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GREENHOUSE CLIMATE CONTROL IN MEDITERRANEAN GREENHOUSES

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SUMMARY

An overview of the good agricultural practices for greenhouse horticulture in the Mediterranean and South East Europe regions is presented and discussed. In these areas, natural ventilation and whitewashing are the most common methods/systems used for greenhouse climate control during summer, since it require less energy, less equipment operation and maintenance and are much cheaper to install that other cooling systems. However, generally these systems are not sufficient for extracting the excess energy during sunny summer days and therefore, other cooling methods such as forced ventilation combined with evaporative cooling (mist or fog system, sprinklers, wet pads), are used. On the other hand, during winter period, heating and dehumidification are necessary for a standard quality production. Optimal greenhouse climate control become more important in the latter part of the twentieth century, when concerns about food safety, environmental pollution stimulated extensive research in the development of Integrated Production and Protection systems aiming at a significant reduction of pesticides use. The prospective and needs for future research and development in greenhouse climate control are presented in the conclusion.

RESUMEN

En este artículo presentamos una revisión de buenas prácticas para la horticultura de invernadero en el Mediterráneo y en las regiones del sureste europeo. En las áreas, la ventilación natural y el blanqueo son los métodos más usados para el control durante el verano, dado que requieren menos energía, menos equipamiento para operarlos y mantenerlos y son mucho más baratos que el resto de sistemas de enfriamiento. Sin embargo, no son suficientes para extraer el exceso de calor durante los días soleados de verano y por ello se utilizan otros sistemas de enfriamiento, como la ventilación forzada combinada con enfriamiento por evaporación (nebulizadores, aspersores o wet pads). Por otra parte, durante el invierno, es necesario calentar y deshumidificar para lograr una producción de calidad estándar. La optimización del control de clima en los invernaderos ha ido ganando importancia desde finales del pasado siglo, cuando la preocupación por la seguridad alimentaria y la contaminación ambiental estimularon la investigación sobre sistemas de producción y protección que redujeran significativamente el uso de pesticidas. En las conclusiones se hace una prospectiva sobre la investigación y el desarrollando de nuevas fórmulas de control de clima haciendo hincapié en la combinación de estudios físicos y ecofisiológicos.

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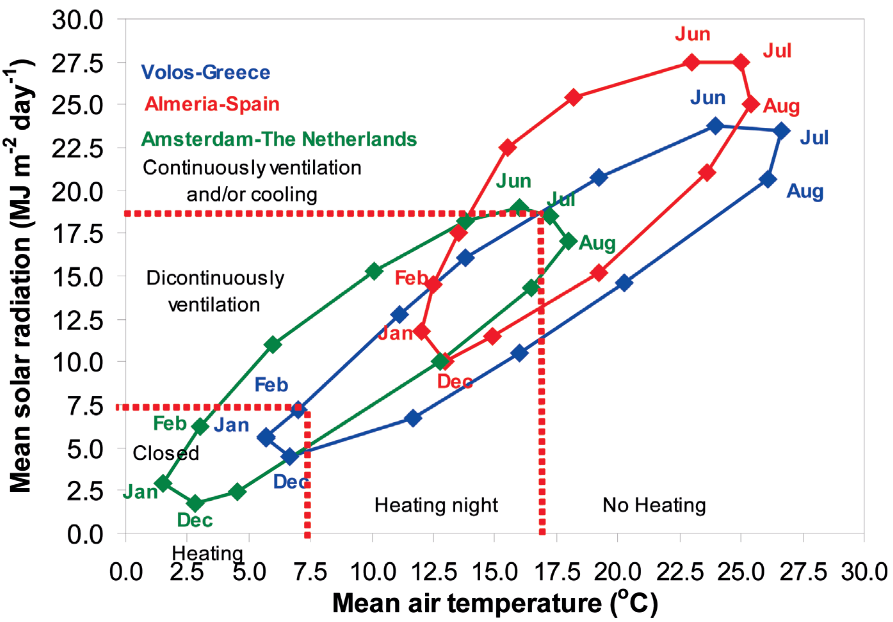
1. Driving forces for greenhouse climate control and sustainable energy use in Mediterranean Greenhouse

All greenhouse cultivation systems, regardless of geographic location, consist of fundamental climate control components, and depending on their design and complexity, they can provide a greater or lesser amount of climate control, and subsequent plant growth and productivity.

Temperature is the most important variable of the greenhouse climate that can and needs to be controlled. The majority of plants grown in greenhouses are warm-season species and are adapted to average temperatures in the range 17-27 °C, with approximate lower and upper temperature limits of 10 °C and 35 °C. If the average minimum outside temperature is below 10 °C the greenhouse is likely to require heating, particularly at night. When the average maximum outside temperature is less than 27 °C ventilation will prevent excessive internal temperatures during the day; however, if the average maximum temperature exceeds 27-28 °C then artificial cooling may be necessary. The maximum greenhouse temperature should not exceed 30-35 °C for prolonged periods. The climograph of some Mediterranean and North Europe regions is shown in Figura 1. This shows that in temperate climates e.g. in the Netherlands, heating and ventilation enables the temperature to be controlled over the whole year, however, at lower latitudes, e.g. Almeria-Spain and Volos-Greece, the daytime temperatures are too high for ventilation to provide sufficient cooling during the summer. The attainment of suitable temperatures then requires cooling.

The second important variable of the greenhouse climate is humidity, which has traditionally been expressed in terms of relative humidity. Relative humidity within the range 60-90 % is suitable to plant growth. Values below 60 % may occur during ventilation in arid climates, or when plants are young with small leaves, and this can cause water stress. Serious problems can occur if the relative humidity exceeds 95 % for long periods, particularly at night as this favours the rapid development of fungus diseases e.g. *Botrytis cinerea*. Maintaining the VPD above some minimum value helps to ensure adequate transpiration and also reduces disease problems. During the day, humidity can usually be reduced using ventilation. However, at night, unless the greenhouse is heated, the internal and external temperatures may be similar and if the external humidity is high; reducing the greenhouse humidity is not easy.

Figure 1. The mean solar radiation vs. mean air temperature for several locations around Europe: The climograph. Dotted lines indicate border lines for different control action in the greenhouse



After the first "energy crisis" in the early 1980ies, where the limited supply of energy caused the first significant increase in energy prices, the energy use of greenhouses has become a major economic and research issue. There are mainly two ways to increase the energy efficiency: a) reduction of the energy input into the greenhouse system and b) increase the production per unit energy. The major challenge is to find ways which meet both needs: improved energy efficiency combined with an absolute reduction of the overall energy consumption and related CO_2 emission of the greenhouse industry. Technological innovations must focus on the energy consumption for the return on productivity, quality and societal satisfaction.

Clearly there are numerous technologies for greenhouse systems which can be adopted by the growers enabling a better and more efficient climate control and energy use. However, many obstacles and constraints remain to be solved. The existing technology and know-how developed in Northern Europe countries are generally not directly transferable to the Mediterranean growers: high-level technology is out of reach for most of the Mediterranean growers because their cost is too high compared to the modest investment capacity of these growers. Know-how from Northern Europe growers is often inappropriate to the problems encountered in the Mediterranean shelters (Figure 2).

The issues that are addressed in this paper concern the means and best practices by which Mediterranean growers can alleviate the climate-generated stress conditions that inhibit the growth and the development of the crops during the long extending warm season in a sustainable and energy friendly way.

Figure 2. Internal view of a (a) Parral (mainly found in Almeria, Spain) and Venlo (mainly found in The Netherlands) type greenhouse

2. Climate Control

2.1. Ventilation Cooling and Shading

Getting rid of the heat load is the major concern for greenhouse climate management in hot climate conditions. This can be realised by: (1) reducing incoming solar radiation; (2) removing the extra heat through air exchange; and (3) increasing the fraction of energy partitioned into latent heat.

Shade screens and whitewash are the major existing methods used to reduce the income of solar radiation; greenhouse ventilation is an effective way to remove the extra heat through air exchange between inside and outside, when outside air temperature is lower; and evaporative cooling is the common technique to reduce sensible heat load by increasing the latent heat fraction of dissipated energy. Other cooling technological solutions are available (heat pump, heat exchangers), but are not yet widely used, especially in the Mediterranean countries, because investment cost is yet very high.

2.1.1. Ventilation

One of the simplest and more effective ways to reduce the difference between inside and outside air temperature is to improve ventilation. If the greenhouse is equipped with ventilation openings (Figure 3), both near the ground and at the roof, then this type of ventilation replaces the internal hot air by external cooler one during the hot sunny days with weak wind. The external cool air enters the greenhouse through the lower side openings while the hot internal air exits through the roof openings due to density difference between air masses of different temperature causing the lowering of temperature in the greenhouse.

Figure 3. Greenhouses with different type of ventilation openings

Sufficient ventilation is very important for optimal plant growth, especially in the case of high outside temperature and solar radiation, which are common conditions during summer in Mediterranean countries. In order to study the variables, determining the greenhouse air temperature and to decide about the necessary measures for greenhouse air temperature control, a simplified version of the greenhouse energy balance is formulated. According to Kittas *et al*. (2005), the greenhouse energy balance can be simplified to:

$$V_a = \frac{0.0003\tau R_{s,\,o-\max}}{\Delta\ T} \tag{1}$$

where:

V_a is the ratio Q/A_g, Q is the ventilation flow rate, in m^3 [air] s^{-1} and A_g is the greenhouse ground surface area, in m^2

τ is the greenhouse transmission coefficient to solar radiation

$R_{s,o-max}$ is the maximum outside solar radiation W m^{-2},

ΔT is the temperature difference between greenhouse and outside air, in ºC.

Using eqn. (1), it is easy to calculate the ventilation needs for several values of $R_{s,o-max}$ and ΔT. Figure 2.2 presents the variation of V_a for several values of $R_{s,o-max}$, τ and ΔT.

From Figure 4 it can be seen that for the area of Magnesia, Greece, where during the critical summer period, values of outside solar radiation exceed the value of 900 W m^{-2} (Kittas *et al*., 2005), a ventilation rate of about 0.06 m^3 s^{-1} m^{-2} (which corresponds, for a greenhouse with a mean height of 3 m, to an air- exchange of 60 h^{-1}) is needed in order to maintain a ΔT of about 4 ºC.

The necessary ventilation rate can be obtained by natural or by forced ventilation. For effective ventilation, ventilators should, if possible, be located at the ridge, on the side walls and the gable. Total ventilator area equivalent to 15-30 % of floor area was recommended by White and Aldrich (1975). Above 30 %, the effect of additional ventilation area on the temperature difference was very small.

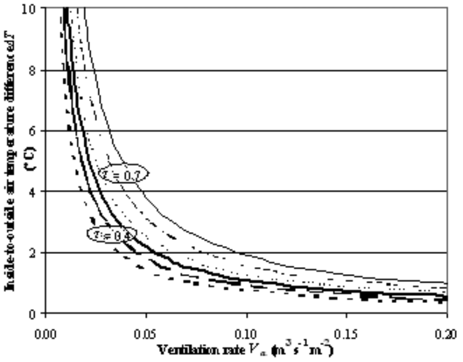


Figure 4. Inside-to-outside greenhouse air temperature difference ΔT as a function of ventilation rate Va as calculated using eqn. (3), for a greenhouse with a regularly transpiring rose crop. Thin lines correspond to a greenhouse cover transmission to solar radiation τ of 0.7. Heavy lines correspond to a τ of 0.4. (—): Rs,o = 900 W m-2, (— —): Rs,o = 750 W m-2, (- - -): Rs,o = 600 W m-2. (Kittas *et al.*, 2005).

Systems like exhaust fan; blower, etc. can supply high air exchange rates whenever needed. These are simple and robust systems and significantly increase the air transfer rate from the greenhouse and allow maintaining inside temperature to a level slightly higher than the outside temperature by increasing the number of air changes. The principle of forced ventilation is to create an air flow through the house. Fans suck air out on the one side, and openings on the other side let air in. Forced ventilation by fans is the most effective way to ventilate a greenhouse, but consumes electricity. It is estimated that the annual needs for electrical energy for greenhouse ventilation in the Mediterranean is about 100.000 kWh per greenhouse ha.

Some key elements are: Ventilation fans should develop a capacity of about 30 Pa static pressure (3 mm on a water gauge), should be located on the leeside or the lee end of the greenhouse and the distance between two fans should not exceed 8-10 m. Furthermore, an inlet opening on the opposite side of a fan should be at least 1,25 times the fan area. The velocity of the incoming air must not be too high, in the plant area; the air speed should not exceed 0,5 m s^{-1}. The openings must close automatically when the fans are not in operation.

Many researchers also studied the effects of insect-proof screens in roof openings on greenhouse microclimate. However, the obstruction offered by fine mesh screens to flow through the openings results in air velocity reduction and higher temperature and humidity as well as an increase of the thermal gradients within the greenhouse (Katsoulas *et al.*, 2006).

Guidelines

- For effective ventilation, ventilators should, if possible, be located at the ridge, on the side walls and the gable.
- Total ventilator area equivalent to 15-30 % of floor area is recommended for natural ventilation. Above 30 %, the effect of additional ventilation area on the temperature difference is very small.
- When not limited by too low external wind speed, natural ventilation may be more appropriate as it creates a more humid and cooler environment, although less homogeneous, around the canopy.
- With roof ventilators, the highest ventilation rates per unit ventilator area are obtained when flap ventilators faced the wind (100 %), followed by flap ventilators facing away from the wind (67 %). The lowest rates of roof ventilation are obtained with the rolling ventilators (28 %).
- Forced ventilation by fans is the most effective way to ventilate a greenhouse, but it consumes electricity.
- Ventilation fans should develop a capacity of about 30 Pa static pressure, should be located on the leeside or the lee end of the greenhouse and the distance between two fans should not exceed 8-10 m. Furthermore, an inlet opening on the opposite side of a fan should be at least 1,25 times the fan area. The velocity of the incoming air must not be too high, in the plant area; the air speed should not exceed 0,5 m s^{-1}. The openings must close automatically when the fans are not in operation.
- With fan cooling alone (no evaporative cooling) little advantage could be derived from increasing airflow rates beyond 0,05 m^3 m^2 s^{-1}.

2.1.2. Shading

The entry of unwanted radiation can be controlled by the use of shading or reflection techniques. Shading can be obtained by various methods such as by the use of paints, external shade cloths, use of nets (of various colors), partially reflective shade screens (Figures 2.3) and water film over the roof and liquid foams between the greenhouse walls. Shading is the ultimate solution to be used for cooling greenhouses, because it affects the productivity. However, in some cases, a better quality can be obtained from shading. One of the most used methods adopted by growers due its low cost is white painting, or whitening, the cover material. The use of screens has progressively been accepted by growers and has gained, through the last decade, a renewed interest as shown by the increasing area of field crops cultivated under screenhouses (Cohen *et al*. 2005), while roof whitening, due to its low cost, is a current practice in the Mediterranean Basin.

Baille *et al*. (2001) reported that whitening applied onto a glass material enhanced slightly the PAR proportion of the incoming solar irradiance, thus reducing the solar infrared fraction entering the greenhouse. This characteristic of whitening could represent an advantage with respect to other shading devices, especially in warm countries with high radiation load during summer. Another advantage of whitening is that it does not affect the greenhouse ventilation, while internal shading nets.

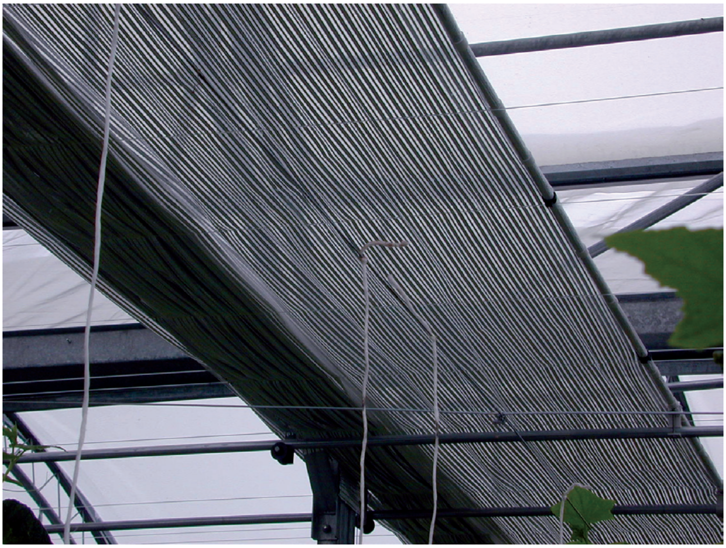


Figure 5. Thermal screen used for energy saving and greenhouse shading

2.1.3. Evaporative cooling

One of the most efficient solutions for alleviating the climatic conditions is to use evaporative cooling systems, based on the conversion of sensible heat into latent heat by means of evaporation of water supplied directly into the greenhouse atmosphere (mist or fog system, sprinklers) or through evaporative pads (wet pads). Fog system is based on spraying the water as small droplets with high pressure into the air above the plants in order to increase the water surface in contact with the air (Figures 2.4a). Free fall velocity of these droplets is slow and the air streams inside the greenhouse easily carry the drops. This can result in high efficiency of water evaporation combined with keeping the foliage dry. The fan-and-pad cooling system (Figures 2.4b) is most commonly used in horticulture. Air from outside is blown through pads with as large a surface as possible. The pads are kept permanently wet by sprinkling. The water from the pads evaporates and cools the air. For this reason, the outside air humidity must be low.. In order to achieve an optimal cooling the greenhouse should be shaded. The water flow rate, water distribution system, pump capacity, recirculation rate and output rate of the fan-and-pad cooling system must be carefully calculated and designed to provide a sufficient wetting of the pad and to avoid deposition of dissolved material in it. The advantage of fog systems over wet pad systems is the uniformity of conditions throughout the greenhouse, therefore eliminating the need for forced ventilation and airtight enclosure.

Guidelines

- Fog systems can be high (40 bars) or low (5 bars) pressure systems. High pressure systems produce droplets of 10-30 μm while low pressure systems produce droplets with diameter higher than 200 μm. High pressure systems are more effective than low pressure.

- The nozzles of the fog system should be located at the highest possible position inside the greenhouse to allow water evaporation before the water drops to crop or the ground.

- During the operation of the fog system a vent opening of 20 % of the maximum aperture should be maintained.

- The pad material should have high surface, good wetting properties and high cooling efficiency. A suggested pad thickness is 200 mm. It is very important that there are no leaks in the pad where the air can pass through without making contact with the pad.

- The pad area depends on the air flow rate necessary for the cooling system and the permissible surface velocity over the pad. Average face velocities are 0,75 - 1,5 m s^{-1}. The pad area should be about 1 m^2 per 20-30 m^2 greenhouse area. The maximum fan-to-pad distance should be 40 m.

- Fans should be placed on the lee side of the greenhouse. If they are on the windward side, an increase of 10 % in the ventilation rate will be needed. The distance between the fans should not exceed 7,5-10 m, and the fans should not discharge towards the pads of an adjacent greenhouse less than 15 m away.

- When starting the cooling system, the water flow through the pad should be turned on first to prevent the pads from clogging. When stopping the cooling system in the evening, the fan should be turned off before the water flow through the pad.

- A basic air flow rate of 120-150 m^3 per m^2 greenhouse area per hour will permit satisfactory operation of an evaporative cooling system.

Figure 6. Evaporative cooling systems: (left) fog system, (right) fan and pad cooling system.

2.2. Heating

Greenhouse heating is essential even in countries with temperate climate, like the Mediterranean region, in order to maximize crop production in terms of quantity and quality and thus to increase the overall efficiency of greenhouse. Heating costs not only have a critical influence on the profitability, but in the long term may also determine the survival of the greenhouse industry. Apart from the costs problems associated with high energy consumption, heating is associated with environmental problems through the emission of noxious gases.

Heating needs

There are number of formulations for calculating greenhouse heating needs (H_g) (W) among which the simplest is that proposed from ASAE (2000):

$$H_g = U A (T_i - T_o) \tag{2}$$

where,

U = heat loss coefficient (W m^{-2} K^{-1}), see table 1

A = exposed greenhouse surface area (m^2)

T_i = inside air temperature, (K)

T_o = outside air temperature (K)

Table 1. Total heat loss coefficient U at wind speed of n ms^{-1} (ASAE, 2000)

Covering materials	U value, W m^{-2} K^{-1}
Single glass	6,0-8,8
Double glass, 9mm air space	4,2-5,2
Double acrylic 16mm	4,2-5,0
Single plastic	6,0-8,0
Double plastic	4,2-6,0
Single glass plus energy screen of:	
Single film, non-woven	4,1-4,8
Aluminized single film	3,4-3,9

Note the estimation of greenhouse needs using equation 2 did not take into account the heat loss due to infiltration.

Calculate yours greenhouse heating needs

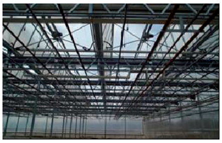
Steps		How you can do this
1.	Measure the first three dimensions of the greenhouse	First measure the length, width and height of the structure (till the point that the roof begins).
2.	Measure the ridge of the greenhouse	Measure the distance between the ground and the tip of the greenhouse's roof.
3.	Measure the slope of the greenhouse's roof	The slope is the distance from the tip of the roof to the bottom of the roof
4.	Determine the surface area of the greenhouse's roof slope and two walls	To do this use the formula: 2 x (H + S) x L Where H=height, S=roof slope and L=length
5.	Determine the surface area of the remaining two walls	To do this, use the formula:(R + H) x W Where R=ridge, H=height and W=width.
6.	Determine the total surface area of your greenhouse	To do this, add together the results from Step 4 and Step 5.
7.	Calculate the desired temperature different	Determine the best temperature for the interior of the greenhouse. Determine the average coldest temperature for the area surrounding your greenhouse. Determine the difference between the two temperatures
8.	Estimate your overall heat loss coefficient	According to your covering material refer to table 1
9.	Estimate the heating needs of your greenhouse	Multiply the total surface area of the greenhouse (step 6) by the temperature difference (step 7) by the overall heat loss coefficient (step 8)

Unit Heaters, In this systems, warm air is blown from unit heaters that have self-contained fireboxes. Heaters are located throughout the greenhouse, each heating a floor area of 180 to 500 m^2).

Central Heating. Heat is half dissipated through radiation and half through convective transfers. Unlike unit heater systems a portion from the heat from central boiler systems is delivered to the root and crown zone of the crop. This can lead to improved growth of the crop and to a higher level of disease control.

Wall Pipes coils: Perimeter-wall heating can partially provide the additional heat required and contribute to a uniform thermal environment in the greenhouse. Both bare and finned pipe applications are common.

Overhead pipes coils: Heat loss through the roofs and gables is supplied through an overhead coil of pipes that is situated across the entire greenhouse. The overhead coil is not the most desirable source of heat because it is located above the plants

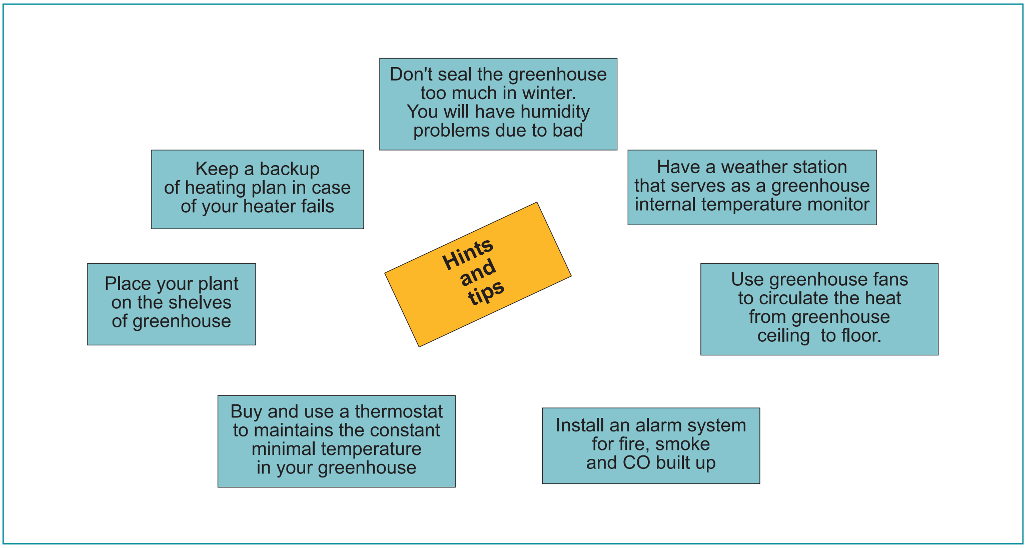


In bed-pipe coils: By placing the heating pipes near the base of the plants, the roots and crown of the plants are heated better than in the overhead system. Air movement caused by the warmer underbench pipe reduces the humidity around the plant.

Pipe/Rail Heating Systems: maintain uniform temperatures and positively affect the microclimate of plants. Air movement caused by the warmer pipe/rail reduces the humidity around the plant. Such systems are suitable for vegetable production systems.

Heating for antifrost protection: In these greenhouses heating was used to protect crops from freezing. It is also used to keep air temperature in greenhouse in levels above critical thresholds for condensation control. These greenhouses are not equipped with heavy and complicated heating systems. Usually a unit heater is enough. Other useful recommendations for heating a greenhouse in order to avoid freezing of plants are:

- To back the north wall to an existing structure such as a house or outbuilding. This rear wall offers extra wind protection and insulation.
- Use water to store heat (a simple passive solar heating system). We can use barrels or plastic tubes filled with water, inside the greenhouse to capture the sun's heat. The heat accumulated during the day will be released at night when temperatures drop.
- Insulate your greenhouse. If your greenhouse is constructed of plastic, insulate with a foam sheet. These sheets can easily be placed over the structure at night and removed during the day. Also install an additional layer of plastic to the interior of the green house for added insulation.



2.3. CO_2 enrichment

Inside an un-enriched greenhouse, the CO_2 concentration drops below the atmospheric level whenever the CO_2 consumption rate by photosynthesis is greater than the supply rate through the greenhouse vents. The poor efficiency of ventilation systems of the low-cost greenhouses in Mediterranean countries, coupled with the use of insect proof nets (Muñoz *et al*., 1999) explains the relatively high CO_2 depletion (about 20% or more) reported in southern Spain (Lorenzo *et al*., 1990). The solution is to increase the ventilation rate through forced air, to improve design and management of the ventilation system, or to provide CO_2 enrichment. The latter is common in the greenhouse industry of Northern Europe as a means to enhance crop photosynthesis under the low radiation conditions that prevail during winter in those regions. Enrichment reportedly increases crop yield and quality under a CO_2 concentration of 700– 900 μmol mol^{-1} (Nederhoff, 1994). One of the main restrictions is the short time duration available for an efficient use of CO_2 enrichment, due to the need to ventilate for temperature control (Enoch, 1984). The fact that greenhouses have to be ventilated during a large proportion of the daytime makes it uneconomical to maintain a high CO_2 concentration during the daytime. However, some authors advise supplying CO_2 even when ventilation is operating (Nederhoff, 1994) to maintain the same CO_2 concentration in the greenhouse as outside and enriching to levels of about 700–800 μmol mol^{-1} during the periods when the greenhouse is kept closed, usually in the early morning and the late afternoon.

Optimal CO_2 enrichment depends on the margin between the increase in crop value and the cost of providing the CO_2 gas. Attempting to establish the optimal concentration by experiment is not feasible because the economic value of enrichment is not constant but varies with solar radiation through photosynthesis rate, and with greenhouse ventilation rate through loss of CO_2 (Bailey & Chalabi, 1994). The optimal CO_2 set point depends on several influences: the effect of CO_2 on the photosynthetic assimilation rate, the partitioning to fruit and to vegetative structure, the distribution of photosynthate in subsequent harvests, and the price of fruit at those harvests, as well as the amount of CO_2 used, greenhouse ventilation rate and the price of CO_2. Stanghellini *et al*. (2008) applied a simple model for estimating the potential production loss, through data obtained in commercial greenhouses in Almeria Spain and Sicily Italy. They analysed the cost, potential benefits and consequences of bringing more CO_2 in the greenhouse either though increase in ventilation, at the cost of lowering temperature, or through artificial supply. They found that whereas the reduction in production caused by depletion is comparable to the reduction resulting from the lower temperature caused by ventilation to avoid depletion, compensating the effect of depletion is much cheaper than making up the loss by heating. The two principal sources of CO_2 for enrichment are pure gas and the combustion gases from a hydrocarbon fuel such as low sulphur paraffin, propane, butane or natural gas.

2.4. Dehumidification

Condensation is a symptom of high humidity and can lead to significant problems, including germination of fungal pathogen spores, including Botrytis and powdery mildew. Condensation occurs when warm, moist air in a greenhouse comes in contact with a cold surface such as glass, fiberglass, plastic or structural members. Condensation can be a major problem and it is unfortunately one which, at least at certain times of the year, is almost impossible to avoid entirely.

How to dehumidify your greenhouse

Combined used of heating and ventilation systems

By opening the windows, moist greenhouse air is replaced by relatively dry outside air. This is common practice to dehumidify a greenhouse. This method does not consume any energy when excess heat is available in the greenhouse and ventilation is needed to reduce the greenhouse temperature. Though, when the need for ventilation to reduce the temperature is less than the ventilation needed to remove moisture from the air, dehumidification consumes energy. The warm greenhouse air is replaced by cold dry outside air, lowering the temperature in the greenhouse.

Absorption using a hygroscopic material

The research on the application of hygroscopic dehumidification in greenhouses is minimal because the installation is too complex and the use of chemicals is not favourable in greenhouses. During the process, moist greenhouse air is in contact with the hygroscopic material releasing the latent heat of vaporisation as water vapour is absorbed. The hygroscopic material has to be regenerated at a higher temperature level. A maximum of 90 % of the energy supplied to the material for regeneration can be returned to the greenhouse air with a sophisticated system involving several heat exchange processes including condensation of the vapour produced in the regeneration process.

Condensation on cold surfaces

With this system wet humid air is forced to a clod surface which is located inside the greenhouse, different than the covering material. In the cold surface condensation occurs, the condensate water is collected and can be re-used and absolute humidity of the wet greenhouse air is reduced.

One metre of finned pipe used in their study at a temperature of 5 °C can remove 54 g of vapour per hour from air at a temperature of 20 °C and 80 % relative humidity.

Forced ventilation usually with the combined use of a heat exchanger

Mechanical ventilation is applied to exchange dry outside air with moist greenhouse air, exchanging heat between the two airflows.

Based on the results of Campen *et al*. (2003) a ventilator capacity of 0,01 m^3 s^{-1} is sufficient for all crops. The energy needed to operate the ventilators is not considered because the experimental study by Speetjens (2001) showed that the energy consumption by the ventilators is less than 1 % of the energy saved.

Anti-drop covering materials

The use of anti-drop covering materials is an alternative technology for greenhouse dehumidification. The "anti-dripping" films that contain special additives which eliminate droplets and form instead a continuous thin layer of water running down the sides. The search for anti-drip cover materials has been mainly focused on the optical properties of the cover materials.

When to dehumidify?

Dusk:	Reduce humidity to 70-80 % as night falls to prevent condensation
Dawn:	Reduce humidity to prevent condensation, and jumpstart transpiration as the sun rises

Hints and tips

- Open the windows or the door to your greenhouse and allow excess moisture to escape ventilation
- Remove any excess sources of water that you have in your greenhouse
- Purchase a humidity controller or a dehumidifier for use in your greenhouse
- Place radiant heat sources near the crop to keep plant surfaces slightly warmer than air
- Turn on your greenhouse fan to improve the air circulation
- Use thermal screens at night to prevent radiative heat loss from plant surfaces

3. Rational use of Energy and Renewable Energy Sources

3.1. Rational use of energy

The need for rational use of energy is critical since energy forms a substantial fraction of total production costs. For North Western European conditions, with heated greenhouses, the annual energy use for conditioning is very high, e.g. for Scandinavia: 1.900 MJm^{-2}. In Mediterranean areas, the energy use for a tomato crop is roughly 50 % of this. However the range of energy consumption in southern regions seems broader (Vésine *et al*., 2007). In these areas heating is more and more commonly used to obtain early production and a constant quantitative-qualitative yield, leading to a higher energy use. Improved environmental control (e.g. more CO_2 supply, additional lighting), intensified production schemes and use of cooling systems all cause an increase in energy consumption. On average the energy use ranges from 10-30 % of the total production costs, depending on the different regions.

The increase of production per unit of energy (energy efficiency), can be achieved by reduction of the energy use and/or improvement of production. The major challenge in greenhouse operation is to find ways to contribute to improved energy efficiency combined with an absolute reduction of the overall energy consumption. The emission of CO_2 depends on the total use and the type of fossil fuel. E.g. when coal is used, the CO_2 emission is 80-100 kg/MJ; for diesel 75 kg/MJ; for propane 65 kg/MJ, while for natural gas it is about 58 kg/MJ.

In general the same objectives hold for Mediterranean as well as Northern European regions with respect to optimizing the production efficiency: during fall/winter the objective is to maximize the radiation quantity and minimize the energy loss; during the spring/summer the objective is to reduce high temperatures. The rational use of energy (or fossil fuels) can be achieved by three steps:

1. Efficient use of energy (i.e. amount of product per input of energy)

2. Reduction of the energy requirement of the greenhouse

3. Replace fossil fuels by more sustainable sources.

In general these steps require increasing investments, and should therefore be considered as logical steps for the greenhouse operator to follow in order to reduce his energy consumption.

3.1.1. Energy efficient climate control

Rational use of energy largely depends on an (energy) efficient greenhouse environmental control which requires knowledge of the physiological processes, like photosynthesis and transpiration, crop growth and development in relation to the various environmental factors temperature, light, humidity and Carbon dioxide. However, for maximal benefit of energy efficient environmental control, it is essential that the greenhouse itself and the control equipment, (heating and ventilation system, CO_2 supply, lighting) are properly designed and frequently checked (at least at the start and once during the growth season). E.g. optimized designs of pipe heating systems may prevent uneven temperature distribution and subsequent loss of energy and crop production.

Although the introduction of new innovative environmental control technologies will add to energy efficiency, large improvements can already be made by simply improving the hardware design like heating and ventilation systems and improving both accuracy and frequently control of the sensor network. Taking this into consideration, the major practical recommendations for rational use of energy largely depend on the operational control by the grower of his available hardware in terms heating, ventilation and cooling systems, screens etc.:

- Take care of regular maintenance, check and calibration of devices, sensors, pumps, valves, ventilators etc. at least at the start of each cropping period.

- Do not place thermostats/ sensors in direct sunlight, use aspirated sensors

- Make as much use as possible of the incoming solar energy under cold conditions by delaying ventilation or the opening of thermal screens

- Use larger differences between day and night temperature settings for ventilation (4-6^{o}C) or use automatic Temperature Integration if available

- Pay attention to the settings of your environmental control system or thermostats and check regular if these still fit with your production strategy

- Consider using higher humidity setpoints during periods with lower irradiation in heated greenhouses

- When using a thermal screen, always open the screen first to reduce humidity rather than the vents.

- When available: apply CO_2 at least to ambient concentration (i.e. 340-370 µmol mol^{-1}), this will not reduce the use of energy but significantly contribute to crop growth and production.

3.2. Energy saving: Reduction of Energy requirement of the Greenhouse

The major processes of energy loss in natural ventilated greenhouses are: (1) convection and radiation from the greenhouse cover, and (2) thermal and latent heat transfer through ventilation. Improved insulation and reduced ventilation are therefore the first steps to create energy conservative greenhouses. The basics for energy reduction are good maintenance of the greenhouse hardware (doors, cover, side walls, foundation). The practical measures to be taken first of all, deal with preventing unnecessary air leakage form the greenhouse eg by keeping greenhouse doors closed, sealing of air leakages, repair of broken cover material and side walls and uniform closure of natural ventilators.

In almost all regions world wide, and especially at Southern latitudes, there is a large surplus of solar energy requiring efficient cooling systems to reduce the air temperature. Natural ventilation is the most common method of cooling and optimizing the greenhouse geometry can be used to enhance natural ventilation. As greenhouses with series of ventilator openings and/or at different heights perform better with respect to static or wind driven ventilation, traditional horizontal roof greenhouses are being replaced with symmetrical or asymmetrical greenhouses. Windward ventilation is more efficient than leeside ventilation, so new greenhouse constructions have bigger-size openings facing the prevailing winds, requiring adapted mechanical constructions to withstand the stronger wind loads.

Shading to reduce the solar energy flux into the greenhouse during periods with an excessive radiation level is a common way of passive cooling. Mobile shading systems mounted inside or outside have a number of advantages, such as the improvement of temperature and humidity, quality (e.g. reduction of Blossom End Rot in tomato crops) and a clear increase in water use efficiency. Especially for southern regions, movable and external shading are very efficient cooling systems to improve the energy efficiency.

Specific materials which absorb or reflect different wave lengths or contain interference or photo or thermochromic pigments may be used to bring down the heat load but mostly these materials also reduce the PAR level. Materials reflecting part of the sun's energy not necessary for plant growth (the near-infrared radiation, NIR) show promising results (e.g. Garcia-Alonso *et al*., 2006 and may be applied either as greenhouse cover or as screen material.

Mechanical cooling using fans, heat pumps and heat exchangers can be used to maintain the same greenhouse temperature as with natural ventilation or even further reduce the greenhouse temperature especially under high ambient temperatures and/or high radiation levels. With high cooling capacity it is even possible to keep the greenhouse completely closed, even at maximum radiation levels. However all practical and experimental experience show that return on investment for these systems is poor for all regions in the world, except for the direct evaporative cooling by fogging/misting and indirect evaporative cooling (pad and fan).

This is most likely the result of the positive effect of the lower temperature and higher humidity since increasing humidity in the lower ranges, generally shows positive effects on growth and production, at least with major fruit vegetables. So direct evaporative cooling by misting and pad and fan cooling still give the best economic results and increase the energy efficiency primarily through the impact on production.

The reduction of the energy requirement of the greenhouse is related to the more strategic choices of the grower in relation to his greenhouse construction, cover and environmental equipment in terms of heating system, ventilation, cooling, screens etc. Several recommendations on this equipment have been presented already in Chapter 2.1. Each decision on equipment always should be considered in terms of return on investments. Although each specific situation will lead to different final choices, the more general recommendations for this step from the viewpoint of energy consumption are:

- Take care of regular maintenance of the greenhouse hardware (doors, cover, side walls, foundation, ventilators, pad/fan, screen material etc).

- Keep doors closed, seal of air leakages, replace broken cover material and ripped screens.

- Select a greenhouse cover materials with a low IR transmission.

- Use (moveable) thermal screens for area's with low average and/or night temperatures.

- Replace horizontal roof greenhouses with symmetrical or asymmetrical greenhouses with series of ventilators.

- When using natural ventilation: Build greenhouses with large windward ventilation openings located to the prevailing wind direction.

- If cooling is required: preferably use misting or pad and fan cooling and if not sufficient: add a shading screen.

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