Greenhouse Technology for Sustainable Production in Mild Winter Climate Areas: Trends and Needs

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Keywords: ventilation, screens, NIR radiation, CO_2 enrichment, life cycle assessment

Abstract

Greenhouse production in the near future will need to reduce significantly its environmental impact. For this purpose, elements such as the structure, glazing materials, climate equipments and controls have to be developed and wisely managed to reduce the dependence on fossil fuels, achieve maximum use of natural resources such as solar radiation and water, and minimize the input of chemicals and fertilizers. This paper discusses the most relevant developments in greenhouse technology for mild winter climates. Regarding greenhouse structures, recent studies based on computational fluid dynamics have been conducted to investigate the effect of parameters such as ventilator size and arrangement, roof slope and greenhouse width and height on the air exchange rate. Next generation greenhouses are expected to incorporate some of the innovations derived from recent ventilation studies. Covering crops with screens is becoming a common practice. Main advantages and limitations of screenhouses are discussed in this paper. Thermal storage is increasingly applied in closed or semi-closed greenhouses. Under some conditions semi-closed greenhouses could mitigate day/night while reducing the use of water and the entrance of pest. Photo selective films that reflect a fraction of NIR radiation are effective at lowering greenhouse temperature and, in some cases, may be cost effective. NIR reflective films have side effects of major importance in greenhouse production. The CO_2 enrichment strategy in computer-controlled greenhouses is based on determining the benefits of increasing the CO_2 concentration against the cost of it. No clear strategies have been defined for the application of CO_2 in unheated greenhouses, where most of the time the source of carbon dioxide is the external air. Some authors suggest ventilating as little as possible and fertilizing with bottled carbon dioxide at least up to the external concentration. Improving greenhouses by introducing new technologies may have an additional impact on the environment. From an environmental point of view, the incorporation of technology needs to increase yield to compensate for its associated environmental burden. Previous results have shown that forced ventilation and heating are the main reasons for the increase in environmental impact in climate controlled greenhouses. Additional results on the area of technology and its associated impact are discussed in this paper.

INTRODUCTION

Greenhouse production in mild winter climates is a long established agricultural activity. Since the early sixties, greenhouses and related plant protection structures have spread out firstly around the Mediterranean basin and later across a wide number of countries, some as distant as Mexico or China from the Mediterranean. In times that energy for heating threatened the greenhouse industry, mild winter climate areas required soft, if any, heating technology, and relatively cheap passive greenhouses with little

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climate control became an alternative to the solid, better controlled but energy consuming Northern greenhouse type.

Since its beginning, greenhouses in mild winter areas have been evolving from very simple locally made wooden structures, without climate control other than natural ventilation, to more complex industrial-type greenhouses, typically the multi-span arched-roof structure with a wide range of equipments. The subject of how much technology is nowadays needed to have an efficient greenhouse is hotly debated. Frequently one can visit a successful grower that believes in high technology and accurate climate control and next to him another profitable operation can favour simple technology, passive control and efficient use of available natural resources. Both approaches coexist but the fact is that plastic-clad simple greenhouses predominate over the more complex ones in most countries where the climate is mild.

A number of comparative tests have been conducted in order to find the most profitable combination of greenhouse types and associated technology (Castilla, 2007). If properly designed, simple greenhouses can have similar light transmission and similar ventilation rates than industrial greenhouses as a consequence, for vegetable production in Mediterranean areas, locally-made greenhouses could reach similar cost-benefit balance than arched-roof industrial-type greenhouses with climate control equipments. This conclusion is valid for "regular" years, in which extreme temperatures, intense high humidity periods or severe virus attacks do not take place, but when one of these circumstances happen, the industrial greenhouse can modulate the unfavorable external conditions and offer more reliability to the grower. Perhaps the main advantage of applying technology in the sort of climates we are discussing is to add security and stability to the greenhouse operation, which, on its own, could increase profitability in the present market conditions. In any case any greenhouse production system benefits from innovation and better knowledge of the production process achieved through research. This paper discusses the most relevant and recent developments in greenhouse technology for mild winter climates.

Needless to say that the environmental concern leads any future development, also in the greenhouse industry. There are quantitative tools such as the Life Cycle Assessment (LCA) to evaluate the environmental impact of protected cultivation, referring the impact to a group of selected environmental categories, viz global warming, risk of eutrophication, etc., LCA has been applied to greenhouse production (for instance, Anton, 2004) and the main factors responsible for the environmental impact have been identified. Results on previous environmental studies applied to existing greenhouses are discussed in this paper. Regarding technology developments, innovations will be adopted only if they increase business profitability. So, new technologies have to be economically sound and environmentally friendly as well. The incorporation of new technologies has an unavoidable environmental cost that needs to be compensated by an increase in efficiency of all inputs. That is, if the environmental impact is referred to the Kg of produce per unit of greenhouse area, the new technology should produce more Kg per unit area to compensate for the extra input in energy, materials, etc that the new technology requires. Previous results on this area (technology and its associated impact) are discussed in this paper.

INNOVATIONS IN GREENHOUSE TECHNOLOGY

Trends in Natural Ventilation

The term "mild winter climates" may tend to overlook one of the main problems faced by greenhouse production in those areas, which is the need of greenhouse cooling. Year-round production in greenhouses is one of the primary concerns to increase the greenhouse efficiency and plant productivity. Technologies to cool greenhouse air on hot sunny days have become more important, particularly, natural ventilation systems, which are significantly less energy intensive than fan ventilation systems (Sase, 2006).

Boulard (2006) made a survey of the different approaches to study natural ventilation. He concluded that analytical models based on the principle of energy and mass balance (basically water vapour) are essential for the determination of ventilation rate and energy consumption of a whole greenhouse. From this knowledge it is possible to progress on the design of greenhouse control devices or to derive more efficient control algorithms or strategies.

However the latest advances on ventilation are not based on analytical models but in numerical models. These methods (called computational fluid dynamic methods or CFD) use a fine discretisation of the domain studied and allow performing a very precise solving of the ventilation transfers on very large domains. By using CFD models it is possible to obtain detailed vector fields of air velocity in and around the greenhouse, or precise scalar fields of temperature, humidity or any other variable relevant to greenhouse climate studies.

CFD studies have evolved from the early work of Okushima et al. (1989) on a single-span empty greenhouse to the more complex models of large-span greenhouses that incorporate the interaction of crop with the environment (for instance, Fatnassi et al, 2006). For better ventilation design, even the simplest CFD models that take into account only the air flow movement of an empty greenhouse under isothermal conditions are extremely useful.

Sase (2006) reviewed the primary airflow characteristics for single and multi-span greenhouses and the effect of external air speed and direction on climate uniformity in ventilated greenhouses. The two main case-studies to be considered are leeward ventilation and windward ventilation. Windward ventilation is preferred to leeward ventilation for greenhouses located in warm areas, since windward ventilation clearly increases the ventilation rate (Pérez-Parra, 2002). Nevertheless, the internal climate is generally less uniform for windward ventilation.

Windward ventilation. For windward ventilation the external air is “captured” by the vent opening of the first span (Figure 1a). This creates an internal flow with the same direction of the external air. The first windward roof ventilator has the most significant effect on the intensity of air exchange and internal air flow. Windward ventilation has some drawbacks. As pointed out by Sase, the incoming air mainly follows the inner surface of the roof and creates a cross flow above the crop. There is the risk that the incoming air may exit the greenhouse through the second or third ventilator, without mixing with the air in the crop area. To avoid this problem, the use of screens or deflectors to re-direct the air stream is being recommended. Nielsen (2002) offered a method to direct the passing airflow at the hinged ridge vents into the crop space (Figure 2). Using a 1-m high vertical screen mounted to the ridge, improvements were achieved in the air exchange in the plant zone of about 50% on average. Montero et al. (2001) also proved the efficiency of an air deflector on a jack-roof ventilator to avoid the passing of air through the roof vent. Increasing the roof slope also helps to direct the incoming air to the crop area. Baeza (2007) compared the air exchange rate and internal air flow of greenhouses with slopes ranging from 12 to 32 º. Ventilation sharply increased with roof slope up to 25º. After this slope, the increase in ventilation was rather small.

Baeza (2007) analysed the effect of ventilator size on greenhouse climate. He increased the flap ventilator size from 0.8 to 1.6 m in the first two spans and the last two spans while keeping the regular size of 0.8 m in the central spans. For a ten-span greenhouse the increase in ventilator size had a strong effect on the ventilation rate. Besides, air movement in the crop area was enhanced. As a consequence the temperature field was more uniform, the temperature gradient in relation to the exterior was reduced and the number and size of stagnant air (warm spots) areas were significantly less. This study suggested that the greenhouse climate can me ameliorated by making modest investments only in ventilators located in the first and last spans, which are critical on the air exchange process.

Side wall ventilation is similar to windward roof ventilation, since for side wall ventilation the external air also enters the greenhouse by the windward side and passes along the greenhouse width. Kacira et al. (2004) conducted CFD simulations to investigate the effect of side vents in relation to the span number of a gothic greenhouse with a continuous roof vent on the leeward side of each ridge. Compared to roof ventilation only, it was found that when both sides were fully open the ventilation rate increased strongly. However, the ventilation rate decreased exponentially as the span number increased up to 24. This reduction is reasonably explained by the fact that the area of side vent openings is kept constant and the area per greenhouse floor decreases with an increase in the span number.

All this recently developed knowledge can be put together to produce better ventilation designs. It is expected that upcoming greenhouse models, if they rely on windward ventilation, have to be narrow enough (typically no more that 50 m wide) to avoid excessive temperature gradients. Besides, they are expected to have bigger-size ventilators, especially in the first span facing prevailing winds. They will incorporate screens or deflectors to redirect the air flow towards the crop area producing a homogeneous mixture of the incoming and internal air, to have uniform growing conditions. Effective windward ventilation will require keeping an area between greenhouses free of obstacles. For proper ventilation, future greenhouse designs will not consider a single greenhouse, but a group or a greenhouse cluster, since the airflow in a greenhouse is affected by its surroundings.

Leeward ventilation. For leeward ventilation, the external wind follows the windward roof of the first span and accelerates along the roof. The external flow separates from the greenhouse structure at the ridge of the first windward span and creates an area of low speed above subsequent spans. Greenhouse air exits the greenhouse through the first roof ventilator, creating an internal flow which is opposite to the external flow (Figure 1b). As for windward ventilation, the first ventilator plays the leading role in the air exchange process.

This is the general outline of air pattern for leeward ventilation, but in very wide greenhouses the internal air movement may be different. Mistriotis *et al.* (1997) used the CFD simulation for a parametric study of the effect of the greenhouse length (32 m, 64 m, 96 m long) on the inside flow pattern. The behaviour of the 96 m greenhouse was different from the other as a second outflow occurred at the back of the greenhouse. Reichrath and Davies (2001) confirmed the occurrence of this reverse flow in the windward part of the greenhouse and of a dead zone with low velocity at approximately 60 % of the total glasshouse length for a very large Venlo type greenhouse (60 spans) under similar pure leeward ventilation conditions.

Side wall ventilation may help to reduce this dead zone with high temperatures, but this is not a very acceptable solution for many growers who are reluctant to open the side wall and roof ventilators towards the wind, as they want to protect their crops and greenhouse frames from potential wind damage.

Attempts are being made to ameliorate the climate of multy-span greenhouses under leeward ventilation (Montero et al, 2007). Based on a study of the static pressure field around a 15 span structure, simulations showed that significant improvements in temperature and uniformity could be achieved with relatively minor modifications to the ventilation system. For instance, an area of low pressure was observed on the roof, near the gutter of the first span facing the wind (Figure 3). A ventilator built in this area proved a very efficient air outlet. Furthermore, keeping the windward side of the greenhouse closed and the lee side wall open greatly favoured the entry of air on the lee side. It was also detected that an area of hot air was created at or around every fourth span of the structure. This problem was solved by increasing the ventilation area at five-span intervals (Figure 4). The study showed that it is possible to design efficient leeward ventilation systems by arranging the openings more efficiently and by making minor modifications to existing ventilation systems.

Screen-covered Greenhouses for a Full-season or Part Time Production

Covering crops with screens is becoming a common practice. The so called "screenhouses" are effective and economical structures for shading crops, protecting them from wind and hail, improving the temperature and humidity regimes, saving irrigation water and excluding insects and birds (Tanny et al., 2006).

The challenge to supply year-round high quality horticultural products can be afforded either by growing in high-tech greenhouses or by producing in two different locations, whose harvesting periods are complementary (Castilla and Hernandez, 2007). In the south of Spain, the absence of greenhouse production in coastal areas during the summer months is being substituted by the vegetable produce from screenhouses in the highlands, enabling the year-round market supply. In addition, the highlands where these screenhouses are spreading are economically depressed areas with important problems of agricultural unemployment (Romacho et al., 2006).

There is a relationship between the porosity of a screen and its transmission in the solar range, but other parameters also influence diffusion effects on the incident radiation and, consequently, on shading and transmission levels (Sica and Picudo, 2007). Romacho et al., 2006) reported transmission values of 62 and 58% for a clear and a green 15 mesh screenhouse. Dust deposition on the screen can widely alter its transmission in the field, from 73 to 56% global radiation in a 35 mesh screenhouse (Santos et al., 2006). The reduction of incoming solar radiation can be considered a positive effect for shading installations, whilst in other agricultural applications, like anti-insect or anti-hail, it is considered as a negative consequence of screen performances (Candura et al., 2007).

The screens are effective protection against potential wind damage. Moller et al. (2003) found a reduction of 75 to 95% in wind speed referred to the outside air. In big size screenhouses, ventilation near the edges was more sensitive to variations in wind speed than in the centre (Tanny et al., 2003, 2006).

Several mathematical models to predict the inside temperature of screenhouses have been developed (e.g. Desmarais et al., 1999). As for standard greenhouses, ventilation rate plays a major in the internal climate of screen covered structures, and ventilation is strongly influenced by the screen porosity. Mean air temperatures were slightly lower (up to 1ºC) in screenhouses of 15 mesh (Raya et al., 2006; Romacho et al., 2006), whilst denser screens (35 mesh) induce 1ºC higher mean air temperatures (Santos et al., 2006). The average maximum and minimum air temperatures are more extreme and persist longer in low screenhouses (3.5 m high) than in higher ones (5.0 m high) Raya et al., 2006). Thermal inversion during clear nights is not unusual (Raya et al., 2006). A significant rise in maximum air temperatures appears when ventilation rates are low (Santos et al., 2006; Tanny et al., 2006)

During daylight hours, only minor reductions of vapour pressure deficit (VPD) have been reported in screenhouses with a fully developed canopy (Romacho et al., 2006). More interestingly, screenhouses can save around 30% of the annual irrigation water required for outside conditions, without any loss of yield and even improving quality (Tanny et al., 2006).

The use of coloured screens, instead of the conventional white or black screens, to manipulate the crop vegetative growth and improve the yield and quality has been recommended (Oren-Shamir et al., 2001). In coloured screens, the spectral manipulation is aimed at specifically promoting desired photomorphogenic/physiological responses, while light scattering improves light penetration into inner canopy (Shahak, 2008). In order to limit the visual environmental impact of screenhouses, the colour of the material should be considered (Castellano et al., 2007; Romacho et al., 2006)

Closed or Semi-closed Greenhouses

Active thermal storage in natural or artificial aquifers is increasingly applied in closed or semi-closed Dutch greenhouses. Thermal storage could mitigate day/night excursion in un-heated greenhouses and lengthen the growing season, while reducing the use of water and the entrance of pest. Through the application of a general model, Vanthoor et al. (2008, this symposium) have shown that enhancing the natural thermal storage of the soil does increase productivity in all conditions when the ventilation capacity is the limiting factor (summer Mediterranean climate). They have shown, however, that the effect can be opposite in the winter when the presence of the storage may result in a lower daytime temperature.

Using the greenhouse itself as a solar collector was one of the solutions tested in the eighties to reduce the dependence on fossil fuels (for instance, Baille et al, 1987; Levav, N., 1987). The thermal performance and energy consumption of these closed or semi-closed greenhouses was very positive, but the cost of the facilities and the reduccion of fuels prize prevented the dissemination of this technology. Some recent attempts have been made to develop closed greenhouses in Mediterranean areas, such as the Watergy project (Buchholz et al., 2006) since not only the need of conserving fossil fuel but the requirement of saving water for irrigation makes the closed-greenhouse concept attractive again. The main innovative element of the Watergy greenhouse is a cooling tower in the centre of the greenhouse where during the day time, hot air is rising from the vegetation area through the roof area into the tower. To increase the energy and water content of the rising air, it is further humidified in the roof area by sprinklers on an inner roof plastic layer.

During springtime evaluations the daytime temperatures ranged from 20 to 35°C, while the relative humidity oscillated between 80 to 90 %. Around 75% reduction of water consumption was achieved without the need of using additional energy and without pesticides applications. Also, no problems with fungi were observed. Nevertheless, the control of excessive humidity in closed or semi-closed greenhouses has to be improved since not all crops can grow under high humidity regimes. It would be desirable that the condensed water in the inner roof could be collected and reused. This goal can not be achieved in the majority of plastic-clad greenhouses available today. Innovative greenhouses should be able to provide better humidity control, since fungal diseases are known to produce severe losses in yield and quality of horticultural crops (Baptista, 2007).

Developments in Greenhouse Cladding Materials

There is still an enormous scope for improvement of the thermal and optical properties of the cover materials, both plastic films and glass. Waaijenberg (2006) reviewed the possibilities for improving plastic films for greenhouses. The main possibilities are

- Blocking NIR to reduce the natural warming up effect.
- Blocking UV radiation to limit the activity of harmful insects
- Improving the greenhouse effect (blocking the transfer of long wave radiation)
- Improving the anti-fog and anti-dust properties.

In particular, the most promising new plastic films are those that incorporate NIR blocking additives. Only about half of the energy that enters a greenhouse as sun radiation is in the wavelength range that is useful for photosynthesis (PAR, Photosynthetically Active Radiation). Nearly all the remaining energy fraction is in the Near InfraRed range (NIR) and warms the greenhouse and crop and does contribute to transpiration, none of which is necessarily always desirable.

Hemming et al. (2006) investigated new plastic film prototypes containing NIR-reflecting pigments with several concentrations, Fig. 5. The figure shows that a significant reduction of the sun radiation energy content in the NIR range is possible without much reduction in the PAR range. The effectiveness of NIR films on the reduction of greenhouse air and crop temperatures and their effects on crop yield and quality depends on a number of factors, such as the amount of NIR filtered by the film, the ventilation capacity of the greenhouse, the crop density and the canopy transpiration. The desk study of Hemming et al. (2006) showed that under Dutch conditions, the mean air temperature in a Venlo-type greenhouse can be reduced by about 1ºC during the summer months and increased energy consumption for heating in the winter months. Field tests conducted in

Southern Spain produced more optimistic results. Temperature reductions up to 4ºC during summer months have been reported. The NIR film gave an increase in yield and quality on a pepper crop (Garcia-Alonso et al., 2006). Probably the field study was carried out in a greenhouse with limited ventilation rate, and any sort of shading or radiation reduction has a stronger effect in poorly ventilated greenhouses.

Besides lowering greenhouse temperature (which is the primary aim), a NIR excluding cover has quite a few side-effects, that may become quite relevant in the passive or semi-passive greenhouses typical of mild climate. For instance, by lowering the ventilation requirement, such a cover may hinder in-flow of carbon dioxide, thereby limiting the photosynthesis rate. In addition, particularly in passive greenhouses cutting off a significant fraction of sun energy is certainly detrimental in some conditions.

The NIR-selective filters that are commercially available can be applied in three fashions: as permanent additives or coatings of the cover; as seasonal "whitewash" and as movable screens. It seems reasonable that it is the combination of external climate conditions and type of greenhouse that determines the most appropriate form of application in a given place. Some of these factors have been taken into account in the simulation study of Kempkes et al., (2008, this symposium) quantifying the expected benefits, in terms of inside climate. They show that year-round filtering of the NIR component of sun radiation is unlikely to increase productivity, even in mild winter climates, unless the reflected energy can be used otherwise. Sonneveld et al. (2008, this symposium) describe an advanced application aimed at transforming the excess energy into electric power.

In conclusion, whereas a permanent filter may have a useful application in tropical environments, it seems that in Mediterranean climates there is a huge potential for either movable screens, seasonal filters or filters whose optical properties vary with temperatures, presently under investigation.

Climate Control: Wise Use of CO_2

All technical improvements that reduce the ventilation requirement of the greenhouse may have the unintended consequence of limiting the natural inflow of carbon dioxide, thereby limiting photosynthesis and reducing yield. Stanghellini et al. (2007) have shown that in mild winter conditions, poor ventilation may be the ultimate limiting factor for production, through its effect on internal carbon dioxide concentration. In fact, ventilation is a trade-off between a sound management of temperature and of carbon dioxide inflow. Since bottled CO_2 is becoming commercially available in many greenhouse regions, and its price is going down, thanks to the European tax on emission of CO_2. After comparing results of growers applying quite different strategies, Stanghellini et al. (2008, this symposium) conclude that injection of bottled CO_2 up to at least the outside concentration is a technology most likely to be profitable also in simple greenhouses, provided that the injection rate may be linked to the ventilator opening.

Environmental Issues in Protected Cultivation

Many people give a light opinion on environmental issues. Perhaps such opinions are not based on solid data, and as a consequence intensive production systems such as greenhouse horticulture are perceived as artificial processes and therefore are considered as highly pollutant. But quantitative environmental assessments not always agree with this point of view. For instance, Muñoz et al. (2007) conducted a Life Cicle Assessment (LCA) to compare the environmental impacts of greenhouse versus open-field tomato production in the Mediterranean region. Results suggest that greenhouse production, <u>if properly managed</u>, has a smaller environmental impact than open-field crops in most of the evaluation categories considered. As yield (Kg of tomato) was chosen as the basic functional unit to wich impacts categories are referred to, most of the impact categories studied were adversely influenced by low production in open-field. It is relevant to stress the great advantage that could be gained by reducing the consumption of water in greenhouses systems located in semi-arid regions. In this comparative study, the water consumption to produce one Kg of tomato was 24.2 liter for greenhouse production and 42.8 liters for open field production (Table 1). The tendency to ventilate less (semi-closed greenhouses) could even reduce further the amount of water consumed.

This is not meant to say the greenhouses do not have a negative burden on the environment. For instance, large areas covered with greenhouses create a big visual impact, a factor which is especially important in the highly touristic Mediterranean Coast. Our intention is to identify the main factors affecting the environmental impact associated to greenhouse production and to suggest solutions to mitigate the problems. Referring back to the work of Muñoz et al. (2007) it was observed that the greenhouse structure had the greatest influence in the global warming category with the highest values being due to emissions of CO_2 during the production of the structure itself (using steel and concrete). The use of recycled materials or extending the lifespan of the materials used could help to reduce this impact. Additionally, structural analysis can help to lessen the amount of materials of the greenhouse structure, since, for instance, the footing of locally made greenhouses is mostly designed by experience rather than based on structural analysis.

Other LCA studies (Anton, 2004) show that fertilizer production and use is the main factor that influences the environmental burden associated with acidification and eutrofization. In the first case, this is due to emissions of SO_2 and NH_3 during the production process, and in the second to the leaching of NO_3 to water. In a study conducted on cut flower production it was concluded that soil-less cultivation reduced the pollutant burden on the environment, above-all, by virtue of productivity more than double with respect to soil production (Scarascia Mugnozza et al., 2007)

In recent years, some growers seeking to improve product quality and income have made improvements to the traditional structure and introduced new equipment such as forced ventilation and/or heating. However, these modifications have also led to an increase in the consumption of energy and other resources with direct implications for environmental impact. LCA studies are being conducted to evaluate the environmental impact of improved technology in Mediterranean greenhouse systems (Antón, unpublished data). Results show that the greatest environmental impacts are due to the management of the different climate systems (forced ventilation and heating) in the industrial greenhouse. According to the environmental category in question (risk of eutrophication and depletion of non-renewable resources), a 1.1 to 3.5 fold increase in the tomato yield with respect to traditional passive-greenhouse productivity would be necessary to justify the increased investment in equipment and energy. An increase of 10% is attained by most technologies whereas a 3.5 fold increase is achieved by none.

<u>The greenhouse of the future will have nearly zero environmental impact</u> (EUPHOROS EU Project). Appropriate climatic conditions in mild winter climates are the most important factor for determining sustainability in passive greenhouses. In these areas with favourable climate, a wise use of the available natural resouces together with the contribution of well selected technology to overcome situations of unfavourable weather conditions is the key factor to achieve sustainability. For mild winter areas, the greenhouse of the future will have good light transmission, covering materials especifically chosen for each crop requirement and adequate and controllable natural ventilation combined with insect protection. Good agricultural practises especially regarding irrigation and fertilization programmes are a must to reduce emissions. Waste management by composting the biomass and recycling materials is another obligation for future sustainable greenhouses.

Finally it is worth mentioning that individual greenhouses may not be able to achieve the goal of zero environmental impact, but grouping them into <u>clusters</u> provides additional environmental advantages. Possibly the greenhouse of the future will be part of a complex with a centralised water treatment plant that supplies water for irrigation and reuses lixiviates, centralised energy supply perhaps based on renewable energies, a shared waste treatment plant for composting biomass and recycling materials and, among other features, common areas where biodiversity is fostered to compensate with the loss in biodiversity due to land occupation.

One has to be optimistic, since there is enough knowledge already to design profitable and sustainable production systems. It is time to continue developing solutions, to disseminate the available knowledge and, most important, to take actions to remove the obstacles that hinder implementation in commercial practice of the existing solutions.

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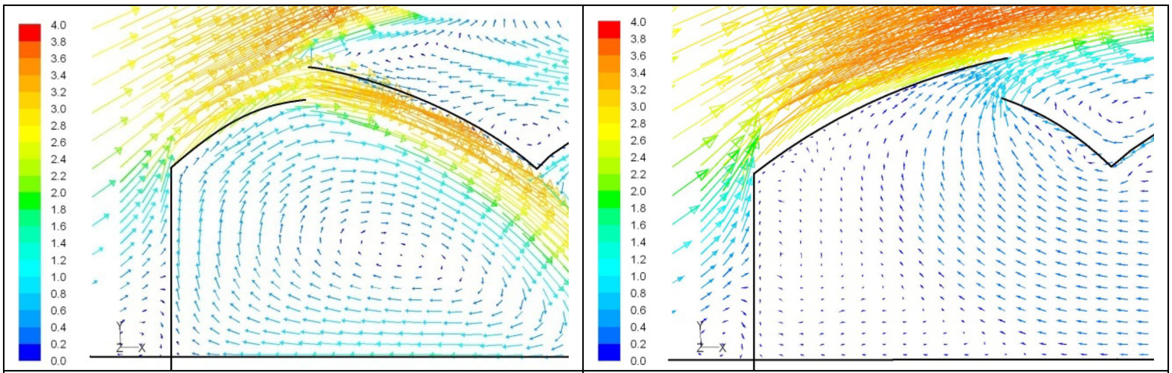
Tables

Table 1. Overall environmental impact results for greenhouse (G) and open-field (O) systems to produce 1 kg of tomatoes (Muñoz, et al 2007).

Impact categories	Units	Greenhouse	Open-field	O/G
depletion of non-renewable resources	Kg Sb eq.	3,65E-04	4,79E-04	1,31
global warming	Kg CO_2 eq.	7,44E-02	5,01E-02	0,67
ozone depletion	Kg CFC-11 eq.	8,97E-09	8,95E-09	1,00
acidification	Kg SO_2 eq.	4,84E-04	6,38E-04	1,32
eutrophication	Kg PO_4^{-2} eq.	1,23E-04	1,52E-04	1,24
energy consumption	MJ eq.	0,94	1,19	1,27
water consumption	L	24,24	42,84	1,77

Figures



a. Windward ventilation | b. Leeward ventilation

Fig. 1. Velocity vectors in and around the first greenhouse span for windward ventilation and leeward ventilation.

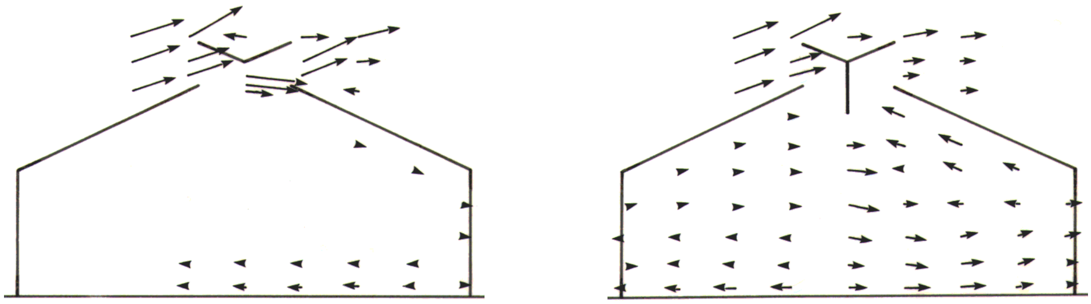


Fig. 2. Effect of a deflector at the roof ventilator on the internal air circulation. Nielsen, 2002.

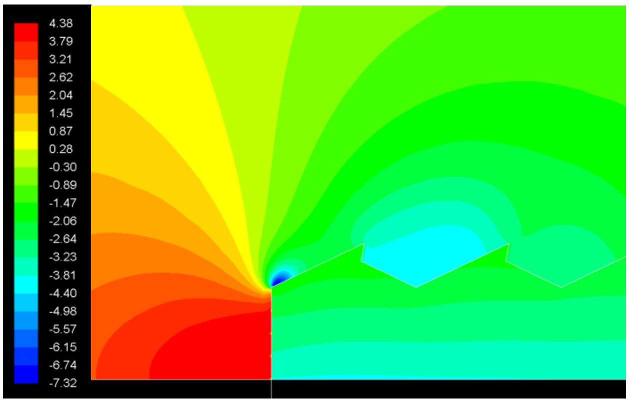


Fig. 3. Scalar pressure field in a greenhouse with leeward ventilation. Red areas are positive pressure. Green and blue areas are negative pressure.

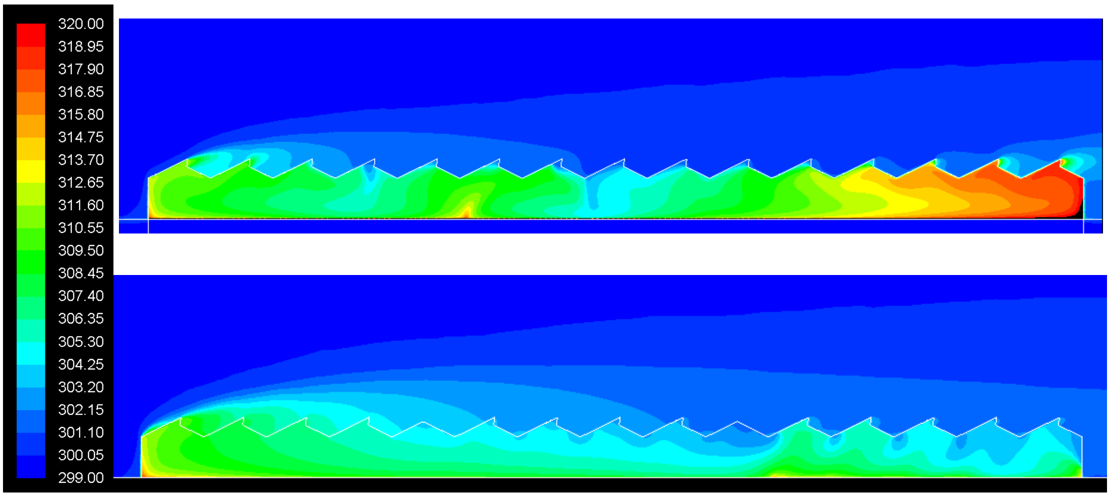


Fig 4. Scalar temperature field in a greenhouse with leeward ventilation. a) side walls closed. b) lee side wall open and increased ventilation area at five-span intervals**.**

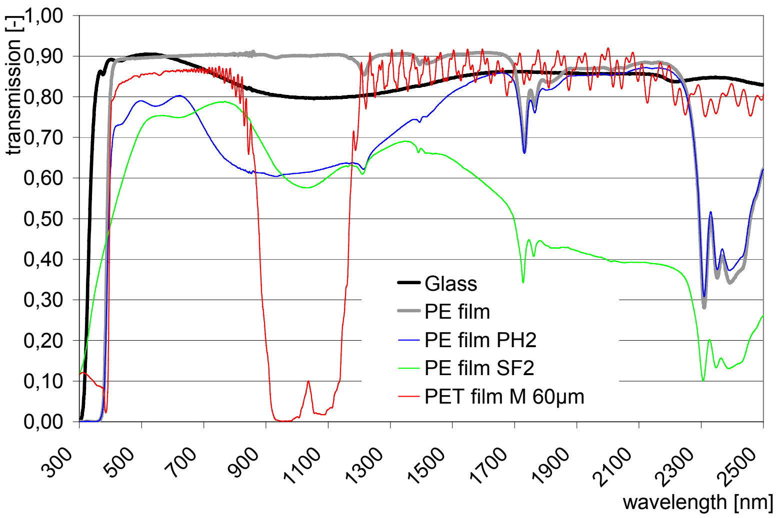


Fig. 5. Spectral transmission of different greenhouse cladding materials.