Abstract

Controlled environment agriculture (CEA)/greenhouse vegetable production is one of the most exacting and intense forms of all agricultural enterprises. In combination with greenhouses, hydroponics or soilless cultivation is becoming increasingly popular. It is high technology and can be capital intensive. CEA is highly productive, conservative of water and land and protective of the environment. There are many types of CEA systems. Not every system is cost effective in each location. While the techniques of hydroponic culture in the tropics may be quite similar to those used in deserts and temperate regions of the world, the greenhouse structures and methods of environmental control can differ greatly. 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 controlled environment agriculture is changing rapidly with systems today producing yields never before realized.

1. Introduction

Controlled environment agriculture (CEA) is the modification of the natural environment to achieve optimum plant growth. Modifications can be made to both the aerial and root environments to increase crop yields, extend the growing season and permit plant growth during periods of the year not commonly used to grow open field crops. All aspects of the natural environment may be modified for maximum plant growth and economic return. Control may be imposed on air and root temperatures, light, water, humidity, carbon dioxide, and plant nutrition.

Of equal importance in the design of a controlled environment greenhouse system is the structural design, the environment control and the growing or plant culture system. 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. Structural design of a greenhouse must provide protection against damage from wind, rain, heat, and cold. At the same time, the structural members of a greenhouse must be of minimum size in order to permit maximum light transmission to the crop. 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.

Not every system is cost effective in every location. The design of a CEA system can vary greatly depending on whether it is located in a desert, the tropics or in a temperate region.

Hydroponic culture is possibly the most intensive method of crop production in today’s agricultural industry. The technology for this system of food production has advanced a great deal in the last 20 years. 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. The future growth of greenhouses or CEA, where hydroponics is used for vegetable production, will depend greatly on the development of production systems that are competitive, in terms of cost, with open field agriculture.

2. Economics of CEA food production

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). Yields are 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 most often 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 are no shortcuts in environmental control, competent management, or any other factor of production. In the United States, retailers commonly double their sale prices over the wholesale price to the grower. Such a high mark up can cause consumer resistance. Today, many of the greenhouse vegetable cultivars have better flavor than those grown 15 years ago, especially if grown during winter in the high light desert regions of the world.

3. Structures and environmental control

The total world area of glasshouses is estimated to be over 41,000 ha, with most of these found in northwestern Europe. In contrast 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.

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. 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 the largest user 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.

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. 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. Newer materials, such as polycarbonates and acrylics have become much more common, but their popularity has been offset by high costs.
Greenhouses are expensive, however, and controlling the environment within a greenhouse requires considerable energy. 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.

3.1. Environmental control differences between regions

Heating greenhouses is optional in all regions of the world, although heating is normally not necessary in the tropics. When heating is not used in the temperate and desert regions of the world, crop production is seasonal, usually during spring, summer and fall. Most of the greenhouse structures in Asia are non-heated. In China, approximately 15,000 ha. are heated while 352,000 ha of lean-to solar greenhouses are non-heated with fossil fuels. If year-round production is desired, heating is most often required in temperate regions as well as in desert regions especially during winter. While a greenhouse can be expensive to heat, it can be profitable if high quality cost competitive products are grown. The selection of heating equipment depends on the size and type of operation, the greenhouse structure, fuel availability and cost, and the cost of the system components. The fuel can be gas, oil, coal, or wood. A heating system consists of a fuel burner, heat exchanger, distribution system and controls. The fuel burner can be located within the greenhouse with the heat delivered to the crops by convection and radiation. These direct-fired units use either air or water as the heat transfer fluid. Central boilers are often used in large operations where gutter-connected greenhouses are used. Either water or steam acts as the heat transfer unit. Most steam systems use a low pressure boiler, with enough pressure to push the stream to all greenhouses in a range.

Air movement in a greenhouse is needed for acceptable carbon dioxide distribution and to maintain uniform temperature within the crop zone. Natural convection air movement will develop in a closed greenhouse when, warm light air rises, is cooled against the roof surfaces, and then falls back to the ground to be warmed. The result is a warm air mass in the attic of the greenhouse and large temperature variations occurring between the upper part of the greenhouse and ground level. Uniform temperatures can be obtained with the use of small horizontal airflow fans to create a slow horizontal movement of the air mass. In greenhouses containing plants that have tall, dense foliage such as roses, tomatoes, or cucumbers, air movement can be provided by using perforated polyethylene film ducts to discharge air within the crop. To assure relatively uniform distribution, total fan capacity should be equivalent to moving about one-quarter of the greenhouse volume per minute.

Ventilation requirements for greenhouses very greatly, depending on the crop grown, the season and region of production. The ventilation system can be either a passive system (natural ventilation) or an active system using fans for forced ventilation. Greenhouses used seasonally usually employ only natural ventilation; those in year-round production, especially in arid regions of the world, use fan ventilation. Evaporative cooling is often part of a fan ventilation system. Ventilation/cooling equipment includes such items as vents, fans, shading, and evaporative pad systems, as well as control components. Passive ventilation on glass structures consists of ridge and side vents that are opened or closed manually or by modernized vent thermostats. With plastic greenhouses, passive or natural ventilation is a key challenge, especially without the aid of exhaust fans. The major differences between greenhouse structures built in temperate regions versus those designed for deserts and tropics are the accommodations for ventilation. With the exception of
glasshouses which have ridge vents, most polyethylene greenhouses use side vents on structures which are predominantly hoop houses/high tunnels. When ventilation is required, the sides of the greenhouses are simply rolled up or lowered. The disadvantage to this method of ventilation, especially in the tropics and deserts is the trapping of heat in the attic or upper part of the greenhouse.

In the desert regions and in many temperate regions, mechanical ventilation is required if year round crop production occurs. While high tunnel greenhouses are mostly found in temperate regions of the world, they are also used in many desert regions for the production of winter vegetables. Retractable roof greenhouses are rapidly gaining popularity in both the temperate and desert regions of the United States. Such structures are mainly dedicated to ornamental plants and vegetable transplant production. Growers are giving more attention to conditioning the plants for transplanting to open field production rather than hardening the plants, which can delay optimum growth of plants once transplanted to the field.

For active or mechanical ventilation, low pressure medium volume propeller blade fans, both directly connected and belt driven, are used for greenhouse ventilation. They are placed on the end of the greenhouse opposite the air intake, which is normally covered by gravity or motorized louvers. The fan vents, or louvers, should be motorized, with their action controlled by fan operation. Motorized louvers prevent the wind from opening the louvers, especially when heat is being supplied to the greenhouse. Wall vents should be placed continuously across the end of the greenhouse to avoid hot areas in the crop zone.

Evaporative cooling in combination with fans is called **fan and pad cooling**. The cooling pads can be made from a number of materials; most often they are made of a cellulose material, usually aspen wood, or a multi-celled/honeycombed material called Akool-cel. Evaporative cooling systems are especially efficient in low humidity environments. There is increasing interest in building greenhouses combining both passive and active systems of ventilation. Passive (natural) ventilation is utilized as the first stage of cooling: fan-pad evaporative cooling takes over when the passive system is not providing the needed cooling. At this point, the vents for natural ventilation are closed. Initial costs of installation are greater when both options for cooling are designed into greenhouse construction. Even so, long-range operational costs are minimized, since natural ventilation will, most often, meet the needed ventilation requirements.

Fogging systems can be an alternative to evaporative pad cooling. They depend on absolutely clean water, free of any soluble salts, in order to prevent plugging of the mist nozzles. Such cooling systems are not as common as evaporative cooling pads but, as they become more cost competitive, fog may be used more frequently. Fogging systems can be the second stage of cooling when passive systems are inadequate. Evaporative cooling is only efficient in low humidity environments and not effective in areas such as the tropics.

In the tropics, the sides of greenhouse structures are often left open for natural ventilation. A tropical greenhouse is primarily a rain shelter, a cover of polyethylene over a crop to prevent rainfall from entering the growing area and, in turn, mitigate the problems of foliage diseases. To prevent insects from entering, especially those which are vectors for virus diseases, the side areas are covered with screens. The use of these nonchemical means of insect control becomes increasingly important
as concerns mount about the long-term effects of chemicals entering the food chain or the environment, and the exposure of workers to toxic compounds. Screens, must have holes large enough to permit free flow of air; screens with small holes block air movement and foster a build-up of dust. Greenhouses can be cooled by using the natural forces of wind and temperature; however, a mechanical system is required for fine temperature control. At night energy curtains are often used during winter in greenhouses located in temperate and desert regions. Such energy conservation technologies can provide up to 50% fuel savings.

4. 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, CO$_2$, 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 CO$_2$ status for a given day, or over a longer period of time.

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.

5. 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 is 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.

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. 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.

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.

5.1. 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
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.

**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. 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).

5.2. 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. 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, China, Malaysia, etc.

In a growing media trial at the University of Arizona, five different media were tested for their yield potential. There were no significant differences in yield (Table 2) although coconut coir did exhibit excellent physical properties, regarding air porosity and water holding capacity, both important in high temperature desert and tropical regions.
6. The future of food production in greenhouses

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

Table 1. Estimated world use of plastic greenhouses.

<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>467,300 (367,100 in China)</td>
</tr>
<tr>
<td>World Total</td>
<td>594,900</td>
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</tbody>
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*Source: In part from Wittwer, Castilla 1995*

Table 2. Tomato yield comparison.

<table>
<thead>
<tr>
<th>Growing Media (bag culture)</th>
<th>Yield kg/m²</th>
<th>Size gms/fruit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coconut Coir</td>
<td>26.58</td>
<td>196</td>
</tr>
<tr>
<td>Perlite (3 plts/bag)</td>
<td>25.69</td>
<td>195</td>
</tr>
<tr>
<td>Peat-lite</td>
<td>24.81</td>
<td>193</td>
</tr>
<tr>
<td>Coir/Perlite</td>
<td>24.27</td>
<td>192</td>
</tr>
<tr>
<td>Rockwool</td>
<td>24.02</td>
<td>185</td>
</tr>
<tr>
<td>Perlite (6 plts/bag)</td>
<td>23.40</td>
<td>192</td>
</tr>
</tbody>
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Paper # I-125933-03-00. Supported by CEAC, the Controlled Environment Agricultural Center, College of Agriculture and Life Sciences, and The University of Arizona. (Jensen Taiwan World Review of CEA.doc) C:\AG\JENSENMS\Tropics.ms November 15, 2010