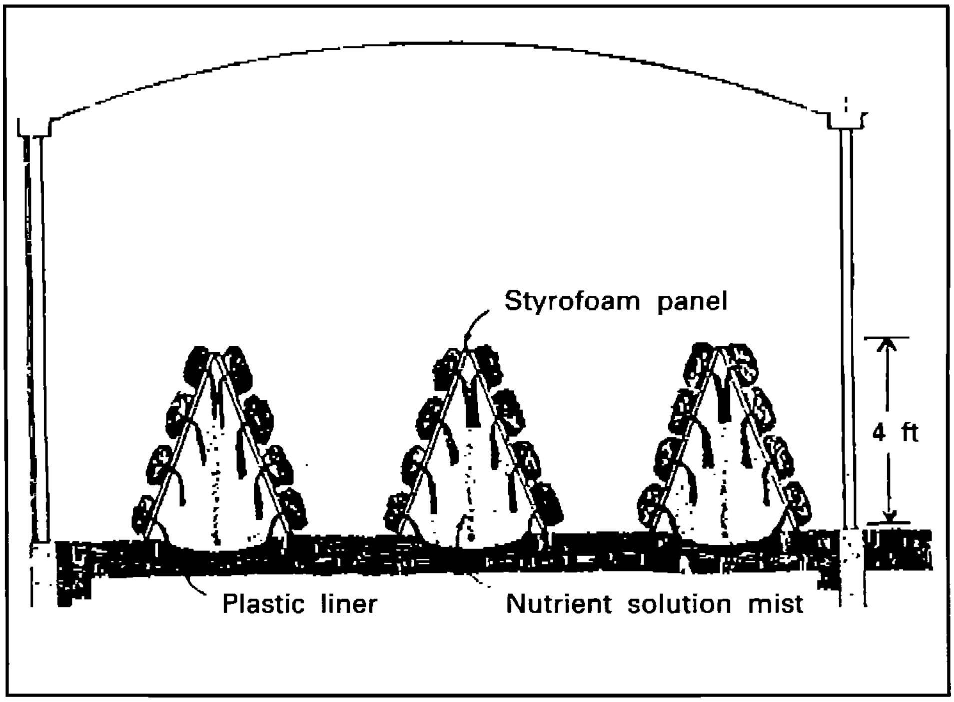

Fig. 3. Aeroponic A-frame unit, developed at the University of Arizona, makes better use of greenhouse space (Jensen and Collins 1985)

length is about 35 m. The slope should have a drop of at least 15 cm per 35 m for good drainage, and there should be a perforated drain pipe of agriculturally acceptable material inside the bottom of the trough beneath the growing medium.

As open systems are less sensitive than closed systems to the type of growing medium used, a great deal of regional ingenuity has been displayed in locating low-cost inert materials for trough culture. Typical media include sand, vermiculite, sawdust, perlite, peat moss, mixtures of peat and vermiculite, and sand with peat or vermiculite.

Bag Culture

Bag culture is similar to trough culture, except that the growing medium is placed in plastic bags which stand in lines on the greenhouse floor, thus avoiding the cost of troughs or trenches and complex drainage systems. The bags may be used for at least two years, and can be steam sterilized much more easily and cheaply than bare soil.

The bags are typically made of UV-resistant polyethylene, which will last in a CEA environment for two years, and have a black interior. The exterior of the bag should be white in deserts and other regions with high light levels, in order to reflect radiation and inhibit heating of the growing medium. Conversely, a darker exterior color is preferable in northern, low-light latitudes to absorb winter heat. Bags used for horizontal applications, the most common, are usually 50-70 liters in capacity. Growing media for bag culture include peat, vermiculite, or a combination of both to which may be added polystyrene beads, small waste pieces of polystyrene or perlite to reduce the total cost. In Scotland, the use of pure perlite in bags is becoming increasingly popular. When bags are used horizontally, they are sealed at both ends after being filled with the medium.

The bags are placed flat on the greenhouse floor at normal row spacing for tomato and other vegetables, although it would be beneficial to first cover the entire floor with white polyethylene film. Jensen demonstrated with trough culture in New Jersey that 86% of the radiation falling on a white plastic floor is reflected back up to the plants, compared with less than 20% when the light strikes bare soil (Jensen and Collins 1985). Such a covering may also reduce relative humidity and the incidence of some fungus diseases.

Paired rows of bags are usually laid horizontally a short distance apart in rows. Holes are made in the upper surface of each bag for the

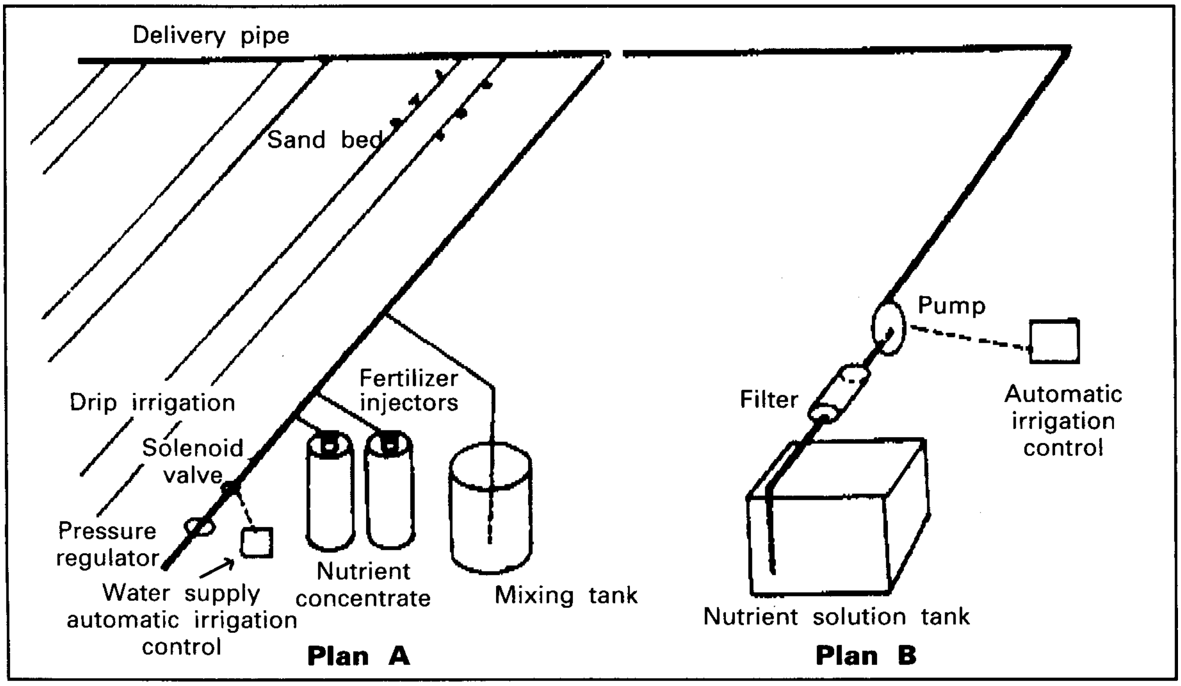

Fig. 4. Nutrient introduction in an open hydroponic system. Plan A uses a fertilizer proportioner; Plan B uses a sump mixing tank.

introduction of transplants, and two small slits are made low on each side for drainage or leaching. Some moisture is introduced into each bag before planting. Less commonly, the bags are placed vertically with open tops for single-plant growing. Vertical bags have the disadvantage that they are less convenient to transport, require more water, and maintain less even levels of moisture.

Drip irrigation of the nutrient mix, with a capillary tube leading from the main supply line to each plant, is recommended. Plants growing in high-light, high-temperature conditions will require up to two liters of nutrient solution per day. Moisture near the bottom of the bagged medium should be examined often, and it is better for the bags to be too wet than to be too dry.

The most commonly grown crops in bag culture are tomato and cucumber, and also cut flowers. When tomato are grown, each bag is used for two crops per year for at least two years. It has not yet been established how many crops may be grown before the bags must be replaced or steam-sterilized. Steam sterilization is carried out by moving the bags together under a tarpaulin, at an estimated cost of less than $1000/ha. The use of bag culture is greatly dependent on the availability and cost of growing media. When such materials must be imported, the cost may be prohibitive.

Rockwool Culture

The use of horticultural rockwool as the growing medium in open hydroponic systems is increasing rapidly. Such systems now receive more attention from research stations than any other type in Europe. Cucumber and tomato are the principal crops grown on rockwool, and in Denmark, where rockwool culture originated in 1969, virtually all cucumber crops are grown on rockwool. This technology is the primary cause of the rapid expansion of hydroponic systems in the Netherlands, where the use of this system has grown from 25 ha in 1978, to 80 ha in 1980 and to more than 500 ha by the end of 1982 (Van Os 1983).

In the Westland region of the Netherlands, which has the highest concentration of CEA greenhouses in the world, soil was used and steam-sterilized as necessary until the late 1970s. Until then, inexpensive natural gas was available for sterilization. When fuel costs increased, Westland growers turned to methyl bromide as a soil fumigant. However, bromides began to build up in the groundwater, while at the same time salinity increased due to saltwater intrusion from the expansion of regional shipping canals. The Dutch government then began to prohibit the use of methyl bromide (Van Os 1983). Lacking other inexpensive means of soil sterilization, increasing numbers of Dutch growers turned to hydroponics, experimenting first with such growing media as peat and even bales of straw, with NFT and bag culture, until the rockwool culture was developed.

As a growing medium, rockwool is not only relatively inexpensive but is also inert and biologically nondegradable, takes up water easily, is approximately 96% "pores" or interstitial air spaces, has evenly sized pores (which is important in water retention), lends itself to simple low-cost drainage systems, and is easy to heat from below during winter or steam sterilized. It is also lightweight when dry, and easily handled, and may simply be discarded or incorporated as a soil amendment after crops have been grown in it for several years. Its versatility is such that rockwool is used in plant propagation and potting mixes, as well as in hydroponics. A typical layout for an open-system rockwool culture is shown in Fig. 5.

An open system with rockwool permits accurate and uniform delivery of nutrient solution, can be installed for lower equipment, fabrication, and installation costs, and entails less risk of crop failure from the breakdown of pumps and recycling equipment. The obvious disadvantage is that rockwool may be relatively costly unless it is manufactured within the region. Another disadvantage is what to do with the rockwool once it is discarded and replaced with new material. In Holland, research is being carried out on mixing used rockwool with cement for the manufacture of light-weight building blocks. There is also a great deal of emphasis on developing a cultural system that requires less rockwool.

Sand Culture

At the same time that rockwool culture was beginning in Denmark in 1969, a type of open-system aggregate hydroponics, initially for desert applications and using pure sand as the growing medium, was under development by researchers at the University of Arizona (Jensen 1973). Because other types of growing media must be imported into desert regions and may require frequent renewal, they are more expensive than sand, a commodity usually available in abundance.

The Arizona researchers designed and tested several types of sand-based hydroponic systems. The growth of tomato and other greenhouse crops in pure sand was compared with the growth of the same crops in nine other mixtures (e.g. sand mixed in varying ratios with vermiculite, rice hull, redwood bark, pine bark, perlite and peat moss). There were no significant differences in yield (Jensen and Collins 1985). Unlike many other growing media which undergo physical breakdown during use, sand is a permanent medium. It does not require replacement every year or two.

Pure sand can be used in trough or trench culture. However, in desert locations, it is often more convenient and less expensive to cover the greenhouse floor with polyethylene film and install a system of drainage pipes (PVC pipe 5 cm in diameter, cut one third through diagonally every 45 cm along the length of the pipe, with the cuts facing downward) and then to backfill the area with sand to a depth of approximately 30 cm. If the depth of the sand bed is shallower, moisture conditions may not be uniform and plant roots may grow into the drainpipes. The area to be used as planting beds may be level or slightly sloped. Supply manifolds for nutrient solution must be sited accordingly.

Various kinds of desert and coastal sand with different physical and chemical properties have been used successfully by the University of Arizona workers. The size distribution of sand particles is not critical, except that exceptionally fine material such as mortar sand does not drain well and should be avoided. If calcareous sand is used, it is important to maintain a nutrient solution with a neutral pH, and increased amounts of chelated iron must be applied to the plants. Sand growing beds should be fumigated annually to prevent the introduction of soil-borne diseases and nematodes.

Irrigation practices are particularly critical during the high-radiation summer months, when crops may have to be irrigated as many as eight times per day. Proper irrigation is indicated by a small but continuous drainage, 4-7% of the application, from the entire growing area. Evaporation of water around small summer tomato transplants is often high, which can lead to a slight buildup of fertilizers in the planting bed. Extra nitrogen causes excessive vegetative growth, and reduces the number of fruits. This can be avoided by reducing the amount of nitrogen in the solution from the time of transplanting until the appearance of the first blossoms. Drainage from the beds should be tested frequently, and the beds leached when drainage salts exceed 3000 ppm.

The principal crops grown in sand culture systems are tomato and cucumber, and yields of both crops can be high. Seedless cucumber production

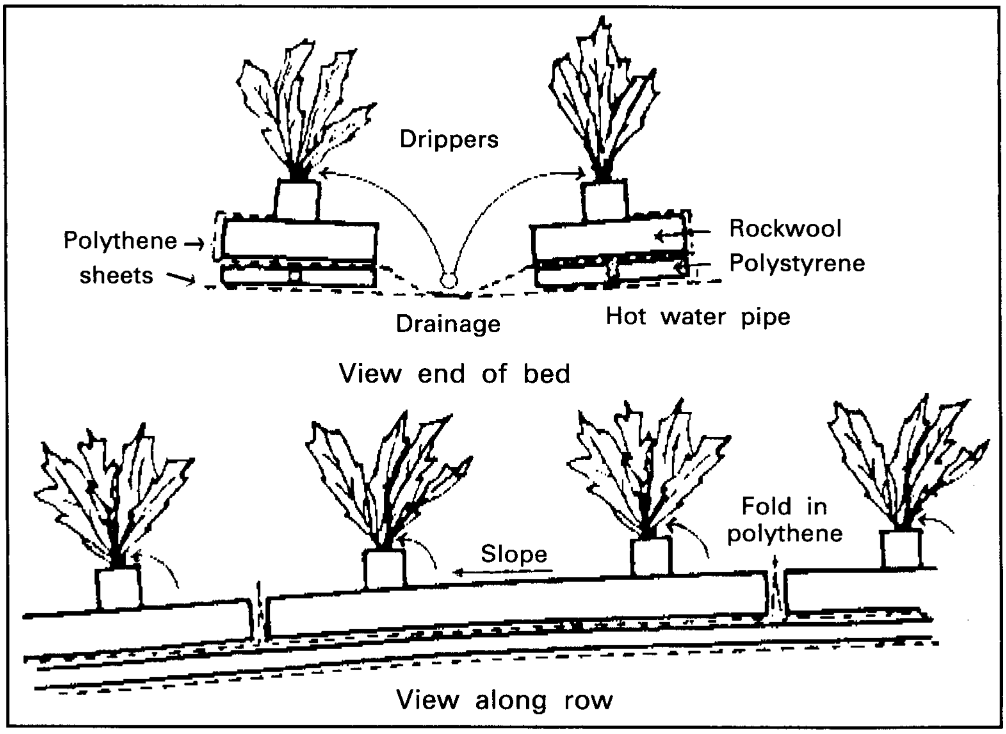

Fig. 5. Typical layout for rockwool culture. Rockwool slabs are positioned for ease of drainage and use of bottom heating, (Hanger, 1982b).

has exceeded 700 mt/ha.

B. Closed System

Gravel

Closed systems using gravel as the aggregate material were widely used in commercial and semicommercial or family hydroponic CEA facilities 20 years ago. For the most part, these installations have been superseded by NFT systems or by the newer, open aggregate systems described in the previous section. As in all closed systems, a water agricultural suitability analysis must be done. Great care must be taken to avoid the buildup of toxic salts and to keep the system free of nematodes and soilborne diseases. Once certain diseases are introduced, the infested nutrient solution will contaminate the entire planting. Such systems are capital intensive because they require leak-proof growing beds, as well as mechanical systems and nutrient storage tanks below the ground surface. Gravel used as an aggregate in a closed system is not recommended.

NFT and Rockwool

A more recent development in Europe is the combination of NFT and rockwool culture, which is by definition a closed aggregate system. In this system, plants are established on small rockwool slabs positioned in channels containing recycled nutrient solution. Compared to the open rockwool system described above, this procedure reduces the amount of rockwool needed, a big advantage when the used rockwool has to be discarded. Rockwool used in a NFT system acts as a nutrient reservoir in case of pump failure, and helps anchor the plants in the nutrient channel.

Nutrient Solutions

Many formulas for hydroponic nutrient solutions have been published, but they are all quite similar, differing mostly in the ratio of nitrogen to potassium. It is unlikely there are any "secret ingredients" that make one formula better than another. Most recommendations are based on the early work of Hoagland and Arnon (1950).

There can be a significant difference in the cost, purity, and solubility of the chemicals comprising a nutrient solution, depending on the grade (pure, technical, food, or fertilizer) used. Smaller operations often buy ready-mixed nutrient formulations to which only water need be added to prepare the nutrient solution. Larger facilities prepare their own solutions to standard or slightly modified formulae. A complete description of nutrient solution formulae, mixing, etc., is in an article published by Jensen and Collins in 1985.

Cultivar Selection

It is important to select cultivars that are tolerant to the high temperature-humidity environments common in the tropics. Often those cultivars commonly grown in temperate regions do not do well in tropical climates. The University of Arizona has done extensive trials in selecting greenhouse cultivars suitable for production in the tropics (Jensen 1972). Table 2 lists those cultivars that have the best tolerance to high temperature-humidity conditions. The list of seed companies does not imply endorsement, nor does it necessarily indicate that more recent cultivars from those listed or from other seed companies may have cultivars which perform as well or better. It is recommended that cultivars from the companies listed in Table 2 be compared with those from other seed companies, especially those conducting breeding programs in tropical regions.

STRUCTURES AND ENVIRONMENTAL CONTROL

There has been little change in the design of the basic greenhouse structure over the last decade. The most common type of covering, polyethylene sheet film, is fairly standard, except that some films recently introduced on the market retard the loss of infrared heat. Such films are reported to reduce the heat loss from a greenhouse by 20%, and will probably be widely used for polyethylene covered structures in the future. Other glazing materials such as fiberglass, polyvinylchloride, Mylar, and Tedlar have proven either inappropriate, inconvenient or, in most cases, much more expensive than polyethylene, even though polyethylene may need replacement more frequently. In the tropics, it is not uncommon for liquid honeydew from such insects as *Bemisia* sp. and *Aphis* sp. to collect on permanent covers, supporting a growth of a ‘sooty mold’ causing blockage of incoming light. For this reason, permanent covers are not advisable if high density foliage, which might support a high population of these insects, borders the structure.

Newer materials are now in research use — for example polycarbonates, acrylics, double-skinned panels and light-selective films laminated to polyethylene – but their technical promise is offset at present by high costs. The limited size of the North American greenhouse industry, and the resulting small market potential, has inhibited research and development by manufacturers of plastics.

Greenhouses are expensive, and controlling the environment within a greenhouse requires considerable energy. A major research emphasis over the past 15 years has been on the use of solar energy and reject heat from large industrial units (Jensen 1977). Although solar energy as a greenhouse heat source is technically feasible, it does not yet appear to be economical, because of the high collection and storage costs.

Whatever the source of energy, it is important to conserve it once it is in the greenhouse, to limit capital and operating costs. Thermal curtains of porous polyester or an aluminum foil fabric may reduce night heat loss by as much as 57%. In Japan during night periods of cooler temperatures, growers will place a removable sheet of polyethylene over the crop and a row cover over each plant row in order to reduce any heat loss from the greenhouse during the night. The plastic row covers are pulled to the side during the day to maximize incoming light.

During the winter, this method of retaining heat energy collected in the greenhouse during the day may be an important consideration in high-altitude regions of the tropics. With regard to greenhouse ventilation, there is increasing interest in new types of natural or passive ventilation systems which save on electrical energy costs. These may be coupled with fan and pad active ventilation systems, where natural ventilation is utilized as the first stage of cooling, but when evaporative cooling is required, the vents for natural ventilation are closed and the fan-pad system is then utilized for the second stage of cooling. Initial capital costs are greater when installing this system of cooling a greenhouse, but operational costs are minimized since natural ventilation will usually be enough to meet ventilation requirements.

In the tropics, a greenhouse is often only a rain shelter, a cover of polyethylene over a crop to prevent rainfall from entering the growing area, namely the hydroponic beds. This can also lessen the problem of foliage diseases. In such cases, the sides of the structures are left open for natural ventilation. To prevent insects from entering, especially those

Table 2. Cultivars Suited for Hydroponic Vegetable Production in the Tropics

Vegetable	Cultivar	Source
Cantaloupe	Perlita	Petroseed Co., Inc.
Chinese cabbage	Saladeer; W-R Super 80	Takii & Co., Ltd.
Cucumber (Long Dutch type)	Corona; Toska 70	DeRuiter Seeds, Inc.; Nunhems
Eggplant	Black Magic	Harris Moran Seed Co.
Head lettuce	Minetto	Burpee
Bibb lettuce	Ostinata;	DeRuiter Seed Inc.
	Salina;	Len de Mas Zaden
	Summer B:66	Harris Moran Seed Co.
Leaf Lettuce	Waldmann's Green; Grand Rapids	Harris Moran Seed Co.
Green pepper	Takii's Ace; New Ace	Takii & Co., Ltd.
Tomato	N-65	Takii & Co., Ltd.

which are vectors for virus diseases, the side are covered with screens. With the increasing concern over chemicals, that they might enter the food chain or the environment and expose workers to toxic compounds, alternatives are being investigated. Such an alternative is the careful monitoring and control of incoming plant and growing materials and the use of screens to reduce entry of pests and diseases into the growing structure. Preliminary results indicate that the following hole sizes (or smaller) will exclude the respective insects; 640 microns for the leafminer *Liriomyra trifolii*, 340 microns for the melon aphid *Aphis gossypii*, 462 microns for the sweet potato whitefly *Bermisia tabaci*, and 192 microns for the western flower thrips *Franklinella occidentalis* Sase 1990.

Care must be taken not to install screens in which the holes are too small, as the air movement through the screen will be greatly impaired, and dust will eventually collect on the material. For complete details on engineering considerations in installing screens, see Sase 1990. Construction materials for a greenhouse can be wood, bamboo, or galvanized steel. It is important that consideration be given to using materials indigenous to the region, which are often more economical than imported materials.

CONSTRAINTS FOR THE FUTURE

In many regions of the world, it is difficult for greenhouse vegetables to compete with field crops. In North America, it is almost impossible. There are five separate but interacting reasons for this.

- There is a diversity of climates in North America (unlike the fairly homogenous climates of tropical Asia, or of Europe) which permits conventional field production of almost any vegetable somewhere on the continent during any time of the year. In 1983, Mexico exported over 1 million mt of fresh vegetables to North America, representing a 12% increase from 1982.
- The USA and Canada have rapid and effective nationwide transportation systems. Local food production for individual regions or communities is unnecessary.
- The already high capital and energy costs for greenhouse vegetable production increased alarmingly during the 1970's. There were no concomitant breakthroughs in design or materials to mitigate these costs.

- Few chemicals for disease and pest control have been cleared by the Federal Government for use in greenhouses. The market is too small for manufacturers to undertake the expense of certification.
- The technical and economic perils of hydroponics require an unusual management mixture of biological and engineering sciences, as well as informed and aggressive marketing. Such combinations have been rare.

While greenhouse vegetable production in association with hydroponics has some advantages, the technology is often over-simplified, and is far easier to promote than to sustain. A weakness in any number of technical or economic links snaps this complex chain. Deficiencies in practical management or scientific and engineering support result in low yields of nutrient-deficient and unattractive crops; plant diseases; insect infestation; summer overheating; winter chilling; under-capitalization; bizarre promotion schemes; and indifferent cost accounting, all of which, separately or together, have caused greenhouse vegetable businesses to fail. As mentioned above, hydroponic production is possibly the most intensive form of agriculture in existence. There is no margin for poor management or mistakes.

THE FUTURE

In spite of the deterrents listed above, optimism remains high for this industry in North America, as in other regions of the world. The future does not necessarily need any dramatic scientific breakthroughs, but rather, a series of relatively modest technological improvements in comparative economics.

A summary of research needs includes, but is not limited to, the following:

- Designing a lowest-cost greenhouse structure to be ventilated, heated, and cooled as much as possible by solar and solar-effect phenomena and other alternative energy sources;
- Developing better covering materials, particularly low-cost, long-lived, selectively transparent plastic film for greenhouse roof structures;
- Developing lower-cost nighttime insulation devices and techniques where required;
- Designing a plant bio-engineering program to develop new greenhouse cultivars which are tolerant of high temperatures can be harvested by machine, and are resistant to disease.
- Root temperature studies to determine influences on growth rates and plant development;
- Disease control of water-borne pathogens in closed hydroponic systems (i.e., filtration, UV radiation);
- Integrated pest management systems for greenhouse applications, in order to minimize pesticide use;
- Government approval of chemicals for disease and pest control in greenhouses;
- New aggregate material(s) for lower-cost installation and maintenance i.e., a counterpart of European rockwool.

While research is being conducted on many of the above topics, it is very limited and underfunded. Improvements to increase crop yield and reduce unit costs of production are important if hydroponic vegetable production is to become more competitive.

As the consumer becomes increasingly aware of quality differences, especially the high quality of tomatoes, cucumbers, and leafy vegetables coming from greenhouses, the demand will increase. This, along with the increased emphasis on eating more vegetables for dietary and health reasons, will surely help the greenhouse industry.

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DISCUSSION

Q. Did the high temperatures in Arizona give you problems of a low oxygen level in the nutrient solution?

A. Yes, at high temperatures the length of flow in an NFT system has to be limited. The greenhouse cultivation of vegetables is not common in the USA. Instead, during the winter vegetables are grown in Mexico in the open field, and shipped to USA and Canada. I feel that a NFT system is difficult to operate, and would not recommend it except as a modified system used for crops such as lettuce.

Q. Why don't you like the NFT system? This type of system is said to have a high failure rate. What are the reasons for these failures?

A. These are sometimes due to improper sanitation; sometimes they are caused by a lack of understanding of the roots' need for oxygen, or how to make up the nutrient as it is needed. NFT is an intensive system, and even in the United Kingdom where it was developed is not common. There are easier systems which work just as well. When we develop a hydroponics system, we must keep in mind that it is not only we scientists who are going to use it, but the farmer as well.

Q. In soilless culture, are there any problems in reusing the medium for the following crop?

A. I chose to use sand, because it can be sterilized easily and thoroughly. There is no cation exchange capacity, so that sand cannot hold fumigants for any length of time. When organic material such as peat moss is used, it tends to become finer as it breaks down, especially under hot conditions, and waterlogging may soon occur. I prefer a growing medium which has no ion CEC and contains no organic materials. Otherwise it is difficult to remove the salts from fertilizers applied to previous crops, and the medium has to be thoroughly leached.