Controlled Environment Agriculture Scoping Study

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CONTENTS

Section	Page

Section	Page

Executive Summary

Controlled Environment Agriculture (CEA)

Controlled Environment Agriculture (CEA) is an advanced and intensive form of agriculture where plants are grown within controlled environments in order that horticultural practices can be optimized. The most advanced forms of commercial CEA use hydroponics instead of either soil or a soil substitute as a root medium. (Three types of hydroponic growing systems are described in this report.)

CEA techniques are not simpler than older systems for growing plants. Indeed, they demand sound knowledge of chemistry, horticulture, engineering, plant physiology, plant pathology, computers, and entomology. A wide range of skills as well as a natural inclination to attend to details are necessary for a person to operate a successful CEA production in either a research or commercial setting.

Importance. Today's consumers increasingly demand a diet that includes fresh, high-quality vegetables free of pesticides and other agricultural chemicals. Local production is also a major factor when fresh vegetables are purchased. In many regions of the United States and the world, climate makes it impossible to meet this need year-round with only local produce. Produce imported into the United States may be from other regions of the country (California, Florida, and Texas are major exporting states) and from other countries (primarily Mexico, Netherlands, and Israel).

When fresh produce is transported great distances there can be a significant loss of quality. Furthermore, energy requirements for transport can be significant. Local production in CEA facilities can also require significant energy inputs for heating, venting, and, possibly, supplemental lighting. Studies have suggested the (non-solar) energy required to grow and transport fresh produce at least 1000 miles is equivalent to the energy required for local production within CEA facilities in cold and cloudy climates such as the Northeast and upper Midwest.

Transportation relies on liquid fuels, the price of which is predicted to rise faster than the general inflation rate. Production in CEA facilities relies on electricity and natural gas, the prices of which are predicted to rise no faster than inflation. These factors suggest CEA production of fresh vegetables can become a significantly greater component of commercial agriculture in the coming decades.

Benefits to Consumers. Well-managed, local CEA operations can provide fresh produce (as well as flowers) of high quality and free of agricultural chemicals. Furthermore, CEA facilities can be closed in terms of discharging liquids either to surface or ground waters. CEA facilities can also be located in urbanized areas, thus not requiring the conversion of open or agricultural land to greenhouses. CEA facilities add to local tax bases and bring net income to a community.

Benefits to Agriculture. Certain sectors of the agricultural industry face increasingly difficult economic outlooks. This is especially true of the dairy industry. Diversification is one means to improve the economic stability of small farmers and CEA is an option to diversify. Furthermore, many family farms can not be divided among two or more children wishing to remain in agriculture. Adding a robust CEA facility provides the opportunity for more than one child to remain.

Benefits to Utilities. The two most important environmental variables for growing plants are temperature and light. Both parameters must be controlled to be uniform from one location to another in a greenhouse, and consistent from day to day. The only method available to achieve consistency is to use supplemental lighting. Where the climate is cloudy, electricity needed yearly for suitable lighting can be as much as one hundred kilowatt-hours per square foot of lighted area. This load is primarily during off-peak hours and can be interrupted for short periods. These features should make CEA electricity loads highly attractive to many local utilities.

Recommendations

The Electric Power Research Institute (EPRI), working through its Agricultural Technology Alliance (ATA) should support both research projects and the development of economically viable CEA demonstration projects. Existing technologies should be combined with innovative and new technologies to address needs in systems, processes, equipment, and control.

It is recommended that research and demonstration projects be coordinated through an ATA CEA Advisory Board. The Advisory Board should be made up of members of the ATA and, possibly, others with special expertise in various aspects of CEA (researchers as well as commercial growers). The function of the Board should be to receive advice from the ATA and then decide on priority items for advancing CEA technologies. Proposals should be actively sought from researchers and others known to have expertise and experience in the priority items. Additionally, the Board should actively seek financial support beyond current ATA funding from utilities for the projects. Such support could be from member utilities, governmental agencies, and industry.

1. Introduction

Brief History of CEA in the United States

Controlled Environment Agriculture (CEA) is the most intensive form of crop production in agriculture today. CEA is highly technical and uses electrical energy at a significant rate for the physical size of each operation, but not necessarily for each unit of product that reaches the customer. CEA is capital-intensive but labor efficient. CEA need have no environmental discharges to ground water or surface waters. Pesticide use is minimized through environmental manipulation and biological controls. Yearly production per unit of covered ground area can be an order of magnitude greater than from the best outdoor production. However, this degree of sophistication in what is, in effect, a form of applied biotechnology, is not a sudden development. Rather, its foundations are in the long history of growing plants in protected cultivation and an evolution and amalgamation of technologies.

The CEA industry specialized for growing vegetables in the United States is currently small. Thirty years ago hundreds of acres of greenhouses for vegetable production were found in the United States, especially in Ohio. However, production at that time was with crops planted directly into the ground (e.g., tomatoes and lettuce). Crops were often seasonal or, in the case of lettuce, slow-growing, because greenhouses were kept cold during the winter. Environmental control did not approach that which defines CEA.

During the 1970s, spurred by concerns about heating energy, alternate sources of space heat for greenhouses were sought, such as solar energy, geothermal energy, and waste heat from a variety of sources, including power generation stations. Some of these greenhouse installations were erected for flower production, but others were intended for vegetables, and a few were for herbs. Except for the sources of heat, there was little difference between these greenhouses and other, conventional greenhouse operations.

During the same era, an interest in community greenhouses and similar systems led to numerous small greenhouse operations that focused primarily on vegetables and herbs. Such systems often included a wide variety of crops within the same air space, and a desire to create a pesticide-free, organic production system was often foremost. Environmental control was often lax, and the systems could not be truly defined as representing CEA.

The potential for economic profit from high-technology, year-round vegetable production in CEA systems has enticed several large companies to enter the industry. Examples include General Mills, General Foods, Weyerhaueser, General Electric, and Archer Daniels Midland. By and large, these operations have not been successful. Historically, it has proven difficult for large companies to enter agriculture, and the highly technical aspects (and the need for an intense attention to detail) of CEA were not readily adaptable to the management structure typical of large companies.

The past decade has seen several large vegetable-producing CEA operations established in the Southwest (Colorado and Arizona, for example). Crops have included tomatoes and peppers, crops that can be shipped to all points within the United States. Location in the Southwest is an acknowledgment of one of the important needs of a true CEA production system, the need for a good light environment. Regions having extended cloudy periods experience such a slowing of production that remaining competitive becomes difficult. However, the Southwest has several disadvantages in terms of CEA production. High temperatures during the summer can inhibit production of all but the most heat-tolerant crops. Water quality is problematic. Distances to the best markets (e.g., the Northeast corridor from Boston to Washington) are great.

Three technologies in particular have permitted crop production within greenhouses to evolve to the sophisticated techniques of CEA possible today. One technology is digital control of the environment, that is, computerized environmental control. The second is mechanization and automation. The third is the advancement of hydroponics technologies for plant production. The success of each is based on the approach of considering CEA production to be a system consisting of numerous interacting components. Future growth of CEA will be based on further applications of the systems approach.

Definition of CEA and Contrast to Other Systems

Several terms are commonly applied to structures and methods used to grow plants under protected conditions:

(1) low tunnels,

(2) high tunnels,

(3) protected cultivation,

(4) greenhouse growing,

(5) Controlled Environment Agriculture (CEA), and

(6) Environmental Control and Life Support Systems (ECLSS).[1]

The progression of terms shows the level (low to high) of technical sophistication involved in the plant-growing systems. Each term is described in greater detail in the following discussion. Table 1.1 contains criteria proposed as a means to define systems and contrast each system to the others.

(1) <u>Low tunnels</u> (see figure 1.1), also called row covers, are used primarily to advance the growing season for outdoor crops (for example, tomatoes, melons, sweet corn). Low tunnels are created using long, narrow strips of transparent plastic material (often polyethylene) buried in the ground along their

[1] Other terms used for the same systems include Controlled Ecological Life Support System (CELSS), Advanced Life Support (ALS), and Bioregenerative Life Support (BLS).

outer edges to cover one or several adjacent rows of plants grown directly in the ground. Low tunnels may be supported by hoops over crop rows, or the plastic may be placed directly on top of the growing plants. The material may be solid or vented by slits or holes and may be made of extruded films or woven materials. Fresh vegetables planted before the frost season ends are protected by the plastic cover through its action to suppress frost while simultaneously creating a greenhouse effect and warming the cold soil. Row covers are usually removed or cut open when all danger of frost passes and overheating is an imminent risk. French cloches and traditional hot caps are variations of this technology.

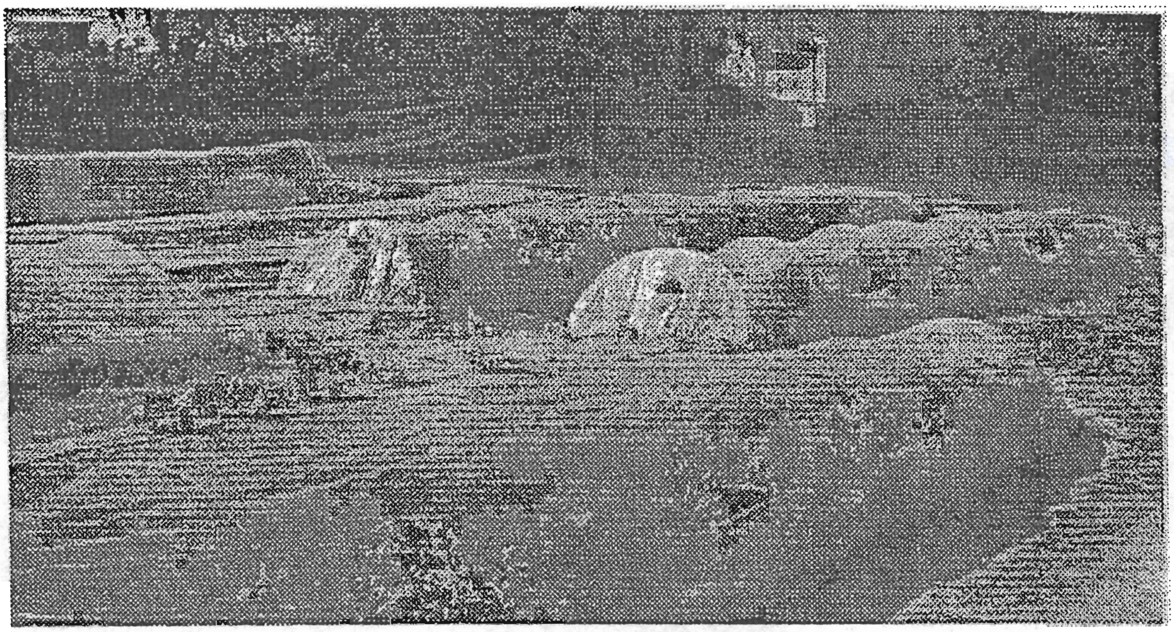

Figure 1.1. View of low tunnels (row covers) constructed of plastic film supported off the ground on metal hoops. Also called cloches. Metal support hoops are not always used when the canopy is sufficiently sturdy that it can support the plastic by itself. Further, cover material may be plastic film with holes, slits, or closed, or may be spun-bonded materials to permit slow ventilation and moisture diffusion.

(2) High tunnels (see figure 1.2) are large versions of low tunnels and are raised sufficiently above the ground that people can walk within them. The tunnels are typically six feet high, six to ten feet wide, and constructed of plastic film placed over hoops anchored into the ground. High tunnels are used as low-cost greenhouses in many parts of the world and in the U.S. as overwintering facilities for nursery products, for example. They may be heated using portable heaters and cooled by natural ventilation, but environmental control is limited.

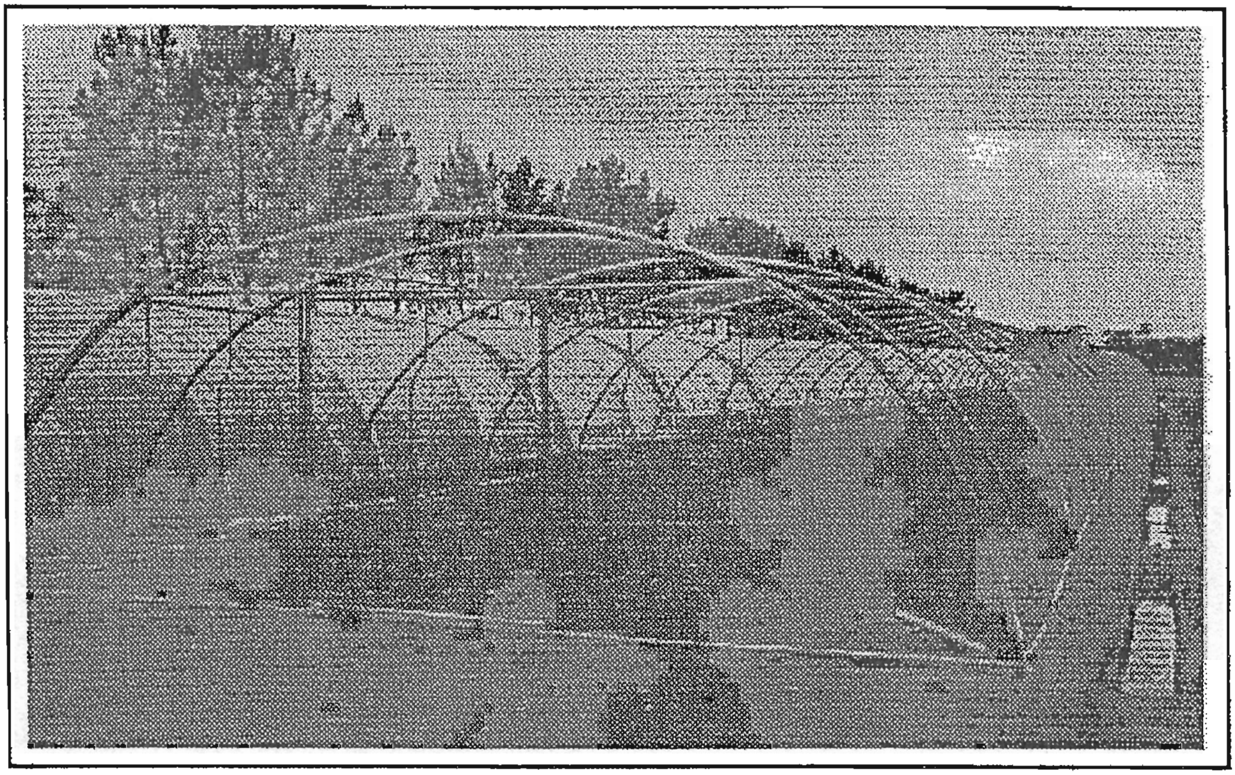

Figure 1.2. View of high tunnels made from metal hoops that span approximately 12 feet and are 6 feet high in the center. Covering is typically plastic film. Slits in the plastic seen in the view are used for ventilation when weather becomes warmer.

(3) Protected cultivation is a generic term that applies to a range of technology, from high tunnels to relatively sophisticated greenhouses. As such, it defines an approach to plant growing rather than a specific system designed for plant growth. It is a term widely used in Europe to identify any method of growing crops under cover (including sophisticated greenhouses) and, in warm climates, to identify simple, unheated greenhouse crop production, often based on high tunnels.

(4) Greenhouse (or glasshouse) growing is a term that generally implies plant growing within a relatively permanent structure (glass or plastic) equipped with several means of environmental modification - usually at least heating and mechanical or natural ventilating systems. Environmental control systems can range from simple thermostats to computer controllers (although one still finds hand operation used in isolated instances). The term "greenhouse" is also generic in that high tunnels can be called greenhouses, and highly sophisticated controlled environment plant growing systems are also described by some as greenhouses. However, for the purposes of this report, the term "greenhouse growing" will not be applied to sophisticated growing systems with mechanization and sophisticated environmental control, where the various components have been designed to provide an integrated, total system, especially with regard to controlling aerial and root environments. Such highly sophisticated systems will be termed "Controlled Environment Agriculture", as described in the next paragraph.

(5) Controlled Environment Agriculture (CEA) is a term applied to growing plants at a level of sophistication that includes coordinated environmental control (temperature, light, air movement, and carbon dioxide control as examples, with some control of relative humidity); integrated production systems; mechanization and automation where appropriate; and superior attention to detail with a focus on plant quality, timing, and quantity. The most typical plant production technique used in CEA is hydroponics, and the term "hydroponics" is often used interchangeably with "CEA". The two terms are not synonymous, however, for hydroponics systems are often used in greenhouses having relatively low levels of technology and control. In Figure 1.3 is a view of typical CEA facility.

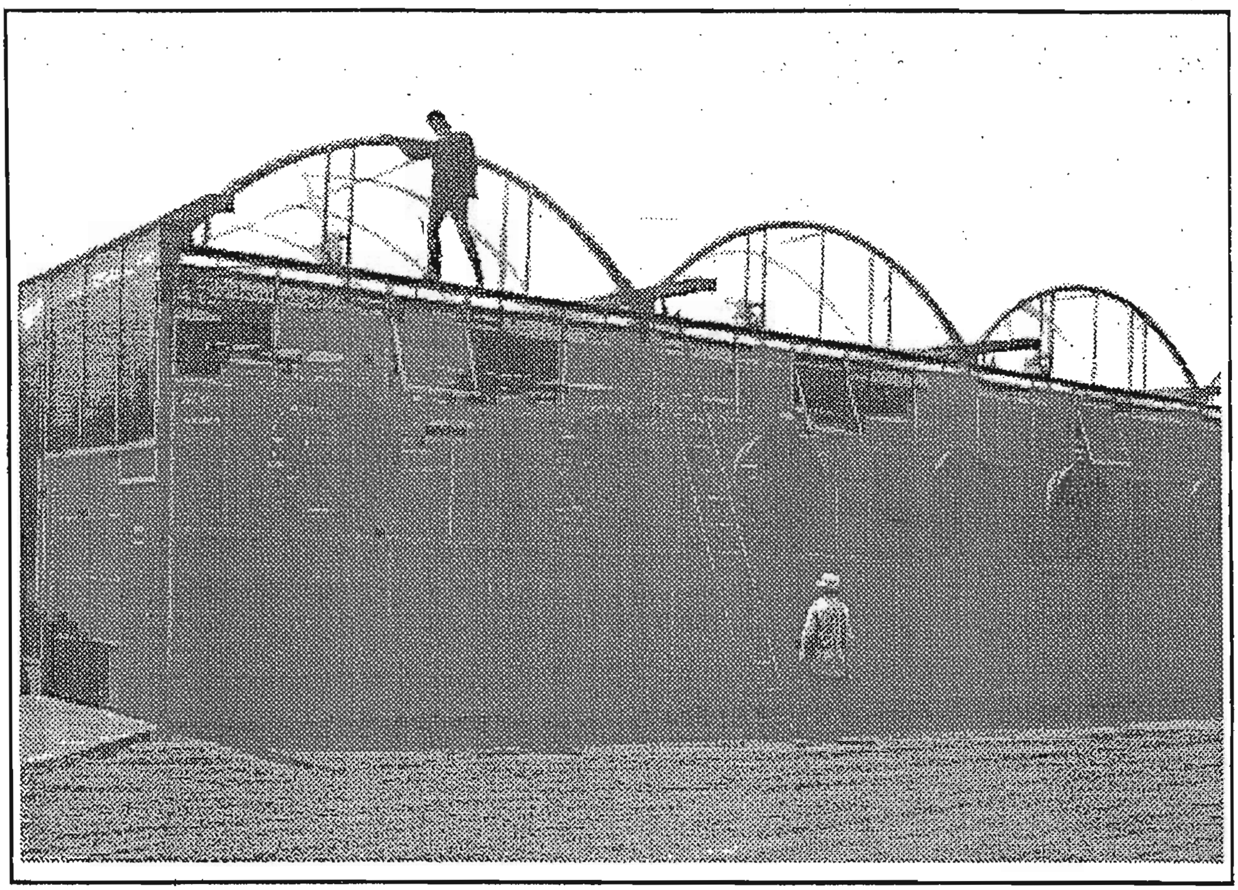

Figure 1.3. View of commercially available greenhouse structures suitable for Controlled Environment Agriculture.

The goal of CEA is to avoid, to the extent practical, any imposed stresses or external limits on the plants and, thereby, achieve the full genetic growth and production potentials of the plants. Both aerial and root environments are monitored and controlled. Energy use is optimized and environmental discharges are limited or nonexistent. Integrated pest management techniques reduce or eliminate the need for pesticides. Energy and material requirements on a unit area basis are high, but production is so enhanced that input per unit of output is often less than with conventional greenhouse plant production.

One aspect of CEA that separates it from other plant production systems is the degree of system integration used. The aerial and root environments are controlled together. Heating, cooling, lighting, carbon dioxide addition and air movement are coordinated. Such coordination requires computerized control to be totally effective. As a visual method to understand the degree of system integration used, see figure 1.4 which contains a concept map that shows one approach to integrating CEA sub-systems into a specific production system for lettuce, the deep trough system described later in this report.

It must be noted that, as any manufacturing system becomes more sophisticated, the need for careful control and optimization increases to take advantage of the higher level of sophistication. CEA is a form of manufacturing, and the same is true for it. Very careful attention must be given to every detail. Any component of the system not operating at peak efficiency should be replaced, and any condition that might suppress productivity should be assiduously avoided. This concept suffuses this report and will be returned to repeatedly as various aspects of CEA production are reviewed.

(6) Environmental Control and Life Support Systems (ECLSS) are totally closed systems designed to provide a healthy and productive working environment for people away from the Earth's biosphere. Food production, carbon dioxide and oxygen exchange, biodegradation of organic wastes, and regeneration of potable water are features of such systems. Plants, humans, microorganisms, and possibly animals interact in closed systems in hostile external environments, such as space stations or on the lunar or Martian surfaces. This is currently an area of significant research as scientists and engineers plan for space exploration and settlement. Significant overlap occurs between the knowledge and technology bases of CEA and ECLSS, for they have many characteristics in common. However, because this term is reserved for applications outside the Earth's biosphere, it is held separate from CEA.

See table 1.1 for a summary of attributes of the various plant production systems discussed above and as used in this report.

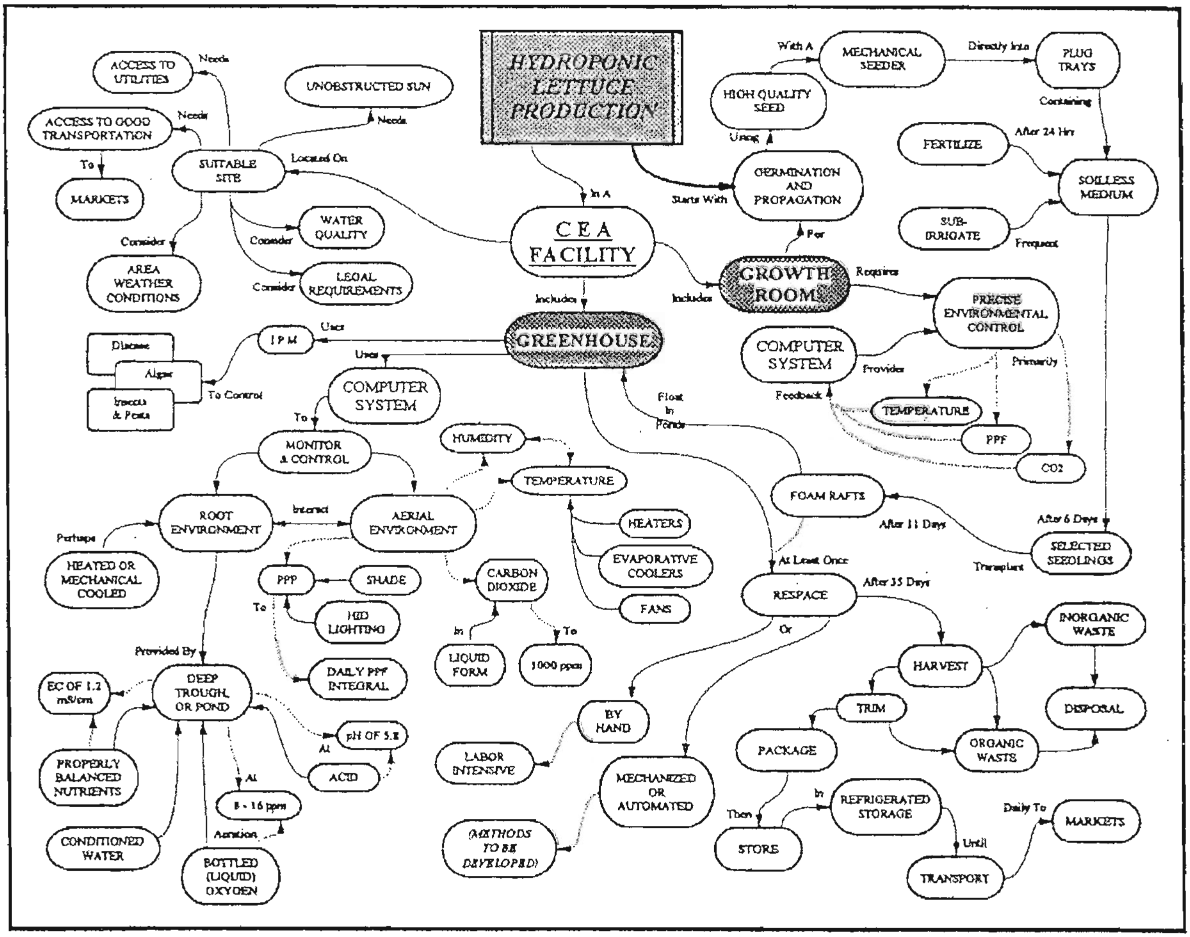

Figure 1.4. Concept map example of hydroponic lettuce production system using a deep trough system in CEA. (Sketch adapted from Danish, W. E. D., Jr., 1994. Project report; A grower's guide to lettuce crop production using nutrient film technique in controlled environment agriculture facilities. Project report submitted in partial fulfillment for the degree of Master of Professional Studies (Agriculture). Cornell University, Ithaca, NY). 65 p.

Table 1.1. Plant production system attributes

Attribute	*Low Tunnel*	*High Tunnel*	*Prot Cultivation*	*Greenhouses*	*CEA*	*ECLSS*
Space heating	No	Maybe	Maybe	Yes	Yes	Yes
Natural ventilation	Maybe	Yes	Yes	Yes	Yes	No
Mechanical ventilation	No	Maybe	Maybe	Yes	Yes	Yes
Evaporative cooling	No	No	Maybe	Maybe	Yes	No
Mechanical cooling	No	No	No	No	No	Yes
Carbon dioxide supplemented	No	No	Maybe	Maybe	Yes	Yes
Hydroponics implemented	No	No	Maybe	Maybe	Likely	Yes
Automated plant watering	No	No	Maybe	Maybe	Yes	Yes
Controlled root environment	No	No	Maybe	Maybe	Yes	Yes
Limited supplemental lighting	No	No	Maybe	Maybe	No	No
Intense supplemental lighting	No	No	No	No	Yes	Yes
Photoperiod lighting	No	No	Maybe	Maybe	Yes	Yes
Liquid water discharge	n/a	Yes	Yes	Yes	No	No
Pesticides used	Yes	Yes	Yes	Yes	Slight	No
Integrated Pest Management (IPM)	No	No	Maybe	Maybe	Yes	Yes
Computer control of environment	No	No	Maybe	Maybe	Yes	Yes
Integrated computer control	No	No	No	No	Yes	Yes
Weather-dependent production	Yes	Yes	Yes	Yes	No	No
Temporally consistent quantity	No	No	No	No	Yes	Yes
Temporally consistent quality	No	No	No	Maybe	Yes	Yes
Temporally consistent timing	No	No	No	No	Yes	Yes
Spatially consistent quantity	No	No	Maybe	Maybe	Yes	Yes
Spatially consistent quality	No	No	Maybe	Maybe	Yes	Yes
Spatially consistent timing	No	No	Maybe	Maybe	Yes	Yes

Note: For classification purposes, if a system does not meet all requirements of a candidate category, it is moved to the next lower category, where the technology hierarchy is from lowest (left) to highest (right).

Market Potential for CEA Vegetable and Fruit Crops

The paramount questions regarding the viability of a CEA industry for food crops are the perceived attributes of CEA produce, the size of potential markets, the value of the crop, and the costs of production. Marketing and economic studies are needed to address these questions and assess the potential size of the market and estimate potential revenues. As a metric for comparison, USDA data show fresh vegetable imports into the United States from October 1994 through September 1995 (the latest data available) totaled 1,916,393 metric tons, with a combined value of $1,144,646,000. Much of these imports were comprised of vegetables with significant CEA potential: tomatoes and lettuce, for example.

The variety of crops which could be produced using CEA technologies includes fresh leaf and fruit vegetables, small fruits, culinary herbs, and crops grown for chemicals such as pharmaceuticals. Crops suitable for CEA must be selected based on evaluations of production time, planting density, marketable yield, production costs, and probably wholesale value. The crop status pages that follow in section 4 of this report provide a sample selection of possible CEA crops. Some are obvious choices. Others are suggested because of current niches already established in the fresh vegetable and culinary herb markets in the United States. The production potential of CEA opens additional niches limited only by imagination. For example, an emerging fresh market exists for miniature or exotic vegetables. The public's ongoing fascination with the new and unusual opens potentially profitable niche markets within larger metropolitan areas.

A virtually unexplored market development potential for CEA crops relates to the ability to control CEA environments within tight constraints. This includes controlling root environments and plant nutrition. Fragmentary data suggest that plant nutrition can be manipulated to affect the human nutrition characteristics of the resulting product.

In spite of the obvious potential to develop large markets for CEA products, marketing is a key problem that will be faced by CEA enterprises. Organized and cooperative marketing systems have been developed in other countries. The Netherlands is an excellent example, but that model has not worked well in the United States. Reluctance in some cases, rejection in others, have greeted proposals for cooperative marketing arrangements. A key reason for failures of cooperative marketing organizations is the inability of the resulting organization structure to protect the individual grower from interference from groups of growers. Individuals are often reluctant to submit their independence to group enforcement of product quality standards while, at the same time, losing any ability to control postharvest storage, packing and transport. Individual arrangements for direct marketing are likely to be the model for at least the near-term. Such arrangements can be direct between a grower and a retailer, such as a supermarket chain, or through an intermediary such as a vertical integrator.

2. CEA-Hydroponics Systems

Components and Systems

The term "hydroponics" has often been used interchangeably with "Controlled Environment Agriculture". Controlled Environment Agriculture has been defined above; the term describes the highly controlled and precise method of growing plants under cover for optimized productivity. Hydroponics, in contrast, may be defined as the process of growing plants without the use of natural soil. Although many CEA operations can be expected to use hydroponics as a growing technique, the two terms are not synonymous. Hydroponics growing systems have been used within CEA facilities, but also outdoors with no structural cover or environmental control.

Hydroponics may be further divided into cultural techniques where (1) an inert substance is used as a root medium and (2) no root medium other than nutrient solution is used. The first technique has been termed "soilless culture". The inert material may be any of several substances such as gravel, sand, peat, perlite, rockwool, or bark.

Numerous variations of hydroponics may be found in the extant literature. However, for this report, three very common systems will be described; two use no root medium, the third does. The first is the nutrient film technique, commonly termed NFT. The second has been termed, variously, as the pond, raft, floating, or deep trough system. The third, which uses an inert root medium, has no commonly accepted generic label but will be called here, as a means of identification, soilless culture.

Nutrient Film Technique (NFT)

General. The nutrient film technique (NFT) for plant production is a closed system for growing plants so their roots remain in a shallow stream of recirculating nutrient solution. There is no root medium other than the nutrient solution. However, seedlings are typically started in a small cube of root medium, which is then transferred to the NFT system when roots begin to emerge from the cube. All required nutritional elements are dissolved in the nutrient solution. The system typically uses shallow troughs or channels to support the plant roots and contain the flowing nutrient solution. Plant roots usually grow together to form a thin mat within the trough or channel. Plant tops are supported by clips or ties if they are of a crop such as tomato or cucumber that have a naturally vining and indeterminate growth habit. Otherwise, support of the root cube provides adequate support of the top. See figure 2.1 for a view of plants in a NFT system.

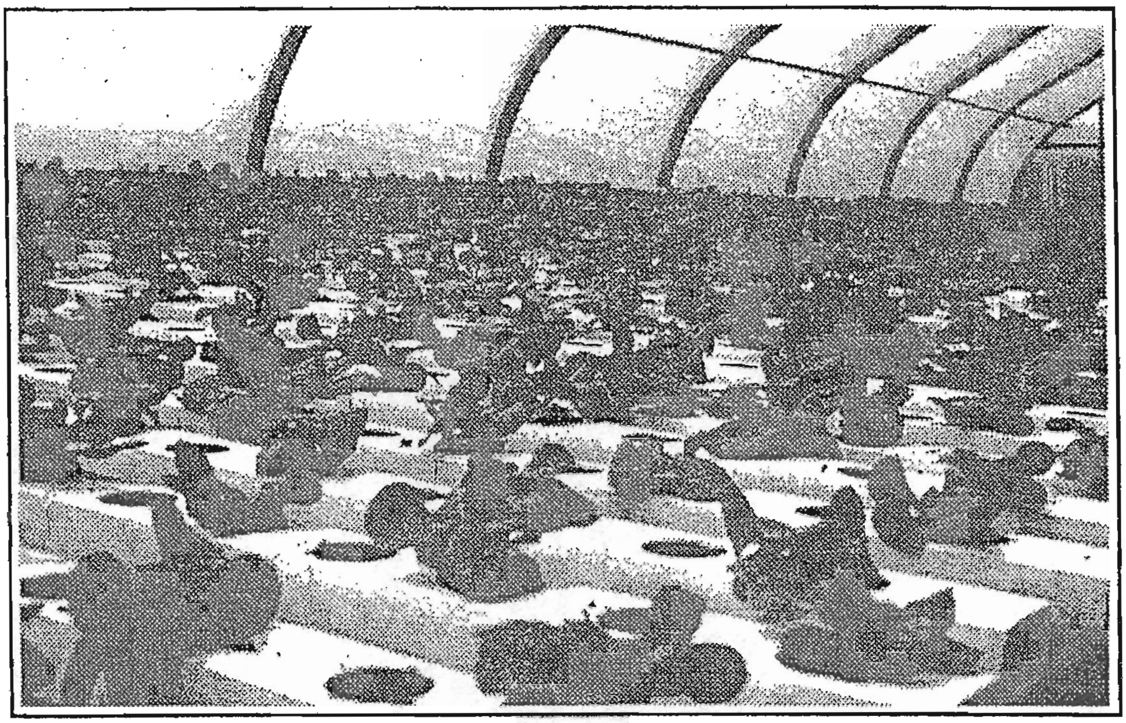

Figure 2.1. Example of lettuce production using the NFT system.

The defining characteristic of true NFT is that the nutrient stream is very shallow. Plant roots rest partly within the stream and partly within the air above. However, nutrient solution moves by capillary action around the roots that extend into the air to bathe them in water and nutrients while, simultaneously, permitting free access by the roots to oxygen. The nutrient stream may flow continuously or may be intermittent with the roots alternately submerged and exposed to air (on a rapid cycle of several times each hour so even the smallest roots do not desiccate).

The basic components of a NFT culture system are:

- a storage reservoir for holding nutrient solution;
- a method to aerate the recirculating nutrient solution;
- flow channels, typically long and narrow and parallel to each other, with one end raised to provide sufficient slope for nutrient drainage;
- a pump to circulate nutrient solution from the storage reservoir to the upper ends of the flow channels;
- emitters to discharge water into each flow channel at a measured rate;
- a return flow system to catch excess nutrient solution at the lowest ends of the flow channels and return it to the storage reservoir;
- sensors to monitor nutrient solution pH, EC, and solution level, and possibly the continuity of solution flow; and
- pumps for fertilizer and acid injection.

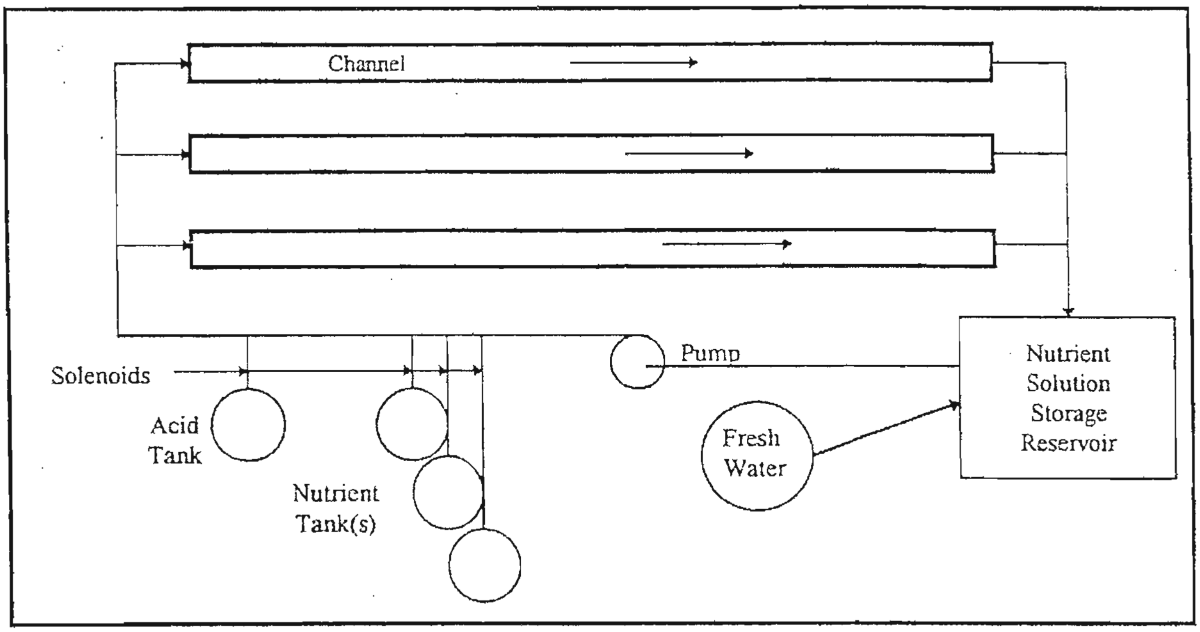

Figure 2.2 Sketch of NFT system, showing major components.

Material Selection. Many components of a NFT system may be made of plastic. Additionally, various adhesives may be used to assemble components. It is critical that no materials used within the system are phytotoxic. Plastics that have been shown to be generally safe include: polyethylene, polypropylene, ABS (acrylonitrile butadiene styrene), and rigid PVC (polyvinyl chloride). Care should be exercised if using products made from recycled plastics to avoid possible contamination from poorly controlled sources. Additionally, metals from plumbing systems (e.g., copper, and zinc from galvanized piping) can accumulate to toxic levels. It is suggested that all materials where safety has not been established be tested prior to use to assure there is no phytotoxic effect. Extended soaking of the material in a nutrient solution that is then applied to plants and shows no negative effect on plant health or growth is an indication, although not proof, that the material will be safe to use.

Storage Reservoir. The storage reservoir is usually the lowest point of the system, placed so nutrient solution will drain from the rest of the system into it. Typically this means the reservoir will be below ground. Although the reservoir need not be designed to hold all of the nutrient solution within the system, operation is likely to be simpler and the danger of environmental contamination less if such capacity is provided. The tank should be covered to exclude all light to suppress algae growth. The capability to empty the tank to waste should be provided should such a need arise.

An option is to move the reservoir to the highest point of the system (or, perhaps, add an intermediate reservoir at the high point), to drain slowly into the NFT channels. This option adds safety should a power failure disable the nutrient pumps for a time.

Tank construction may be concrete, sealed inside with an epoxy resin (non-phytotoxic) to prevent etching by the (acidic) nutrient solution. Tanks made of sheet plastic, reinforced with metal bracing, have been used. Fiberglass tanks work well for small systems. However, any tank placed below grade must be guarded against the exigency of being empty, as the presence of high groundwater could float the tank out of the ground.

A reservoir capacity of approximately 3,000 gallons per acre of growing area has been suggested (Schwarz, 1995) to contain the full volume of the nutrient solution. This is only a rough estimate, for the lengths and sizes of flow lines, desired depth of nutrient solution within the channels, and closeness of channel spacing are factors that influence the total system capacity. Capacity to contain all the recirculating nutrient solution may mean more expensive tanks, but the management is significantly simpler in case of pump failure which, with an inadequate tank size, will lead to overflow and loss of part of the solution.

Nutrient solution can be pumped directly from the storage reservoir to the inlet ends of the flow channels, or there can be an intermediate (at a high level) header tank. A header tank adds cost to the system but provides an additional margin of safety should the nutrient solution pump fail. Additionally, if supply water is plumbed directly to the header tank but with its flow closed by a submerged float valve, water will continue to reach the plants until the nutrient solution pump is repaired or replaced. Of course, with such an arrangement, an anti-siphon valve or fail-safe chamber (check valve) should be installed to prevent back flow of nutrient solution into the water supply.

Aeration. Several methods are suggested to maintain aeration within the nutrient solution. One is to use splashing of the solution, through free fall into the storage reservoir, for example. Falling over slats can increase contact time with air and improve aeration.

A venturi-type aerator can be used within a recirculating bypass around the circulating pump. The continuous aeration of part of the nutrient solution assures the solution within the storage tank will remain well-aerated. This method of aeration is very popular in NFT systems.

A third method of aeration is to pump air into the nutrient solution in the storage tank, through small holes in a pipe or through an air stone to ensure many small air bubbles are formed to enhance oxygen dissolving into the solution.

Finally, pure oxygen may be diffused into the nutrient solution through air stones to form very small bubbles to dissolve quickly. Although pure oxygen may seem at first more costly than free "air," there will not be the cost of operating an air compressor. Furthermore, carbon dioxide is not added (which can unbalance the pH) and oxygen levels up to and over saturation levels can be attained.

Flow Channels. Many techniques have been devised to fabricate flow channels. Regardless of design, the channel slope must be sufficient to assure steady nutrient solution flow from end to end. The channels can be supported above ground or rest on grade. Grading should be sufficiently accurate that no local lengthwise depressions are formed to hold water that can become anoxic. A slope between 1/50 and 1/100 is suggested. Channels are closed to limit algae growth. Individual plants are placed through holes lined along the channel cover. Channel lengths greater than 50 feet are not recommended, because poor aeration of the solution within the channels leads to nearly anoxic conditions at the exit ends due to oxygen uptake by roots along the flow path.

Simple channels may be devised from lengths of polyethylene folded and stapled around the root cubes or pots holding the plants. Polyethylene that is black on one side and white on the other is preferred; heating of the roots is limited when the white surface faces out, and the black side reduces light penetration and algae growth. However, plastic film channels must not be too tight or ethylene gas can accumulate within the channel and suppress plant growth. Today's NFT systems are more likely to rely on specially made plastic troughs having integral holes for plants or removable covers, although systems using plastic drainage pipes, rain gutters, and other forms of rigid channels have been devised.

Narrow (2 inch) capillary matting may be placed in the bottoms of flow channels to enhance the even spread of nutrient solution and somewhat improve oxygenation of the solution. Mats are particularly useful when plants are young and their root systems small. Matting materials are available from greenhouse suppliers. If plants placed in the channels are contained within small plastic pots that have integral "feet" to raise them slightly, care must be taken to assure adequate capillary contact between the mat and the bottom of the pots.

Although most NFT systems are based on fixed channels, methods have been developed based on movable channels, where movement is used to vary plant spacing during the growing cycle (for example, lettuce). Plant numbers can be increased by thirty to fifty percent for the same total growing area. This is an especially attractive management option where supplemental lighting is to be used, for close spacing when plants are small increases lighting system effectiveness. Labor costs, naturally, increase.

Circulating Pump. Recirculating pumps are typically electrically driven and must be sufficiently robust to withstand the acidic (normally pH 5.5 to 6, although below 5 can be encountered for short periods) and slightly corrosive nutrient solution (an electrical conductivity greater than 5 mS/cm may be encountered for short periods). Redundancy is critical with the pump and at least one spare should be included in the plumbing system to be activated in case the primary pump fails. Because plant death can occur in much less than an hour if the pump fails, alarms must be included in the control system. A filter ahead of the recirculating pump is necessary to capture plant debris and materials from any root cubes/pots. Pumping capacity to circulate the nutrient solution at a rate of one to two reservoir volumes per hour should be adequate to assure freshly aerated solution is in constant contact with plant roots.

Emitters. Emitters are spaced along a header pipe to distribute nutrient solution to each flow channel. Flow rates of at least several gallons per hour are required for typical channels. Emitters are easily clogged, so the nutrient solution should be filtered prior to reaching the nozzles. One system is to use a 100-mesh followed by a 200 mesh filter downstream of the recirculating pump to catch debris. Simpler systems using a header pipe with small holes located over the beginning of each channel also may be used, with flow into the header pipe controlled by a valve. Filtering is also required for this system but not to such a fine level as with emitters.

Return Flow. The return pipe is located perpendicular to the flow channels and should be covered to limit algae growth. A filter where the return flow re-enters the storage reservoir is recommended to capture plant debris, etc.

Sensors. Sensors within the nutrient flow supply stream are recommended to monitor pH, electrical conductivity, and dissolved oxygen. Temperature may also be monitored when high ambient temperatures are expected to be a frequent problem that raises root temperatures above 75°F. Additionally, a mass flow sensor to monitor for continuous flow and an alarm for pump or other flow failures is suggested.

pH control is important because of its influence on availability of nutrient salts. If pH is too low or too high, important nutrients will be less available. Excessively low pH will damage or destroy plant roots. Further, pH higher than approximately 5.8 can lead to build-up of mineral deposits on emitting nozzles if they are used (as in an NFT hydroponic system). A pH range from 5.5 to 6.0 is generally recommended for hydroponic systems.

Because an error in pH control can be devastating to root health, practical considerations suggest using three measuring elements and voting logic in the control algorithm, with alarms if one of the elements is highly disparate. Further, extreme care is required to assure the pH sensors reflect what the plant roots experience and are not affected by inadequate mixing a short distance from the acid injection location.

Electrical conductivity is a measure of nutrient solution strength — the dissolved salts in the solution. Salts may be mixed and dissolved into a stock solution that is metered into the nutrient solution, or nutrient stock solutions may be metered separately if a sensor for each important nutrient is included in the system. A carefully balanced stock solution can provide nutrients at the rates plants use them, avoiding the problem of certain elements accumulating in the nutrient solution. If such accumulation occurs, the solution must be dumped and replaced as frequently as every week.

Conductivity measurements are not specific (although they can be selective) but they do provide an indication of nutrient strength, while careful formulation of the solution provides assurance of proper nutritional balance. Conductivity measurements are accurate, repeatable and stable, and the sensors are easily interfaced with digital control methods. While conductivity sensors are temperature-sensitive, automatic temperature compensation can be incorporated.

Dissolved oxygen at a level of at least 4 ppm (mg/l) is recommended for root respiration and health. (Saturation at room temperature is approximately 8 ppm at the dissolved salts levels typical of nutrient solutions.) Oxygen can be added from ambient air by bubbling ambient air through the nutrient solution, but carbon dioxide in the air dissolving into the solution may induce pH problems within the solution, and the energy cost of compressing and pumping the air can be significant. An alternative is to use pure oxygen and meter it into the nutrient solution in a way that provides sufficiently long contact within the recirculating system piping that it becomes dissolved and does not bubble out of the solution to be lost. The amount of oxygen needed daily is small, and its cost is comparable to the energy cost of operating an air compressor.

Numerous sensors are available commercially. It is important, however, if continuous monitoring and control are implemented, to use sensors that are physically rugged and suitably stable without needing frequent calibration. If continuous monitoring and control is not used, spot measurements are suggested to identify aeration problems before the root environment becomes anoxic.

Fertilizer and Acid Injection. Automatic control equipment can continuously monitor electrical conductivity and inject stock solutions into the recirculating nutrient stream to maintain EC within the desired range. Similar equipment can inject acid (or a base) to maintain pH. Acids suitable for pH control include phosphoric, sulfuric, and nitric. A potassium hydroxide solution provides a suitable base. Equipment to inject fertilizers and acids can be found through greenhouse supply catalogs and sized by the supplier.

Care is required to assure adequate mixing of fertilizer stock solution and, especially, acid or base prior to contact with plant roots. A pH of 3.5, for example, can severely damage plant roots. Thus, a slow feed of fertilizer stock solution, and acid or base, into the nutrient storage tank is suggested, with thorough mixing within the tank. Variable-speed pumps may be used to control the rate of addition when only small adjustments are needed.

Water Quality. Anything supplied to the nutrient solution in a quantity greater than the plants take up will accumulate to excess unless the solution is periodically discharged to waste. This applies to the fertilizer and the supply water. Ground water and surface water are often of uncertain quality, and the quality can vary, for example, with seasonal changes of groundwater recharge. Additionally, water hardness can influence and subvert pH control. If a high-quality water supply cannot be assured, consideration should be given to a water purification process such as reverse osmosis (RO). RO water is significantly less expensive to produce than distilled water, and its level of purity is high. Quality must be checked frequently, of course, to assess integrity of the membrane. Other water treatment methods such as electrodialysis (de-ionization) may be considered depending on local water quality and economic circumstances. Rainwater collected from roofs and mixed with the replacement water stream has been used to improve water quality, but zinc from galvanized rain gutters or bar caps may accumulate to excess levels in a recirculating nutrient solution system. Use of galvanized pipes within the water supply and/or recirculating solution stream can lead to the same problem.

Deep Trough Systems

General. The deep trough system for plant production in closed systems is also identified as ponds, deep flow hydroponics, and raft systems. The system originated, apparently, in Japan, but was proposed independently during the 1970s in the United States and Italy. The concept is that plants float on a raft (typically a sheet of foam plastic such as polystyrene) in a shallow, rectangular tank less than one foot deep. The tank, or pond, is filled with nutrient solution, and the plant roots hang down into the solution. The nutrient solution is monitored, oxygenated, replenished, and recirculated as required (usually nearly continuously). Seedlings are placed in the floating rafts when they are approximately the size of a U.S. half dollar. Although the ponds may be supported above the ground, placement on or in the ground is simpler. However, when troughs are at grade level, work pits for humans should be located at each workplace to avoid stoop labor situations. See figure 2.3 for a view of lettuce production in a large deep trough system.

The mass of water in the troughs provides several distinct advantages. First, it provides significantly greater buffering than do other hydroponic techniques such as NFT. Changes of nutrient levels, pH, temperature, and dissolved oxygen (DO) concentration (as examples) are significantly damped. Additionally, the ponds can be used for material movement with a minimum of mechanization or physical effort. That is, plants are placed on rafts at one end of the pond and pushed a small distance each day until arriving at the other end ready for harvest or respacing. Of course, this convenience has a price. Such a continuous flow system requires that growth be consistent from day to day, which means environmental control (aerial and root) must be carefully managed. A section of rafts with lettuce that has not grown as rapidly as expected cannot be readily pushed to one side and held for several more days until size is sufficient. Instead, growers would be forced to sell the smaller heads "two-for-one".

Deep trough systems have been used commercially in several regions of the United States and abroad but are generally limited to crops such as lettuce, where growth is vegetative and the plants never grow very large (as do, for example, cucumbers and tomatoes). Lettuce has been the crop produced most commonly and commercially in deep troughs. Where summers are long and hot, the nutrient solution may require artificial cooling to prevent overheating plant roots, with subsequent damage and the likelihood of a resulting disease outbreak. However, if plant roots are maintained in a healthy state, experience has shown deep troughs can be used continuously for years without disease problems, apparently because of the healthy and complex microbial ecology that develops if the nutrient solution is maintained with DO levels at or above saturation. Fortunately, the solution is entirely covered with rafts, which suppresses oxygen loss to the atmosphere if DO levels are above saturation.

Figure 2.3. View of lettuce growing in a deep trough hydroponics system.

The basic components of a deep trough hydroponic system are:

- large, shallow ponds normally rectangular in shape and 10 to 12 inches deep;
- a means to recirculate the nutrient solution to facilitate nutrient, DO, and pH control;
- sensors to monitor nutrient solution pH, DO, EC, and water levels, and possibly the continuity of solution flow;
- pumps for fertilizer and acid (and possibly base) injection;
- metering devices for oxygen addition, or means to aerate the recirculating nutrient solution; and
- rafts, or floating panels, to support the plants above the nutrient solution, yet permit roots to be suspended in the solution.

Material Selection. The troughs can be either prefabricated or constructed in place. If constructed in place (for example, poured concrete, or concrete blocks covered with plastic sheet), care is required to assure extended operation without serious water leaks. Pond liner material (thick plastic film) can be used under the ponds to capture any leaks. Rafts are typically made of plastic foam (1 to 2 inches thick). A closed-cell foam will absorb less water and remain more buoyant, and a light color will reflect light back into the plant canopy. As with all hydroponic systems, the recirculating nutrient solution is destructive to metals, thus plastic piping is typically used. Plastic pipes have the additional advantage of not causing elements such as zinc to accumulate to toxic levels. Plastics such as polyethylene, polypropylene, ABS, and rigid PVC have been found to be safe to use with plants (phytotoxic materials are not emitted).

Deep Trough Construction. The deep trough system can be viewed as created from a series of parallel raceways, most likely to be shaped as long rectangles. The width of each trough can vary from less than 1 to more than 10 yards. The length can range up to at least 100 yards. There are no specific operating constraints that limit width or length. However, the depth is typically slightly less than 1 foot. The largest deep trough system known to the authors of this report is a single greenhouse of 7 acres producing bibb lettuce year-round in Canada.

Trough construction can range from concrete structures cast in the ground, to concrete blocks stacked two high and lined with a heavy plastic sheet, to wood-sided rectangles lined with plastic film. The first type of construction is more permanent. Furthermore, commercially available tanks can be purchased. Whatever the construction, it is recommended an underlying heavy plastic film (for example, a 20-mil thick pond liner) be placed approximately 1 foot beneath the lowest level of the troughs, with drain lines and sand fill, to capture nutrient solution in the event of a leak (inevitable in any system operated for years, as in a commercial venture). The troughs do not slope.

The troughs can be open across their widths with the rafts packed together to form a solid mass, or long guides along the length of the trough can be installed to create individual rows of rafts, guided to move from one end of the trough to the other. Either system works, although it is suggested the rafts be thicker than one inch when there are no guides to prevent rafts from possibly bobbing and riding over the tops of their neighbors.

Plant Support Rafts. Rafts to space and support plants in deep troughs are typically modular (for example, 4 feet wide and ranging from 6 inches to 2 feet in length), and it is this modularity, plus the desired daily average production rate, that dictates the width and length of the pond. Multiple ponds operating in parallel are typical. Rafts are typically made of 1-inch-thick foam plastic boards (for example, high-density, closed-cell Styrofoam used for house construction). Rafts float in the troughs and touch on all sides to suppress the algae growth that would overwhelm the system if light should reach the nutrient solution for an extended period. The rafts simplify transport, for they can be pushed as a group from one end of the trough to the other, with harvested plants removed first, the rest moved down the trough, and new plants transplanted into empty and cleaned rafts at the other end. Rafts are cleaned with a 10% (approximately) bleach solution between crops to remove algae and limit the accumulation of disease organisms.

Oxygenation. An essential difference between deep trough hydroponics and other hydroponics systems is that the nutrient solution is separated from the ambient air by the floating rafts supporting the plants. The rafts suppress convection of gaseous constituents between the atmosphere and the nutrient solution. Thus, it is more critical that mechanisms be provided to add oxygen to the solution, for oxygen cannot diffuse into the solution directly. Concomitantly, oxygen concentrations higher than saturation (in contact with ambient air) can be maintained without rapid diffusion of excess oxygen into the air. At temperatures typical of greenhouse crop production, nutrient solution in contact with pure oxygen will have a DO level above 40 ppm.

In general, oxygen may be added to the nutrient solution in two ways: by aeration and by oxygenation (adding pure oxygen). If aeration is used, the nutrient solution is either pumped from the pond and splashed through air to absorb oxygen, or air is diffused directly into the ponds, as by air stones or through pipes containing many small holes. Sufficient aeration is always of concern, and the lower yields noted when crops are grown in deep troughs may be attributed, at least in part, to inadequate oxygen in the root environment. Furthermore, as with NFT systems, carbon dioxide air dissolves to create carbonic acid, which increases pH control problems.

Pure oxygen has been found to be an economical means to oxygenate the nutrient solution in deep troughs because the oxygen concentration can be maintained at or above the saturation level with air, and the costs of operating an air compressor can be avoided. Pure oxygen is relatively inexpensive when purchased in bulk, and it supplies its own pressure to create the fine bubbles that encourage rapid diffusion into water. Commercial deep trough systems have used pure oxygen and maintained a dissolved oxygen (DO) concentration between 10 and 15 ppm (8+/- ppm is saturated in equilibrium with air). Although there is no direct evidence that concentrations above saturation provide direct benefit to the plants, they may enhance the vigor of the microorganism ecology that develops in deep troughs and, thereby, suppress disease. This is speculation at this point, based on observation of operating systems.

One variation of the deep trough system proposed to improve root zone aeration is to fabricate the rafts to create an air space between the bottoms of the rafts, and the nutrient solution. The air space is at approximately 100% relative humidity, and "aerating" roots can develop within this air space.

Plant Spacing and Respacing. Efficient use of space in deep troughs is a particularly difficult problem without extensive use of hand labor. When plants are first transplanted to the rafts, close spacing is desired to make better use of space, supplemental lighting, heating, etc. However, the projected area of plants such as lettuce increases dramatically from transplant to harvest. At least one respacing (somewhere near the midpoint of their time in the troughs) for lettuce is recommended, and two respacings may be justified, especially when supplemental lighting is used extensively. At present, respacing is by hand.

Nutrient Temperature. The roots of many commercially useful CEA crops do not tolerate high temperatures. For example, lettuce may grow well with a root temperature at 75 F, but not at 85 F. At the higher temperatures, root diseases (such as *Pythium sp.* and *Fusarium sp.*) are encouraged. Chilling of the nutrient solution provides a solution for this problem when deep trough systems are used in warm climates. The troughs can be insulated, and the rafts provide insulation from above. Because of the high salt levels of the nutrient solution, stainless steel units are recommended for designs where the solution comes into direct contract with the chiller. Chilling, oxygenation, nutrient resupply, and pH control can all be provided within the recirculation loop.

Circulation Pump. As with all hydroponics, recirculating pumps should be fabricated of materials able to withstand the corrosive environment of the nutrient solution. As a general rule, pump capacity should be sufficient that the nutrient solution is recirculated for pH and nutrients adjustments approximately once every 24 hours.

Sensors. Sensors should be placed so as to reflect the averaged conditions of nutrient solution within the troughs. Because the solution may not be circulated vigorously for other reasons, a small recirculating system that includes the sensors may be incorporated. Solution pH, electrical conductivity, and dissolved oxygen should be monitored. A water level sensor may be included, or nutrient solution may be added by hand. The mass of solution in the troughs reduces the sensitivity of the system to normal water losses through transpiration, but a sensor may be desired to alert the grower of sudden leaks. Other cautions as listed in the section above on NFT systems apply. Additionally, a dissolved oxygen concentration near or above saturation (by using pure oxygen) is suggested to maintain a robust microorganism ecology within the nutrient solution.

Soilless Culture

General. Soilless culture encompasses a wide variety of plant culture, all depending on the use of an inert material to support plant roots, and nutrient solution flooded through the medium frequently for water supply and nutrition. Inert media include gravel, sand, perlite, sawdust, rockwool, pumice, and various combinations of these materials. Today, rockwool culture is arguably the most popular soilless culture and will be the example described in this section. See figure 2.4 for a view of bell peppers growing in a soilless (rockwool) hydroponics system.

Whereas NFT and deep trough systems are most frequently used for smaller, vegetative crops such as lettuce, soilless culture has been widely applied to vining crops such as tomato, cucumber, and peppers. Soilless culture also differs from NFT and deep troughs in that it is typically an open, non-recycling hydroponics system, whereas the other two are usually closed, recirculating systems. Overwatering by 15 to 20% is common to avoid the build-up of salts. Developing environmental considerations have led to recirculating rockwool systems wherein the rockwool slabs lie in plastic, semi-rigid channels to collect excess nutrient solution for recirculation.

The basic components of a rockwool, soilless culture system are:

- rockwool granules, cubes, blocks, or slabs;
- irrigation (nutrient solution distribution) system;
- nutrient solution holding tanks;
- pumps; and
- sensors.

Rockwool. Rockwool is available commercially in either granular form or formed into shapes for efficient spacing of plants. Rockwool granules must be held within a separate container for support, which is an advantage when non-standard growing systems are designed. However, rockwool also is available in shapes ranging from small cubes to long slabs, and the forms need no additional support.

Granular rockwool may be used in trays for germinating seeds. After reaching a suitable size, the seedlings (with their root medium) are transplanted into larger rockwool units, with the trays re-used for the next crop. Rockwool blocks are available in many sizes, ranging from approximately 3-inch cubes to slabs perhaps 3 feet long, 1.5 feet wide, and 3 inches high. The rockwool units typically are formed with small holes on one face in which seeds are germinated, or larger holes into which germinated plants (plugs) are transplanted.

Rockwool slabs may be covered with a plastic film (usually white on the outside to reflect solar heat and black in the inside to retard light transmission) to limit evaporation and prevent the growth of algae. With long-season crops such as tomatoes and cucumbers the rockwool units may be discarded after each crop or may be sterilized between crops and used for several years.

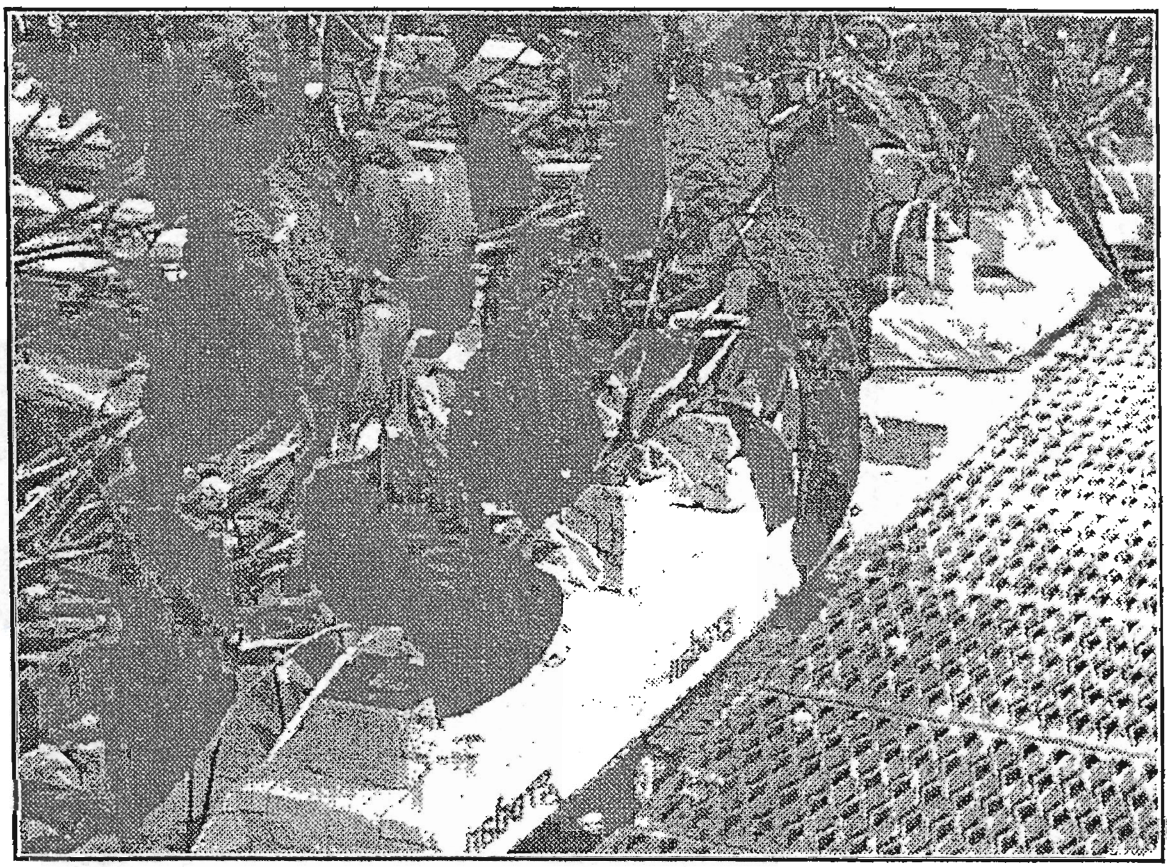

Figure 2.4. View of bell peppers growing in a soilless (rockwool) hydroponics system.

Irrigation System. The typical method of crop watering in rockwool soilless systems is through drip-line irrigation. That is, nutrient solution is fed near the base of each plant by an emitter operating with a continuous drip, or operating on a cycle that is sensitive to plant water needs. A recommendation for tomatoes, as an example, is to irrigate each fruit-producing plant once or twice each hour during daylight hours, delivering up to half a pint of solution in each cycle. Timers can be used to cycle operating irrigation lines.

Drip emitters are available commercially to provide a full-flow rate of approximately one-half gallon per hour to each plant. The emitters are placed on thin, plastic tubes connected to laterals (perhaps one-half- to three-quarter-inch plastic pipes) that are connected in turn to a header pipe perhaps 3 inches in diameter, also of plastic. These sizes must be adjusted, of course, to accommodate each physical installation. See figure 2.5 for a sketch of an irrigation systems for rockwool culture.

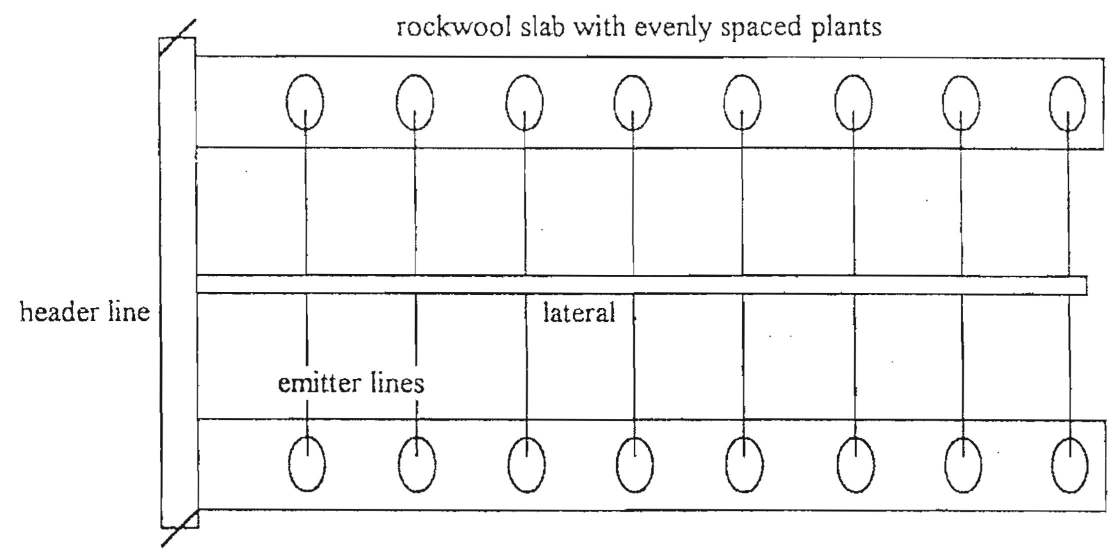

Figure 2.5. Sketch of irrigation system for soilless (rockwool) hydroponics system.

Nutrient Solution Holding Tanks. All materials must be able to withstand the corrosive nature of the nutrient solutions. Large storage volume is not necessary. A volume to provide all the solution for one following day without recharge is adequate. Typically, stock solution is held in two separate tanks, with the mixed solution held in a larger tank for recirculation. An alternative is to use injectors to mix the nutrient solution without separate stock tanks. The latter is more often seen in large hydroponic systems where computerized control of the injectors is implemented.

Pumps. As with all other hydroponic systems, pumps must be made of materials able to withstand the corrosive environment of nutrient solutions. Additionally, if each emitter is to deliver one-half gallon of solution each hour, the pump size must be adequate to supply all the emitters at the pressure drops expected. Redundancy — having a back-up pump in the event of primary pump failure — is critical for a mature tomato crop, for example, will use up the available water in its root zone very quickly on a warm, sunny day.

Sensors. Sensors for pH, EC, DO, etc., are required as for the other hydroponic systems described above. The same cautions and recommendations apply.

Site Analysis, Selection, and Resource Identification

General. CEA operations need not be located in a rural environment. In reality, access to utilities and better roads may make urban locations preferred, as long as the location is not characterized by phytotoxic air pollution. For example, air adjacent to a busy highway may exhibit high levels of ozone, which suppress plant production. Exhausts from industrial facilities, such as combustion gases, may be phytotoxic, or at least suppress plant growth.

A CEA operation is a relatively benign neighbor, as it does not discharge either aerial or water pollutants. Noise from ventilation fans and refrigeration system condensers could be a concern, as could light pollution during the night, especially during the winter. Side wall curtains can be used to limit light spilling directly onto neighboring property.

Site analysis prior to construction is important for virtually all buildings. For CEA operations there are several critical aspects of a potential site that must be considered. In addition to adequate drainage and topography considerations, access to roads for transport vehicles, accessibility of sufficient electric and (possibly) natural gas utility capacity, and protection from winter winds without shading from the sun are important. Discussions of specific items follow.

Criteria for a Potential Site. Ground slope at the site, and nearby, are important. Drainage paths away from the building site, parking areas, loading area, and access roads are required for both surface and subsurface waters. Access roads must be adequate for the largest size of transport vehicle expected to pick up the product and deliver supplies. Year-round maintenance of the access road is critical in regions where winter storms can occasionally close secondary roads. The truck loading area must be sized to allow for the largest transport vehicles to turn around. Where winter snows can be expected, the area must be large enough to accommodate snow plowed into piles after heavy storms. And, importantly, the site should be evaluated in terms of potential future expansion.

Electrical service capacity is important in evaluating a site. Access to natural gas for heating will usually be desirable if available. Electric service capacity is required equivalent to installed luminaire capacity, plus fans, refrigeration capacity, and miscellaneous needs. Lighting will frequently provide the dominant electric load, with installed capacity depending on the installed lighting PPF intensity, as listed in table 2.1.

Although a greenhouse structure can be heated by several possible fuels, the least expensive and least polluting is likely to be natural gas, making access to this fuel source an important consideration. However, if natural gas is not available, heating oil, propane, or coal can be considered. If the fuel of choice is to be coal, covered space on the site should be reserved for storing both the coal and the resulting ashes, with surface drainage diverted away from the storage area.

Table 2.1. Installed electricity capacity as a function of lighting capacity.

Installed Capacity of Supplemental Lighting, $\mu mol/m^2 s$	*Electricity Required for Lights, W/ft^2*
50	7.5
100	15
150	22.5
200	30

Good light exposure is important for a CEA facility. Nearby tall buildings and trees must be avoided. Location in a deep valley, or on a north-facing slope, will reduce available sunlight. The preferred exposure is on a south slope, or an open and level area. Additionally, a generally recognized rule is that the ridge lines of a greenhouse should be oriented east-west in latitudes above 35 degrees, and north-south below 35 degrees latitude (or east-west orientation above a line connecting North Carolina and central California).

If municipal sewage disposal is not available, the site must accommodate a septic system. In this case, sufficient land area and proper water percolation rates through the soil are required and, if not possible for the soil type available, other means such as sand-filled septic fields must be permitted under local ordinances. Septic tank capacity is typically specified under local ordinances; if not, a minimum tank capacity of 150 gallons per worker, with a minimum tank capacity of 500 gallons, is recommended.

Criteria for Electric Power Outages. The thermal time constant of a greenhouse (rapidity of air temperature change in response to a change of its environment) is only a few minutes. Thus, provisions must be made for emergency electricity generating capacity to operate at least heating systems or ventilation fans in case of electric power outages. The emergency generating capacity should be sufficient to operate the larger of the following two loads:

- The heating system with its attendant circulating pumps, fans, etc., as well as nutrient solution pumps, the computer control system, refrigeration systems for product storage, and emergency lights.

- The ventilation and air recirculation fans, as well as nutrient solution pumps, the computer control system, refrigeration systems for product storage, and emergency lights.

As a general criterion, the emergency power should be capable of providing continued operation of the entire system, without the supplemental lighting.

Criteria for Heating/Cooling Systems. The heating system for a greenhouse can be sized using the procedure described in Aldrich and Bartok, 1994. In Appendix B of this report is a copy of a suggested worksheet (from Aldrich and Bartok, 1994) that can be used to determine the design heat loss from a greenhouse structure. The worksheet requires knowledge of the thermal resistances of typical greenhouse materials, and an estimate of the air infiltration rate. Suggested data for unit area thermal conductance are in table 2.2.

Table 2.2 Thermal conductance data for various greenhouse components.

Material	*Thermal Conductance, Btuh/ft²*
Glazing: Single-layer glass	1.1[a]
Double-layer plastic film	0.7[a]
Double-layer acrylic extrusion	0.5[a]
Concrete, standard blocks, 8 inches	0.51[a]
poured 6 inches	0.75[a]
Softwood, 1 inch nominal	0.60[a]
Cellular polyurethane, 1 inch	0.17[b]
Expanded polystyrene, extruded, 1 inch	0.2[b]
Perimeter, not insulated	0.80 Btuh/ft[a]
insulated	0.40 Btuh/ft[a]

[a] **from Aldrich and Bartok (1994)**

[b] **from ASHRAE: Fundamentals (1993)**

Design air infiltration rates suggested for greenhouses are 0.75 to 1.5 air exchanges per hour for new, glass structures and 0.5 to 1.0 air exchange per hour for new, double-layer polyethylene structures. One air exchange is defined as the entire volume of the greenhouse. These values are typically used for design; they can be halved if the structure is sheltered from the wind, as by an upwind shelter belt of trees, for example.

The design temperature difference to calculate heat loss is the difference between the minimum inside air temperature and the design (97.5%) outside cold temperature. The minimum allowable inside air temperature is the night temperature, which is somewhat crop dependent. If nothing is known, a priori, regarding planned night temperature, a value of 62 °F can be assumed for design purposes. In climates where snow can be expected, the heat capacity designed using this criterion will usually suffice to melt snow as it accumulates.

Although supplemental lighting and movable curtains can be expected to reduce the demand for heating, the heating system should be designed assuming they will not operate. If there were an electric power outage, supplemental lights would not be used. Additionally, the higher heating capacity calculated by the above method assures sufficient capacity to melt snow during a storm to prevent structural collapse, in climates where such events can occur.

Water Quality Criteria. All water from natural sources contains impurities, some of which are critical for plant growth, others not. Some impurities may even be beneficial as micronutrients.

Water characteristics that may cause problems for plant production include many of the same ones that can cause problems in potable water for human consumption: pH, alkalinity, soluble salts, carbonate, hardness (calcium and magnesium), boron, chloride, sodium, sulfates, and iron.

Numerous laboratories exist that perform water analyses. When a CEA facility is first considered, the water source should be analyzed to assess its suitability. Then, on an on-going basis, routine monitoring of the water is necessary for proper plant nutrition management. The quality of water sources can drift due either to seasonal variations, or long-term changes arising from causes such as increased demands on an aquifer as it is developed. Most analytical laboratories supply plastic sample bottles for shipment, but between sampling and shipment the water sample should be refrigerated to impede microbial activity. Metal caps should be avoided, and slow leaching of contaminants such as boron can occur in glass bottles. When a sample is taken, the water system must be run for a sufficient time that pipes and pressure tank are flushed to remove any contaminants (for example, copper or zinc) that may leach from them.

Analytical laboratories frequently report results on a weight basis (ppm, parts per million; or mg/l, milligrams per liter). Plant nutritionists, in contrast, frequently view nutrient analysis on a molar basis (mMol/l, millimols per liter). To convert, divide the weight of the element (mg/l) by the element's atomic weight to obtain mMol/l. Atomic weights of macronutrients and micronutrients are in table 2.3, in addition to values for typical tap water.

Water quality is critically important in a hydroponics CEA system, even more important than when plants are grown using a solid root medium. Sudden changes of root environment are detrimental to plant growth and development, and the buffering capacity of certain components of solid root media help suppress sudden changes of pH or nutrient concentrations. Hydroponic systems have essentially no buffering beyond the storage capacity of the nutrient reservoir itself, which is often small relative to the daily need for water. This situation can lead to consideration of a reverse osmosis (RO) water system for a CEA greenhouse, particularly when production is through hydroponic systems. As water quality in many regions deteriorates, RO water units are gaining popularity.

The unit cost of producing RO water on a large scale is relatively minor. RO water is typically produced for approximately $4 per 100 gallons. For example, to use RO water to produce hydroponic lettuce can be expected to add less than a penny to the cost of each head of lettuce. This small added cost can be viewed as insurance against what might be sub-clinical, but long-term, suppression of growth and production because of marginal or poor water quality. When water quality is marginal, some growers have mixed RO and raw water in a 1:1 ratio, for example. Unfortunately, a RO unit wastes a significant fraction of the water entering it, and impurity concentrations in the wasted water may create a disposal problem.

Other sources of water often viewed as "pure", such as rainwater collected from roofs, may contain numerous contaminants deposited on the roof by air pollution. This problem can be reduced by wasting the first runoff. Additionally, a toxic level of zinc may possibly be leached from structural framing members and rain gutters.

Table 2.3. Nutrient solution macro- and micronutrients, their atomic weights, and typical concentrations in tap water (Weiler and Sailus, 1996). Elements indicated by a * are considered essential for most higher plants. Values in the table represent "typical" tap water prior to the addition of any plant fertilizers, and are not suggested as a water quality standard, or "best". Data obtained from averaged city/well/surface water sources.

Nutrient	*Atomic or Molecular Wt.*	*Typical Tap Water, ppm*	*Typical Tap Water, mMol/l*
Macronutrients			
*N, Nitrogen	14	<10	<0.7
*P, Phosphorous	31	0.3-0.9	0.01-0.03
*K, Potassium	39	<10	<0.3
*Ca, Calcium	40	<100	<2.5
*Mg, Magnesium	24	<24	<1
*S, Sulfur	32	<96	<3
Si, Silicon	28	<10	<0.4
Micronutrients			
*B, Boron	11	0-.4	0-0.04
*Fe, Iron	56	0-4	0-0.07
*Mn, Manganese	55	0.1-0.5	0.002-0.009
*Zn, Zinc	65	.06-0.12	0.001-0.002
*Cu, Copper	64	0.02-0.04	0.0003-0.0006
*Mo, Molybdenum	96	0.02-0.04	0.0002-0.0004
F, Fluoride	19	0-0.2	0-0.01
Na, Sodium	23	<30	<1.3
Al, Aluminum	27	<0.2	<0.007
*Cl, Chloride	35	<50	<1.4
HCO_3, Bicarbonate	61	<180	<3

NPDES Permit Specifications and Insurance Needs. Whether a discharge permit will be required depends, in part, on whether the CEA facility manages its nutrient solution properly. Allowing certain elements to accumulate leads to wasting nutrient solution and starting over frequently.

In addition to basic insurance for theft, liability, etc., greenhouse structures may be insured for glass damage. Such damage can be extensive in a hailstorm, for example. When film plastic glazings are used, such insurance coverage is less common because the cost of glazing replacement is lower. However, some plastics used for glazing are flammable, and fire insurance may be expensive and difficult to obtain.

Site Permitting Constraints. Constraints to siting a CEA facility vary widely from one governmental jurisdiction to another. In many rural areas, agricultural facilities are subject to relatively few constraints. Conversely, other growers have been prevented from building greenhouses because of the inability to design a greenhouse that can meet local energy codes for industrial buildings (average wall R-values, for example) and still transmit sufficient light for plant growth. An occasional problem arising with greenhouses is confusion of whether the greenhouse is an agricultural or industrial building. Greatly different codes apply in most jurisdictions.

Permitting constraints for greenhouses usually involve meeting local building codes. Discharge regulations are being increasingly imposed, as are regulations concerning traffic and noise and other aesthetic considerations when construction is in a built-up area.

Criteria to Evaluate Public Perceptions. As previously stated, the absence of odors and surface water discharges make CEA operations relatively benign neighbors. However, noise from ventilation fans make it unwise to locate a CEA greenhouse within 200 yards of human housing, or other locations where quiet is desired such as near a school or church. Additionally, supplemental lighting at night can cause significant light pollution within a few hundred yards of CEA greenhouses. Even though side wall curtains can be installed to limit light pollution through the sides of a greenhouse, light reflected up and through the roof will impair the ability of neighbors to see their night sky. Night lighting could also be objectionable if a CEA operation is located where nearby neighbors can look directly down onto the facility, as from a tall apartment building or steep hillside. The degree to which light pollution will be serious will depend, to a large extent, on the presence of nearby facilities that may also be lit at night — for example, a shopping center.

Criteria to Define Existing Organic Waste Streams. Three organic waste streams can be anticipated. One is residue left from the harvested product as it is processed and packaged. This may be roots and some leaves discarded daily, as in a CEA lettuce system. The second waste stream is culled or trimmed plant material discarded directly from the greenhouse. Such waste may include disposal of whole plants several times during the year, as in CEA tomato production. Such waste will be generally innocuous if no pesticides have been used and may be used for composting or soil incorporation, or disposed of in a landfill. The magnitude of this waste stream will be a function of the crop being produced and the method of production. For example, plant waste from a lettuce crop produced hydroponically can be expected to be approximately 1-2 ounces per head of harvested crop. Plant waste produced from other crops can be quantified after specifying the management system to be used.

The third organic waste stream will be sewage from lavatory facilities. Such a waste stream can be handled through municipal sewage lines, if available, or in a septic system designed and operated according to local ordinances.

Criteria to Determine Sewage/Waste Discharge Streams. Standard design data used to design lavatory facilities in industrial buildings can be used to determine human waste streams. Additional waste, as from showers, is unlikely, as workers should typically not be exposed to materials that will require them to shower prior to leaving work. However, because greenhouse conditions can be very hot during the summer, shower facilities for workers may be included as a morale booster.

Although the concern for environmentally sensitive areas is forcing CEA facilities not to permit runoff of nutrient-rich water or discharge of waste nutrient solution, hydroponic facilities may still be operated in a batch mode in many locations. More will be closed in the future as nutrient management becomes more sophisticated. (See the section on Nutrient Management that follows this section.)

If nutrient solution is dumped (for example, weekly to limit the possibility of root disease developing in the solution), the quantity of discharge is not large but the water is rich in elements for good plant growth. Discharge to the environment is not likely to be permitted today. Instead, a first choice is to develop agreements to use sites for disposal that constitute, in reality, re-use. Such sites include fields for farm crops, golf courses, public parks, airports, and sports parks. The discharge can be substituted for ordinary turf (or crop) fertilization during the outdoor growing season. During winter, all discharge must be stored, contracts must be developed with local municipal waste treatment facilities for discharge, or possibly the solution can be re-used in other horticultural operations such as by potted plant growers (for example, poinsettias or chrysanthemums).

Other Waste Streams. In addition to organic wastes, CEA operations can be expected to produce waste streams of office-type paper, plastics, and other miscellaneous wastes such as emptied fertilizer bags and acid bottles, inorganic root medium, cardboard boxes, discards from greenhouse system maintenance, and construction materials from renovations. If coal is used for heat, ashes will form a waste stream. If the greenhouse used for CEA production is glazed with air-inflated double polyethylene, the old polyethylene film must be disposed of every two or three years when the structure is re-glazed. Paper, cardboard, and plastics can be separated for recycling.

Magnitudes of other waste streams will depend on the crop to be grown and the growing system used (as well, of course, as the daily quantity of product). General design data do not exist to estimate magnitudes of plant waste streams without knowledge of these parameters.

Nutrition Management

Numerous references exist (see the References at the end of this report) that describe plant nutrition requirements in detail. The focus here will be on a general overview of plant nutrition for hydroponic growing systems. An advantage of hydroponics for plant nutrition management is that changes in nutrition levels can be made very quickly in response to factors such as the stage of growth, recent weather, and the onset of physiological problems with growth. Conversely, the lack of buffering within the system can lead to significant instability of control, with rapid and possibly detrimental changes of nutrition levels unless there is careful and continual monitoring and control.

Two methods of nutrient solution management are used in hydroponics. One method relies upon frequently discarding the nutrient solution (perhaps weekly). Two reasons are advanced for this practice. The first is that any disease organisms growing in the solution will be discarded before reaching a population density where plant damage will become serious. A second is that plants may not take up nutrients in the same proportion as are present in the nutrient solution, leading to excesses of certain minerals. If some minerals reach high levels of excess, they can become toxic.

On the other hand, ample evidence exists in the research environment as well as in commercial hydroponics that, at least for some crops, if fertilizers are applied in a molar ratio that approximates the ratio within the dry matter of the whole plant, uptake rates will essentially balance and there will not be accumulations of certain minerals. Furthermore, in some hydroponics systems and for some crops, disease is less of a concern. For example, in deep troughs used for lettuce production, a balanced microbial ecology appears to develop that suppresses, naturally, a population explosion of disease organisms.

It is believed that sixteen elements are essential for plant growth, including carbon, oxygen, and hydrogen. Minerals required for plant nutrition have traditionally been grouped into two categories: macronutrients and micronutrients. The difference is based on the quantity of the nutrient required for good plant growth. Micronutrients are also termed "trace elements". Elements considered for each category are listed and grouped in table 2.3.

The available hydroponics literature shows a significant diversity in nutrient solution formulations. Schwarz (1995) refers to over 300 formulas, many published for specific crops and local conditions. It is not clear that such a degree of crop-specific formulation is necessary, or even desirable, for although a formula may have been published for a specific crop, that is not evidence that another formula might not be even better. Additionally, some nutrients are brought into the plant by active transport mechanisms (as required) at specific locations on roots, thus the advantage of a specific formulation is open to question. Obviously, there is a lower threshold for each ion below which nutrient deficiencies will arise, and an upper threshold above which nutrients subject to luxury consumption may be taken in at extreme levels that could be detrimental.

Plant fertilizers are composed of a mix of salts, which are electrically conducting when dissolved into water. This characteristic leads to the use of electrical conductivity (EC) as a measure of fertilizer concentration. Conductivity is typically reported in millisiemens per centimeter (mS/cm), where a millisiemen is equivalent to a millimho. Water by itself is not pure, and the EC of the water source should be subtracted from the EC of the nutrient solution to obtain a measure of the nutrient concentration. Although each ion contributes to the EC reading, if the nutrient solution is held to a standard molar ratio of elements, the EC reading provides a useful measure of concentration. EC is monitored using any conductivity meter, but units specifically for the greenhouse industry are available from greenhouse suppliers. Such meters are useful when the two-tank, two-proportioner method of solution adjustment is used.

Ion-specific electrodes can be used within a recirculating hydroponics system to adjust specific elements. Such electrodes are available for a number of plant nutrients, including ammonium, calcium, chloride, dissolved oxygen, fluoride, nitrate, potassium, and sodium.

Hydroponic solutions are typically formulated as stock solutions which are then mixed with fresh water using a fertilizer proportioner system (commercially available from greenhouse supply companies) as needed. A typical dilution rate is 1:100. Stock solutions are made of individual soluble chemicals, or from a commercially available blend of chemicals balanced to provide a desirable molar ratio of elements. Warm (150 °F) water is recommended to speed dissolving. However, higher concentrations (such as 1:200) may lead to difficulties with dissolving, and precipitates may form when the water cools. Precipitation incompatibilities include:

- sulfates in the same tank as calcium (calcium sulfate precipitates)
- phosphates in the same tank as calcium (calcium phosphate precipitates)
- phosphates in the same tank as iron (iron phosphates precipitate)
- potassium bicarbonate in the same tank with other fertilizers (raises pH so high that other fertilizers may precipitate)

A two-tank, two-injector head plant nutrition system is often used to avoid problems such as those listed above. More sophisticated systems use more tanks and injector heads to control each nutrient source. However, it must be noted that elements are not added individually, making the problem of achieving a desired mix a somewhat subtle problem, and an exact formulation may not be possible. For example, potassium may be obtained by adding potassium nitrate, and calcium obtained by adding calcium nitrate. Each contributes nitrate nitrogen, probably not in the precise molar ratio that a preliminary formulation may have specified. However, as stated above, exact formulations are not critical because plants generally do well over a concentration range for each nutrient. This is not to suggest, however, that a formulation should be treated casually, for if it is missed by a significant margin and the nutrient solution is not discarded periodically, certain nutrients may accumulate to a undesirable, unbalanced level. Computer programs have been developed suitable for balancing a nutrient mix to achieve a close approximation to a desired molar ratio of elements.

pH Management

The management of nutrient solution pH is important for two reasons. First, pH levels too far from neutral (e.g., 3.0, very acidic) can cause physical damage to roots. Secondly, the pH can affect availability of nutrients in the solution. A great deal is understood regarding nutrient availability as a function of pH in various soils. Additionally, several theories exist regarding the mechanisms of ion transport across active membranes at the root surface. The theories are based on the balance between electric potential difference and chemical potential difference across the membranes. The pH of the nutrient solution apparently interacts with these potentials to affect the degree to which each nutrient is available for uptake. Recommended nutrient solution pH ranges for several potentially important CEA crops are in table 2.4.

Table 2.4. Recommended nutrient solution pH ranges for hydroponic culture of selected CEA crops. (From Schwarz, 1995.)

Crop	*pH Range*
Cucumber	5.5-6.5
Lettuce	5.5-6.0
Pepper	5.5-6.5
Spinach	6.0-6.5
Strawberry	5.5-6.5
Tomato	5.5-6.5

Acids and bases can be used to adjust nutrient solution pH. The more typical adjustment is to add acid to reduce pH, for the greatest uptake of nutrients from the solution involves anions (such as NO_3^-), which results in the release of a hydroxyl ion (OH^-) from the root to maintain electrical neutrality. Excessive acid or base for a short time near a root will cause severe tissue damage. Thus, acids and bases must be metered carefully and thoroughly mixed with the nutrient solution prior to being passed by the plant roots. The type of acid that is used will influence the concentration of certain elements in the nutrient solution. That is, nitric acid affects the nitrogen concentration, sulfuric the sulfur concentration, etc., which will require adjusting the solution formulation.

Dissolved Oxygen Management

Dissolved oxygen (DO) monitoring and control is particularly important in hydroponic plant-growing systems. Root health depends heavily on adequate access to oxygen, as does a healthy microbial ecology of the correct (aerobic) type. The amount of oxygen that can dissolve into water depends on water temperature, with more dissolved at lower temperatures. At the temperatures typical of CEA facilities, the oxygen saturation concentration is between 8 and 8.5 ppm. Dissolved oxygen sensors are available to monitor the oxygen level on a continuous or intermittent basis.

Nutrient solutions can be oxygenated by providing good contact with air over an extended water surface (as by bubbling air through the solution, or letting the solution fall several feet through air at some point in the system). Another method is to diffuse pure oxygen into the solution. Oxygen can be diffused readily into water by using air stones or a network of pipes having small holes drilled into their walls. Because pure oxygen has a concentration roughly five times the concentration in air, pure oxygen can raise the DO level in a nutrient solution approximately five times above the saturation level for air. Such a high DO level is not generally required for root health, however. Although pure oxygen is an added cost of production, its use eliminates the need for compressing air, which can require a significant input of electricity.

Furthermore, when a nutrient solution is aerated rather than oxygenated, carbon dioxide in air dissolves to produce carbonic acid (H_2CO_3), which compromises the ability to control nutrient solution pH.

Root Disease Management

General. As environmental regulations increasingly focus on agriculture and Controlled Environment Agriculture, closed systems for CEA are becoming the norm and may be required in virtually all new CEA facilities before long. Within a closed system, and if a proper balance of nutrients is added, the nutrient solution continues to recirculate indefinitely. Water and nutrients are added to the reserve capacity, and transpiration and harvested product are the removal mechanism. Some concern arises related to the possible development and spread of root diseases. The spread is particularly worrisome because the nutrient solution is typically recirculated within the entire system. Isolation of sections to restrict the spread of disease is possible, but isolation is not normally the practice. While experience has not shown the problem to be as worrisome as first anticipated, occasional outbreaks of disease are of concern and lead to potential involvement of the electric utility industry through application of high-tech water disinfection methods.

Proven methods of disinfecting nutrient solutions include: heat treatment, ozonation, uv irradiation, sand filters, and iodation. Disinfection cannot be total, but the goal is a high rate of organism removal. A goal expressed in the Netherlands is 99.9% kill of water-borne bacteria and fungi to limit the pressure of infection. A quick review of each method that has been proven in CEA follows. A newer disinfection method using hydrogen peroxide is currently in the research and development stage in Europe. Even though hydrogen peroxide is not as strong an oxidant as ozone, it has been shown to be effective against water-borne fungi and is more environmentally friendly than ozone. pH adjustment after treatment is necessary, however, for its use lowers the pH significantly.

Heat Treatment. Heat treatment has been used for the past decade in Europe. The solution is first filtered (50 to 70 micron filter) and acidified to a pH of approximately 4.0 to 4.5 to limit the precipitation of salts during heating. Heat recovery is used to preheat the entering solution, after which the solution is heated to 200 °F for at least 30 seconds. Equipment for such treatment is available commercially in sizes ranging from 450 to nearly 3,000 gallons per hour. Heating is by natural gas, normally, and a heating capacity of approximately 300 Btu/hr is required for each gpm of flow capacity.

Ozonation. Ozone is a very strong oxidizing agent that is commonly used for water treatment or effluent treatment (as from a waste treatment plant). After filtering (50 to 70 micron filter) and adjusting the pH to 4.0 to 4.5, the recirculating solution is treated for one hour by injecting one-half ounce of ozone for every 1,000 gallons. Commercial ozonation units are available in sizes from 350 to over 1,000 gallons per hour.

uv Irradiation. Ultraviolet radiation with wavelengths between 200 and 280 nm (uv-C band) is highly lethal to microorganisms. As with the other disinfection methods, the recirculating nutrient solution must first be filtered (50 to 70 micron filter). The required dose rate depends on the organism to be destroyed and the clarity of the water. It is suggested manufacturers be consulted regarding specific installations to develop the best design for each situation. Dosing rates up to 250 mJ cm^{-2} are required to destroy viruses.

Sand Filtration. Sand filtration is preferred over Reverse Osmosis (RO) filtration because RO systems remove fertilizer salts from the water as well as particles and microorganisms. Slow sand filters have shown some benefit against certain organisms, but not all. Their use is still in the research stage in Europe.

Iodation. Iodine is used to treat drinking water to eliminate viruses. It is also used at low concentrations in cooling towers, for example, to eliminate the various microorganisms that grow in such continuously wet conditions. Iodine has been shown to be effective at eliminating fungi at a concentration of 0.7 ppm for 8 to 10 minutes. Viruses require much higher levels but are not the typical root disease organism. Iodine can then be removed from the solution by a charcoal filter. However, some micronutrients may also be removed by charcoal filters, so the solution must be rebalanced after treatment.

Table 2.5 (adopted from van Meggelen-Laagland, 1996)[1] summarizes the options and anticipated efficacies.

Table 2.5. Summary of options to disinfect hydroponic solutions and estimates of efficacies.

Option to Disinfect Nutrient Solution	*Eliminate Viruses*	*Eliminate Bacteria and Fungi*	*Eliminate Nematodes*
1. Heat treat at 200 °F for 30 seconds	Yes	Yes	Yes
2. Ozonation for one hour	Yes	Yes	Yes
3. uv radiation at 250 mJ cm^{-2}	Yes	Yes	Yes
4. Hydrogen peroxide at 400 ppm	Yes	Yes	Yes
5. uv radiation at 100 mJ cm^{-2}	No	Yes	Yes
6. Iodine treatment at 0.8 ppm	No	Yes	Yes
7. Slow sand filtration	No	Yes	Yes

[1] van Meggelen-Laagland, I., 1996. High-tech ways to sterilize irrigation water. Grower Talks 60(3):114-123.

3. Opportunities for CEA Development and Research Needs

General

Research opportunities can be grouped into four categories: systems, processes, equipment, and controls. This section will consider all four categories. As a background perspective, an economic and operating analysis example of a CEA lettuce production facility is presented first. The example is based on a module to be constructed during 1996/97 at Cornell University as a demonstration of a commercial unit designed to be cloned throughout the Northeast and adaptable to many other localities. The lettuce production systems is based on the Deep Trough technique.

It should be noted that many topics related to CEA are not yet completely defined and understood. However, the research opportunities identified below have been selected to represent problems related to the use of electricity within CEA production facilities.

Example Costs and Operating Parameters of a Hydroponic Lettuce Production CEA Module

The baseline assumption for this example is that two people will operate the unit and produce 1,000 heads of lettuce every day of the week so as to be able to provide fresh product to the market every day. The two persons are likely to be a family unit, but that is not necessary. Although work is required every day of the week, the embedded assumption is that the two persons, working together, can complete all tasks within six hours. They may choose to operate this way every day, or they may each take off one or two days each week, with the other person working eight (or possibly more) hours on those days. Tasks that can be completed ahead of time (such as: washing lettuce transport rafts, seeding plug trays, general maintenance, and clean-up) can be scheduled for days when the two persons work together, making it possible for one person to complete the necessary tasks of transplanting, respacing, harvesting, etc., in an eight-hour day. Many small business owners work far more than forty hours each week, and the two persons operating this module may choose to do the same to gain higher productivity and greater income.

The module is assumed to operate within a vertically integrated larger unit, wherein a vertical integrator provides the marketing and supplies, freeing the two persons to specialize in the fine details of consistent production of lettuce having the highest quality. Labor is not included as a cost because the two workers are assumed to be the owners and thus receive all net proceeds as personal income, as is the case in most small businesses.

Costs are based on 1996 prices of greenhouse equipment and construction charges in central New York State. A daily goal of 17 mol of integrated Photosynthetic Photon Flux (PPF) per square meter is assumed, with electricity prices (usage and demand charges) representative of the utility serving that region. Secondary voltage of 120 to 480 volts is assumed to be delivered.

Greenhouse areas are:

• Gross greenhouse area:	8,232 ft^2
• Net production area (pond area):	6,279 ft^2
• Nursery area:	177 ft^2
• Work area:	2,400 ft^2

Lettuce production data are:

- First ten days in growth chamber
- Number heads of #1 bibb lettuce produced per year: 360,000
- First greenhouse production spacing, at 10 days: 21 in^2/plant
- Second greenhouse production spacing at 14 days: 42 in^2/plant

Other data are:

- Peak power kWh charge: $0.087
- Off-peak power kWh charge: $0.0561
- Demand charge per kWh: $11.37
- Cost of capital: 7.50%
- Straight-line depreciation over 10 years

Greenhouse cost elements and estimated values (U.S. dollars) are shown in tables 3.1 and 3.2.

Based on these data, the break-even cost for the first year is $0.361 per head of #1 bibb lettuce. Based on current retail market price, a wholesale value greater than $0.50 per head can be anticipated, leading to a net income of at least $0.14 per head, or at least $50,000 yearly net income for the two persons operating the module. Of course, as the investment is paid off, the return improves in this simplified analysis as less debt remains to be serviced. Furthermore, a better position to limit taxes is not considered.

The return on investment (ROI) is at least 12.5%, based on the assumptions listed above. This analysis has focused on lettuce production in a deep trough system and should not be extrapolated to other growing systems for lettuce or other crops. However, economic analysis data applied to other systems is sparse, and what has been presented here are data from one of the more complete CEA analyses available. Anecdotal evidence suggests that a properly designed and operated CEA system scaled to permit owner/operator management can be profitable.

Table 3.1. Example CEA module, capital costs.

Element	*Total Cost*	*$/ft² of Greenhouse*	*% of Total Investment*
Land and site preparation	$17,500	2.13	4.24
Site preparation hookups	7,000	0.85	1.73
Structures			
Greenhouse	100,000	12.15	24.78
Head house	40,000	4.86	9.91
Cooler	12,000	1.46	2.97
Construction	28,000	3.40	6.94
(Total Site & Structures)	(204,500)	(21.87)	(44.60)
Systems			
Ponds	35,000	4.25	8.67
Carbon dioxide	9,000	1.09	2.23
Lighting	58,000	7.05	14.37
Power distribution	29,000	3.52	7.19
Boiler system	40,000	4.86	9.91
Material handling	1,000	0.12	0.24
Control/monitoring	12,000	1.46	2.97
Floaters (rafts)	7,000	0.85	1.73
Seeder	3,000	0.36	0.74
Pond heater	2,000	0.24	0.50
Backup generator	3,000	0.36	0.74
(Total Systems)	(199,000)	(24.16)	(49.29)
Total Capital	**$403,500**	**$49.01**	**100**

Opportunities for Research Related to Systems

Many CEA systems exist today. The opportunities for research may be greater, however, in making current systems more workable and profitable rather than in developing entirely new systems.

A subject of great importance to the future growth of the CEA industry, and that relates to the total system, is the influence of the local utility rate structure on operating costs. For example, where weather is usually warm and sunny, ventilation is used extensively and fans operate mostly during on-peak hours. Conversely, where the climate is cold and dark, the major need for electricity is for supplemental lighting, much of which can be accomplished off-peak. Additionally, CEA facilities can usually be operated as interruptable loads, and the loads do not show sharp, unexpected peaks. These factors suggest the usefulness of a thorough study to evaluate interactions of local climate, CEA systems (including the crops to be grown), and rate structure. Such a study could provide recommendations of rate structures conducive to CEA development and recommendations for situations to avoid.

Table 3.2. Example CEA operation, operating costs.

Element	*Total Cost*	*$/ft² of Greenhouse*	*% Annual Operating Cost*
Fixed Expenses			
Depreciation, Structures	$20,450	$2.48	15.74
Systems	19,900	2.42	15.32
Cost of Capital	30,263	3.68	23.30
(Total Fixed Expenses)	(70,613)	(8.58)	(54.36)
Controllable Expenses			
Pond power/peak	9,100	1.11	7.01
/ off-peak	15,800	1.92	12.16
Nursery power/peak	1,850	0.22	1.42
/ off-peak	1,250	0.15	0.96
Other power/peak	1,250	0.15	0.96
/ off-peak	1,400	0.17	1.08
Pond demand charge	19,000	2.31	14.63
Nursery demand charge	725	0.09	0.56
Other demand charge	950	0.12	0.73
(Total Controllable Expenses)	(51,325)	(6.24)	(39.51)
Direct Crop Expenses			
Nursery/media	1,250	0.15	0.96
Seed	1,050	0.13	0.81
Packing material	3,900	0.47	3.00
CO_2	1,750	0.21	1.35
(Total Crop Expenses)	(7,950)	(0.96)	(6.12)
Total Annual Expenses	**$129,888**	**$15.78**	**100**

Economic analyses of CEA operations are limited. This is a developing industry, and the past has been marked by numerous failures of systems improperly designed and operated. Numerous examples exist of small operations that are profitable, and a few large systems are profitable. However, data from these private operations are not available. Thus, a second "systems" study would be to develop a matrix useful to analyze CEA operations in a more general sense. The work could result in a spreadsheet or other computerized means for local utilities to work with potential customers to design (financially) the best operation to suit local conditions.

Deregulation within the electric utility industry is close. Furthermore, co-generation to provide electricity and heat is growing more sophisticated and acceptable. These factors suggest the usefulness of a study to evaluate where co-generation may be attractive to a CEA operation, and where it may not be. This sort of study parallels, in some ways, the study suggested above to evaluate how electricity rate structures and CEA operations mesh.

Opportunities for Research Related to Processes

Water quality and disease control in recirculating hydroponic systems continues to be a significant concern and of great importance in the developing CEA industry. Research in this area can move in at least two directions important to the electric utility industry. One is to explore new methods of killing disease organisms in hydroponic solutions without affecting nutrient concentrations in the solution. Another is to complete a definitive study to evaluate the various water disinfection methods as they apply to the different CEA systems: NFT, deep trough, soilless culture, etc.

Interest continues in joining CEA with recirculating aquaculture systems. However, the dynamics of joining the two systems remain largely unexplored from the viewpoint of potential benefits to the plants. Dynamics of interest include:

- matching the rate at which fish waste is produced to the rate plants can use it;
- plant responses to temporally varying fertility levels, as might exist in a batch mode of operation, wherein fish waste is introduced into the nutrient solution, but then time is permitted for the plants to draw the various elements down to concentrations that allow the water to be recirculated safely back to the aquaculture unit;
- transformation rates (and the best processes) necessary to convert nitrogen in the ammonia form in fish waste to the nitrate form best utilized by plants;
- rates of acid addition required to adjust fish wastes to the desirable pH for hydroponic systems. The dynamics as a function of fish feed quality and plant type are required for a complete evaluation of combining the two systems; and
- microbial population dynamics, especially those microbes that are potential disease-causing agents for both plants and fish.

Opportunities for Research Related to Equipment

A major equipment component of a modern CEA facility will be luminaires for supplemental plant lighting. This is also the component providing the greatest electricity load and, as shown in table 3.2, electricity is nearly 40% of the annual operating expenses in a cold and cloudy climate. Therefore, a major research opportunity exists to improve plant lighting system design and control.

In the near term, it is unlikely that new lighting methods for CEA crops will be devised. The current standard is High-Pressure Sodium (HPS) luminaires to supplement sunlight. The HPS spectrum is adequate, when mixed with natural light, for quality plant growth. Although Low-

Pressure Sodium (LPS) lighting systems have been available for a number of years, the spectrum from LPS lamps has not been shown to provide a light spectrum adequate for quality plant production. Electrodeless lamps, such as the microwave-powered light system developed by Fusion Lighting Technologies, Inc.[1] , can provide excellent spectra for plants, but the current cost is prohibitive.

Although new lighting systems may not be of immediate interest, the design of lighting systems using current technologies is an area where fruitful work can be accomplished. The design of such systems should focus primarily on the luminaire to achieve a compatability with lighting system designs that promotes the uniformity of PPF, the photosynthetic energy used by plants.

PPF uniformity is critical if quality, size, and timing are to be achieved in a CEA operation. Whereas the human eye responds logarithmically to light and thus does not notice a difference of illumination unless there is nearly a 2:1 difference, plants respond linearly to PPF. That is, if one plant receives 10% more PPF than another, its growth will be 10% faster, at least during the vegetative stage. Perfect uniformity cannot be achieved, but currently suggested standards for plant lighting (Dietzer, et al., 1994) propose that greenhouse lighting uniformity within 15% of the spacial mean (measured at plant canopy height) should be the goal.

Various computer programs (proprietary) are available to design lighting systems. Luminaire manufacturers offer their own services, and architectural programs (such as Lumen Micro[2]) can be purchased. The difficulty in using lighting design programs is the lack of data files, in IES (Illumination Engineering Society) format, that describe luminaire output in the photosynthetically active part of the radiation spectrum (400 to 700 nm). Additionally, luminaire efficacy data are not easily obtained. The opportunity exists to fund an organization to provide on-going testing of plant-lighting luminaires, with the results published as data files in electronic form in IES format available to be distributed to designers of greenhouse lighting systems (and growth chambers, growth rooms, etc.). Such a project would be analogous to the funding of the Bioclimatic Laboratory at the University of Illinois to conduct fan efficiency testing.

Opportunities for Research Related to Control

For many years, the environmental parameter to be controlled in greenhouses has been air temperature. Based on this interest, numerous commercially available, computer-based environmental control systems are available to growers. The range of sophistication (and thereby price) is large. Such systems generally are sold as package units, to include sensors, leads, processors, and output devices. However, control of parameters other than air temperature are at a primitive level. Yet, other parameters, such as light, are as important as the temperature environment.

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[1] Fusion Lighting Technologies, Inc., Rockville, MD.

[2] Lighting Technologies, Inc. , Boulder, CO.

An opportunity exists to improve, significantly, the control of supplemental lighting for plant growth. Control by time of day, or current PPF level, is not difficult. However, plants in their vegetative stages have been shown to grow in proportion to the integrated light they receive. Further, if CEA is to imply control of the plant environment, light should be controlled as surely as is temperature. A very useful development for the CEA industry would be research that identifies one or more control strategies for achieving a consistent PPF integral each day. Strategies should be sensitive to local climate, time of year, crop demands, availability of off-peak power, and perhaps other factors.

Although a growing body of literature exists related to nutrient management in hydroponics systems, work remains to achieve a standardized method for each of the plant growing systems. This work should extend beyond control of injector pumps, which has been a major focus of prior research. Matching of recirculation rates with total systems, and then with fertilizer, acid/base, and oxygen is required for optimal system management.

4. Species Status Reports

Introduction

Many crops have been raised in greenhouses, especially in other parts of the world. The fifteen crops listed below are suggested as suitable for CEA production in the United States. Some of the crops are familiar to the general public. Others will appeal only to niche markets. Vegetables, fruits, and herbs are included for variety, and their CEA potential. Floral crops are also suitable for CEA production but are omitted here because of their long history of greenhouse production and the large body of knowledge available on their requirements and market potentials.

- Arugula
- Basil
- Cilantro
- Cornsalad
- Cucumber
- Endive and Escarole
- Lettuce
- Melon
- Pak-choi
- Pepper
- Raspberry
- Spinach
- Strawberry
- Tomato
- Watercress

Within each species, the following criteria are noted:

- General description
- Common types and cultivars
- Environmental requirements
- Typical production methods
- Production and growth rates
- Human nutrients provided
- Fresh market potential
- U.S. sources and amounts
- Imported sources and amounts
- Diseases and pests
- Physiological concerns

- Postharvest concerns
- Opportunities for CEA
- Challenges for CEA

Definition of Environmental Requirement terms

The following table defines terminology used in the species status reports:

Table 4.1. Terminology for environmental requirements.

Environmental Requirements	*Range*
Temperature: High	75-80 F day, 65-70 F night
Temperature: Intermediate	70-75 F day, 60-65 F night
Temperature: Low	65-70 F day, 55-60 F night
Carbon Dioxide: High	1000 ppm
Carbon Dioxide: Intermediate	600 ppm
Carbon Dioxide: Low	ambient (350 ppm)
Relative humidity: High	70-90%
Relative humidity: Intermediate	50-75%
Relative humidity: Low	30-50%
Lighting: High	> 20 mol/m2-day
Lighting: Intermediate	15-20 mol/m2-day
Lighting: Low	10-15 mol/m2-day

Notes Regarding Production Data

Although the U.S. Department of Agriculture gathers statistics regarding many crops grown in and imported into the United States, their focus is on crops with greatest economic importance. Limited data exist for many minor crops, such as specialty crops grown in a limited way in greenhouses. Production and importation data in the species reports that follow have been obtained from various governmental sources and may not differentiate between field-grown and greenhouse crops. For the most part, data are reported in hundredweight (**cwt.**).

Notes Regarding Human Nutrient Data and Cultivars

Other data, such as for human nutrients provided by each crop, have typically been obtained from crops grown outdoors. It is not clear that CEA crops will have identical nutritional value. While there will be equivalencies, opportunities exist to manipulate the (human) nutritional content of vegetables through manipulation of crop environment and nutrition. Further, field-grown crops have been subjected to various stresses that will not exist in a well-operated CEA facility, stresses that undoubtedly lead to differences in taste and nutrition between crops grown in the two methods. Finally, if CEA production expands with many of the lesser crops, plant breeding to obtain better cultivars will be more attractive to seed companies.

Arugula

(Eruca vesicaria)

Description

A small salad green with a sharp, peppery, tangy flavor. Because of its pungency, arugula is usually added to salads in small quantities. It is also called *rocket salad, rucola,* or *roquette.*

Common types and cultivars[1]

French Arugula, Italian Wild Rustic Arugula

Environmental requirements

- *Temperature:* the highest-quality arugula (i.e., the least bitter) is grown in low temperatures
- CO_2: high
- *Relative humidity (RH):* intermediate
- *Lighting:* high

Typical production methods

Outdoors, greenhouse, hydroponics

Production/growth rates[2]

Approximately 40 days from seed to harvest.

Human nutrients provided[2]

High in vitamin C – 20 mg per one-cup serving.

Fresh market potential

This crop is increasing in popularity. It is a common component of mesclun (mixed salad greens).

U.S. sources and amounts

Data not available.

Imported sources and amounts

Data not available.

Diseases and pests

Rarely a problem with arugula.

Physiological concerns

Bolts and becomes increasingly bitter with increasing temperature.

Postharvest concerns

Perishable. Store at 32–36°F and 90–98% relative humidity.

Opportunities for CEA

Requires little space. Year-round production possible. Environmental control permits consistent production rates and quality, including prevention of bolting and bitterness. Local production reduces quality loss during shipping.

Challenges for CEA

Establish a market for product. Develop a CEA production system that optimizes production and quality. Determine best cultivars for CEA.

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1 Cultivars suitable for CEA production need to be determined.

2 For field-grown arugula.

Basil

(Ocimum basilicum)

Description

Basil is an aromatic herb that has a warm, spicy smell and flavor. It is used most often in Mediterranean cooking and is the main component of pesto.

Common types and cultivars[1]

- *Italian basils:* Basil Genova Profumatissima, Basil Napoletano
- *Purple basils:* Dark Opal, Purple Ruffles, Red Rubin Purple Leaf
- *Bush basils:* Fino Verde Compatto, Spicy Globe
- *Thai basils:* Maenglak Thai Lemon Basil, True Thai Basil

Environmental requirements

- *Temperature:* intermediate
- CO_2: intermediate
- *Relative humidity (RH):* intermediate
- *Lighting:* high

Typical production methods

Outdoors, greenhouse, hydroponics (in rockwool, NFT, peat, and perlite)

Production/growth rates[2]

60–75 days from seed to harvest. Monthly production rates can be near 1 lb/ft^2.

Human nutrients provided[2]

Per 1-ounce portion: 0.9 g protein; 0.3 g fat; 2 g carbohydrates; 91 mg Ca; 0.6 mg Fe; 12,380 IU vitamin A; 8 mg vitamin C

Fresh market potential

Data not available. Much field production is dried or distilled for oils.

[1] Cultivars suitable for CEA production not yet determined. Basil Genova Profumatissima has been shown to do well in hydroponics.

[2] For field-grown basil.

U.S. sources and amounts

Data not available. Fresh basil is usually locally grown.

Imported sources and amounts
(in cwt, for 1991)[3]

1. Mexico–14,006
2. Israel–905

Diseases and pests

- *Diseases:* damping off, downy mildew, pythium
- *Pests:* aphids, spider mites, whiteflies

Physiological concerns

Plants need support and pinching for continuous production.

Postharvest concerns

Needs cool, dark storage at 55-60°F and 85–95% relative humidity.

Opportunities for CEA

Basil is sensitive to cold periods, so it is well-suited to CEA. Greenhouse-grown basil tends to be more tender and flavorful than field-grown. Niche markets exist for fresh basil, especially near larger cities and ethnic communities. Fresh basil is in large demand for restaurants.

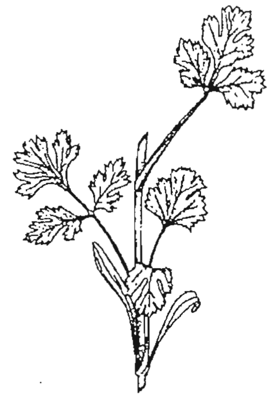
Challenges for CEA

Market development. Developing production system to assure efficiency and quality.

[3] Does not include imports from Canada.

Cilantro

(Coriandrum sativum)



Description

The feathery leaves of this herb have a pungent, citrusy flavor. Cilantro is used most often in Indian, Mexican, and Spanish cuisine; it is a common component of salsas and chutneys. The herb is also referred to as *coriander* or *Chinese parsley*.

Common types and cultivars

Cultivars of cilantro have not yet been developed.

Environmental requirements

- *Temperature:* intermediate
- *CO_2:* high
- *Relative humidity (RH):* intermediate
- *Lighting:* high

Typical production methods

Outdoors, greenhouse

Production/growth rates[1]

About 65 days from seed to first harvest.

Human nutrients provided[1]

For fresh leaves (quantities in %): moisture, 86–88; protein, 3.3; fat, 0.6; carbohydrates, 6.5; phosphorus, 0.06; iron, 0.02; vitamin A, 10,460 IU/100g; niacin (mg %), 0.8; vitamin B2 (mg %), 60; vitamin C (mg %), 150–200

Fresh market potential

Data not available.

U.S. sources and amounts

Data not available. Fresh cilantro is usually locally grown.

Imported sources and amounts (in cwt, for 1991)[2]

1. Mexico–151,324
2. Trinidad–3,853
3. Dominican Republic–3,075
4. Costa Rica–1,976

Diseases and pests

- *Diseases:* damping off, pythium, powdery mildew
- *Pests:* aphids, whiteflies

Physiological concerns

Bolts in very warm temperatures.

Postharvest concerns

Leaves lose fragrance and flavor upon drying—best if fresh. Store at 32–36°F and 90–98% relative humidity.

Opportunities for CEA

A niche market exists for fresh cilantro, especially near large cities. Cilantro is widely used in restaurants. Environmental control possible with CEA can prevent bolting and allow optimal conditions throughout the year.

Challenges for CEA

Market development. Designing an optimal system to produce cilantro in CEA conditions.

[1] For field-grown cilantro.

[2] Does not include imports from Canada.

Cornsalad

(Valerianella locusta)

Description

A delicate leafy green cultivated largely in France and Italy. It is a common component of mesclun (mixed salad greens). Cornsalad is also know as *mâche* or *lamb's lettuce.*

Common types and cultivars[1]

Coquille, D'Etemps, Elan, Gayla, Piedmont, Vit

Environmental requirements

- *Temperature:* low to intermediate
- *CO_2:* high
- *Relative humidity (RH):* intermediate
- *Lighting:* high

Typical production methods

Outdoors, greenhouse, hydroponics (in rockwool and NFT).

Production/growth rates

Requires approximately 40–60 days from seed to harvest under greenhouse conditions

Human nutrients provided[2]

Per 100-gram portion: 2 g protein, 3.6 g carbohydrate, 0.8 g fiber; also a source of vitamin C

Fresh market potential

This crop, currently very popular in Europe, is increasing in popularity in the United States.

U.S. sources and amounts

Data not available.

Imported sources and amounts

The U.S. imported 75 cwt from France in 1991.

Diseases and pests

Rare with cornsalad.

Physiological concerns

None documented — very easy to grow.

Postharvest concerns[3]

Perishable. Store at 32°F (0°C) and 95–100% humidity.

Opportunities for CEA

Very compact plant — requires little space. Can be sown successively for continuous production. Niche markets near larger cities, at least intitially. Control achievable using CEA leads to the high quality that can help when establishing market channels. Clean product.

Challenges for CEA

Market development. Developing an efficient production system to guarantee consistent quality and quantity.

1 Cultivars suitable for CEA production not yet determined.
2 For field-grown cornsalad.

3 Based on storage conditions for similar leafy greens.

Cucumber

(Cucumis sativus)

Description

The most common type of cucumber in U.S. markets is a relatively short, fat fruit with a "warty" skin. Less common is the European long type, which is seedless, has smooth, tender skin, and can grow to about 12 to 15 inches. The latter type is proposed for CEA.

Common types and cultivars[1]

Ariston, Atlanta, Bambina, Cargo, Corona, Discover, Falko, Famosa, Farbio, Farbiola, Farona, Forotu, Fytos, Grandiosa, Marillo, Millagon, Nordica, Primera, Salvador, Sortena, Sound, Stereo, Titleist, Vitalis

Environmental requirements

- *Temperature:* high
- CO_2: high
- *Relative humidity (RH):* high
- *Lighting:* high

Typical production methods

Outdoors; significant greenhouse production; grown hydroponically in NFT, rockwool, sand, perlite, and other soilless substrates.

Production/growth rates

60 days from seed to first harvest; greenhouse yield at least 10 lbs/ft^2/year.

Human nutrients provided[2]

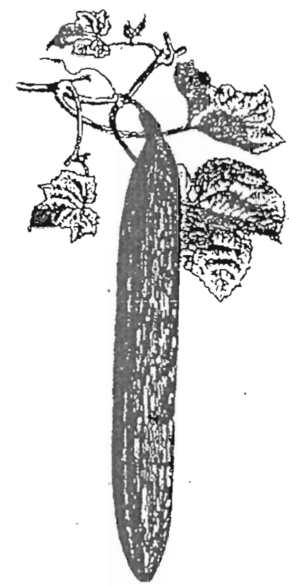
Per 100-gram portion: 0.5 g protein, 2.9 g carbohydrate, 0.6 g fiber, 14 mg Ca, 17 mg P, 0.3 mg Fe, 2 mg Na, 149 mg K, 45 IU vitamin A, 0.03 mg thiamine, 0.02 mg riboflavin, 0.3 mg niacin, 4.7 mg vitamin C, 0.05 mg vitamin B_6.

Fresh market potential

Value of 1994 fresh market crop (primarily field-grown): $254 million.

[1] All are European long types.

[2] Determined for field-grown types.



U.S. sources and amounts

(in cwt for 1994)

1. Florida–3.3 million
2. Georgia–1.3 million
3. California–950,000

Imported sources and amounts

(in cwt for 1994)

1. Mexico–5 million (field-grown)
2. Canada–91,000 (greenhouse-grown)
3. Netherlands–7,000 (greenhouse-grown)

Diseases and pests

- *Diseases:* Alternaria leaf blight, anthracnose, cucumber mosaic virus (CMV), downy mildew, fusarium and verticillium wilt, gummy stem blight or black rot, phytophthora blight, powdery mildew, pythium root rot, scab, septoria leaf spot, ulocladium leaf spot
- *Pests:* aphids, whiteflies, spider mites, thrips

Physiological concerns

Plants must be trellised to evenly distribute the foliage so leaves get maximum light. Periodic pruning is required.

Postharvest concerns

Seedless cucumbers can be stored several days at 45–50°F (7–10°C) and 85–95% relative humidity. Cucumbers cannot be stored with other ethylene-producing products. Shrink wrapping greatly extends shelf life.

Opportunities for CEA

Cucumbers need high temperatures and a high light intensity. CO_2 supplementation is beneficial. Slight variations from optimum conditions can markedly reduce growth and yield, so cucumbers are well-suited to CEA.

Challenges for CEA

Cucumbers ship and store well; local production may not provide a quality advantage.

Endive/Escarole

(Cichorium endiva)

Description

Endive, also known as frisée, is a bitter green with fine, curly leaves that vary from green to pale yellow. Escarole, or broadleaf endive, is less bitter and has darker, less curly leaves.

Common types and cultivars[1]

- *Endive:* Fin des Louviers, Fine Curled, Frisan, Green Curled Ruffec, Nina, Salad King, Tosca, Très Fine
- *Escarole:* Broadleaf Batavian, Cornet d'Anjou, Florida Deep Heart, Full Heart Batavian, Nuvol, Sinco, Twinkle

Environmental requirements

- *Temperature:* cool to intermediate
- *CO_2:* high
- *Relative humidity (RH):* intermediate
- *Lighting:* medium

Typical production methods

Outdoors, greenhouse, hydroponics (in NFT and aggregate culture).

Production/growth rates[2]

50–90 days from seed to harvest.

Human nutrients provided[2]

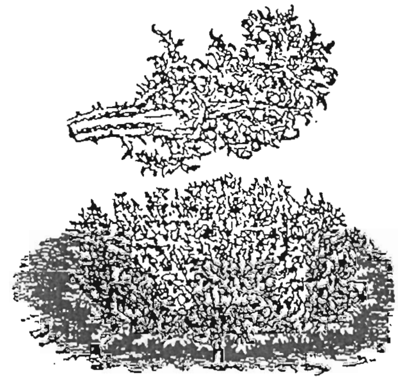
Per 100-gram portion: 1.25 g protein, 3.35 g carbohydrate, 0.9 g fiber, 52 mg Ca, 0.83 mg Fe, 15 mg Mg, 28 mg P, 314 mg K, 22 mg Na, 0.79 mg Zn, 0.099 mg Cu, 0.420 mg Mn, 6.5 mg vitamin C, 0.080 mg thiamine, 0.075 mg riboflavin, 0.400 mg niacin, 0.900 mg pantothenic acid, 0.020 mg vitamin B6, 142 µg folacin, 2050 IU vitamin A

Fresh market potential

Value of 1994 fresh-market crop, excluding imports: $11 million (primarily field-grown).

1 Best cultivars for CEA production to be determined.

2 For field-grown escarole or endive.



Endive

U.S. sources and amounts (in cwt for 1994)

1. Florida–221,000
2. Ohio–161,000
3. New Jersey–120,000

Imported sources and amounts

The U.S. imported a total of 158,000 cwt (primarily greenhouse-grown) in 1994.

Diseases and pests

- *Diseases:* bottom rot, damping off, downy mildew, drop, lettuce mosaic and cucumber mosaic viruses, broad bean wilt viruses, yellows
- *Pests:* flea beetles, aphids, loopers

Physiological concerns

Blanching is desirable to reduce bitterness. Plants bolt and become increasingly bitter as temperature increases. Tipburn may be a problem.

Postharvest concerns

Maximum storage time: 2–3 weeks at 32–36°F and 95% or higher relative humidity.

Opportunities for CEA

Niche markets exist, especially near cities. Good environmental control enhances quality.

Challenges for CEA

Market establishment. Developing efficient and optimal growing system.

Lettuce

(Lactuca sativa)

Description

Three types of lettuce proposed for CEA production are bibb, leaf, and Romaine. *Bibb lettuce* develops a small, loose heart with crunchy, bright green or red leaves. *Leaf lettuce* does not develop a heart and has shiny, frilly red or green leaves. *Romaine lettuce* is tall with firm leaves that have a central rib. *Head (or iceberg) lettuce* is not recommended for CEA.

Common types and cultivars

- *Bibb:* Ostinata, Rex, Diego, Vivaldi, Maestro
- *Leaf:* Cultivars ideal for CEA remain to be determined.
- *Romaine:* Cultivars ideal for CEA remain to be determined.

Environmental requirements

- *Temperature:* intermediate
- CO_2: high
- *Relative humidity (RH):* intermediate
- *Lighting:* intermediate

Typical production methods

Outdoors, greenhouse, CEA, hydroponics

Production/growth rates

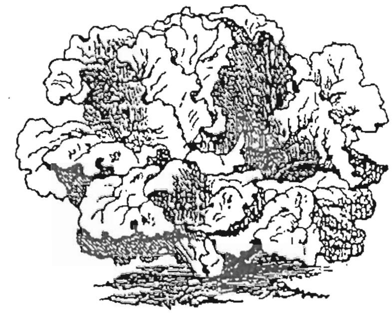
30–40 days from seed to harvest under CEA conditions.

Human nutrients provided[1]

Per 100-gram portion: 1.3 g protein, 3.5 g carbohydrate, 68 mg Ca, 25 mg P, 1.4 mg Fe, 264 mg K, 9 mg Na, 18 mg vitamin C, 0.05 mg thiamine, 0.08 mg riboflavin, 0.4 mg niacin, 1900 IU vitamin A

Fresh market potential[2]

Value of 1994 fresh-market crop, excluding imports: $288 million (primarily field-grown).



Leaf lettuce

U.S. sources and amounts
(in cwt for 1994, primarily iceberg type)[2]

1. California–10.8 million
2. Arizona–1.9 million
3. Ohio–235,000
4. Florida–151,000

Imported sources and amounts[3]

86,000 cwt imported into the U.S. in 1994.

Diseases and pests

- *Diseases:* pythium, fusarium
- *Pests:* occasional problems with aphids

Physiological concerns[4]

Tipburn when growth is too rapid. Bolting in some varieties.

Postharvest concerns

Short storage life. Packaging for shipment.

Opportunities for CEA

Lettuce is the second largest supermarket produce item. Local production provides excellent quality. Excellent environmental control in CEA avoids problems such as tipburn and bolting. Yields very clean product.

Challenges for CEA[4]

Developing a market identity for quality and avoiding identification as a commodity. Total system development that is labor efficient and provides consistent high quality.

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1 For field-grown leaf or Romaine lettuce.
2 Includes leaf and Romaine lettuces.
3 Includes Romaine, bibb, Boston, and red and green leaf lettuces.
4 A continuous supply of air to the leaves has been shown to reduce tipburn in lettuce.

Melon

(Cucumis melo)

Description

The fruit of any of various cucurbitaceous plants, such as cantelope and watermelon. There are dozens of varieties of melons that vary in color, shape, size, taste, and texture. Some show promise for CEA.

Common types and cultivars[1]

Cantelope: Passport, Ajax, Pedro

Environmental requirements

- *Temperature:* high
- CO_2*:* high
- *Relative humidity (RH):* low
- *Lighting:* high

Typical production methods

Outdoors, greenhouse, hydroponics (in NFT, rockwool, and aggregate culture).

Production/growth rates[2]

70–90 days from seed to harvest.

Human nutrients provided

Per 100-gram portion: 0.8 g protein, 7.7 g carbohydrate, 14 mg Ca, 16 mg P, 0.4 mg Fe, 12 mg Na, 251 mg K, 40 IU vitamin A, 0.04 mg thiamine, 0.03 mg riboflavin, 0.6 mg niacin, 23 mg ascorbic acid

Fresh market potential[3]

Value of 1994 fresh-market crop: $523 million (all field-grown).

U.S. sources and amounts[4]

Total U.S. production in 1994: 23 million cwt (all field-grown).

Imported sources and amounts

(in cwt for 1994, all field grown)

1. Mexico–2.8 million
2. Costa Rica–1.6 million
3. Honduras–1.3 million
4. Guatemala–1 million

Diseases and pests

- *Diseases:* downy mildew, fusarium and verticillium wilt, powdery mildew, pythium root rot
- *Pests:* aphids, spider mites, whiteflies

Physiological concerns

Plants must be trellised, pollinated, and pinched back.

Postharvest concerns

Store at 32–36°F (0–2°C) and 95% relative humidity. Storage life is 5–14 days.

Opportunities for CEA

Niche markets exist for melons not commonly produced in the field. Melons are a specialty, high-value crop in Japan. Dwarf varieties provide niche market opportunities. Imported product has high transportation cost compared to many other crops.

Challenges for CEA

Labor-intensive to trellis and pinch back plants. Competing with field-grown product.

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1 Varieties and cultivars of melons most suitable for CEA production need to be determined.
2 For field-grown melons.
3 May include melons other than cantaloupe.
4 Includes only honeydew and cantaloupe melons.

Pak-Choi

(Brassica rapa, Chinensis group)

Description

A succulent Chinese cabbage with long, white stalks topped by green, oval leaves. Pak-choi is usually stir-fried or steamed and has a mild flavor when cooked. Available in a range of sizes. Also known as *bok choy.*

Common types and cultivars[1]

Canton, Hypro, Japro, Joi Choi, Lei Choy, Mei Qing Choi, Pai Tsai White Stalk, Prize Choy, Shanghai, What a Joy

Environmental requirements

- *Temperature:* low to intermediate
- CO_2*:* high
- *Relative humidity (RH):* high
- *Lighting:* intermediate, short days

Typical production methods

Outdoors, greenhouse, CEA, hydroponics (in NFT, sand, and rockwool).

Production/growth rates

40–60 days from seed to harvest; yield from hydroponic greenhouse production is 2 lbs/ft^2/crop.

Human nutrients provided[2]

Per 100-gram portion: 1.5 g protein, 2.18 g carbohydrate, 0.6 g fiber, 105 mg Ca, 0.8 mg Fe, 19 mg Mg, 37 mg P, 252 mg K, 65 mg Na, 45 mg ascorbic acid (vitamin C), 0.04 mg thiamine, 0.07 mg riboflavin, 0.5 mg niacin, 3000 IU vitamin A

Fresh market potential

Data not available.

U.S. sources and amounts

Most U.S. production is in California. Other sources and amounts are unknown.

Imported sources and amounts

18,180 cwt imported from Mexico in 1991.

Diseases and pests

- *Diseases:* Fusarium, downy mildew, alternaria leaf spot
- *Pests:* aphids

Physiological concerns

Tipburn may be a problem. Long days induce flowering in some cultivars.

Postharvest concerns

Stores very well. Can be stored at 32°F and 95–100% relative humidity. Spacing in storage should allow for air circulation.

Opportunities for CEA

Pak-choi grows very rapidly under optimum conditions, such as can be provided by CEA. Uses water rapidly, as provided by CEA. CEA production methods can avoid tipburn. It is a major crop in Asian communities.

Challenges for CEA

Market development. Production system development. Maximizing growth without tipburn or flowering.

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1 Cultivars suitable for CEA production need to be determined.

2 For field-grown pak-choi.

Pepper

(Capsicum annuum)

Description

Fruits of the bell pepper are available in red, green, orange, purple, and other colors. There are many varieties of hot peppers in varying intensities of hotness.

Common types and cultivars

- *Sweet:* Alberto, Cadete, Cascade, Cubico, Daphne, Delgado, Evident, Flair, Goldflame, Isabel, Joy, Kelvin, Locas, Maral, Maribel, Marvello, Medeo, Multi, Plutona, Purpleflame, Reflex, Samanta, Savanne, Spartacus, Roscana, Whiteflame
- *Hot:* Flamy, Flash, Furila, Moyad Z89, Murad, Torito

Environmental requirements

- *Temperature:* intermediate to high
- *CO_2:* high
- *Relative humidity (RH):* intermediate to high
- *Lighting:* high

Typical production methods

Outdoors; significant greenhouse production in Europe; grown hydroponically in NFT, rockwool, sand, and other soilless substrates.

Production/growth rates

Approx. 60–90 days from seed to first harvest. Current greenhouse production is 8 lb/ft^2/yr.

Human nutrients provided[1]

Per 100-gram portion: 0.85 g protein, 5.31 g carbohydrate, 1.2 g fiber, 6 mg Ca, 1.27 mg Fe, 14 mg Mg, 22 mg P, 195 mg K, 3 mg Na, 0.18 mg Zn, 0.14 mg Mn, 128 mg Vitamin C, 0.085 mg thiamine, 0.05 mg riboflavin, 0.55 mg niacin, 0.036 mg pantothenic acid, 0.164 mg vitamin B_6, 16.9 μg folacin, 530 IU vitamin A

Fresh market potential

Value of 1994 fresh market crop: $660 million (primarily field-grown).

[1] For field-grown peppers.

U.S. sources and amounts (cwt for 1994)[2]

1. Florida–6.3 million
2. California–5.7 million
3. New Jersey–1.6 million

Imported sources and amounts (cwt for 1994)[3]

1. Mexico–3.2 million (field-grown)
2. Netherlands–378,000 (greenhouse-grown)
3. Canada–85,000 (greenhouse-grown)

Diseases and pests

- *Diseases:* anthracnose fruit rot, bacterial leaf spot, bacterial soft rot, blossom-end rot, damping off, phytophthora
- *Pests:* aphids, flea beetles, leaf miners

Physiological concerns

Crop time extends another month for color beyond green.

Postharvest concerns

Should not be stored with other ethylene-producing fruits. Waxing extends shelf life. Maximum storage time: 2–3 weeks.

Opportunities for CEA

High temperatures needed to mature quickly; CEA can provide such conditions. The piquancy of hot peppers can be controlled by environmental manipulation.

Challenges for CEA

Weekly pruning of side shoots necessary. Plants must be trained similar to tomatoes.

[2] Bell peppers only; incl. some for processing.
[3] Includes bell peppers and hot peppers.

Raspberry

(Rubus)

Description

Bramble fruits; small; juicy; red, black, or pale yellow; forms a detachable cap about a convex receptacle.

Common types and cultivars

- *Everbearing (primocane-fruiting):* Autumn Bliss, Heritage
- *Summer-bearing (floricane-fruiting):* Chilliwack, Royalty, Titan

Environmental requirements

- *Temperature:* low to intermediate
- *CO_2:* high
- *Relative humidity (RH):* high
- *Lighting:* high

Typical production methods

Outdoors; start in pots in the field, then move into the greenhouse for fruiting; hydroponic production in sand, perlite, and rockwool .

Production/growth rates

Field production can yield 10,000 lbs/acre/fruiting cycle; hydroponic production has yielded 3-4 lbs/plant/year.

Human nutrients provided[1]

Per 100-gram portion: 1.1 g protein, 14.24 g carbohydrate, 3.69 g fiber, 27 mg Ca, 0.7 mg Fe, 22 mg Mg, 15 mg P, 187 mg K, 0.57 mg Zn, 1.25 mg Mn, 30.8 vitamin C, 1.1 mg niacin, 0.07 mg vitamin B6, 160 IU vitamin A

Fresh market potential

Large demand, especially in the off season.

U.S. sources and amounts (in cwt, for 1995)[2]

1. Washington–520,000
2. Oregon–170,000

Imported sources and amounts

Canada–310,000 cwt for 1995

Diseases and pests

- *Diseases:* mildew
- *Pests:* mites, thrips

Physiological concerns

Plants must be trained and periodically pruned. Some varieties require a cold period of dormancy. Some types do not produce fruit until the second year. Pollinators (e.g., bumble bees) required for CEA production.

Postharvest concerns

Extremely perishable—not adapted to storage. Fruit should be rapidly precooled to 32-36°F (0-2°C) and kept at 90-95% relative humidity. A high CO_2 level in the storage area may lengthen storage life.

Opportunities for CEA

A high-value crop that is extremely perishable; closeness to market is advantageous. Upscale restaurants are a possible market. There is a year-round demand for fresh raspberries.

Challenges for CEA

Production is labor-intensive. Plant material might not be available year-round. Total CEA production system requires development.

1 For field-grown raspberries.
2 Most of this fruit was processed.

Spinach

(Spinacia oleracea)

Description

The dark green, crinkly leaves and stems of this crop are eaten fresh or cooked. Excellent source of iron and some vitamins.

Common types and cultivars

Nordic, Tyee

Environmental requirements

- *Temperature:* intermediate
- *CO_2:* high
- *Relative humidity (RH):* intermediate
- *Lighting:* high, with a photoperiod < 16 hrs

Typical production methods

Outdoors, greenhouse, hydroponics (in NFT, rockwool, and ponds), CEA

Production/growth rates

20–40 days from seed to harvest under optimum conditions.

Human nutrients provided[1]

Per 100-gram portion: 2.86 g protein, 3.5 g carbohydrate, 0.89 g fiber, 99 mg Ca, 2.71 mg Fe, 79 mg Mg, 49 mg P, 558 mg K, 79 mg Na, 0.53 mg Zn, 0.13 mg Cu, 0.897 mg Mn, 28.1 mg vitamin C, 0.078 mg thiamine, 0.189 mg riboflavin, 0.724 mg niacin, 0.195 mg vitamin B6, 194.4 µg folacin, 6715 IU vitamin A

Fresh market potential

Value of 1994 fresh market crop, excluding imports: $57 million (all field-grown).

U.S. sources and amounts
(in cwt for 1994)

1. California–1.2 million
2. Colorado–289,000
3. New Jersey–209,000
4. Texas–115,000
5. Virginia–68,000

[1] For field-grown spinach.

Imported sources and amounts
(in cwt for 1991)[2]

1. Mexico–46,933
2. Trinidad–29
3. Jamaica–10

Diseases and pests

- *Diseases:* damping off, downy mildew, white rust, cucumber mosaic virus (CMV), fusarium, crown rot (root rot), pythium
- *Pests:* aphids, leaf miners, spider mites

Physiological concerns

Bolting, tipburn. Plants are very susceptible to water quality (chlorine) and are photoperiod-sensitive.

Postharvest concerns

Perishable. Can be stored 10–14 days at 32°F and 95–100% relative humidity. Most fresh-market spinach is packaged in perforated plastic bags to reduce moisture loss and physical injury.

Opportunities for CEA

Year-round CEA production is possible. CEA-produced spinach is of exceptional quality, and has no grit. Spinach is a good source of iron for vegetarians.

Challenges for CEA

Labor needed to respace crop. Tipburn may limit marketability. Crown rots develop 3–4 weeks after seeding.

[2] Does not include imports from Canada.

Strawberry

(Fragaria x ananassa*)*

Description

The succulent fruit of strawberries, like raspberries, are in high demand year-round and sell for very high prices in the off season.

Common types and cultivars

- *Day-neutral varieties:* Seascape, Tristar
- *Short-day varieties:* Chandler, Elsanta, Jewel

Environmental requirements

- *Temperature:* intermediate
- *CO_2:* high
- *Relative humidity (RH):* high
- *Lighting:* high

Typical production methods

Outdoors, greenhouse, hydroponics (in rockwool, peat bags, and troughs filled with gravel, perlite, or granulated rockwool).

Production/growth rates

Greenhouse production is 1 lb/ft^2 per fruiting cycle; can get 3–4 fruiting cycles per year.

Human nutrients provided[1]

Per 100-gram portion: 0.61 g protein, 7.02 g carbohydrate, 0.53 g fiber, 14 mg Ca, 0.38 mg Fe, 10 mg Mg, 19 mg P, 166 mg K, 1 mg Na, 0.13 mg Zn, 0.049 mg Cu, 0.290 mg Mn, 56.7 mg vitamin C, 0.059 mg vitamin B6, 17.7 µg folacin, 27 IU vitamin A

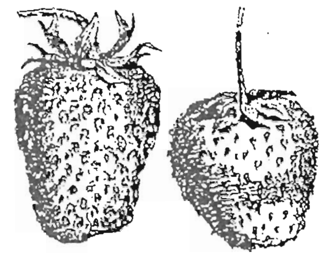
Fresh market potential[2]

Value of 1994 fresh market crop, excluding imports: $858 million (primarily field-grown).

U.S. sources and amounts

(in cwt for 1994, primarily field-grown)

1. California–13 million
2. Florida–1.7 million
3. Oregon–702,000



Imported sources and amounts

(in cwt for 1994)

Mexico–418,000 (primarily field-grown)

Diseases and pests

- *Diseases:* powdery mildew, gray mold
- *Pests:* shore flies, fungus gnats, two-spotted spider mites, aphids, thrips

Physiological concerns

Plants must be pollinated mechanically or using bumblebees. Some types are daylength-sensitive and require a period of cold dormancy. Early flowers may need to be removed to prevent premature fruiting. Plants may need to be derunnered.

Postharvest concerns

Fruit is highly perishable. Can be stored for 5–7 days at 32°F (0°C) and 90–95% relative humidity. A high CO_2 level in the storage room may extend storage life.

Opportunities for CEA

Day-neutral varieties make year-round CEA production possible. High-value crop.

Challenges for CEA

Production is labor-intensive. A year-round supplier of plant material may be difficult to find. Day-neutral varieties may develop problems with diseases or pests (e.g., thrips) over time.

---

1 For field-grown strawberries.

2 Includes some strawberries for processing.

Tomato

(Lycopersicon esculentum)

Description

A native of South America, tomato is a slightly acid fruit used as a vegetable. A favorite of home gardeners. Cherry tomatoes are popular garnishes.

Common types and cultivars

- *Tomato:* Ammarida, Belcanto, Cameo, Capello, Caruso, Contento, Forlano, Furon, Katinka, Larma, Laura, Madrila, Match, Rakata, Rashida, Recento, Romatos, Rondello, Sarras, Switch, Tipico, Trend, Trust, Turalia, Vendor, Wirantos
- *Cherry tomato:* Evita, Cheresita, Favorita

Environmental requirements

- *Temperature:* intermediate
- *CO_2:* high
- *Relative humidity (RH):* intermediate
- *Lighting:* high, needs >= 4 hr dark period

Typical production methods

Outdoors; hydroponically grown in NFT, rockwool, peat bags, and other soilless media.

Production/growth rates

90 days to first harvest; greenhouse yield can be 30-40 lbs/ft^2/yr.

Human nutrients provided[1]

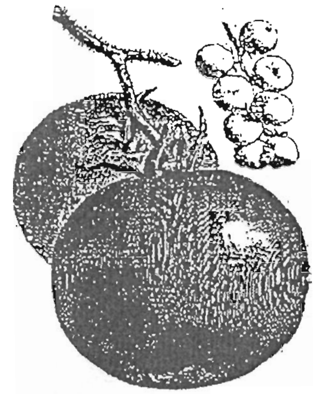
Per 100-gram portion: 0.89 g protein, 4.34 g carbohydrate, 0.47 g fiber, 7 mg Ca, 0.48 mg Fe, 11 mg Mg, 23 mg P, 207 mg K, 8 mg Na, 17.6 mg vitamin C, 0.046 mg vitamin B_6, 1133 IU vitamin A

Fresh market potential

Value of 1994 fresh market crop: $1.3 billion (primarily field-grown).

U.S. sources and amounts

(in cwt for 1994, primarily field-grown)
Florida–16 million ; California–10 million



Imported sources and amounts

(in cwt for 1994)

1. Mexico–8.3 million (field-grown)
2. Canada–169,000 (greenhouse-grown)
3. Netherlands–166,400 (greenhouse-grown)

Diseases and pests

- *Diseases:* anthracnose, bacterial speck and spot, blossom-end rot, early blight, fusarium crown and root rot (FR), leaf mold, Septoria leaf spot, tobacco mosaic virus (TMV), tomato canker, tomato spotted wilt virus
- *Pests:* whiteflies, leaf miners, aphids, thrips, spider mites

Physiological concerns

Must be pruned, supported, and pollinated. Plants are photoperiod-sensitive.

Postharvest concerns

Fruit is easily bruised and is chill-sensitive. Tomatoes cannot be stored with other fruits.

Opportunities for CEA

Enormous fresh market. Local production can be "vine-ripe"; imported product can not.

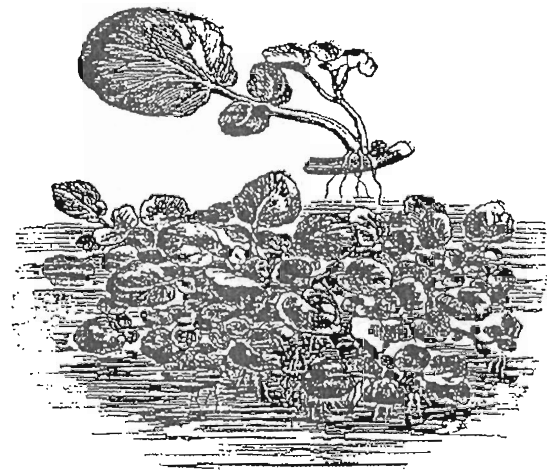
Challenges for CEA

Reduce labor requirements. Develop methods to produce and handle "vine-ripe" fruit. Establish identity distinct from currently available "hothouse" tomatoes.

[1] For field-grown tomatoes.

Watercress

(Nasturtium officinale)



Description

Watercress is a member of the mustard family. It has a peppery flavor and is a good addition to salads. It is also used to flavor soups, sandwiches, and egg dishes.

Common types and cultivars[1]

Improved Broad-Leaved

Environmental requirements

- *Temperature:* low
- *Carbon dioxide:* high
- *Relative humidity:* intermediate
- *Lighting:* low

Typical production methods

Outdoors, greenhouse, hydroponics

Production/growth rates

50 days to maturity (outdoor production)

Human nutrients provided

Per 100-gram portion: 2.3 g protein, 1.29 g carbohydrate, 0.70 g fiber, 120 mg Ca, 0.2 mg Fe, 21 mg Mg, 60 mg P, 330 mg K, 41 mg Na, 43 mg vitamin C, 0.090 mg thiamin, 0.120 mg riboflavin, 0.200 mg niacin, 0.310 mg pantothenic acid, 0.129 mg vitamin B6, 4700 IU vitamin A

Fresh market potential

Not documented.

U.S. sources and amounts

Data not available.

Imported sources and amounts (in cwt for 1991)

1. Netherlands–330 (greenhouse-grown)
2. Mexico–300 (field-grown)

Diseases and pests

- *Diseases:* crook root disease, chlorotic leaf spot
- *Pests:* algae

Physiological concerns

Root growth must be monitored so roots don't overtake the plant.

Postharvest concerns

Stores at 32°F (0°C) and 95–100% relative humidity for 2–3 weeks.

Opportunities for CEA

Niche markets exist, primarily near large cities. Grows in water, thus is a natural opportunity for hydroponics production.

Challenges for CEA

Labor needed to re-space crop. Establishing a CEA identity for marketing and developing stable markets. Optimizing the production system, including best cultivar determination for high-productivity opportunities. Provide optimal growth conditions while suppressing algae growth.

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[1] Cultivars suitable for CEA production need to be determined.

5. Integrating Controlled Environment Agriculture with Conventional Agriculture and Recirculating Aquaculture Systems

Introduction

As has been defined previously in this report, CEA involves a highly technical biological, chemical, and physical system that requires a strong work ethic and great attention to detail on the part of the operators, as well as very carefully controlled environments, both aerial and root. If a CEA operator is to be successful, the system must be carefully watched every day and must be a primary focus of the operator so details are not missed. This requirement places certain limits on how CEA can be integrated with conventional agriculture and recirculating aquaculture systems, and the limits differ. The opportunities and limits are discussed below for each.

Available Resources for Potential Integration of CEA with Conventional Agriculture

Conventional farms have several resources that could contribute to operation of a CEA facility.

- The first resource is land. If several acres of level space are available and accessible to a road during all seasons, such a site is likely to be suitable for a CEA operation. Larger land areas may also be available for larger CEA facilities, but would be required only if the CEA operation is to become perhaps the dominant part of the agricultural operation, not merely an opportunity for diversification.

- A second possible resource is labor. A typical farm does not have surplus labor that could be diverted frequently to a CEA enterprise. However, in some instances, as children reach adulthood and wish to remain in agriculture, a CEA operation can be one means to achieve that goal through diversification. Labor is a major cost item for CEA production.

- A third possible resource is access to water. As envisioned here, an idealized CEA operation will be closed and have no environmental discharges of liquid water. Water is necessary to replace plant transpiration and makes up most of the product sold. As an example, each 5-ounce head of hydroponically grown bibb lettuce has typically transpired from one-half to three-quarters of a gallon of water (nutrient solution) during its lifetime. Added to the transpired water is water needed for evaporative cooling of the CEA facility during hot weather. The degree of evaporative cooling needed will depend, of course, on the local climate. However, the quantity of water needed for evaporative cooling during warm weather is likely to be the same order of magnitude as that evaporated through transpiration.

Limits to Integrating CEA with Conventional Agriculture

Conventional agriculture is experiencing difficult times in many parts of the United States. Primary, but not exclusive, examples are dairy farmers in the Northeast and upper Midwest. Their difficulties have led to considerable focus on diversification — of crops as well as complete enterprises. However, diversification by patching a CEA operation onto an existing farm is not likely to be successful unless certain conditions are met. Specifically, diversification should not further fragment the attention of the individual farmer. Modern farming is sufficiently complicated that to add another complex component is likely to degrade the operator's ability to do well with either. It is assumed existing farming operations will not be abandoned if a CEA unit is added, which would be replacement, not integration.

On the other hand, farms have sufficient land that small areas (as little as an acre or two) can be set aside for CEA facilities. It is unlikely that many farms are of sufficient size that they can be split into separate farming units if more than one child wishes to remain in farming. CEA provides the possibility for one or more children of a farm family to remain on the farm while not detracting from the production capacity of the basic farm unit. Because CEA requires significant specialization, a total split of effort is likely to lead to greater success than involvement of several persons, each on a part-time basis. This is not a serious limit but a willingness to divide responsibilities completely should be acknowledged before diversification through CEA is attempted.

Limited utilities access has the potential to hinder integration of CEA and conventional agriculture. In particular, many rural areas lack access to natural gas, the heating fuel likely to be the least expensive for the foreseeable future. Greenhouses must be heated, at least a little, every month of the year in northern climates and during at least winter months in all but tropical climates. Additionally, a CEA facility having supplemental lights will require a significant electrical service. Rural locations near the end of a distribution line may not have access to adequate capacity and, even if the capacity is nominally adequate, may impose excessive line voltage drop when all the luminaires are active if installation does not account for this potential problem.

General Areas for Potential Integration with Recirculating Aquaculture Systems

Two reasons are frequently cited as advantages for integrating CEA using hydroponic growing systems with recirculating aquaculture systems:

- To make use of fish waste as a source of plant nutrition. This is often motivated by a desire to treat the fish waste and permit continuous recirculation of the water.

- A second is to find a use for any hydroponic solution that may be dumped periodically (for example, to prevent root disease outbreaks) by using it for fish production.

This section will explore some of the requirements for CEA if such integration is attempted. It must be noted this section is written from the perspective of potential advantages and disadvantages for CEA, not for recirculating aquaculture systems. It should be noted that some of the skills and knowledge necessary for successful CEA operations are also required for successful aquaculture operations. Examples include a knowledge of water chemistry and experience with mechanical systems such as for pumping.

Several aspects of plant production in hydroponic CEA systems would be affected by integration with recirculating aquaculture systems, including:

- System management and control
- Nutrient solution pH level and control
- Nutrient availability within the hydroponic solution

System Management and Control. Management is critical for profitable CEA production. Attention to every detail is necessary. Quality and productivity suffer when careful attention to every small detail is omitted, even for a day. The same can be claimed for recirculating aquaculture systems. Plants and fish can be grown in many ways, at differing levels of management intensity. However, if a grower is to make use of currently available technologies in the most efficient and effective way, productivity must be optimized (maximized). Failures cannot be tolerated. This requirement works against integrating CEA and aquaculture facilities within the same business unit, under the same manager.

Nutrient Solution pH Level and Control. Most recommendations for nutrient solutions for plant growth suggest a pH in the vicinity of 5.8. No recommendations are found that suggest a pH near or above neutrality. Most references that detail the characteristics of water from aquaculture units state the water's pH is greater than 7.0. This presents a challenge if the recirculating water from an aquaculture unit is to be used for plant nutrition. Adjusting the pH by adding acid, normally nitric acid, would be required. Unfortunately, the additional acid contributes additional nitrogen to the solution, and nitrogen is one of the elements important to remove from fish waste. Other acids may be used, such as sulfuric, but a careful evaluation would be required to assure the addition of large quantities of any acid will not upset the nutrient balance in a way that could be damaging to the plants, the fish, or both.

Nutrient Availability Within the Hydroponic Solution. Limited data exist to show nutrient availability in a hydroponic growing system. Extensive data exist for growing in soil, and the graph in Figure 5.1 is often used to describe the availability as a function of pH. The pH is important in soil through its effect on the exchange capacity of the soil. It is not clear the graph applies to hydroponic solutions, however, and the recommendation for a pH near 5.8 is based on more than nutrient availability (the low pH helps keep minerals in solution, preventing nozzle clogging, for one example).

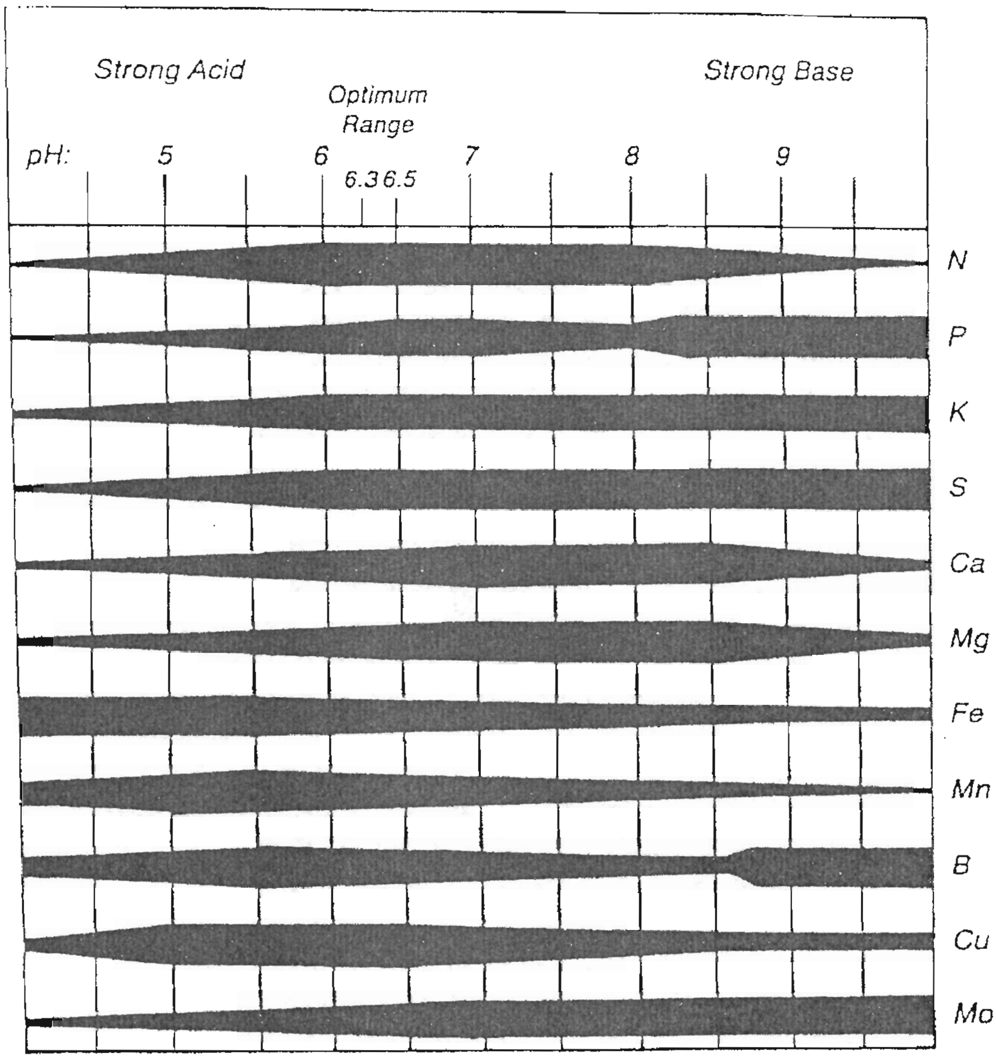


Figure 5.1. The availability of plant nutrients in soil as a function of soil pH. (From Hydroponic Food Production, by H.M. Resh, 1995, page 37.)

6. Potential Cooperating and Participating Utilities

The Agricultural Technology Alliance (ATA) of EPRI is made up of utilities having an interest in various areas of agriculture. The ATA meets twice yearly. The utilities that have sent representatives to the meetings form the core of the list that follows.

Alabama Power Company
Birmingham, AL

Association of Illinois Electric Cooperatives
Springfield, IL

Baltimore Gas & Electric
Lusby, MD

Bartholomew County REMC
Columbus, IN

Basin Electric
Bismark, ND

Buckeye Power
Columbus, OH

Carolina Power and Light
Raleigh, NC

Daviess-Martin REMC
Washington, IN

Duke Power Company
Hickory, NC

Georgia Power Company
Grayson, GA

Idaho Power Company
Boise, ID

Illinois Power Company
Decatur, IL

Jackson County REMC
Brownstown, IN

Minnesota Power Company
Little Falls, MN

Mountain View Electric Association, Inc.
Limon, CO

National Rural Electric Cooperative Association
Washington, DC

New York State Electric and Gas
Ithaca, NY

Oglethorp Power Corportion
Tucker, GA

Southern California Edison
Irwindale, CA

SW Arkansas Electric REA
Texarkana, AR

Tennessee Valley Authority
Knoxville, TN

Tri-State G&T Association
Denver, CO

TU Electric
Dallas, TX

Wabash Valley Power
Indianapolis, IN

Wisconsin Power & Light Company
Madison, WI

APPENDIX A

Glossary of CEA Terms, Abbreviations and Acronyms

Terms

Aeroponics	Form of hydroponics where plant roots hang in air but are sprayed continuously or frequently with nutrient solution.
Active transport	Movement of nutrients into plant roots by an active (energy-expending) mechanism within a specific region of the plant root.
Availability	The condition where a plant nutrient (element) is in a form that permits roots to absorb the nutrient.
Bag culture	A plant-growing technique where plants are grown in bags of soilless mix into which nutrient solution is added as needed.
Buffer capacity	The ability of the root medium to resist changes of pH.
Canopy	The matrix of leaves of many plants grown closely together, or of a single plant.
Chlorosis	Yellowing of leaves or other plant parts that indicates some nutrient deficiency.
Closed hydroponics	Hydroponic system where nutrient solution is recirculated and not discarded.
Deficiency	Condition where an essential plant nutrient is not present in adequate concentration for rapid growth or production.
Dissolved oxygen	Concentration of oxygen dissolved in water (or nutrient solution).
Efficacy	A measure of lighting efficiency, e.g., mol (of PPF photons) – kWh^{-1}.
Essential element	An element required for the growth of plants (see micro- and macronutrients).
Evaporative cooling	Air conditioning by means of evaporating water into air to reduce the temperature.
Exchange capacity	The measure of the capacity (ability) of a soil to exchange and hold anions or cations in solution with water in the soil. Soil particles such as clay provide the greatest portion of the capacity, and each ion has its own exchange capacity with a particular soil.
Floating hydroponics	Hydroponic system for plant growth where the plants float on rafts over a trough or pool of nutrient solution.
Gravel culture	A hydroponics method where plant roots grow in a gravel bed and nutrient solution is periodically provided.
Horizontal air flow	Air-mixing process in greenhouses created by a series of fans to direct air to flow in a racetrack fashion along one side of the air space, and return along the other long side.

Hydroponics	The technique of growing plants without the use of natural soil. An inert medium may be used to support the roots, or no medium may be used. The term arises from two Greek words, HYDRO (water) and PONOS (working). In this report, the term is used only for systems where no root medium is employed.
Langley	Meteorological unit of solar irradiation, cal – cm^{-2}.
Luminaire	Unit to provide supplemental light; includes lamp, reflector, ballast, wires, and other components.
Macronutrients	Elements required for plant growth in significant quantities: N, P, K, Ca, Mg, S, Si.
Make up water	Fresh water added to nutrient solution to replace that transpired by the plants.
Micromol	10^{-6} part of a mol.
Micronutrients	Elements required for plant growth in small quantities: B, Fe, Mn, Zn, Cu, Mo, F, Na, Al, Cl.
Millisiemens	A measure of electrical conductance.
Mol	Avargadro's number of atoms, molecules, or photons — $6.023 \bullet 10^{23}$.
Open hydroponics	Hydroponic system where the nutrient solution is discarded after passing through the growing system.
Osmotic pressure	Pressures that develop from concentrations of elements in a nutrient solution that differ from their concentrations in plant roots.
Pad and fan	A system used to provide evaporative cooling; fans draw air through wetted pads.
Passive transport	Movement of a plant nutrient into the roots by being carried along with the water.
pH	Degree of acidity
Phytotoxic	A condition or chemical presence leading to rapid plant death.
Plugs	Seedlings grown at high density in plastic trays using very little root medium for each plant. Transplanting is required soon after the first true leaves emerge.
Proportioner	Device used to meter nutrient solution into water (as in a hose) in a predetermined concentration.
Reverse osmosis	A method of purifying water by means of a membrane that permits water to pass but not ions.
Sand culture	A hydroponics method where plant roots grow in a sand bed and nutrient solution is periodically provided.
Soilless culture	A form of hydroponics where an inert medium is used to support the plant roots.
Soluble salts	The concentration of plant nutrients (dissociated into ions) in water.
Supplemental lighting	Plant lighting by luminaires to enhance growth.
Senescence	Normal aging and death of a plant (or part of a plant such as a flower).
Transpiration	Evaporation of water from a plant canopy.

Abbreviations and Acronyms

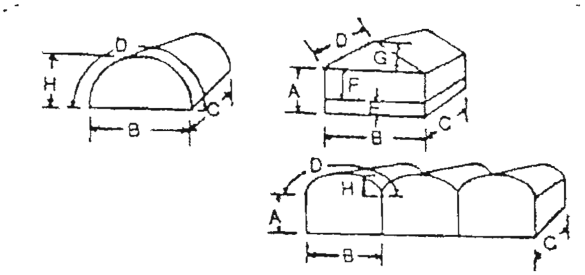
ATA	Agricultural Technology Alliance (of EPRI)
Btuh	Btu per Hour (typically of heat flow)
CEA	Controlled Environment Agriculture
cfm	Cubic Feet per Minute (typically of air flow)
cwt	Hundredweight, standard unit for marketing many agricultural products
DFT	Deep-Flow Technique, pond system for hydroponics
DO	Dissolved Oxygen
DW	Dry Weight
EC	Electrical Conductivity (typically of nutrient solution)
ECLSS	Environmental Control and Life Support Systems
EPRI	Electric Power Research Institute
Fl	Fluorescent (lamps)
FW	Fresh Weight
INC	Incandescent (lamps)
gpm	Gallons per Minute (typically of water flow)
HID	High-Intensity Discharge (lamps)
HPS	High-Pressure Sodium (lamps)
IES	Illuminating Engineers Society
IPM	Integrated Pest Management
kWh	Kilowatt-Hour
LPS	Low-Pressure Sodium (lamps)
MH	Metal-Halide (lamps)
μmol	Micromol
mS	Millisiemens
NPDES	National Pollutant Discharge Elimination System
NFT	Nutrient Film Technique
nm	Nanometer, 10^{-9} meter
PAR	Photosynthetically-Active Radiation (400 — 700 nm)
PPF	Photosynthetic Photon Flux
ppm	Parts per Million
RH	Relative Humidity
RO	Reverse Osmosis (method of water treatment)
VER	Ventilating Efficiency Ratio (cfm – W^{-1}, of ventilating fans)
VPD	Vapor Pressure Deficit (a measure of evaporative potential based on partial pressures of water vapor)

APPENDIX B

Worksheet for Greenhouse Heat Loss Calculations

See the next page for a copy of a blank worksheet. The worksheet is taken from Aldrich and Bartok, 1994.

The dimensions defined in the diagrams below are used throughout the Heat Loss Calculations:



Step 1. List greenhouse dimensions in feet:

Wall height,	A	=
House width,	B	=
House length,	C	=
Rafter length,	D	=
Lower wall height,	E	=
Upper wall height,	F	=
Gable height,	G or H	=

Step 2. Calculate the appropriate surface areas and perimeter. N is the number of individual house sections forming each greenhouse range.

N = 1 for a single house.

Lower wall area:
2N(E x B) + (E x 2C) =

Upper wall area:
2N(F x B) + (F x 2C) =

Single material wall:
2N (A x B) + (A x 2C)=

Gable area:
N x B x G =

Curved end area:
1.3N x B x H =

Gable roof area:
2N x D x C =

Curved roof area:
N x D x C =

Perimeter:
2 [(N x B) + C] =

Step 3. List construction materials and U factors for each surface .

Location	Construction Material	U Factor
Lower wall		U_1 =
Upper wall		U_2 =
Single material wall		U_3 =
End area		U_4 =
Roof		U_5 =
Perimeter		U_6 =

Step 4. Calculate appropriate conduction heat loss, h_c.

h_c = Area x U x ΔT
ΔT = Inside night temperature – minimum outside temperature

Lower wall area x U_1 x ΔT	=
Upper wall area x U_2 x ΔT	=
Single wall area x U_3 x ΔT	=
Gable or curved end area x U_4 x ΔT	=
Roof area x U_5 x ΔT	=
Perimeter length x U_6 x ΔT	=
Total = Q_c	=

Step 5. Calculate greenhouse volume.

Gable house volume:
N [(A x B x C) + (B x G x C/2)] =

Single curved roof house volume:
2H x B x C/3 =

Multiple curved roof volume:
N [(A x B x C) + (2H x B x C/3)] =

Step 6. Calculate air infiltration losses, h_{inf}.

h_{inf} = 0.02 x ΔT x Volume x Air changes/hour
=

Step 7. Calculate total heat loss, h_t.

h_t = h_c + h_{inf}
=

REFERENCES

Not all the following are referenced directly in this report. They do, however, make up a basic collection of references to CEA production and hydroponics. The list is not meant to suggest these are the only available literature, but the references form a solid, yet practical, library to cover the horticulture, engineering, and pathology aspects of CEA production.

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