Greenhouse Production Systems for People

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Abstract

Environmentally sound greenhouse production requires that: demand for market products is understood; greenhouse design addresses the climate circumstances; input resources are available and consumed efficiently, and; there must be a reasonable balance of production products to the environmental impacts from system. Engineering greenhouse production systems to meet these requirements must include: a cost-effective and structurally sound facility; various sub-systems controlled to interact harmoniously together; and educated and experienced system operators. The major components of the environmentally sound greenhouse are: Super-structure and glazing (for a specific location and climate conditions); Climate control sub-systems (ventilation, heating, cooling, CO_2 control, pest protection, energy conservation, shading/lighting); Monitoring and control (for system operations data; decision-support systems; and, operations control procedures); Automation systems (for quality control, and effective resource utilization); and Crop nutrient delivery system (for control of plant root zone environment). Effective greenhouse engineering design, operations and management, must incorporate input from academic, private and public sectors of society. Therefore this team of researchers, educators, industry/ business, and experienced crop production operators has cooperated to include a current real-world applications perspective to the presentation. Greenhouse production systems are described that not only include the fundamentals for success, but also the combination of sub-systems, at appropriate technological levels to meet the design requirements and restrictions for success. The collaborators on this presentation have capabilities and experiences of successful greenhouse production systems from around the world that range from simple, low-input systems to highly complex production systems. Our goal is to emphasize the current basics of greenhouse design, and to support the symposium about greenhouse production systems for people.

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INTRODUCTION

Vox et al. (2010) provide an excellent discussion on “sustainable” greenhouse designs and the considerations necessary to develop such greenhouses. Gafsi et al. (2006) explain that sustainable systems are those that can survive into the future while preserving natural resources and without limiting capabilities of future generations of farmers. Furthermore, for a system to be sustainable it must be socially acceptable, economically viable and environmentally aware, and include cultivation procedures, structural facilities and equipment that will be resource effective [energy and water], limit waste, and limit the use of petroleum-based chemicals (Vox et al., 2010). Giacomelli et al. (2007) outline similar related goals for the future of the greenhouse controlled environment industry. This writing will extend the above discussions toward application for this time in the world history of greenhouse food crop production, and the challenges of implementing and maintaining viable production systems given the social, environmental, economic and technological factors.

Modifying the greenhouse design and its operation to meet performance standards, will always create subsequent consequences, some which are anticipated, but others unknown. Thus there will be need for trial and error testing with evaluation. For example, making a greenhouse more environmentally friendly may add burden to operational demands. Using fossil fuels and chemical fertilizers are less labor intensive during production than biofuels and compost, at least with current technologies. Market demands on quality and yields must be maintained, and if either noticeably changes as a result of greenhouse design and operation modifications, then income and profits will drop. Changes made to reach sustainability that reduce production and labor efficiency, as measured by production per unit area and labor input per unit product, are themselves not maintainable. Finally, new technology that adds variability into the production process, such as inconsistent energy content of biofuels, or variable nutritional value of the compost, would be a major concern of any competent grower, who requires that a successful and quality crop is produced every cycle.

Success in production practice provides nutritional foods within viable technological and marketing systems. To do so requires education. Technology is employed in an evolutionary process with varying degrees and measures of success. At a given location in the world, the implementation of new technology and/or operational procedures must be proven technically viable; and then, an educational process must provide a sufficient knowledge/experience base for the support of operations.

As described by van Weel (2010), food production in modern, technology-based greenhouses is characterized by large inputs of energy, carbon dioxide, water, fertilizers, substrates and pesticides to meet production expectations. Climate change and water quality problems have forced drastic changes to the greenhouse systems. The hydroponic cultivation of crops is believed the best solution to prevent emission of fertilizers and pesticides to the environment from the greenhouse. New systems have been developed that overcome specific problems of hydroponic cultivation such as plant support, oxygen depletion and spread of diseases. This has led to better opportunities for robotic crop harvest, optimized plant spacing schedules, and improved climate conditions.

Maximizing the use of the greenhouse production area is essential for profitability. Certain costs are incurred regardless of how the production area is used; therefore unit production costs can be reduced by careful management. Furthermore the effective use of a plant propagation area, separate from the production area, can reduce crop production time and increase the number of crops per year. Maintaining optimum crop density within the production area at all times is vitally important. However it should never become a negative factor to desired market quality.

Computer-based monitoring using plant sensors that provide information about water balance, carbon dioxide consumption and plant growth currently exist in commercial operations. In conjunction with climate control computer systems and Internet tools it is now possible to view and measure the real-time condition and performance of the crop; and, provide data and production information to experts, colleagues, growers or students throughout the world. This will lead to a rapid distribution and development of knowledge and understanding, with subsequent technological improvements.

Other considerations include the health and long-term welfare of the greenhouse worker. We must consider the working conditions and provide sufficient protection from chemicals and thermal stress. Also as we exploit advantages in local resources, whether natural or human, we must maintain a high ethical standard to prevent extensive or long lasting harm. Finally, projects should be evaluated on a spatial, as well as, temporal basis. Scale offers benefits in terms of knowledge base or technology utilization or buying power. Larger groups of growers could invest collectively in research, development, energy and other resources that would be independently impossible. Useful service life (5 versus 50 years) must be considered in design costs and productivity.

FUNDAMENTALS

Engineering greenhouse production systems to meet design and operations requirements, as well as product market requirements, must include:

- Cost-effective and structurally sound greenhouse structures, absorbing the optimal amount of solar energy and limiting resources and waste discharge to the environment;
- Sub-systems within the greenhouse to interact harmoniously to provide the environment for the biological processes, labor, automation, internal transport and distribution for product;
- System operations that are monitored and controlled by educated and experienced operators; production of products of defined quality, desired quantity and timing, and;
- Monitoring and data collection systems to inform the consumer about the product, and in conjunction with climate control systems, provide the optimal environmental conditions for healthy plant growth and for biological pest control, stimulation of natural defences, and, when desired, to incorporate the basics of organic crop production.

The major components of the greenhouse crop production system include: Super-structure and glazing (for a specific location and climate conditions); Climate control sub-systems (ventilation, heating, cooling, CO_2 control, pest protection, energy conservation, shading); Energy collection, storage and production systems; Monitoring and control (for system operations data; decision-support systems; and, operations control procedures); Automation systems (for quality control, effective resource utilization, and, safety); Crop nutrient delivery system (for control of plant root zone environment).

Super-Structure and Glazing

Greenhouse structures and glazing must be appropriate for the crops that may be grown during the planned life of the structure and for the location. The investment in these components should consider reducing risk to the systems, crops and workers. Building codes, municipal zoning rules and structural design standards must be met for many applications.

1. Super-Structure. Traditionally greenhouses were wooden or steel framed structures covered with glass glazing. A variety of new greenhouse designs use lightweight rigid or flexible film plastics, allowing for innovative forms of arch-shaped greenhouse structures. These are characterized by single-spans, having short or no side walls (currently called high tunnels), or multi-span greenhouse structures with larger sidewalls. These lightweight structures provide improved solar radiation transmission at reduced costs with a minimum of material and profile such that plant production can be maximized with uniformly distributed solar radiation transmission. Generally the long-lasting supporting structures for greenhouses are made of high strength zinc coated steel members (sometimes painted white for light reflection and reduced surface temperature in contact with plastic film covers) of large prefabricated spans that are easy to transport and install.

Investment capital must be carefully used within projects that are appropriately designed to meet local climate difficulties or the specific crop environmental demands.

The distribution of cost for the structure, environmental control and growing systems should be appropriate for the crop and local conditions. In some areas worldwide there is an over emphasis on structure and a lack of knowledge and implementation of environmental and crop production systems. The greenhouse manufacturer, engineer and designer must have knowledge of crop production requirements such as environmental and nutritional needs so the result is maximizing the crop growth potential.

Whether glass or plastic is chosen for glazing may generally be decided by the limitation of capital investment. However, glazing longevity, building codes and safety should contribute to the final choice of glazing.

2. Glazing. The glazing or covering of the greenhouse must protect the crop against external climatic conditions and provide beneficial microclimatic conditions for the crop. The spectral and physical distribution and the intensity of wavelengths transmitted into the greenhouse directly influence the growth rate and developmental quality of plants. Glass panels, in single or double layer, remain the best materials that satisfy the radiometric properties. Low emissivity glass reduces the nighttime long wave infrared (LWIR) losses. New developments in glass include non-iron glass, anti-reflection coatings and extremely large hardened panels which have further improved the transmission. Diffusive properties of glazing transmit direct light deep into the crop, leading to extra growth. The operations knowledge for adjusting the greenhouse climate to new glass types has just started to develop. Developments for high investment greenhouses are the partially transparent photo-voltaic glass panels to be installed on the southern oriented pitched roof and can represent a potential solution for an energy self-sufficient greenhouse for heating, cooling, shading and lighting requirements.

Prior to 1950, greenhouses were only covered with glass. Today plastic covering materials for all crops are more common, including Europe 120,000 ha (Pardosi et al., 2004), China more than 3,000,000 ha (Chen, 2010), Japan/Korea/Taiwan 150,000 ha, (Kacira et al., 2004), North America 100,000 ha (Calvin and Cook, 2005), and they provide a good alternative to glass primarily for their low cost, high strength to weight ratio, and structural adaptability. The useful life of plastic films (3-4 years) is short compared to rigid plastics (more than 15 years), or glass which can last as long as the physical structure, barring catastrophic damage by hail.

Single or double-layer films are used. Double-layer films are separated and held semi-rigid by air pressure (25-50 Pa), providing heating energy savings of 33% compared to the single layer, while reducing solar radiation transmission by 10-20% compared to a single layer. Furthermore, double layer films, can provide better heating energy savings than a single glass cover, because of reduced infiltration losses. Double film layers reduce water condensation on inner surface of the cover and the subsequent water dripping to crops below, while it helps avoid the thermal inversion of the inside air temperature (2-3°C) that can occur on clear winter nights within unheated structures with a single plastic film covering.

Rigid plastic sheets may be single layer, usually corrugated, or double layer of various dimensions. The various plastic materials differ in mechanical properties, radiometric characteristics, and for the presence or absence of additives in the chemical composition to provide energy-saving, anti-fog, anti-drip, and/or light spectral modifying characteristics There are many factors which influence the useful life of the plastic, including the specific polymer, composition of additives, thickness, method of attachment to the structure, exposure to agrochemicals, and solar exposure hours.

Sometimes overlooked when comparing glass to double-layer air-inflated plastic film structures, is their survivability in wind and hail storms. Double-layer air-inflated film structures allow deformation of the outer layer to accommodate fluctuating wind loads thus reducing the maximum stress on the film and structure (Mears et al., 1976).

Climate Modification

Climate control systems can improve sustainable greenhouse production practices not only by maintaining optimum crop climate, but also by providing information which leads to knowledge about the plant microclimate and its influence on plant growth and development. The light, air temperature and relative humidity, root zone temperature, carbon dioxide, water and nutrients are monitored and controlled to provide a biological balance for the plant in relation to the outside environment. This requires carefully located and calibrated sensors to provide information about the environment and the plant reaction, as well as, information for control systems to provide a uniform and predictable response. Wireless sensor technology is being developed for use with the Internet for direct communication and cooperation among growers, researchers, advisors and suppliers in the field by sharing real-time environment and plant data and interpreting their meanings with growers. This knowledge and the subsequent response will be based on laws of physics, in addition to the qualitative grower experience.

1. Ventilation. Moist air exchange by ventilation is essential to control air temperature, relative humidity, carbon dioxide concentration, and subsequently leaf temperature. Ventilation can be quantified as volume air change per hour of the greenhouse. Much study has focused on greenhouse volume air change per hour which offers insights into the effectiveness of natural ventilation. However for design and operation purposes the ventilation should be based on area of solar interception, thus 2-3 m tall structures or modern 5-7 m tall greenhouses require a minimum of 3 m^3 min^{-1} per m^2 floor area for ventilation. The focus should be on air temperature control within the approximate volume space where the crops are growing (to 3.3 m average height).

Multiple span greenhouses with continuous ventilation openings on the side walls and on the roof, providing maximum air exchange, can achieve more than 50 h^{-1} (volume air changes per hour) with wind speed greater than 2 m s^{-1} perpendicular to greenhouse walls, and decrease to 20 h^{-1} in case of roof ventilation openings only, with the same wind speed. Side wall openings must be designed to protect the crop from direct effects of excessive air speeds (greater than 1.5-2 m s^{-1}).

For forced ventilation the greenhouse is almost always under negative pressure, therefore the air enters through controlled openings on the end wall and is discharged through fans installed on the opposite end wall. The distance between the fan and the inlet opening depends on local climate but should generally be less than 50-60 m to limit air temperature rise from inlet to fan to less than 5-7°C. All the side windows and doors should be closed to effectively achieve this directed flow.

Insect screens can be installed at the openings for natural and forced ventilation systems to prevent insects and virus vectors from entering, thus reducing need for chemical pest control. They are made of minute threads in a close mesh format, creating opening sizes of 0.2-3.0 mm. All insect screens reduce air flow because of their very low porosity and, therefore, require an appropriate design of surface area to meet airflow requirements. However, one major cause of crop loss, low production quality and disease in the greenhouse is the conflicting relationship between the need for insect control and for ventilation. Some solutions are based on crop management (lower plant density) and some on the design of the greenhouse (taller structure, higher side walls and smaller units. Recent designs using positive pressure ventilation which provides air exchange by forcing insect-free outside air (using screens) into the greenhouse environment has been effective for insect control and ventilation, but it has been limited in commercial use.

A significant improvement of ventilation in a greenhouse with insect screening can be achieved by changing the physics of energy exchange in a greenhouse from large volumes of air, which are limited by the resistance of screening, to evaporation of water in combination with a direct exchange of the water vapor with the outside world. Much lower amounts of air exchange are required because of the very high energy content of water compared to air. Practical challenges still exist with this method, such as uniformly distributing the fresh air throughout the greenhouse to prevent horizontal air temperature gradients.

Ventilation air must penetrate into the plant canopy, through the leaf boundary layer and into the leaf, thereby maintaining good crop health by photosynthesis with CO_2-O_2 exchange, cooling the leaf with water-water vapor exchange, and reducing disease.

Proper crop spacing can enhance these actions. Mechanical HAF (Horizontal Air Flow) fans installed above the crop (1 per 250 m^2) create air flow in the upper region of the crop, resulting in improved overhead air uniformity along the length of the greenhouse.

Without ventilation the atmospheric carbon dioxide will be depleted inside the greenhouse under daylight conditions (to 150-200 ppm) providing reduced crop photosynthesis. Co-generation procedures using energy storage provides carbon dioxide as a by-product which can enrich the closed or semi-closed greenhouse atmosphere (up to 1000-1500 ppm).

2. Heating. Energy consumption for heating within temperate and cold climate regions is an important factor affecting environmental and economic sustainability of greenhouse production. Energy use can be more than 50% of the production cost. Typically non renewable energy sources such as coal, oil, natural gas are used which consume valuable resources and provide emission of gases (CO_2, CO, NO_x) to the atmosphere. Prior to designing a heating system it is necessary to limit the required energy, for example, by including insulation measures such as energy screens, reduced ventilation and double glazing

Heating energy demand may vary from 1600 MJ m^{-2} yr^{-1} in northern countries like Norway, to 1400 in temperate countries like The Netherlands, to 700 in mild countries like Italy, to less than 400 MJ m^{-2} yr^{-1} in southern Mediterranean countries (Scarascia-Mugnozza, 1995), and to minimal or none required in the tropics. Heating system design is based on the energy balance for the highest expected heating demand determined by the heat loss due to infiltration, conduction/convection and LWIR radiation through the greenhouse covering material of the side walls and roof, and through the soil. It depends on the outside climate conditions (air temperature, RH, wind speed, cloud cover), the desired inside air temperature set point, the surface area of the cover, and the design of the cover material. Equipment must be chosen to meet the energy demands and to distribute the heat uniformly.

The most common heating systems use water or air as the heat transfer media. Hot water systems with the layout design of plain or finned pipe with pumps to provide uniform heat delivery and to prevent icing in gutters when that can be an issue. Heating pipes under benches or plastic piping in floors or benches provide independent control of the root zone and air temperatures, and greatly improve plant temperature uniformity. Circulating water temperature is modulated to meet demand rather than cycling the flow on and off with very hot water. Achieving uniformity with forced hot air systems is more difficult and distributing the air through perforated clear plastic tubes helps, particularly in systems where multiple air tubes with air blowers can be installed under benches or suspended crop rows.

Sustainable greenhouse heating systems from energy sources include cogeneration systems, waste heat from industrial plants, biomass energy, geothermal energy, solar thermal or photovoltaic and wind energy. Electric energy produced with solar photovoltaic and wind energy systems (Vox et al., 2008) can be associated with heat pump equipment connected with a geothermal system in deep soil or in a relatively shallow aquifer. An advantage of the heat pump is its inherent coefficient of performance (COP), with ability to transform 1 kWh of electric energy in 3 to 5 kWh of heating energy.

Partially transparent photovoltaic glass or plastic panels have been designed and are being tested as part of the south oriented roof of the greenhouse, providing crop protection, shading and electrical energy. The high investment costs are expected to amortize in 10-15 years based on increased cost of fossil fuels, and to government incentives for renewable energy sources.

In mild and warm winter climate areas, like Mediterranean, Semi-arid, and Subtropical regions, greenhouses are not typically heated although crops would benefit in morning starting growth if heated. They may instead be equipped with simple emergency air heating system (anti-frost systems). With clear sky winter nights and single plastic film covering, a “thermal inversion” can occur, causing the inside air temperature to become 2-3°C below the outside temperature due to radiant energy (LWIR) loss through the glazing (Scarascia-Mugnozza, 1995). In addition, the greenhouse air relative humidity rises and water condensation occurs on the inner side of the covering. Reducing energy loss by double plastic glazing or with LWIR absorbing plastic covering films, or internal thermal screen can resolve this problem.

Practical applications of heat delivery systems require an understanding of the air temperature and humidity demands of the crop, and a control system that can monitor greenhouse or plant microclimate conditions and provide an appropriate response. Combinations of heating systems, when properly installed and controlled, offer opportunities of improved conditions and energy savings. For example, hot air heating above the crop is challenged to provide heat deep within the crop canopy; bottom heating the floor directly warms the soil or the plant root system, but can only slowly modulate the canopy air temperature above; while heated pipe-rails located at floor level can respond to the lower crop canopy.

Heating is also important for dehumidification. Many warm climate greenhouse crops (subtropical regions) benefit from dehumidification using heat pumps to dehumidify, as well as in the systems being used to store summer heat for winter use in large aquifers (Voogt and van Weel, 2008). Relatively small heat pumps with short term storage of warm and cool water can capture heat for night use while cooling the daytime. Both et al. (2007) discuss potential system performance with a heat pump system sized only for 10% maximum required heating and heat storage matched to only 12% the maximum cooling load which can provide 50% of annual heating requirement and many hours of cooling. Such systems allow the greenhouse to remain unvented (closed) for improved atmospheric CO_2 enrichment. The use of warm and cool storages extends the annual beneficial hours of operation of the small heat pump.

3. Cooling. When ventilation alone is insufficient to limit air temperature rise to within an acceptable value, further heat dissipation can be accomplished by either limiting solar entry via shading or heat extraction via supplemental cooling. Satisfying the cooling demands of the greenhouse system to meet the plant needs remains a technical and economic challenge. Passive cooling technologies are preferred over energy intensive mechanical systems. Even when properly designed, passive systems have an inherent unacceptable variability, while mechanical cooling systems offer more direct control potential.

As solar collectors, greenhouses use solar radiation that can vary from 2800 to 3600 to 6000 MJ m^{-2} yr^{-1}, respectively, for northern (Norway), temperate (The Netherlands) and Mediterranean (Italy) countries (Scarascia-Mugnozza, 1995). During clear spring and summer mid-day conditions, the instantaneous solar radiation can be 1000 W m^{-2} and the air temperature can exceed the maximum biological temperature tolerated by the crop (25-35°C), even though the greenhouse is equipped with ventilation and shading systems.

Evaporative cooling with ventilation can reduce the inside air temperature below outside. Evaporative cooling procedures have traditionally been the most cost effective means of cooling (Montero, 2006). Mechanical refrigeration systems have historically been too costly for cooling due to hardware and operation expenses. However, heat pumps have been used in greenhouse compartments used for biological containment and for special applications such as orchid flower spike forcing. There is increasing interest in adapting electrically powered heat pumps in specialized circumstances (high valued crops) due to the 3-5 fold energy advantage, especially when combined with co-generation or geothermal situations where heating, as well as, cooling needs can be addressed.

Either fan and pad or mist/fog systems are used for cooling. While fan/pad systems only affect the air mass entering the greenhouse, mist/fog systems affect the distributed air mass already within the greenhouse. They use the same evaporative process of adding liquid water to warm, dry air and transfer latent heat by evaporation (2.45 MJ kg^{-1}) of water. The process is most effective when their exists large differences of dry and wet bulb air temperatures in the environment. Temperature reductions of 8-16°C are possible with air relative humidity increases from 10 to 90%.

The fan and pad system is made of wet pad panels continuously wetted with water through which the external warm dry air passes because of the suction produced by the greenhouse ventilation exhaust fans. Fog cooling consists of low flow, high-pressure nozzles installed at or above gutter height (well above the plant canopy) which provides micro-droplets (5 to 10 µm diameter) for immediate evaporation and cooling. Controlled ventilation must continue to exchange water saturated greenhouse air with dry outside air. With natural ventilation all ventilators must be fully opened for air exchange, and for mechanical ventilation a reduced fan capacity is required. The cooling efficiency depends on the dry and wet bulb temperature difference of the outside environment, but also on the ventilation system. Difficulties occur when fog nozzles become blocked by water impurities, or when they provide water dripping onto the crop.

Various studies on the performance of evaporative cooling have been reported, including fog cooling in combination with fan ventilation or natural ventilation. Montero (2006) reviewed available information concerning the effect of evaporative cooling on greenhouse microclimate, water use efficiency and plant response. Guerrero et al. (2010) developed a control strategy for a naturally ventilated greenhouse equipped with a variable high pressure fogging (VPF) system. The computer simulation of VPF compared to an on/off fixed pressure fogging system control strategy indicated that the VPF control strategy would provide 14% water and 6.6% energy savings while reducing the pump cycling by 34%. The temporal uniformity of greenhouse air temperature and relative humidity were also improved.

Optimizing ventilation and evapotranspiration during evaporative cooling to provide more favorable growing conditions for plants in semiarid climate and less water use has been completed by Sase (2008). Based on the steady-state energy balance, a decrease in ventilation rate increased relative humidity, resulting in a decrease in plant evapotranspiration. The inside relative humidity in a fog-cooled greenhouse decreased with an increase in ventilation rate, as predicted, while the water use increased (Sase et al., 2006). They tested a control algorithm based on energy balance adjusted ventilation openings and the control of fog to maintain air relative humidity and temperature simultaneously within a desirable range, while reducing the water use. A study for pad-and-fan cooling (Sabeh et al., 2006), demonstrated that there were no significant reductions in average air temperature or relative humidity beyond a specific ventilation rate, while the pad water use increased linearly with ventilation rate.

Net radiation management can help offset the actual cooling demand. Implementing movable or fixed shading systems, in conjunction with glazing, greenhouse site location, and greenhouse orientation contribute to improve effectiveness of cooling systems. However, sunlight for plant growth is generally reduced with this practice.

When shading is employed to control greenhouse air temperature rise, it is better to have moveable shading to prevent reduction of PAR light during periods when crop production is light limited. Exterior shading is generally more efficient than interior shading although interior shading can be accompanied by the dual benefit of night time heat retention as is common with thermal screens. Shading materials should be selected that can block thermal and infrared components of the solar spectra, while admitting most of the PAR light. This can be accomplished by using photo selective materials such as coatings and films, and by selecting materials more reflective rather than emissive to infrared radiation.

4. Pest Protection. The market demand is moving toward pest exclusion in combination with biological controls and with tactically timed applications of agro-chemistry which is safe to the work environment, plant product, air shed and watershed. Pest control procedures will vary according to local climate and inherent pest pressures, but they must include a multidisciplinary approach as a combination of preventative and reactive control actions including mechanical, biological and chemical procedures, and management practices. Management practices such as proper cultivar selection, and production techniques (short term vs. long term crops) can offset problems before they occur. Enhancing air movement and sunlight (UV radiation) at the plant, or use of water sprays have also been used as management procedures.

Mechanical prevention with insect screens can reduce pest pressure while maintaining desired predator/prey population ratios for IPM strategies. Insect screens reduce ventilation air exchange thus material selection with associated hole size and distribution, in addition to design implementation must be carefully completed. Insect screens are typically described based upon their protection against the target insects. The screens which prevent passage of thrips are the most dense and cause the greatest ventilation reduction.

5. Energy Management and Conservation. The fuel energy crisis of the early 1970s stimulated a world-wide effort for improving modern greenhouse technology. Significant changes in energy conservation and management have resulted in a ten-fold reduction in energy consumption in the best managed greenhouses relative to the average greenhouse of 35 years ago.

Management issues such as selecting crops based on their air temperature requirements, equipment efficiency and maintenance, optimizing system design, double glazing, and gutter-connected structures have contributed to energy savings through decreasing energy input per unit crop output. Research on thermal screens and floor heating helped to satiate the demand for energy savings, and their adoption provided benefits of an environmental management tool within the industry. The potential of thermal screens to provide shading in the day, as well as, night energy conservation, with the benefit of root zone heating to improve crop production and quality were quickly evident. Taller greenhouses to accommodate thermal screens, and other mechanical systems helped the evolution to increasing greenhouse gutter heights which provided improved uniformity and control of the aerial environment.

A careful analysis should identify and provide understanding of the greenhouse energy requirements. Conservation opportunities to reduce energy consumption without impacting the production quality or output can eliminate wasteful consumption. Investments in energy efficient hardware such as fans, motors, lamps and also technology such as thermal screens can be used. If light loss is acceptable for the crop and location, then multiple layered glazing materials can reduce greenhouse heat loss. Insulation deployed only at night can maintain solar radiation where natural light limits plant growth. Only after energy consumption has been reduced, then applications of renewable energy sources should be considered. A higher capital cost is inherent in any renewable energy solution that uses low energy density, less reliable or available energy sources.

Monitoring and Control

Basic control systems for greenhouse climate consist of sensors and actuators inside the greenhouse for monitoring and controlling air temperature, while more advanced systems with specific dedicated software includes PAR, humidity, carbon dioxide concentration, and leaf temperature. The system will control the ventilators, heaters, and coolers (pad/fan, fog, shading) such that the resulting climate meets the set points desired by the grower as closely as possible. The climate is highly dependent on the outside weather which is monitored with outdoor sensors for air temperature, humidity, solar radiation, wind speed, wind direction and rain. This data is used to anticipate changes of the outside conditions and prevent a large deviation from the inside set points, as well as, to respond and correct in the most energy efficient manner. Anticipatory control can be implemented and further improve climate operations by providing weather forecast information to the control equipment via the Internet. The effectiveness in conserving resources (energy, CO_2) especially in recent “closed greenhouses” is dependent on precise, plant based, environmental control. Improved climate control strategies will use understanding of plant response to environment, including the control of the stomata opening (Voogt and van Weel, 2008).

1. Monitoring. Real-time monitoring and subsequent archival data storage are fundamental to all production systems, which should monitor indoor and outdoor climate, as well as, plant nutrient and moisture conditions. Sensors must be very reliable, and have sufficient resolution and accuracy to measure the differences important to the grower. They must be properly located, positioned and calibrated so they measure the true conditions. The system must contain sensors for control of equipment. These sensors can also provide crop related information to support crop production decision-making. With additional number of sensor locations within the greenhouse a better perspective on uniformity of environment can be determined, with the goal of improving production quality and yields. Finally, specialized sensors suites used for plant monitoring or energy balance instrumentation can supply information that may require careful interpretation before using to reduce operations costs and improve plant microclimate.

2. Control. Each active mechanical system component requires control. All mechanical systems must be reliable with relatively few failures and/or the system should have redundancy and failure detection and alarming features to notify the operator when failures do occur. While simple control systems are capable to maintain the environment to produce the crop, they cannot achieve top production efficiency, as they are limited in what they monitor and control. Advanced control strategies have two broad applications in greenhouse production systems: equipment modeling, sequencing and coordination allow the greenhouse system to use simpler, less costly equipment, yet still achieve very high levels of control. This transfer of responsibility from the equipment to the control system also provides real-time information about control equipment operation and behavior, thus allowing on or off-site performance review and adjustment, and; despite best efforts and expense, greenhouses are not ‘fully controlled’ environments. Some parameters can only be slightly controlled (solar radiation), or not at all. Others, such as humidity, are generally too expensive for the given application to control. Crop models allow the control system to optimize crop production within a wide range of constraints described and managed by the crop model assuming that proper investment in control system components was completed.

3. Plant Based Climate Control. While the climate control computer effectively manages the climate, the plant response is generally known only after future observed change in growth, and only rarely with some real-time responses, for example, leaf temperature or sap flow. Except for research situations, the plant physiological responses, such as photosynthesis or transpiration are rarely known. Recently information about the plant has been utilized for operational decision-making. For example, should the plant become stressed by excessive air temperature or solar irradiance, the plant stomata will close, causing reduced photosynthesis and transpiration. Therefore disabling CO_2 enrichment during this period may be cost effective. Similarly water and fertilizer use during environmentally stressed condition would change, thus a change in fertigation practice could offer savings of nutrients.

Properties and capabilities of such sensor platforms should include mobility for positioning the sensors anywhere in the greenhouse with wireless communication to a web server. The data can be stored locally and online allowing internet access of the greenhouse climate conditions and the subsequent behavior of the crop by other growers, researchers and consultants throughout the world. This will enable more effective study of innovative greenhouse operational and hardware concepts and new plant growing methods, as well as, internal sharing of experiences among growers within a large company, or among growers of various small companies. It would also enhance development of plant growth, climate control, and business models.

A specific example is the value of climate monitoring and control for crops under a thermal screen. The use of a screen leads to increased air humidity and temperature, especially in combination with artificial lighting. Introducing dry outside air by using plastic ducts under the crop, the screen can be kept fully closed. This permits higher air humidity without condensation problems reducing disease potential, such as botrytis.

Automation Systems

Intelligent systems that can autonomously monitor and control greenhouse operations (climate control), or specific processes (transplanting), or more complex activities (correcting plant nutritional problems) continue to be developed and applied in greenhouse systems. They begin to offer technical alternatives to offset the historical challenges of greenhouse crop production.

Monitoring plant abnormalities such as managing pest control based on sensors mounted on robotic vehicles/manipulators will reduce the use and emission of pesticides. Sensors to visualize insects, or gas sensors (electronic 'noses') to detect plant response to damage caused by insects or fungi, will provide an early detection system and/or help to calculate the development rate of a specific plant disease or insect, thereby making biological control much more effective when distributing the natural enemies.

Movable benches can automate transport which can aid inspection of each individual plant when lifted out of the bench by a machine. Individual and specific treatment is then possible. If a chemical treatment is the only option, individual plants can be sprayed intensely and without emission in a controlled treatment chamber. The result is an environmental and people friendly pest management system based on biological control with natural enemies and minimum emission of pesticides.

1. Nutrient Delivery. The crop nutrient delivery is a specialized automated system for control of plant root zone environment. It must maintain the proper combination of water, dissolved oxygen, nutrient formulation, temperature, and root exudates within the root zone. Some form of root zone substrate is employed to reduce pathogen problems encountered in soil-based production. Additional advantages are obtained, such as improved control over the timing and quantity of nutrient water delivery, adding safe means to impart water stress as desired to manage crop quality. These practices lead to improved yields, and higher crop quality. Also crop models can provide decision-support to grower management practices, which can be implemented because of the control over the root zone with hydroponic technologies.

Traditionally, production systems were 'drain-to-waste', allowing excess watering to be discharged from the nutrient delivery system. With increasing pressures from environmental regulations and escalating fertilizer and water costs, growers can now recirculate or recycle most drain water. Such practices for example in closed or semi-closed greenhouse systems impose enormous management responsibilities and increased risks, such as the spread of pathogens, for which pasteurizing, filtering or UV-C radiation systems have been developed to resolve. In addition, frequent monitoring of nutrient elements, either for minimum, maximum or toxic levels is required. The required technology is costly, complex and requires careful design, maintenance, and operation. Most growers are better served by simple, partially closed nutrient and water delivery systems that can achieve much of the theoretical benefits of fully closed systems, but at much smaller cost, risk and management requirements.

There are two fundamental strategies for managing recirculating nutrient delivery systems, including, either full control of most individual elements based on real-time ion-selective sensors in combination with precise dosing equipment; or, providing luxury consumption to allow the root system to selectively consume from the excessive nutrients. Each would benefit from regularly scheduled accurate and reliable laboratory tests, combined with sufficient system buffer capacity to limit the nutrient solution changes during the testing intervals. They require high quality fertilizers with precise formulations. Neither approach has been proven better, and it remains the choice of the grower to select improved control of the root zone and its associated higher costs, but greater yields, or less control, and greater waste of nutrients and water.

One major concern in recirculating nutrient delivery systems is the increase of unused ions, such as sodium, that have a negative affect on production or crop quality. Practice includes regular discharge of 30% of the nutrient solution and addition of low sodium makeup water.

2. Integration of Systems. Successful greenhouse systems and sub-systems integration, and appropriate technological levels to meet the design requirements and restrictions of the greenhouse application are needed for a harmonious operation. An experienced operator must then understand the integration and respond to benefit the crop. Profitability is at risk if attention is focused on the structure and the separate individual systems rather than the integration of all systems into an environment with a plant growing system.

Failures can occur in numerous ways including the improper use of material and lack of supporting information about the proper use of the products offered by the manufacturer. Greenhouses are often not matched to the application, being overbuilt or under built, and capital is wasted, and operations costs potentially increased. For example, a greenhouse with a properly designed and sized natural ventilation system may suffer from insufficient air exchange if subsequently an insect screen is added to the ventilation openings without consideration of its effect on air movement. Insect screens directly affect and reduce ventilation air exchange. Greenhouses are one of the most innovative examples of modern agriculture and include advanced technological equipment for horticultural production. Many different subsystems are included to obtain the optimum level of quality and quantity of crop production, such as heating, ventilation, cooling, and artificial lighting for supplemental or photoperiodic effect, CO_2 enrichment, irrigation and nutrient delivery, soilless culture, automation systems for parameter control and correlation and equipment regulation. Operations improvements such as rain water collection, or disposal and recycling of materials (plastics, spent nutrients) also need to be considered, as well as the health aspects of human labor working conditions. Environmental stresses (air temperature, relative humidity), exposure to chemicals for plant protection, and repetitive work tasks offer long term concerns for human labor within the production systems.

SPECIFIC EXAMPLE APPLICATIONS OF CURRENT WORLD INTEREST

Semi-Closed Greenhouses

Semi-closed greenhouses may be described as systems with reduced air exchange with the outside environment. The ability to enrich the atmosphere with carbon dioxide is one obvious benefit. Mechanical exclusion of insects by screening inlets and/or positive pressure ventilation, as well as optimized control of Vapour Pressure Deficit are all important. Reduced air exchange also improves crop uniformity and allows more creative ways to manage the air flow and properties within the crop canopy.

Every enclosure makes a plant production system more “closed” than open field production. The initial goal of such structures was to limit ventilation during periods of high radiation, and to collect, store and reuse solar energy with heat exchangers and below ground water storage systems. The operating costs of such systems proved to be much higher compared to an “open” greenhouse and have been abandoned for the goal of limiting ventilation to increase CO_2 during sunlight periods. This can result in extra growth and quality. For example, the GATES (Greenhouse Advanced Technology Environmental System) design currently operating in Texas has reliably achieved tomato yields above 100 kg m^{-2} yr^{-1} with continuous production, compared with 61 kg m^{-2} yr^{-1} in an adjacent open greenhouse design.

Conventional greenhouse designs developed for northern Europe (such as ‘Venlo’) are effective food production systems in low radiation regions. However, in arid climates characterized by high radiation and dry conditions, conventional greenhouse designs can result in excessively high air temperatures, and vapor pressure deficit (VPD), both detrimental to plant growth. The increased need for shading reduces radiation use efficiency (RUE), negatively affecting plant growth and yield. Pad and fan cooling systems are commonly used to reduce air temperature and VPD, but create significant climate and design limitations, such as excessively cold air near the pad, and large air temperature differentials from pad to fan, which in turn limits the distance between pad and fan. Air temperature differentials create non-uniform growth within the crop, and lead to compromises in climate and crop management.

Properly designed ‘Semi-closed’ greenhouses are able reduce all the above limitations, thereby greatly improving greenhouse climate and crop productivity. Employing single point entry of outside air, and controlling the proportion of outside air mixed with greenhouse air the temperature and VPD provided to the crop can be better managed. Proportional control of pad wall wetting provides the opportunity to reduce the VPD without excessively cooling the incoming air. The incoming ventilation air is introduced underneath the crop through fans and a plastic distribution tube. Delivering the air underneath the crop can create large vertical air temperature differences in the crop profile, which have challenged crop management in ‘semi-closed’ greenhouses. However with directed air flow patterns and evaporative cooling this can be resolved.

Ventilation can be minimized if the release of greenhouse heat is based on water vapor exchange instead of air volume exchange, since water vapor contains much more energy per unit mass than dry air. Providing increased moisture within the greenhouse exhaust air, allows for reduced ventilation, resulting in more efficient greenhouse CO_2 enrichment. Studies in Holland within a semi-closed greenhouse have demonstrated this concept, by introducing improved insulation methods and humidity control based on the distribution of dry outside air, underneath the crop with fans and air tubes (Voogt and van Weel, 2008). The result has been a 200 ppm increase in CO_2 without increasing the supply rate.

“Tunnel” Greenhouses

Tunnel greenhouses represent a less complex design than traditional climate controlled greenhouses, providing a modified climate for numerous crops and representing approximately 1.9 million acres worldwide. They have a design structure that is very simple, low cost, unheated, and passively vented. As temporary structures, they are built without concrete foundations. Tunnels can be built on sloping or undulating sites. They are usually covered with a single layer of polyethylene film and require minimal construction time. Their low cost provides a short payback period and they are built as either single bay or multiple bay structures. Tunnels are typically used over field type production systems. With the addition of gutters and motorized venting, they can offer improved climate control at increased investment.

A popular tunnel style is the arch-shaped, multi-bay that uses a rope lacing system over the top of the film cover to secure it to the steel tube frame structure. This system provides opportunity for ventilation air exchange and for fast installation/removal of the film cover. In regions with significant snow/ice loads, single bay tunnels are often designed to support the snow load that slides to the ground, therefore the film cover does not have to be removed. Uncovering in the off season provides other benefits, such as leaching of unused fertilizer salts from the soil by rains, reducing the number of overwintering insects, allowing the use of cover crops and eliminating any chance of structural failure due to snow/ice.

Taller, multi-bay tunnels have gutters, supported by 2.7 m tall posts providing 4.9 m to the ridge, and look much like gutter-connected greenhouses. They are strengthened by a system of overhead cables connected to anchors in the soil. Venting is accomplished by opening the roof, sidewall and/or end wall, either manually or with a motorized system.

“Urban” Greenhouses and Plant Growth Systems

There is an increasing worldwide interest in the local, year round, production of fresh vegetable foods for reasons that include improving sustainability by avoiding long distance transportation, improving produce quality and social concerns such as the support of local employment opportunities. There was significant research on the residence/greenhouse integration concept in the 1970s energy crisis and many systems have been proposed since. Early work did show that from an energy standpoint a well designed, integrated system could provide all the heating requirement for the greenhouse residence combination with less fossil fuel, or none at all if wood biomass were used as a backup (Mears, 1981). Attached greenhouses for urban areas may be quite small relative to the occupied space and for this situation appropriate sizing of heat exchangers and storage capacity is important for good system performance. Okushima et al. (2011), have evaluated such a system and verified parameters for a simple model to help optimize equipment choices. Computer modeling was used to investigate options for integrating greenhouse space with multi-unit residences, and to determine heat pump, storage and heat transfer capacities to meet 90% of greenhouse and residence heat requirements (Mears and Okushima, 2010).

Urban agriculture has also included designs for rooftop greenhouse production of vegetable crops using solar radiation, which are now in development. Recent new production systems will determine the economic viability of such applications within large city markets. In addition, much discussion has focused on "vertical farms" whose concept would include food systems within climate control rooms or even entire buildings, using only partial sunlight or none at all, thus requiring artificial lighting technology for providing energy to the crops for growth. Theoretically, a combination of greenhouses with animal production such as poultry or pigs can be a self-supporting and sustainable system in terms of energy, CO_2, water and nutrients supply (van Weel, 2003). To date no such systems have been created, although development plans for various designs are in progress, none has yet to be demonstrated.

GREENHOUSE PRODUCTION SYSTEMS FOR PEOPLE – FINAL THOUGHTS, DESIGNS, OPERATIONS, AND IMPLICATIONS

Greenhouses have a number of other potential niches, particularly in social engineering. Many societies around the world are working with relatively primitive field production systems that require large amounts of tedious labour. These production systems lack control over production conditions. As such, they do not need advanced automated production systems. Quite the opposite, they need production facilities of reduced production risk, but not necessarily reduce labour input. Greenhouses are generally considered to offer improved work environments. However, the lack of education or capital, difficult political environment, and poor infrastructure are typical limiting factors for such situations.

Greenhouses may also serve a social purpose. People living in industrialized modern societies are increasingly isolated from the environment around them. Roof top greenhouses, green roofs and communal gardens provide some connection to the source of food and life and serve a strong social purpose, regardless of the cost per unit of production.

The industry is basing its future viability on the development of increasingly larger, more complex and costly facilities, but simultaneously on the simple tunnel greenhouses. The capital needed to build large scale facilities puts enormous pressure on the profitability of these operations. While this development work has so far led to increased production at lower energy in-put levels, the industry is essentially still dependent on fossil fuels. Whereas high tunnel designs require less non-renewable resource inputs, they have a much lower yearly production capacity, and cannot always provide production quality when desired.

More research is needed to demonstrate viable "integrated production facilities". The facility would be completely self sufficient and provide all needed electricity, heating, cooling and CO_2 from digesters, gasifiers, solar panels, wind turbines, etc. By combining the greenhouse facility with an operation that produces the required feedstock and resources for the digesters or gasifiers, the greenhouse would no longer be dependent on fossil fuels. An integrated system like this could be truly sustainable. This would of course also require careful capital investments because of the multitude of integrated supporting systems developed for the greenhouse.

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