HYDROPONICS WORLDWIDE - A TECHNICAL OVERVIEW

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ABSTRACT. Growing greenhouse vegetables is one of the most exacting and intense forms of all agricultural enterprises. In combination with greenhouses, hydroponics is becoming increasingly popular, especially in the United States, Canada, western Europe, and Japan. It is high technology and capital intensive. It is highly productive, conservative of water and land and protective of the environment. For production of leafy vegetables and herbs, deep flow hydroponics is common. For growing row crops such as tomato, cucumber, and pepper, the two most popular artificial growing media are rockwool and perlite. Computers today operate hundreds of devices within a greenhouse by utilizing dozens of input parameters, to maintain the most desired growing environment. The technology of greenhouse food production is changing rapidly with systems today producing yields never before realized. The future for hydroponic/soilless cultured systems appears more positive today than any time over the last 50 years.

Introduction

The technology for food production in greenhouses has advanced a great deal in the last 20 years. Greenhouse food production often termed controlled environment agriculture (CEA) usually accompanies hydroponics. Hydroponic culture is possibly the most intensive method of crop production in today’s agricultural industry. In combination with greenhouses, it is high technology and capital intensive. Yet, for most of its employees, hydroponic culture requires only basic agricultural skills. Since regulating the aerial and root environment is a major concern in such agricultural systems, production takes place inside enclosures designed to control air and root temperatures, light, water, plant nutrition and adverse climate.

There are many types of controlled environment/hydroponic systems. Each component of CEA is of equal importance, whether it be the structural design, the environmental control or the growing system. Not every system is cost effective in every location. All too often, importance is given to only one or two of the key components but fails due to the lack of attention given to any one of the components. If improper attention is given to the greenhouse structure and its environment, no hydroponic system will prove economically viable. Since CEA usually accompanies hydroponics, their potentials and problems are inextricable.

History

The earliest food production in greenhouses was possibly the growing of off-season cucumbers under “transparent stone” for the Roman Emperor Tiberius during the first century. The technology was rarely employed, if at all, during the following 1500 years.
During the 1600’s, several techniques were used to protect horticultural crops against the cold. These included glass lanterns, bell jars, cold frames and hot beds covered with glass. In the seventeenth century, low portable wooden frames covered with an oiled translucent paper were used to warm the plant environment much as plastic row covers do today (Dalrymple 1973). In Japan, straw mats were used in combination with oil paper to protect crops from the severe natural environment (Takakura 1988). Greenhouses in France and England during the same century were heated by manure and covered with glass panes (Gibault 1912). The first glass house in the 1700’s, used glass on one side only, as a sloping roof. Later in the century, glass was used on both sides. This glasshouse was used for fruit crops such as melons, grapes, peaches, and strawberries and only rarely for vegetable production (Dalrymple 1973). It would seem that the developers of this new technology kept market profitability in mind: they produced crops which appealed to the wealthy and privileged, the only people who could afford the luxury of fresh fruit produced out of season in greenhouses.

Greenhouse food production was not fully established until the introduction of polyethylene. In the U.S., the first use of polyethylene as a greenhouse cover was in 1948, when Professor Emery Myers Emmert at the University of Kentucky, used the less expensive material in place of more expensive glass. Professor Emmert is considered the father of plastics in the U.S., because he developed many principles of plastic technology for agricultural purposes through his research on greenhouses, plastic mulches and row covers.

The development of hydroponics has not been rapid. In the U.S., interest began to develop in the possible use of complete nutrient solutions about 1925, for large scale crop production.

Greenhouse soils had to be replaced at frequent intervals or else be maintained in good condition from year to year by adding large quantities of commercial fertilizers. As a result of these difficulties, research workers in certain U.S. agricultural experiment stations turned to nutrient solution culture methods as a means of replacing the natural soil system with either an aerated nutrient solution or an artificial soil composed of chemically inert aggregates moistened with nutrient solutions (Withrow, Withrow 1948).

Between 1925 and 1935, extensive development took place in modifying the methods of the plant physiologists to large scale crop production. Workers at the New Jersey Agricultural Experiment Station improved the sand culture method (Shive, Robbins 1937). The water and sand culture methods were used for large scale production by investigators at the California Agricultural Experiment Station (Hoagland, Arnon 1938). Each of these methods involved certain fundamental limitations for commercial crop production which partially were overcome with the introduction of the subirrigation system initiated in 1934 at the New Jersey and Indiana Agricultural Experiment Station (Withrow, Withrow 1948). While there was commercial interest in the use of such systems, hydroponics was not widely accepted due to the high cost in construction of the concrete growing beds.

After a period of approximately 20 years, interest in hydroponics was renewed with the advent of plastics. Plastics were used not only in the glazing of greenhouses, but also in lining the growing beds rather than beds made of concrete. Plastics were also important in the introduction of drip irrigation. Numerous promotional schemes involving hydroponics became common with huge investments made in hydroponic growing systems.

Unfortunately, escalating oil prices, starting in 1973, substantially increased the costs of CEA heating and cooling by one or two orders of magnitude. This along with fewer chemicals registered for pest control caused many bankruptcies and a decreasing interest in hydroponics.
Almost another 20 years have passed since the last real interest in hydroponics. There is again a renewed interest in growers establishing CEA/hydroponic systems. This is especially true in regions where there are environmental concerns in controlling any pollution of groundwater with nutrient wastes or soil sterilants. Today growers appear to be much more critical in regard to site selection, structures, the growing system, pest control and markets.

**Greenhouse Area**

The total world area of glasshouses is estimated to be 40,700 ha (Wittwer, Castilla 1995), with most of these found in northwestern Europe.

In contact to glasshouses, plastic greenhouses have been readily adopted on all five continents, especially in the Mediterranean region, China and Japan. Most plastic greenhouses operate on a seasonal basis, rather than year round, as is the case with most glasshouses. The estimated area of plastic greenhouses is shown in Table 1.

<table>
<thead>
<tr>
<th>Region</th>
<th>Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern</td>
<td>16,700</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>95,300</td>
</tr>
<tr>
<td>Americas</td>
<td>15,600</td>
</tr>
<tr>
<td>Asia</td>
<td>438,200</td>
</tr>
<tr>
<td><strong>World Total</strong></td>
<td><strong>565,800</strong></td>
</tr>
</tbody>
</table>

Source: in part from Wittwer, Castilla 1995

PVC film for greenhouses is still dominant in Asia, especially in Japan (35,200 ha), and low density polyethylene is also used in Italy (500 ha) and Greece. LDPE films cover a total of 149,000-162,000 ha; the average consumption is 1.5 MT/ha/year, with a total world tonnage of over 250,000 MT/year.

In Japan, the area covered by plastic film greenhouses increased 35,000 ha. in just 20 years (1965-85). In Korea, their greenhouses increased 6.3 times, from 3,099 ha. in 1975 to 21,061 ha. in 1986. The People’s Republic of China showed equally dramatic growth: 5,300 ha. in 1978 to 34,000 ha. in 1988. The combined growth for both greenhouses and row covers, in China exceeded 96,000 ha. in just ten years. Undoubtedly, China is one of the largest users of agricultural plastics in the world, where over one billion people - 29 percent of the world’s population - are being fed from only 5 percent of the earth’s cultivated land.

Since 1960, the greenhouse has evolved into more than a plant protector. The greenhouses of today can best be seen as plant or vegetable factories. Almost every aspect of the production system is automated, with the artificial environment and growing system under nearly total computer control. In a research setting, such a totally enclosed system, with artificial light, is called a growth chamber or a phytotron. In the United States and Japan, such systems may cover large areas.

Controlled environment agriculture has gained in horticultural importance not only in vegetable and ornamental crop production but also in the production of plant seedlings, either from seed or through tissue culture procedures.
In the last 15 years there has been increasing interest in the use of soilless or hydroponic techniques for producing greenhouse horticultural crops. The future growth of greenhouse or controlled environment agriculture, where hydroponics is used for vegetable production, will depend greatly on the development of production systems that are competitive, in terms of costs, with open field agriculture.

**Economics of Food Production in Greenhouses**

Balanced against the high capital and operational costs of greenhouses is the significantly higher productivity of such systems in comparison with open field agriculture (OFA). Yield data have been reported in the literature for years; typical yields for crops grown hydroponically in desert greenhouses in the American southwest are compared with typical “good” yields for open field crops in Table 2.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield/Crop</th>
<th>No. Crops/yr</th>
<th>Total Yield MT/ha/yr</th>
<th>Total Yield MT/ha/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cucumber</td>
<td>300.0</td>
<td>2</td>
<td>600.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Eggplant</td>
<td>165.0</td>
<td>2</td>
<td>330.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Green bell peppers</td>
<td>250.0</td>
<td>1</td>
<td>250.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Colored bell peppers</td>
<td>200.0</td>
<td>1</td>
<td>200.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Lettuce</td>
<td>31.0</td>
<td>10</td>
<td>313.0</td>
<td>52.0</td>
</tr>
<tr>
<td>Tomato</td>
<td>550.0</td>
<td>1</td>
<td>550.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

*Source: Knott (1966)*

As the data indicate, the yield per crop is higher in greenhouses than in OFA because of the optimal growing conditions, balanced plant nutrient, etc., provided in controlled environments. Because of the controlled environment, year-round production can be achieved, whereas in the open field crop production is only seasonal.

Gross returns from greenhouse vegetables must be high. This is accomplished by high prices for the product and/or high yields. There is little room for error, therefore, it is imperative that there be no shortcuts in environmental control, competent management, or any other factor of production. Today, in the United States, retailers commonly double their sale prices over the wholesale price to the grower. Such a high mark up can cause great consumer resistance.

In the United States, new tomato varieties from Holland, have good flavor even when grown during the winter in the high light regions of the desert southwest. Consumers are showing much less resistance to higher prices providing the tomatoes are of good appearance and flavor.
Structures and Environmental Control

The European glass structures, which today are commonly being built for vegetable production in the southwestern part of the United States, are very different from the polyethylene/fiberglass houses used in hydroponic production between 1965 and 1990. The height of the European structures is much greater.

To achieve a more uniform growing environment, without rapid temperature fluctuations, more total volume of space is being allotted within a given area of a greenhouse, where today it is common for the gutters of greenhouse structures to reach a height of over 5 m above ground level.

For polyethylene greenhouses, the types of polyethylene sheet films are much the same except those introduced, over a decade ago, which retard the loss of infrared heat. These films are reported to reduce 20% of the heat loss from the greenhouse and have become common in today’s industry, especially in Europe. Other glazing materials such as a fiberglass, polyvinyl chloride, Mylar and Tedlar have proven either more inappropriate, inconvenient or in most cases, much more expensive than polyethylene, even though the latter may have to be replaced more frequently. Newer materials, such as polycarbonates and acrylics have become much more common, but their popularity has been offset by high costs.

Newly developed polyethylene film in Israel has been designed to allow very low levels of UV light to be transmitted. There is good evidence that UV blocking films have an adverse effect on flying insects such as *Bemisia tabacci*, aphids and thrips.

Greenhouses are expensive, however, and controlling the environment within a greenhouse requires considerable energy. Starting twenty years ago, there was major research emphasis on the use of solar energy and reject heat from large industrial units. Although solar energy as a greenhouse heat source is technically feasible, it has not proven economical because of the collection and storage costs. The economics of using waste heat from generating plants favors incorporating the heat-use system into the overall plans for new plants, rather than modifying existing ones. While such designs have been proposed, none were ever actually initiated in the United States.

In the last ten years, there has been interest in the development of co-generation plants, where small electrical plants have received government assistance if there is design to use the waste heat from the electrical generators. Several such facilities have been established where the waste heat was used either to heat greenhouse vegetables or water for fish production. While such opportunities are inviting, excess U.S. government regulation and red tape have discouraged many investors from taking advantage of such opportunities.

Whatever the source of energy, it is important to conserve the energy, once it is in the greenhouse. In regions of cold winter weather, thermal curtains of porous polyester or an aluminum foil fabric are installed to reduce night heat loss by as much as 57%. In the deserts of the southwest, winter temperatures are not severe enough to warrant curtains. While curtains will provide energy savings, it is not enough to warrant the high investment cost of the curtains plus the shade from the curtains, even when rolled up and stored during the day, can be a factor.

In the future, greenhouses will have retractable roofs allowing full light and ventilation if desired.
Computers/Data Acquisition Systems

Today, computer control systems are common in greenhouse installation throughout Europe, Japan, Canada and the United States. Computer systems can provide fully integrated control of temperature, humidity, irrigation and fertilization, carbon dioxide, light and shade levels for virtually any size growing facility. Precise control over a growing operation enables growers to realize savings of 15 - 50% for energy, water, chemical, and pesticide applications. Computer controls normally result in greater plant consistency, on-schedule production, higher overall plant quality, and environmental purity.

A computer can control hundreds of devices within a greenhouse (vents, heaters, fans, hot water mixing valves, irrigation valves, curtains, lights, etc.) by utilizing dozens of input parameters, such as outside and inside temperatures, humidity, outside wind direction and velocity, carbon dioxide levels and even the time of day or night.

Computer systems interrogate all sensors, evaluate all conditions, and send appropriate commands every minute to each piece of equipment in the greenhouse range thus maintaining ideal conditions in each of the various independent greenhouse zones defined by the grower.

Computers collect and log data provided by greenhouse production managers. A computer can keep track of all relevant information, such as temperature, humidity, CO₂, light levels, etc. It dates and time tags the information and stores it for current or later use. Such a data acquisition system will enable the grower to gain a comprehensive understanding of all factors affecting the quality and timeliness of the product.

A computer will produce graphs of past and current environmental conditions both inside and outside the greenhouse complex. Using a data printout option, growers can produce reports and summaries of environmental conditions such as temperature, humidity, and the CO₂ status for a given day, or over a longer period of time.

Scientists are currently developing plant growing models in which computers actually make decision for the greenhouse growers. These “artificial intelligence” systems integrate the latest knowledge about greenhouse growing theory, actual management practices, and environmental conditions inside and outside the greenhouse. The computer will be taught to assess all the variables, make a decision, and give instructions for application. The decisions made by the computer in climate control can provide the grower 24 hour-a-day assistance in the management and production of greenhouse crops. A system can be so reliable that, even if it should fail, it will not only call the grower on the telephone but will also turn key components over to local control.

Unfortunately, such computer systems are expensive and mainly limited to large greenhouse facilities operating year-round. The crops grown are usually of high value and are those that respond to precise control over the environment. Computers are not economically feasible for protected agriculture situations that are seasonal: the added costs outweigh the economics benefits unless used throughout the year.

Despite the attraction of computer systems, it is well to remember that the success of any production system is totally dependent on the farmer’s knowledge and his management skills. Computers only assist by adding precision to these skills. A computer is only as effective as the person who feeds it the data.

As computer costs continue to decrease and as farmers become computer literate, computers will become increasingly popular in greenhouse agriculture. In developing countries, where
farmers lack formal education, financial resources, and the skill to operate computers, the utilization of these systems in greenhouse food production is remote.

Hydroponic/Soilless Culture

The standard method of growing greenhouse vegetable throughout the world is in soil. A successful grower who grows in soil usually has a good knowledge of horticulture, soils, plant pathology, entomology, and plant physiology, as well as the engineering capability to provide an environment best suited for plant growth. Many persons who establish a greenhouse operation fail because they lack the education and training in one or more of the above disciplines.

A major problem in growing crops in soil are soil-borne diseases. Growing plants continuously, without crop rotation or interruption in production as in open field production during northern winters, can lead to an excessive build up of soil pathogens. Because of environmental and health restrictions, there is currently a lack of soil fumigants available for greenhouse use. This problem, added to the high cost of fuel to steam sterilize, is focusing attention on methods of hydroponic controlled environment agriculture.

During the last 12 years, there has been increasing interest in hydroponics or soilless techniques for producing greenhouse horticultural crops. The future growth of hydroponics depends greatly on the development of production systems that are cost competitive with open field agriculture.

There are many types of hydroponic systems, as well as many designs for greenhouse structures and many methods of control of the environment. Not every system is cost effective in each location. While the techniques of hydroponic culture in the tropics may get quite similar to those used in temperate regions, greenhouse structures themselves and methods of environmental control can differ greatly.

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, coir, 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 hydroponics 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 to provide temperature control, reduce evaporative water loss, reduce disease and pest infestations, and protect crops against the elements of weather, such as wind and rain. The latter considerations are especially valid in tropical regions.

The principle advantages of hydroponic CEA include high-density maximum crop yield, crop production where no suitable soil exists, a virtual indifference to ambient temperature and seasonality, more efficient use of water and fertilizers, minimal use of land area, and suitability for mechanization and disease control. A major advantage of hydroponics, as compared with
growth of plants in soil, is the isolation of the crop from the underlying soil, which often has problems of disease, salinity, poor structure and draining. The costly and time-consuming tasks of soil sterilization and cultivation are unnecessary in hydroponic systems and a rapid turnaround of crops is readily achieved.

Hydroponics offers a means of control over soil-born diseases and pests, which is especially desirable in the tropics, where infestations are a major concern. Most temperate regions have climatic changes, such as cold winters, to break the life cycles of many pests. In the tropics, this life cycle continues uninterrupted, as does the threat of infestation. Unfortunately, less is known about many of the diseases that occur in the tropics than those in temperate regions. In comparing three major food crops grown in the tropics and temperate regions of the world, the incidence of disease is much greater in the tropics, as illustrated in Table 3.

The principle disadvantages of hydroponics, relative to conventional open-field agriculture, are the high costs of capital and energy inputs, and the high degree of management skills required for successful production. Capital costs may be especially excessive if the structures are artificially heated and evaporatively cooled by fan and pad systems, systems of environmental control which are not always needed in the tropics. Because of its significantly higher costs, successful applications of hydroponic technology are limited to crops of high economic value to specific regions, and often confined to specific times of the year, when comparable OFA is not feasible.

Table 3. Number of crop diseases

<table>
<thead>
<tr>
<th>CROPS</th>
<th>TEMPERATE</th>
<th>TROPICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>54</td>
<td>500-600</td>
</tr>
<tr>
<td>Corn</td>
<td>85</td>
<td>125</td>
</tr>
<tr>
<td>Beans</td>
<td>52</td>
<td>250-280</td>
</tr>
</tbody>
</table>

Source: (Wittwer 1981)

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 break even. Since then, CEA costs have more than doubled, while crop commodity prices have remained constant. Indeed, in the United States, open-field agronomic crops are usually in surplus, and a significant percentage of the available cropland is deliberately idled. Repeated pricing studies have shown that only high-quality, garden type vegetables - tomatoes, cucumbers, and speciality lettuce - can provide break even or better revenues in hydroponic systems. These are, in fact, virtually the only hydroponic CEA food crops grown today in the United States. In Europe and Japan, these vegetables, and eggplant, peppers, melons, strawberries, herbs are grown commercially in hydroponic systems.

LIQUID (NON AGGREGATE) HYDROPONIC SYSTEMS

By their nature, liquid systems are closed systems in which the plant roots are directly exposed to the nutrient solution, with no other growing medium, and the solution is reused. There are several systems in this category such as the nutrient film technique (NFT) and deep flow hydroponics. The latter, has become possibly the most popular hydroponic system for production of leafy vegetables and herbs.
Deep Flow 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 (Jensen, Collins 1985) in Arizona and Massantini (1976) in Italy. Large-scale production facilities are now common and are quite popular in Japan. In the Caribbean, lettuce production has been made possible by combining this system of hydroponics with cooling the nutrient solution, which stops the bolting of lettuce.

The production system consists of horizontal, rectangular-shaped tanks lined with plastic. Those developed by Jensen measured 4 m x 70 m, and 30 cm deep. The nutrient solution was monitored, replenished, recirculated, and aerated. Rectangular tanks have two distinct advantages: the nutrient pools are frictionless conveyor belts for planting and harvesting movable floats, and the plants are spread in a single horizontal plane for maximum interception of sunlight.

Nutrient Film Technique (NFT). The nutrient film technique was developed during the late 1960's by Dr. Allan Cooper at the Glasshouse Crops Research Institute in Littlehampton, England (Winsor et al. 1979); a number of subsequent refinements have been developed at the same institution (Graves 1983). NFT has given rise to several modified systems which are used for leafy vegetable production mainly lettuce.

In a nutrient film system for crops such as tomatoes, a thin film of nutrient solution flows through plastic lined channels, which contain the plant roots. The walls of the channels are flexible; this permits them to be drawn together around the base of each plant, excluding light and preventing evaporation. For lettuce production, the heads are planted through holes in a flexible plastic material that covers each trough.

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 the NFT system in comparison with others is that it requires much less nutrient solution. It is therefore easier to heat the solution during winter months, to obtain optimum temperatures for root growth, and to cool it during hot summers in arid or tropical regions, thereby avoiding the bolting of lettuce and other undesirable plant responses. Reduced volumes are also easier to work with if it is necessary to treat the nutrient solution for disease control. A complete description on the design and operation of an NFT system is published in Horticultural Review, volume 7, pages 1-44 (Graves 1983).

Aeroponics. In an unusual application of closed system hydroponics, plants are grown in holes in panels of expanded polystyrene or other material. The plant roots are suspended in midair beneath the panel and enclosed in a spraying box. 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 tomatoes, although the latter was judged not to be economically viable (Jensen, Collins 1985). In fact, there are no known large-scale commercial aeroponic operations in the United States, although several small companies market 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 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 atop a panel-sized watertight box, 25 cm deep, which contains the nutrient solution and misting equipment (Jensen, 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 on center. The roots are suspended in the enclosed air space and misted with nutrient solution as described previously.

An apparent disadvantage of such a system is uneven growth resulting from 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 areas 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 atop a simple, sloped trough that collects and drains the nutrient solution to a central sump.

Another potential commercial application of aeroponics, in addition to the production of leafy vegetables in locations with extreme space and/or weight restrictions is the rooting of foliage plant cuttings. Such a rooting system works well to control foliage diseases, and is especially important if export requirements dictate that roots of cuttings be soil-free at the time of shipping. While the cuttings require heavy shading at the time of rooting, overhead misting is not required. This greatly reduces the problems of fungal diseases and the leaching of nutrients from the foliage of 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 be either open or closed, depending on whether surplus amounts of the solution are to be recovered and reused. Open systems do not recycle the nutrient solution; closed systems do.

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. These factors have generated experiments with a wide range of growing media and the development of more cost-efficient designs for containing them. In addition to wide growing beds in which a sand medium is spread across the entire greenhouse floor, open systems may use troughs, trenches, bags, and slabs of porous horticultural grade rockwool.

There are numerous types of media used in aggregate hydroponic systems. They include peat, vermiculite, or a combination of both, to which may be added polystyrene beads, small waste pieces of polystyrene beads or perlite to reduce the total cost. Other media as coconut coir, sand, sawdust are also common in some regions of the world.

For growing row crops such as tomato, cucumber, and pepper, possibly the two most popular artificial growing media are rockwool and perlite. Both of these media can be used in either closed or open systems (gravel is not recommended for use as an aggregate in either system). Both media are lightweight when dry, easily handled and easier to steam-sterilize than many
other types of aggregate materials. Both can be incorporated as a soil amendment after crops have been grown in it.

An obvious disadvantage is that rockwool and perlite may be relatively costly unless manufactured or mined within the region. Therefore, it is common for many growers to use growing media that are indigenous to the region, such as sawdust in western Canada, peat moss in Norway and coconut coir in Mexico.

When both perlite and rockwool are used as closed systems, 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. While it is common to sterilize the recirculating solution, there is today on going research to control certain root diseases with surfactants. Such systems can be capital intensive because they require leak proof growing beds as well as subgrade mechanical systems and nutrient storage tanks.

**Disease and Insect Control**

For the past 50 years, crop diseases and insects have largely been controlled by chemicals. This is especially true in Europe, and in most other regions where protected agriculture is widely practiced, for both greenhouse and field crops. In these areas, many apparently effective pesticides and chemicals (none produced specifically or exclusively for greenhouse agriculture) are available and legal.

However, in the United States, where so many of the world’s agricultural chemicals have been invented, few chemicals are legal for use in greenhouses. The effects of chemicals inside CEA structures may be different and more dangerous than they are in open-field crops, and their safety must be documented before federal and state governments will certify their use. However, because of the limited use of CEA in American food production, manufacturers are unwilling to spend the large sums necessary to obtain such documentation and certification.

The frightening ability of some insects to develop resistance to chemical pesticides has revived worldwide interest in the concept of biological control: the deliberate introduction of natural enemies of insect pests, particularly when used in association with horticultural practices, plant genetics, and other control mechanisms. This combined approach, called integrated pest management (IPM), is of particular interest to greenhouse growers throughout the world because of the paucity of pesticides with legal clearance for use in greenhouses.

**The Future of Food Production in Greenhouses**

There seems to be a kind of technological imperative driving development of greenhouse agriculture. Like manufacturing, it generally moves toward higher-technology, more capital-intensive solutions to problems. It is highly productive and suitable for automation.

Given present circumstances, however, there seems to be no rational basis for anticipating a much wider and faster diffusion of technology than is presently occurring. The future growth of controlled environment agriculture depends greatly on the development of systems of production that are cost-competitive with those of open field agriculture.
Continuing research and development, for example, may lead to more cost-efficient structures and materials; to reduced requirements of purchased energy; to new cultivars more appropriate to controlled environments and mechanized systems; to better control (including improved plant resistance) of diseases and pests. To the extent that these improvements increase crop yield and reduce unit costs of production, protected agriculture will become more competitive.

The economic prospects for CEA may change if governmental bodies determine that in some circumstances, politically desirable effects of CEA merit subsidy for the public good.

Such beneficial effects may include the conservation of water in regions of scarcity or food production in hostile environments; governmental support for these reasons has occurred in the Middle East. Another desirable societal effect can be the provision of income-producing employment for chronically disadvantaged segments of the population entrapped in economically depressed regions; such employment produces tax revenues as well as personal incomes, reducing the impact on welfare rolls and improving the quality of life.

CEA is a technical reality. Such production systems are extending the growing seasons in many regions of the world and producing horticultural crops where field-grown fresh vegetables and ornamentals are unavailable for much of the year. The economic well-being of many communities throughout the world has been enhanced by the development and use of CEA. Such systems offer many new alternatives and opportunities for tomorrow’s population, new systems that encourage conservation and preservation of the environment rather than the exploitation of the land and water.

References
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