New Technologies Developed for Conventional Growing Systems: Possibilities for Application in Organic Systems

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Keywords: production, energy efficiency, water use efficiency, sensors, environmental control

Abstract

In conventional greenhouse systems, recent innovations have contributed to increased production levels, and at the same time, to the decreased ecological footprint in terms of the reduction of water use, nutrients and CO_2 emissions. Several examples of application of standard and innovative technologies to improve production, optimize utilization of solar energy and increase efficiency of energy and water use are presented. These technologies can also be applied in organic (soil-based) protected growing systems and the practical application is, as with conventional growing systems, primarily limited by the economic feasibility. The examples include the implementation of modern sensor technology, the use of models in environmental control and innovative covering materials for greenhouses, as well as the latest developments in the field of (semi-) closed greenhouses.

INTRODUCTION

Organic greenhouse horticulture is defined by ISHS as the production of organic horticultural crops using inputs from only natural, non-chemical sources, in climate-controllable greenhouses and tunnels. This method of production differs in many aspects from conventional production and one of the key issues is the approach to soil management (Voogt et al., 2011). Although the differences are pronounced, the basic principle of both organic and conventional production is to optimize the use of all available inputs within the given restrictions (e.g., technical, economical or EU regulations) to achieve a more sustainable production with less impact on the environment. In conventional greenhouse production, yields are usually high and are reached using high inputs and at high investment costs. Currently, three major issues are of concern in greenhouse horticulture: energy use and CO_2 emission, water and nutrients, and integrated pest management to reduce chemical use. Over the last decades, conventional growing has adopted biological control and crop protection technologies which originally tended to be used in organic growing systems. Conversely, technological developments for water use and energy efficiency in conventional growing may be applicable in organic greenhouse production to improve sustainability. However, the application of artificial substrates and recirculation of water and nutrients in organic growing systems is not commonly accepted and sometimes even prohibited by regulatory constraints in various countries. This limits the application in organic systems of a wide range of water and nutrient supply technologies developed in conventional growing systems. This paper therefore focuses on new technologies developed for conventional growing systems which are not linked to substrates or recirculation and also could be applied in organic production systems using climate-controllable greenhouses and tunnels. In general the production levels in organic systems are lower compared with conventional systems (e.g., in The Netherlands, the average yield for tomato is up to 65 kg m^{-2}, while for organic soil-grown tomato, around 45 kg m^{-2} is considered the standard level (Raaphorst, 2011). Depending on the price levels and impact on yield, economic

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feasibility of the implementation of new technologies in organic systems may differ compared with conventional systems.

WATER USE EFFICIENCY

The impact of water use can be expressed in different ways, for instance, *Water Footprint*, *Virtual Water*, *Product Water Use* (*PWU*) and *Water Use Efficiency* (*WUE*) (Nederhoff and Stanghellini, 2010). Water Use Efficiency (WUE) is the yield (kg) divided by the amount of water used for growing (L), and is usually expressed in kg L^{-1}. Although the term WUE is often used, now PWU (L kg^{-1}) seems to be a more preferred term. The Water Footprint Network has collected and published an extensive data set for a large range of products which shows that PWU for fruit vegetables is generally low (Hoekstra and Chapagain, 2008). More detailed data on PWU for tomatoes was presented by Van Kooten et al. (2008), showing that the PWU for tomato ranges between 300 L kg^{-1} for field grown crops, to 15 L kg^{-1} in greenhouses.

Protected cultivation is generally much more water efficient than open field growing (e.g., Klohn, 2002; Nederhoff and Stanghellini, 2010). The higher water efficiency in greenhouses primarily results from a higher yield as the result of better and more optimal environmental conditions (CO_2, temperature, humidity), an extended growing season, and protection from the elements and pests and diseases. The other main factor is that crop transpiration in greenhouses and subsequent water uptake by the crop is much lower compared with the open field due to lower radiation, higher humidity levels and reduced wind speeds in greenhouses. The overall effect of improved production and reduced water use is a significant decrease of PWU by a factor 4–5, on average.

For tomato, the theoretical limit of PWU is about 1.25 L kg^{-1} since 80% of the total fresh biomass in greenhouse tomato is fruit weight (de Koning, 1993). However, the lowest values, as claimed in closed environment greenhouses with full water recovery and recirculation (de Gelder et al., 2005), are around 4 L kg^{-1} (van Kooten et al., 2008). Completely closed greenhouses (e.g., Opdam et al., 2005), or semi-closed greenhouses with reduced ventilation capacity were originally designed to combine improved production with energy savings (Bakker, 2009), and for southern regions, also to improve water efficiency (Buchholz et al., 2005). These greenhouses use (forced) cooling and no or limited natural ventilation. The reduced air exchange with outside air allows higher CO_2 levels to be maintained, even under high radiation levels, thus achieving higher yields. Due to the absence or limited use of the vents, the water that evaporates from the crop does not escape the greenhouse but condenses against the heat exchangers. The first results in completely closed greenhouses with forced cooling have shown production increases up to 20% with tomato (de Gelder et al., 2005). In a recent study, three optimized designs of (semi-) closed greenhouses were tested year-round with different crops (cucumber, tomato, pepper and pot plants), but despite the high production levels (e.g., 76 kg m^{-2} for tomato), none of the systems has shown to be economically competitive (de Zwart, 2010). The high investment costs are still not balanced by the (significant) production increase and savings on energy or water use, making them the major limitation for application of new greenhouse system designs in both conventional and organic production.

Very low PWU's generally can be reached in closed greenhouses using artificial substrates with recirculation of the nutrient solutions. However, the principle of closed-environment greenhouses can also be applied to soil-grown crops. The potential of these systems, in terms of reduced PWU, is high, not only for more moderate climates, but especially for more southern and/or hot arid regions. In these regions, greenhouse cooling is traditionally achieved using pad and fan systems or direct evaporative cooling, which requires large quantities of water, resulting in PWU's of up to 60 L kg^{-1} or higher (van Kooten et al., 2008). Application of closed systems may significantly reduce the PWU, e.g., in the Watergy greenhouse, a closed greenhouse project in Spain, 75% of the irrigation water was recovered (Zaragoza et al., 2007).

Although growing crops in a greenhouse reduces the PWU, good irrigation and water management is crucial to optimize the PWU in both field and greenhouse production. The University of Cordoba in Spain, showed that good water management reduced PWU about three-fold (Nederhoff and Stanghellini, 2010), and the irrigation strategy for soil-grown crops may be improved significantly using different root zone sensors (Pardossi et al., 2009) and transpiration and water uptake models (e.g., Anastasiou et al., 2009). In a recent comprehensive study on irrigation management, different technologies for root zone sensors were compared (Pardossi et al., 2009). The effects on PWU are most pronounced with field crops, but a decrease in PWU of 17% also was reached for a soil-grown greenhouse cucumber crop (Balendonck et al., 2010). The systems described above are based on measurements of the water status in the root environment. Sensors for direct non-destructive measurement of crop water stress also are being developed (e.g., Jalink, 2009; Zygielbaum, 2009). Although these sensors are being developed primarily for research purposes, application of the new innovative sensors in commercial production might be the next step in further improvement of irrigation and nutrient control systems.

ENERGY EFFICIENCY

For European conditions, the energy use in greenhouse production ranges from 10–30% (Bakker, 2009), and energy costs form a substantial fraction of the operational costs. Combined with the latest European targets on reduction of CO_2 emissions, this has led to a renewed interest in innovative technologies to improve energy efficiency. The major challenge is to meet two needs: improved energy efficiency combined with an absolute reduction of the overall energy consumption and related CO_2 emission.

Maximum Use of Solar Radiation

The first step in creating energy efficient greenhouses is to maximize the use from the incoming natural radiation for its positive impact on crop production and the reduction of additional heating requirements. This is obtained by increasing the light transmission of the greenhouse structure and cover and minimizing reflection losses. Considerable enhancement of light transmission can be reached by increasing the roof slope to values close to 30º (Soriano et al., 2004) and optimizing construction components with minimal dimensions, and using wide (>1.7 m) glass panels and white coated frames (Janssen and 't Hart, 2006). However, the major factor influencing greenhouse transmission is primarily the cover material. For energy efficiency and optimal use of solar radiation in the winter period, one should aim for materials which combine a high transmission of visible light with a low transmission of IR radiation and a high insulation value (Hemming et al., 2004). Many film materials are sub-optimal for energy efficient greenhouses since their IR transmission is high, with the exception of the recently introduced ETFE membrane (Hemming, 2005; Waaijenberg et al., 2005).

To further improve the light transmission of materials, several anti-reflective coatings have been developed and introduced to prevent light reflection and have been shown to increase light transmission by 5–6% (Hemming et al., 2006a). Although overall transmission is of major importance, several studies show that diffuse light penetrates deeper into a plant canopy in comparison to direct light (e.g., Farquhar and Roderick, 2003). Covering materials which diffuse the incoming light may improve crop growth (Jongschaap et al., 2006; Hemming et al., 2006b); production increases of 4–8% and a subsequent increase of energy efficiency have been found with cucumber (Hemming et al., 2007) and practical application is considered economically feasible.

Minimizing Energy Loss Using Insulating Materials

The energy loss in naturally ventilated greenhouses depends on two major effects: convection and radiation from the greenhouse cover, and thermal and latent heat transfer through ventilation. Improved insulation is therefore the first step in creating energy-conservative greenhouses, but a major disadvantage of most insulating covers is reduced light transmission and increased humidity. Development of materials which combine high insulation values with high light transmission is one of the most challenging issues. Promising innovative materials are double-side coated Anti Reflex glass (Hemming et al., 2006a), triple layer systems (Bot et al., 2005), or glass with micro-structure to increase light transmission due to multi-reflection (Swinkels et al., 2010). An extensive simulation study showed that double Anti Reflex glass combined a high diffuse light transmission (82–86%) with an energy reduction of 26%, leading to a gain in energy efficiency of 40%. This material is now being tested in an experimental greenhouse at Wageningen UR Greenhouse Horticulture in Bleiswijk (Kempkes et al., 2010).

Energy Efficient Operational Control

Efficient greenhouse environmental control has potential to improve energy efficient greenhouse production, and the increasing knowledge on physiological processes and crop growth – environmental interactions opens new possibilities. One way of substantially reducing energy use is to use temperature integration (TI), the phenomena that (within limits) many crops respond to temperature integral, rather than diurnal variation. The first reported use of TI was to improve energy savings by manipulating set-points based on wind speed and goes back over 20 years. Bailey (1985) predicted a savings of 5–10%. A more common TI strategy is to use higher vent temperatures to maximize natural heating due to solar gain and to compensate these by running lower temperatures at night or on dull days. Energy savings will depend on the crop and the temperature fluctuations that are allowed, but annual savings of up to 16% are possible (Langton and Hamer, 2003).

Humidity control strategies also have a big impact on the energy use, as aggressive humidity control results in increased loss of thermal and latent heat by ventilation. Although high humidity levels are generally associated with increased risk of fungal diseases and reduced quality (e.g., botrytis, blossom end rot), increasing humidity may also be positive for crop production and quality, under moderate as well as under more sub-tropical conditions (e.g., Bakker, 1991; Montero, 2006). Therefore, increasing the humidity level can be considered an effective way of increasing energy efficiency (Körner, 2003).

To gain maximum profit from environmental control in the field of energy efficiency, the control should not be focused on a single environmental factor or actuator like heating, ventilation and CO_2 supply, but on energy efficient crop production. This requires model-based control systems in which the impact of control actions on both crop production and energy consumption is used. This approach has been followed since the early 1980s when Challa and van de Vooren (1980) first described an optimization routine for cucumber crop production. The book by van Straten et al. (2010) summarizes the last 30 years of research and integrates current research into physical modeling of the greenhouse climate with biological modeling of variables such as plant evapo-transpiration and growth and its application in economic and energy efficient greenhouse control.

Although the introduction of innovative environmental control technologies will add to energy efficiency, large improvements compared with the current situation can already be made by simply improving hardware design like heating and ventilation systems (e.g., Campen, 2004), improving both accuracy and frequency control of the sensor network (Bontsema et al., 2005) and checking the set points on a more regular basis.

New Techniques and Concepts

Although implementation of individual energy-saving components can result in energy savings, the only way to reach the ambitious Dutch and EU targets of CO_2 emissions is by integrating energy-conserving methods for greenhouse systems, including covering material, heating and ventilation/dehumidification, control algorithms, and energy conversion systems. A solar greenhouse concept as developed by Bot et al. (2005) is a perfect example of an integral greenhouse system for crop production without the use of fossil fuels, combined with control algorithms for a dynamic control (van Ooteghem et al., 2005). Under this type of system, an energy savings of over 60% is within reach. This enables a sustainable energy supply per ha greenhouse of only 600 kW (e.g., through wind power or Photo Voltaic (PV) Panels).

After the first trials with a full scale closed greenhouse (e.g., Opdam et al., 2005), the idea was developed to extract a heat surplus during the summer and reuse this during the winter for heating the greenhouse itself and neighboring greenhouses or buildings. The basics for this so-called "energy producing greenhouse" are equal to the solar greenhouse: minimized energy requirement during the winter (Waaijenberg et al., 2005) and maximization of heat storage. Tests on a practical scale, however, showed that the aim to collect as much heat as possible was hard to achieve since the performance was restricted by the temperature band widths set by the grower to minimize detrimental effects on his crop (de Zwart et al., 2008). As stated earlier, the more optimized integral designs of (semi-) closed greenhouses are, despite high production levels (e.g., 76 kg m^{-2} for tomato), still not economically competitive (de Zwart, 2010).

Despite this, the recent research on semi-closed and completely closed greenhouses (e.g., Qian et al., 2009) has resulted in new energy conservative growing concepts, resulting in significant reduction of energy use for a range of crops under conventional greenhouse production, like strawberry, tomato and Alstroemeria (Kempkes et al., 2010; Raaphorst et al., 2010; Labrie and de Zwart, 2010) and also in organic greenhouses (Raaphorst, 2011). As with the previous technologies, there are no real general technical limitations for application; investments can only be balanced by a higher product price for the more sustainably-produced product.

The latest developments in design of energy conservative or energy-producing greenhouses are systems which integrate PV cells in the greenhouse design with photo-selective covering materials to combine thermal and electrical energy production with crop production (Sonneveld et al., 2010a; Sonneveld and Swinkels, 2010). A second design includes the integration of static linear Fresnel lenses in the cover with specifically designed PV cells (Sonneveld et al., 2010b). However, the costs for these systems are still very high; therefore, large-scale practical application is to be expected in the near future.

CONCLUSION

Although conventional and organic greenhouse production differ in many aspects, most of the innovative developments on water use and energy efficiency in conventional production are applicable in organic production to improve sustainability. The major limitation for the application of these technologies is the economic feasibility which may, given the current production and price levels for organic growing, largely differ for individual situations.

ACKNOWLEDGEMENTS

Many projects referred to in this paper were funded by the Dutch Ministry of Economics, Agriculture and Innovation and the Dutch Product Board for Horticulture.

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