Innovation in Greenhouse Engineering

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Abstract

Innovations in greenhouse engineering are technical developments which help evolve the state-of-the-art in CEA (Controlled Environment Agriculture). They occur in response to the operational demands on the system, and to strategic changes in expectations of the production system. Influential operational factors include availability of labor, cost for energy, logistics of transport, etc. Influential strategic factors result from broader, regional issues such as environmental impact, product safety and consistency, and consumer demand. These are industry-wide concerns that have the effect of changing the production system in the long term. Global issues are becoming more influential on greenhouse production sustainability, and include less tangible issues such as social acceptance, political stability, quality of life benefits, and environmental stewardship. These offer much more complex challenges and are generally beyond the realm of engineering. However global issues do affect greenhouse engineering innovation. The most effective innovations in greenhouse engineering design, operations and management, will incorporate input from partnerships with the academic, private and public sectors of society. Furthermore, successful applications include, at least to some degree a multi-disciplinary approach of the sciences, engineering and economics, while for ultimate success and sustainability, societal and political support must also be attained. For this overview of innovation in greenhouse engineering a list of influential factors, or "driving forces" affecting the development, application, evolution and acceptance of greenhouse systems have been described. The factors are similar for all greenhouse systems around the world, as they include the plant biology of the crop, the physical components of the structure and production system hardware, the management and logistics of labor and materials, and the mechanism of marketing the crop. Each greenhouse system, wherever located, must resolve similar problems for its specific application. The magnitude of the factors and their relative local importance are different for the specific sites. The design response will be introduced and related to the factors, as examples of innovation.

INTRODUCTION

Protected cultivation or Controlled Environment Agriculture (CEA) systems are used throughout the world as a powerful technology to produce crops. They protect the crops from unfavorable outdoor climate conditions and pests, and offer the opportunity to modify the indoor climate to create an environment that is optimal for crop growth and production, both in terms of quality and quantity (Van Henten et al., 2006). Protected cultivation has proven to be extremely effective and in the last decades, it has spread around the world. Table 1 contains the estimated greenhouse area for various locations on earth. Technology levels also vary widely throughout the world. In most West European countries and North America, protected cultivation started as a slightly more sophisticated version of open-field agriculture by protecting crops against adverse climate conditions such as extremely low temperatures, storm, rain or hail, as well as, pests to prevent production losses and to decrease the risk of complete loss of a crop. Enclosing the crop with a cover had a beneficial effect on the microclimate. Together with simple means of climate conditioning this allowed for improved food production with higher production levels, extension of the growing season and decreased water use compared to open field production. The production technology remained relatively simple, and is still the most common throughout the world today. However, this began to change as the basic food and nutrition needs of the society were satisfied. Since the 1960's, there has been a trend towards more complex, high-tech production systems. This was, in part, directed by the demand for better quality and safer food products, convenience products, and specialty products like flowers and potted plants. Such production required more sophisticated, energy-intensive, resource-intensive technology and required experienced operators, which with greater societal awareness of limited resources such as nutrient and energy sources, as well as, the impact on environment, initiated further technological innovation. The development for sustainability continues until this day.

All protected cultivation systems, regardless of geographic location, consist of fundamental climate control components, and depending on their design and complexity, they can provide a greater or lesser amount of environmental control, and subsequent plant growth and productivity. The fundamental components include the: (1) super-structure or framework construction, which provides physical boundary and structural support; (2) cover material, which provides the environmental boundary and protection from ambient wind and rain, while limiting heat, mass and insect transfer; (3) environmental control equipment to maintain desired air-water vapor properties; and, (4) nutrient delivery equipment to provide the water, fertilizer, and oxygen to the plant root zone. Additionally, cropping systems and internal layout of the greenhouse are designed for efficient crop production in terms of use of the limited available space and labor.

The particular choice of greenhouse systems should be adapted to the local conditions, especially climate conditions of the region. Critical factors to be considered when choosing the design technology level for a particular region have been listed by Hanan (1998), and Van Heurn and Van der Post (2004). The following is a combination and extension of their factors:

1. Market size and regional infrastructure which determines the opportunity to sell products as well as the costs associated with transportation.
2. Local climate which determines crop production and thus the need for climate conditioning and associated costs for equipment and energy. It determines the robustness of greenhouse construction required, being dependent, for example, on wind forces, snow loads and hail.
3. Availability, type and costs of fuels and electric power to be used for operating and climate conditioning of the greenhouse.
4. Availability and quality of water.
5. Soil quality in terms of drainage, the level of the water table, risk of flooding and topography.
6. Availability and cost of land, present and future urbanization of the area, the presence of (polluting) industries and zoning restrictions.
7. Availability of capital for investment.
8. Availability and cost of labor, as well as, the level of education of the labor force.
9. Local availability of raw materials for building the structure, including the availability of equipment, services, repair and maintenance
10. Legislation and government regulations of food safety, residuals of chemicals, the use and emission of chemicals to soil, water and air.

These are the fundamental factors that affect the selection of a particular protected cultivation system at a particular location, and, as these factors are modified or newly developed, due to societal pressures and other forces, the engineering innovation must evolve for the greenhouse design.

Innovations in greenhouse engineering are developments which help promote the evolution of the state-of-the-art in protected cultivations systems, or Controlled Environment Agriculture (CEA). They occur in response to the operational demands on the system, and to strategic changes in expectations of the production system.

Our goal is to discuss greenhouse innovations, which may range from the simplistic to highly complex. We will offer some examples of innovations of today that were a response to the influential factors of the past. It will not be all-inclusive, but it is with great expectations that we offer our insights, and help to support the purpose of this symposium.

CHALLENGES AND DRIVING FORCES FOR INNOVATION

Innovations are initiated by a variety of forces illustrated in Figure 1. The four major forces are the consumers, civil society, government and growers. Demands and conditions are listed by the bolded arrows. Clearly each of these four forces acts simultaneously to affect the changes to the primary production system, changes that are implemented as a result of innovations in engineering design.

These influential factors stimulate innovations at time scales that vary from immediate to long-term strategic-based decisions. Local and day-to-day concerns that have an immediate influence on production system operations include availability of labor, cost for energy, logistics of transport, etc. Whereas influential strategic factors result from broader, regional and societal issues, such as environmental impact, product safety and consistency, and consumer demand. These are industry-wide concerns that have the effect of changing the production system in the long term. Global issues are becoming more influential on greenhouse production sustainability, and include less tangible issues such as social acceptance, political stability, quality of life benefits, and environmental stewardship. These offer much more complex challenges and are generally beyond the realm of engineering. However global issues do affect greenhouse engineering innovation.

For this overview of innovation in greenhouse engineering we have attempted to organize a list of influential factors, or “driving forces” affecting the development, application, evolution and acceptance of greenhouse systems within the local facility and the global society. These influential factors include (in an unprioritized order):

1. Economy-Essentially, to survive, a company needs to make profit. When gross returns are under pressure or operational costs are increasing, technology can be used to improve productivity and efficiency and to improve the net economic return. However, with higher levels of technology, investment costs typically increase. Scale enlargement is a commonly used strategy to cope with this.
2. Labor-Working in agriculture/horticulture is tough, heavy, dirty and not considered to be prestigious. There is growing shortage of sufficiently trained and educated people for this industry. Technology must focus on labor efficiency, labor safety, alleviating tedious jobs and improved management support. Opportunities for educating management and staff need to be developed, in all levels of technology.
3. Energy-Protected cultivation is an energy consuming business. Resources become limited. Energy prices will continue to rise, thus operational costs increase for the businesses. Technological innovations must focus on the energy consumption for the return on productivity, quality, and societal satisfaction.
4. Environmental issues–Energy consumption and the generation of emission products can be compared to the return on productivity to help determine the true cost of a production system. Costs include emissions of byproducts from the production process, such as CO_2, plant nutrients, pesticides, etc. Closing the production process, by developing new techniques of reuse/recycle has begun to seriously consider the concern for emissions.
5. Food safety, Quality and Enhancement–The need to maintain the confidence of the

consumer in the food products from controlled environments is critical for the future of the industry, and must be recognized as a major input for design decisions.

6. Management information for decision-making–Information technology for monitoring and controlling internal information flows are important for decision-support of operations, and tactical and strategic planning. Product flows, logistics, ICT, networks, distributed computing, and wireless technology all offer the potential to inform and support the management of the company especially during daily and seasonal variance of operations. Plant monitoring and control must sufficiently maintain the optimal crop (horticulturally), but also maintain the larger aspect of crop production at the whole company level (sales, marketing, branded product). Communication from the grower through to marketing is required.
7. Societal and consumer acceptance of protected cultivation–Protected cultivation must find an unburdened role and a welcomed position within society. The promise of safe, high quality, locally-grown foods will be weighed against use of urban resources (land, water, waste disposal) to determine its acceptance. Technology should focus on multi-functional production systems, which effectively integrate with urban environment to benefit the urban population and the production practice. We must introduce biotechnological advances with caution, carefully weighing the benefits and the costs.
8. Consumer demand and supply chains–Agriculture is becoming much less production-driven, and more consumer-driven (Murphree, 2007; Castilla and Hernandez, 2006.). The consumer pressures the production chain to meet their market demands. It is necessary to respond quickly to consumer demands in terms of varieties, product quality, environmental impact, etc. Integration of information about the food chain, from the suppliers of production and raw materials (greenhouses, seeds, etc), up through to the markets is necessary to respond to changing market demands.
9. Reuse and recycling of natural resources and new products-Technology should focus on improving the efficiency of using resources and environmental costs and benefits for production of new materials, that requires bioprocessing within controlled environments. These could include biomass for bio-energy, pharma-bioproducts, and nutritionally enhanced foods.
10. Logistics of flow of materials, products and wastes–Using logistical analysis optimize the general materials flows to minimize local energy consumption, limit transport distance, co-location of symbiotic processes thereby maximizing regional resources before committing them to the waste stream. Reducing waste flows, closing cycles, and creating new recyclable materials, all need to be considered.
11. Hardware and materials improvements–Research and develop improved protected cultivation facilities such as the closed greenhouse, or related controlled environment applications, such as the growth room or vertical farm building. This will require new structural and material improvements.
12. Software and computational intelligence–Capitalize on advancements within computational capabilities, and smart, multi-parametric sensors for enhanced monitoring and control.
13. Integrated Systems design-Develop non-traditional agricultural applications for multiple inputs and multiple non-waste outputs for improved environmental stewardship, and maintaining Quality of Life for the local inhabitants.

These factors are similar throughout the world for all greenhouse systems, as they include the plant biology of the crop, the local climate, the physical components of the structure and production system hardware, the management and logistics of labor and materials, the availability of resources and the mechanism of marketing the crop. Each greenhouse system, wherever located, must resolve similar problems for its specific application. The magnitude of the factors and their relative local importance are different for the specific sites. Innovations and their successful application and adoption by the industry will naturally have a time lag between research and development, and implementation with the industry.

LOCATION SPECIFIC TECHNOLOGY LEVELS

Location and site selection are important for developing a profitable protected cultivation facility (Castilla and Hernandez, 2006; van Henten et al., 2006). The climate conditions of the site influence the operational cost and production quality of the product, but also the location determines the distance to the markets, and the transportation costs. The local climate conditions and geographical latitude influence the greenhouse design (von Elsner et al., 2000) or "technological package" (Castilla and Hernandez, 2006) which includes the structure and internal equipment for climate control, and subsequent crop production conditions.

There are important differences in the priorities for greenhouse engineering innovations between developed and developing countries. The high cost and limited labor in developed countries highlights the importance of optimizing its management. Automation and mechanization are increasingly important to limit the production costs. Education and training people for greenhouse operations is critical for increasing labor productivity.

The focus of protected cultivation in many developing countries is on mass production of food, whereas in other countries, protected cultivation shifts from mass production to production of special products, value added for the consumer, and quality instead of quantity. Technology levels are different, as well as, are the available financial resources. For these different conditions, different technologies and innovations are required.

Engineering of workable protected cultivation systems that are environmentally, economically and socially sustainable requires that several questions are answered, including the goal(s) of the system as being for food/floral production, enhanced foods for nutraceuticals, PMP (plant-made pharmaceuticals), bioremediation, life-support systems, etc. Given the goals and knowing the local climate that must be overcome to provide for quality production, then technology level can be determined. Next to determine is to what level of integration of component systems will be required to reach the technology level. Consideration must be given to energy sources, labor and automation, management, logistics, sensing, information flow, mechanization for watering, pesticides, remote sensing, and structure, and finally marketing requirements.

A wide variety of greenhouse technological packages representing low (simple) to high (complex) technology are available for the greenhouse industry, and can vary from simple metal, bamboo, or wooden-framed, plastic-covered structures to very sophisticated, aluminium-framed, glass-covered greenhouses. Achieving an economic compromise between the agronomic performances of each greenhouse design and its cost, in order to produce proper quality commodities at competitive prices, requires different solutions according to the local technical and socio-economic conditions. Each site, according to the selected growing strategy, related with the type of crop (fruit or leafy vegetable, cut flower, etc), growing and marketing calendars, a high level greenhouse technology package can be technically necessary but not always profitable, therefore requiring a lower cost greenhouse package to grow economically. Developing a proper management, adapted to the local conditions (climate, crop, etc) is necessary to reach the best potential results from each greenhouse package.

The agronomic performance of greenhouse crops is related to the technological level of the greenhouse, its equipment and management. The lower level is the passive greenhouse, with no climate control equipment, while the fully equipped greenhouse constitutes the higher level. In between both extremes, according to the local microclimate conditions and the chosen greenhouse production strategy, different "greenhouse technological packages" are available.

The investment costs of low cost packages for those in Mediterranean countries of mild winter climate are around 10% of the cost of a standard, fully equipped Venlo glasshouse in Holland. However, for Mediterranean growers to improve and guarantee the quality of their crops and extend their growing season, a greenhouse package with an air heating system must be chosen (Castilla et al., 2004).

The investment costs for extended season or year around production are offset by the marketing advantage for year around crop production. The challenge to supply high quality, horticultural products the year around can be achieved by two basic strategies, 1) producing within a high technology greenhouse at one site, which can sufficiently modify the local ambient climate for good to optimal crop production throughout the year; or 2) producing within two or more different locations, whose climates provide harvesting periods that are complementary, thus enabling a continuous and coordinated year around supply to the markets (Castilla and Hernandez, 2006). The first strategy using one production site has been successful for growers of the higher latitudes in North America and Europe. With a full complement of environmental control equipment, and even artificial lighting systems, high-quality vegetables can be continuously produced even during the low solar radiation winter season. In temperate, subtropical or tropical areas of the lower latitudes, this strategy is much less economical, because of the competitive field production, or the lower cost, lower technology local greenhouses, whose harvest periods overlap.

The second strategy of producing in two different locations, with different greenhouse design packages, is a popular new strategy. Growers in Holland, operate a farm internationally, for example in Spain, and maintain their greenhouse in the Netherlands, for the primary purpose to have a continuous production throughout the year (Marcelis et al., 2002). In the south of Spain, greenhouse production that ends with each hot summer season in lower coastal areas is being substituted by vegetable produce from the cooler highlands, typically within net-covered greenhouses, thereby enabling the year around supply. Similarly, larger growers in North America are complementing their protected cultivation production, in southeast Canada and northeast USA, with produce from northern Mexico, to achieve the same high quality vegetable production year around.

In North America, Mexico is the most rapidly developing vegetable production area primarily with low technology greenhouse facilities (Costa and Giacomelli, 2005). Canada is stabile with traditional northern European-style high technology greenhouses, and USA arid southwest and temperate north and east grows slowly with both low and high technology greenhouses. The USA has 1500 acres (591 ha) of vegetable production in CEA, out of an estimated 30,000 acres (11,950 ha) of total greenhouse production of nursery, greenhouse, and floriculture (Anonymous, 2002). The traditional production areas of Canada have remained unchanged, with 630 ha of greenhouse vegetables since 1999. Mexico field vegetable production (677,000 ha) has been the traditional but since the mid-1990's the Mexican greenhouse vegetable industry has steadily increased, with 950 ha in 2003(Calvin and Cook, 2005), and now exceeds 2500 ha in 2007.

In Japan, the total greenhouse area was 52,209 ha in 2005, with 80% of the total being simple, pipe-frame structures. Only 4.4% of the total was glasshouses, while all others were covered with plastic films. Polyvinyl chloride (PVC) films (66%) are the most common, but have been decreasing slightly, because the use of the fluoropolymer films (e.g. (ETFE) Ethylene-Tetrafluoroethylene copolymer) that offers increasingly longer useful life. Resource conserving equipment such as thermal screens (44%), and automatic irrigation systems (27%) are in use within the greenhouse industry. Heating systems are in 43% of all greenhouses, and 88% of the systems are hot air heaters (Anonymous, 2007a).

The technology levels of the greenhouse design in Japan are varied. The traditional growers use simple pipe-frame greenhouses and prefer less technology. They rely on their experience for decision-making, instead of using computers for automation. However, some new growers are using highly intensive technologies, which include large, multi-span, glass greenhouses, although there are few growers of 1 ha or larger sizes. The typical greenhouse structure is an average of 0.047 ha, with the average total area for one grower being 0.192 ha.

The total glasshouse area in The Netherlands has increased to 10500 ha from 8750 ha in 1980. The number of companies decreased from 15,750 in 1980 to approximately

8000 in 2006. The average greenhouse company is 1.3 ha, while the number of companies with an area in excess of 3 ha has increased from 130 to 825 from 1980 to 2006 (Anonymous, 2007b).

INNOVATION, A MULTI-DISCIPLINARY PROCESS

Advances in greenhouse system design and management requires a broad array of partnerships with the academic, private and public sectors of society. Successful applications include, at least to some degree a multi-disciplinary approach of the sciences, engineering and economics, while for ultimate success, societal and political support must also be included.

Traditionally, the greenhouse systems symposia, initially known as ACESYS, and more recently GreenSys have been multi-disciplinary in their content and have provided a systematic approach to understanding greenhouse environmental control and crop production technology, while offering a unique and highly successful educational experience within an inclusive collaborative scientific environment. The Naples GreenSys2007 Symposium was the seventh in a series spanning 13 years, five countries and 3 continents (Belgium, Italy, Japan, Taiwan and USA). As a result these symposia, have focused on the complexity and multifaceted aspects of greenhouse design, development and management, have become important venues for inter-disciplinary discussions for those interested in protected cultivation.

New insights and novel approaches to greenhouse design will become successful from a combination of technologies, analytical methodologies and restrictions imposed by design applications. The following examples will focus on Automation, Environmental control and Energy considerations.

Robotics and Automation

Increasing labor costs and a growing shortage of experienced and educated staff have encouraged mechanization and robotics in the greenhouse industry. A wide range of equipment is currently available for the initial tasks (seeding, planting, internal transport), and the final tasks (internal transport, grading, packing, shipping) of the production cycle (Van Henten, 2006). Human hand labor is typically required for crop maintenance and harvesting. During the first and final phases of the production cycle, the position, shape, size and other characteristics of the plant are relatively well defined and uniform, thus, basic industrial automation, based on mechanical solutions, using few sensors and limited computing power can perform sufficiently. Crop maintenance and harvesting are much more difficult to automate, because position, shape, size and color of products vary widely and thus high-tech mechanization, robotics or mechatronic systems are required. These systems rely extensively on sensors and computing power to process data and to mimic the intelligence and very efficient eye-hand coordination of humans. Despite considerable effort on developing high-tech mechanization for greenhouse horticulture in recent years (Kondo and Ting, 1998; Kawolek and Rath, 2008; Yamamoto et al., 2008; Belforte et al., 2008; Henten et al., 2008), practical implementation of these systems is very limited. Examples of commercial high-tech mechanization are the grafting robot based on the work of Kobayashi, et al. (1999), and a robot to produce cuttings of roses, the Rombomatic (Rombouts and Rombouts, 2002). Currently, in the Netherlands, two commercial projects are underway to develop robots for crop maintenance and harvesting. One project, called Tomation, has a goal to develop a leaf removal robot for tomato plants grown in a high-wire cultivation system. Another project proposes building a harvesting robot for roses. In Japan, work is underway to construct a strawberry harvesting robot. Given the growing pressure on horticultural companies to improve the efficiency of their production, high-tech robotics and automation will have an important future in protected cultivation.

System Logistics

Following similar developments as in the automotive and the electronics industry, the horticultural industry is developing procedures to improve the efficiency of the labor force. Especially with the increasing size of facilities, choosing the right layout of main paths and aisles is crucially important (Eben-Chaime et al., 2008). A paradigm shift has become apparent in horticultural industry, and instead of the maintenance staff moving to or through the crop, the crop is transported (on movable benches or movable gutters) and brought to the staff for maintenance and harvest. This approach is common practice in the production of potted plants. Production of roses, gerbera, chrysanthemum and even tomato has been evaluated in the Netherlands. However success of these systems is not guaranteed and research into this direction is required (Blandini et al., 2008; Hayashi et al., 2008; Hidaki et al., 2008; Giacomelli et al., 1994; van Weel et al., 1991).

Sensing Techniques - Monitoring With Sensors

As product quality and efficient use of energy and water resources become critical, the information for decision-making is crucially important. This chain of information flow that leads to control begins with sensing techniques to produce information about the particular processes. Sensing techniques are subject of ongoing research and development, covering solar radiation sensing (Takakura, 2008), soil moisture content sensing (McBurney et al., 2008), sensing light interception by the canopy (Janssen et al., 2008a), a soft-sensor to measure the ventilation rate in greenhouses (Stanghellini and Bontsema, 2008), fruit firmness sensing for tomato (Zsom-Muha et al., 2008) or sensing water stress in tomato transplants by monitoring stem diameter variations, sap flow and leaf temperature (Abdelaziz et al., 2008; Vermeulen et al., 2008). A novel sensing technique for greenhouse horticulture is based on measuring organic volatile components emitted by the plant, when changes in the health and metabolic state of the crop occur (Jansen et al., 2008b).

The plant condition within the greenhouse environment is more important than the greenhouse climate condition. Much study is in progress to monitor the near real-time plant condition, such as leaf temperature, transpiration, or photosynthesis so that the information can be used for decision-making in environmental control. This topic of 'speaking plant' has been discussed for a very long time, and now there are more opportunities than ever to listen to the plant.

Monitoring, Control and Decision Support -Wireless and Remote Sensing

Producing quality crops using available resources as efficiently and cost-effectively as possible has been the motivation for development of new sensing techniques and wireless sensing networks. However, the ultimate challenge will be to translate all the data into management decisions. With the large number of processes within increasingly more complex systems, providing large amounts of data, supporting the grower with definitive and useful information is still a challenging task. This will require more fundamental research in model-based optimization (e.g. Ioslovich and Gutman, 2008; Henten and Bontsema, 2008), evaluation of such control schemes (Kläring et al., 2008), implementation and experience of such schemes in practice (Markvart, et al., 2008), as well as, the transfer of knowledge from research to the growers to improve acceptance of this new technology (Buwalda et al., 2008).

Various sensing techniques are commercially available for measuring the status of the aerial climate in the greenhouse, the conditions in the root zone or the status of the plants. Usually, these measurements are done at a limited amount of locations. Sensing of the spatial distribution of these conditions in horticulture is important. Wireless communication techniques, implementation of distributed sensor networks comprising hundreds of sensors are possible and offer a valuable source of information (Carrara et al., 2008; Tuijl et al., 2008; Lea-Cox et al., 2008). Telepresence can provide a safe virtual environment for monitoring, decision-support, and system diagnostics of a hostile or remote environment with web cameras, climate control computers and the Internet (Giacomelli et al., 2007).

Environmental Control with Natural Ventilation

Natural ventilation is of greatest interest worldwide for air exchange and cooling of the greenhouse climate. Natural ventilation is much less energy consumptive than mechanical forced air systems but they cannot provide the precise air exchange, and evaporative cooling of mechanical fan systems. Therefore techniques to improve the design of naturally ventilated and evaporatively cooled greenhouses are critical for modern, energy saving greenhouses. Many types of naturally ventilated greenhouses are commercially available, and they include a combination of partial roof and sidewall ventilation openings. More recently, open-roof greenhouses have become available. The open-roof greenhouse can provide plant air temperature close to outside temperature during the day, and protect from cool night air temperatures without the need for mechanical fan ventilation (Sase et al., 2002). Computational Fluid Dynamics (CFD) is a mathematical technique to help evaluate the air exchange and temperature distribution within naturally ventilated greenhouses. CFD will help the design of ventilation systems and ventilation control strategies.

Environmental Control with Structure Covering

The selection of greenhouse glazing or covering material has changed dramatically from the traditional glass or simple thin film plastics. New plastic films that promise to improve the available solar energy for plant radiation use efficiency (RUE) inside the greenhouse, and have a longer useful life, reduce energy, and generally provide more optimum conditions for plant production have recently become available. For example, "F-clean", which is a fluorine-based carbon polymer, could become an alternative to the glass, because of its thermal properties that are similar to the glass, but it is lighter, possibly easier to install and safer than glass during high winds.

Films with colored pigments for spectral modification are of interest for plant development, although much has to be proven for their use. Films which reflect or absorb the non-photosynthetic wavelength of solar radiation can be highly valuable. Such films are under development to transmit solar radiation for efficient plant growth, but prevent transmission of unneeded wavelengths, such as NIR (near infra red) which will help to passively manage the climate.

Screen materials are often used for greenhouse cover, to allow air exchange, but to prevent insects from entering the plant production area. The importance of insect exclusion is for viral protection from insect vectors. The optimum design for implementation of screens, especially those with small mesh (0.4 mm or smaller mesh (hole) size is needed to exclude the tobacco whitefly, *Bemisia tabaci*) is a great challenge, because the screens significantly reduce air exchange, especially with natural ventilation, but also with mechanical ventilation. The least energy intensive greenhouse is a passively ventilated structure covered only with insect screen. However this design is not universally acceptable, and at sites of extreme climate (hot or cold) conditions, it will not provide acceptable year around plant environments.

Environmental Control for New Production Ventures

New crops have been proposed for protected cultivation that are much different than current food or floral crops. These new crops may include transgenic medicinal plants for protein production, or functionally enhanced plants for nutraceutical production. New applications may also provide controlled environments for production of plants for their biochemical processing capabilities. These may include: bioremediation of air (e.g. sequestration of combustion products (CO_2, SO_2, NOx)], of water (e.g. phytoremediation of plant nutrients, heavy metals), and of soil (e.g. rhizofiltration of heavy metals, hydrocarbons); and bio-based renewable-energy manufacturing (e.g. biodiesel fuel from algae). Systems for extra-terrestrial applications may utilize similar plant bioprocesses for air/water revitalization in closed life support systems. These Bio-Pharming applications for improving quality of life via medicinal or nutraceutical production are all based on the technology platform of controlled environments and hydroponic plant production. Some applications of plant biotechnology will require biologically closed systems.

New, non-traditional locations for food production systems, such as roof-top urban agriculture, vertical farms, and community-supported agriculture, would serve markets for locally grown foods which benefit from having minimal transportation distance and time, as well as, predictable production of safe, high quality food crops (Vogel, 2008).

Energy Related Issues

The Solar Greenhouse project utilized a deep aquifer for seasonal storage to provide complete summer cooling and winter heating for a closed greenhouse (Bot et al., 2005). This system utilized heat pumps and heat exchangers to move energy into and out from storage. The design included energy conservation procedures that reduced energy demand nearly 50% (compared to a single cover without an internal thermal screen), by improving the characteristics of the greenhouse cover. Both et al. (2007) have investigated the concept of using heat pumps with much smaller storage units with a capacity of a days heating or cooling requirements. A small heat pump (10% peak heating demand) with water storage provided as much as 50% of annual heating demand in one climate scenario.

A closed greenhouse system design has demonstrated increased crop yields resulting from sustained elevated atmospheric carbon dioxide within a ventilation-limited structure that maintained air temperature and humidity control for enhance plant growth. Such interest to approach the ideal energy self-sufficient greenhouse (with zero emissions), will also include research on energy saving systems.

The sudden and dramatic rise in energy costs brought on by the worldwide oil embargo of the 1970's stimulated significant research and development of energy conservation measures for commercial greenhouse production (Mears et al., 1980). In addition, energy sources as alternatives to fossil fuels, including solar and waste heat were studied and implemented as demonstrations (Manning and Mears, 1981; Manning et al., 1983; Mears and Manning, 1996). This decade of energy concerns provided important technological advances that resulted from engineering innovations. These included moveable thermal curtain systems for night heat retention and day time shading, floor heating systems, and improvements in low-cost plastic glazing materials such as polyethylene film that extended useful life, and enhanced energy conservation with double-layer, air-inflation covers and film additives for infrared (IR) heat absorption. It is expected that the rapid fuel costs of the decade of 2000 will provide for further innovative developments. The energy-saving technologies were accepted and remain fundamental within the industry even today, because the grower gained additional management tools which provided more control of the greenhouse climate, resulting in improved plant production and quality. Thus all future acceptable and long-lasting innovations will require similar non-negative impact on production quality or yield.

CONCLUDING REMARKS

There are numerous broad challenges to overcome for future innovations in greenhouse design and applications (Flinn Foundation Report, 2008). First, there is a lack of students studying for careers in Controlled Environments and Protected Cultivation, and there is a lack of educational and research institutions available that will provide the necessary holistic and interdisciplinary education to enable these students to meet the career demands of this important sector of modern biologically-based enterprises. Second, rapidly changing food and fiber production practices mandate intensive, year round production of super-yielding species that must withstand abiotic and biotic stresses, together with meeting specific market requirements that demand highest quality and continuous readily available access. Third, implementation of plant improvement technologies combining both traditional breeding and transgenic approaches, for controlled environment production of plants for food, enhanced nutrition, medicinal needs and environmental remediation remain largely untapped, again primarily from a lack of knowledgeable corporate investors. Fourth, technology for greenhouse system management implies an understanding of the capabilities and control of the technology and the implication of its implementation. This again requires education for society.

Controlled Environments and Protected Cultivation should be considered as a technology platform, to become the production basis for a multitude of commercial ventures involving cross-commodity, plant component, and whole crop production systems. Just as Controlled Environments and Protected Cultivation is today the basis for a commercially viable food production system worldwide, there are many other plant and crop production systems to be envisioned to be grown not for harvest of their products but for the transformation of resources by their biological processes, accomplished with assurance of their production or process output in a safe and secure manner, and to overcome the resource challenges imposed by the political, economic, environmental and social issues.

Finally, it is important to keep in mind that innovation occurs through an evolutionary process, and as innovation becomes accepted, it is no longer innovative, but commonplace. The innovation of today is simply an accepted detail of design at some future time.

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Tables

Table 1. Greenhouse area world wide (adapted from Anonymous, 2007).

Location	Plastic greenhouses and large plastic tunnels (ha)	Glasshouses (ha)	Total
Western Europe	140.000	29.000	169.000
Eastern Europe	25.000	1.800	26.800
Africa	27.000	600	27.600
Middle East	28.000	13.000	41.000
North America	9.850	1.350	11.200
Central/South America	12.500	0	12.500
Asia/Oceania	450.000	2.500	452.500
Grand Total World	692.350	48.250	740.600

Figures

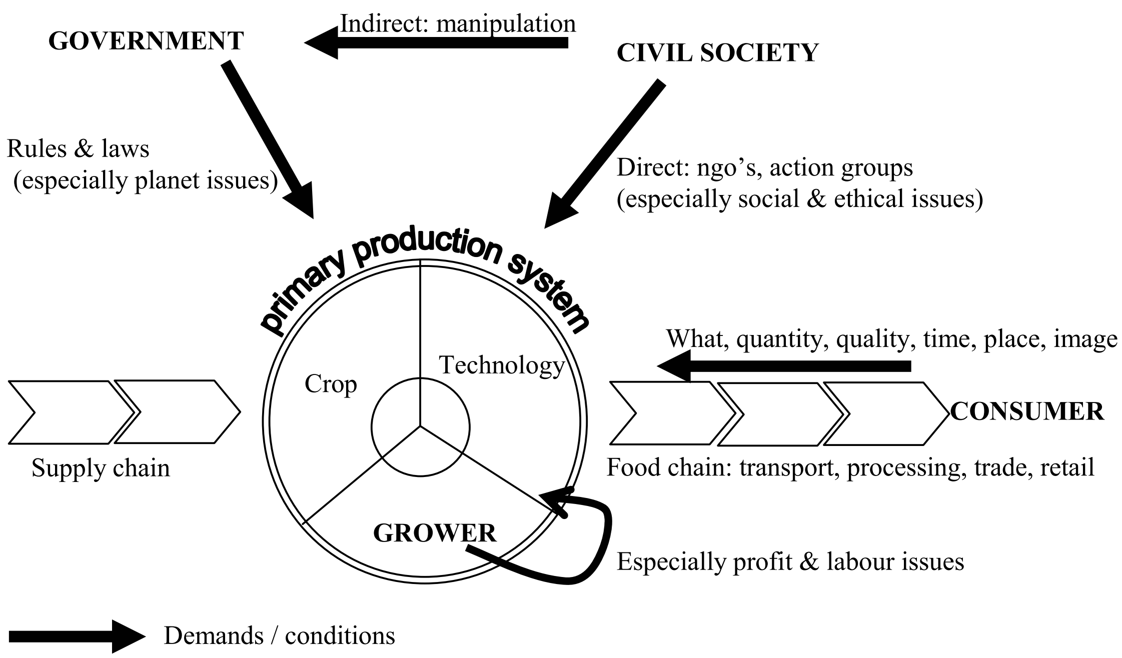

Fig. 1. Schematic model of a plant production system as part of a chain and the outer world. The four major actors are given in bold (adapted from Groot Koerkamp et al., 2007).