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Chapter 1

SUSTAINABLE GREENHOUSE SYSTEMS

Giuliano Vox*[*1], Meir Teitel[2], Alberto Pardossi[3], Andrea Minuto[4], Federico Tinivella[4] and Evelia Schettini[1]

[1]University of Bari, Bari, Italy
[2]Agricultural Research Organization, Bet Dagan, Israel
[3]University of Pisa, Pisa, Italy
[4]Regional Research and Extension Centre for Agriculture (CE.R.S.A.A.) – Special Agency of Chamber of Commerce, Industry, Handicraft and Agriculture of Savona, Albenga (SV), Italy

ABSTRACT

Greenhouse systems improve growing conditions of vegetable, fruit and ornamental crops. Greenhouse coverage protects plants from adverse atmospheric agents and, together with suitable equipment, influences and ultimately modifies the crop microclimate, thus lengthening the market availability of the products, improving their quality and allowing higher yields. Greenhouse production has a higher return per unit area than crops grown in the open field, but it requires the use of large amounts of energy to operate the equipment on one hand and generates huge quantities of wastes to be disposed of on the other hand. Protected cultivation can be environmentally unfriendly, especially in areas with a large concentration of greenhouses. Therefore, the steady worldwide increase in the area covered by greenhouses has generated the need for developing sustainable protected horticulture. Sustainable greenhouse horticulture can be achieved by means of different cultivation techniques, adequate equipment management and innovative materials aimed to reduce agro-chemicals and energy use, water consumption and waste generation. The achievement of optimal greenhouse microclimate conditions, the application of integrated pest management strategies and the use of innovative closed-loop fertigation systems with water recycling result in a significant reduction of plant diseases—and, consequently, of agro-chemicals use—and in a decrease in the consumption of both water and fertilisers as well as in the contamination of water bodies associated with nutrient leaching. Optimal climate control and reduction of energy

* Department of Engineering and Management of the Agricultural, Livestock and Forest Systems (PROGESA), University of Bari, Via Amendola 165/a, 70126, Bari, Italy. E-mail: giulius.vox@agr.uniba.it

consumption can be obtained by using suitable active and passive systems including proper control strategies for equipment and the use of innovative covering materials. Renewable energy sources and technologies, such as solar thermal and photovoltaic systems, can be used to reduce fossil fuel consumption for climate control. Waste generation mainly concerns the use of materials such as covering and mulching plastic films that must be disposed of at the end of their life; the introduction of innovative biodegradable materials can reduce this kind of waste, improving crop sustainability. The chapter presents the design concepts of greenhouse sustainable systems based on the application of innovative covering materials, microclimate control strategies, renewable energy sources and the use of leading technologies. In addition, it considers fertigation and integrated pest management strategies that may contribute to sustainable operations.

1. Introduction

Greenhouse cultivation is the most intensive form of crop production with a yield per cultivated unit area up to 10 times superior to that of a field crop. Vegetable, ornamental and fruits crops are cultivated worldwide under greenhouse conditions. Greenhouse equipment and covering material provide a controlled microclimate that may be adapted to the needs of the crops, resulting in higher yield, quality and in the lengthening of the market availability of the products. Greenhouse production requires the use of large amounts of energy, water and agro-chemicals, and it usually generates huge quantities of wastes to be disposed of. Investment, labour and energy costs per unit area are much larger in the greenhouse industry than in any other agricultural sector.

Gafsi et al. (2006) have defined sustainable agriculture as “the ability of farming systems to continue into the future”; i.e., sustainable agriculture means a “maintenance of the adaptive capacity of farming systems”, which allows preserving the natural resources and the ability to farm and produce food into the future without reducing the options available for following generations. Many advocates of sustainable agriculture claim that modern intensive agriculture, which includes greenhouse horticulture, has undermined values such as the conservation of the natural resources and the safety of food products that are associated with sustainable agriculture (Aerni, 2009). Such growing environmental interest has prompted several authors to study and propose solutions to improve sustainability with regard to particular aspects of greenhouse systems.

Van Os (1999) studied the sustainability of Dutch greenhouse horticulture with emphasis on the systems aimed to reduce the leaching of water and fertilizers into the ground and surface water. Bot (2001) focused attention on energy saving in climate control of greenhouses located in North European maritime climate areas. De Pascale and Maggio (2005) analyzed some aspects concerning the sustainability of Mediterranean greenhouse systems, focusing on the use and management of water, which is a scarce resource in Mediterranean areas. Plant response-based sensing for microclimate control strategies was indicated by Kacira et al. (2005) as a tool to improve greenhouse sustainability.

The effectiveness of innovative technologies aimed to improve protected horticulture sustainability can be evaluated by means of Life Cycle Assessment (LCA), by analyzing the input and output of energy and resources needed per unit of product (Munoz et al., 2008a; Russo and De Lucia Zeller, 2008).

Sustainable greenhouse systems, which must be resource-conserving, socially supportive, commercially competitive and environmentally sound, rely on cultivation techniques, equipment management and constructive materials aimed to reduce agro-chemicals, energy and water consumption as well as waste generation. The objectives can be obtained by means of the following:

i) the efficient management of climatic parameters, i.e., solar radiation, air temperature, relative humidity and carbon dioxide (CO_2) concentration in order to guarantee suitable growing condition for the crop and energy savings;
ii) the use of renewable energy sources in place of fossil fuels;
iii) the use of innovative greenhouse covering materials with suitable physical properties and low generation of after-use waste;
iv) the optimisation of water and nutrient delivery to the plants in order to reduce water and nutrient consumption and drainage with ground water and soil preservation;
v) the integrated management of pests and diseases with a significant reduction of agro-chemical use.

The chapter presents the recent trends of the research aimed to increase the sustainability of the greenhouse industry, investigating aspects concerning the microclimate control and energy sources, covering materials, plant nutrient and water delivery and management of pests and diseases.

2. Microclimate and Energy (*M. Teitel and G. Vox*)

2.1. Introduction

The level of microclimate control varies greatly, from the basic shelter type greenhouse to the fully computerized actively conditioned greenhouse. The aim of full climate control of greenhouses is summarized by Albright (2002) as follows: “Plant production within closed environments strives to bring each plant to its genetic potential”. In principle, in sustainable production the efforts taken to control the microclimate should take into account that the rate of renewable resource consumption should not exceed the regeneration rate. In addition, the rate of non-renewable resource consumption should not exceed the rate of renewable replacement resource development and, finally, the pollutant emission rates should not exceed the environment capacity to absorb and regenerate them (De Pascale and Maggio, 2005).

In the last decade, there have been considerable efforts to manipulate greenhouse microclimate by using sustainable approaches. The focus was mainly on parameters that affect crop microclimate such as temperature, humidity and CO_2 concentration. The following concentrates on the effect of these parameters in greenhouse cultivation and reports on the up-to-date techniques to manage them with emphasis on the use of sustainable approaches.

2.1.1. Temperature

The management of the greenhouse environment is strongly reliant on temperature manipulation. Temperature manipulation is critical to influencing plant growth and morphology and so is a major strategy in environmental modification of crops. The response of plants to increasing temperature is reasonably predictable. There is a temperature range, for most plants, from 10°C to 24°C, over which there is a near linear positive response in terms of increased growth (Nelson, 2002).

There are optimum temperatures for each crop and for each stage of development. At the high end of the temperature range, above the optimum, losses in quality can be experienced such as longer stems, thinner stems, fewer flowers, bleaching of flowers and slower flower bud development. At excessively high temperatures plant damage will occur. The base temperature, below which there is no growth, is also important as it provides a minimum set point for heating. Maintaining the optimum temperature for each stage of growth is the ideal in greenhouse environmental control however many greenhouses have limited capacity to modulate temperature precisely.

The optimum temperature of a crop may not be the temperature that produces the highest yield. The temperature setting for heating controls (set point temperature) is usually a compromise point between the cost of the heat energy and the diminishing crop returns from the elevated temperatures.

The natural diurnal cycle of low night temperature and higher day time temperature can be used by growers to manipulate plant development. As a general rule, under sunny conditions, crops are grown at a day time temperatures of 8°C to 10°C higher than night time temperature (Nelson, 2002).

The use of environmental modification techniques to control the plant form, rather than a chemical (growth retardant) is a positive step towards sustainability. This, for instance, can be done by changing DIF (day time temperature minus night time temperature) values. The normal temperature regime of warm days and cold nights represents a positive DIF. Manipulation of the greenhouse environment using DIF requires precise monitoring and control of the greenhouse environment.

The latest increases in price of fossil fuels created increased interest in improving energy use efficiency and energy savings in production greenhouses. The temperature management of crops is one strategy that is being adopted. The response of the crop to changed temperature regimes is a critical aspect that needs to be understood. The simple approach of reducing set point temperatures reduces energy consumption but may also result in a greater reduction in income. The manipulation of greenhouse air temperatures to achieve energy savings is a common practice. Higher average temperatures can be achieved using higher day time temperatures. This allows lower night time temperatures which results in lower heating fuel costs. Temperature integration aims to maintain the same average temperature while minimizing heating demand (Adams, 2006). Pressman et al. (2006) reported that exposing pepper plants to extremely high day temperatures (day/night temperatures of 36 ± 2/10 ± 2°C), obtained by keeping the greenhouse closed during the day to exploit solar heating, prevented the development of low night temperature symptoms. They indicated that their results could support the development of a novel procedure for producing greenhouse crops with minimum or even with no fuel consumption for heating during the winter nights in regions with bright and sunny days. Anyway, high temperatures in the daytime, which may be stressful for the crops, must be carefully controlled.

2.1.2. Humidity

Humidity in greenhouses is controlled for various reasons. The two main reasons are: avoiding too high humidity to avoid fungal infection and regulating transpiration. As a general guide it is often recommended that greenhouse relative humidity be maintained in the range of 60% to 80% for healthy growth. At high levels of relative humidity the risk for condensation on leaves is high (especially at night) and thus the risk of Botrytis and other fungal diseases to develop increases. In contrast to Botrytis and most other diseases, there are few fungi that thrive under low relative humidity. Renown is powdery mildew caused by different fungi in different crops.

The evaporation rate is driven by the difference in energy levels or pressure of water vapour between the leaf (saturated) and the surrounding atmosphere. This is the vapour pressure deficit (VPD). The temperature of the air, the relative humidity of the air and the temperature of the leaf are required to determine the VPD. The greenhouse environment should be managed to maintain an acceptable VPD.

High values of relative humidity can be reduced by ventilation and/or heating. Minimising the areas of wet surfaces, including plants, soils and floors, is another strategy to minimize elevated relative humidity. According to Campen et al. (2003) the methods used for dehumidification are: natural ventilation, condensation on a cold surface, forced ventilation in conjunction with a heat exchanger and hygroscopic dehumidification. During periods of heat demand, the most economic method of dehumidification is ventilation combined with heating because it has relatively low operating costs (Campen et al., 2003). Energy could be saved by applying heat recovery, and with rising energy prices this will soon be economically viable.

Air circulation within the total greenhouse space is important, as it encourages a more even environment and prevents the localised build up of water vapour. A recent trend to the installation of air circulation fans has proved beneficial in greenhouses where natural air movement is poor. The exact number and arrangement of fans are determined by the greenhouse type and size (Mastalerz, 1977; Hanan, 1998).

The use of covering films, which incorporate anti droplet formulations, is another effective way of treating the symptoms of high humidity. Due to the way in which these chemicals are released from the film, this property only has a limited life of one to two seasons. It is difficult to accurately predict its effectiveness, as it is dependent on several factors, including the rate of formation of condensation on the covering surface, the general greenhouse climatic conditions and the effect of pesticides and fungicides sprayed to protect the crop on the plastic film.

2.1.3. Carbon Dioxide

The production of healthy, high-yielding greenhouse crops can require the uptake of CO_2 at rates higher than the ones allowed by the typical atmospheric concentration (350–370 ppm). The enrichment of the greenhouse atmosphere with CO_2 concentrations in excess of 1,000 ppm has been found to be beneficial, with increases in growth rates and in some cases increases in product quality.

On the other hand, in well sealed greenhouses and in particular in plastic shelters, due to the photosynthesis and to the uptake of CO_2 by plants, internal CO_2 concentration may be much lower than outside ambient levels, thus resulting in dramatic reduction of crop growth and yield. For instance, Baille (2001) has reported CO_2 concentration down to 200 ppm in plastic greenhouses. Mixing of the greenhouse air is required to ensure healthy plant microclimates and prevent localized CO_2 deficiencies. This is achieved by horizontal air flow fans and vertical mixing fans.

Most greenhouse crops show a positive response to increased CO_2 levels up to 1,000 - 1,500 ppm (Nelson, 2002). There is an upper limit for enrichment beyond which there is no additional benefit. There is the risk of plant toxicity and potentially harmful effects for people if the levels are above 5,000 ppm. The response of crops to elevated CO_2 is greatest in the lower concentrations. According to Nederhoff (1995) increasing the concentration from 350 ppm to 400 ppm is the most effective.

Plant response to CO_2 enrichment is dependent on the light intensity. Lower light intensities are associated with lower threshold enrichment levels. Moreover, it is documented in the literature that optimum temperature for crops is higher with raised CO_2 levels. Therefore, another benefit of CO_2 enrichment is the possibility to keep the greenhouse air temperature during the day slightly higher than without enrichment and thus reducing ventilation. This may save energy when forced ventilation is applied.

There are a variety of systems available to CO_2 enrich the greenhouse atmosphere. CO_2 burners using propane gas are commonly used. Pure CO_2 is available as an industrial gas and can be supplied to the greenhouse in a regulated way from an onsite storage tank (Figure 1). This tends to be a relatively expensive enrichment technique and uneconomic if significant ventilation is required to maintain acceptable greenhouse air temperatures.

Figure 1. Pure CO_2 supplied to the greenhouse in a regulated way from an onsite storage tank.

CO_2 can also be extracted from the flue gases of fossil fuel furnaces. Hot water boilers are operated during the day, when the gas can be utilized by the crop, and the generated hot water stored in insulated tanks for night time distribution. Suitable fuels include natural gas, LPG and propane. CO_2 can also be obtained by burning biogas that is generated in municipal solid waste landfills and supplying the purified exhaust gases to the greenhouse (Jaffrin et al., 2003).

The cost of enrichment should be taken into account. The benefits of enrichment depend on increase in yield and quality due to CO_2 enrichment as well as on the price of the produce. Excessive enrichment is sometimes waste of money while moderate enrichment to prevent depletion and keep the concentration at about ambient levels may be more economic and reduce contamination of the atmosphere.

Stanghellini et al. (2009) indicated that allowing for higher than external concentration obviously reduces the efficiency of the supply, but it does not necessarily reduces profit. By applying some economics to a simple assimilation model they showed that in many conditions, particularly with relatively high radiation, maintaining higher than external concentrations does make economic sense, certainly up to ventilation rates of 10 h^{-1}. They concluded that the optimal management of carbon fertilisation should aim at concentrations well above 1,000 vpm in the absence of ventilation, and gradually decrease to maintaining the external value at ventilation rates well in excess of 10 per hour. Market conditions (value of produce vs price of CO_2) should determine the trend between these two extremes. In another paper Stanghellini et al. (2008) analysed costs, potential benefits and consequences of bringing in more CO_2 either through ventilation or artificial supply. They showed that whereas the reduction in production caused by depletion is comparable to the reduction resulting from the lower temperature caused by ventilation (in chilly days) to avoid depletion, compensating the effect of depletion is much cheaper than making up the losses by heating.

Ohyama et al. (2005) indicated that the control strategy that keeps the CO_2 concentration in the greenhouse at about the same level as outside is widely used in European countries with cool climates but is not popular in Asian countries that have a warm climate and require high ventilation rates. Therefore, they have extended the CO_2 concentration control method, which is used in Europe, for greenhouses with higher ventilation rates in moderate and hot climate regions.

Reduction of CO_2 exhaust from greenhouses is important in light of the Kyoto treaty for CO_2 emission levels. The target is that emissions should be reduced by 6% in the period 2006-2010 compared with emission levels in 1990.

2.1.4. Dynamic Climate Control

Sustainability in greenhouse production can be achieved by dynamic control of the microclimate. It is now well established that many greenhouse plants have the ability to tolerate variations in temperature and provided that the average temperature remains approximately constant, production is unaffected. This has resulted in the development of control strategies that are based on temperature integration as a method for reducing energy consumption. Currently this approach is applied to raising the temperature set point for ventilation to increase the average day temperature and lowering night time set point to reduce heating (Dieleman et al., 2005). The average temperature is unaffected. Limits are placed on the permitted temperature deviations and on the duration of the integration period. Trials in greenhouses on commercial nurseries have given energy savings of 5% to 15%. Temperature integration can be extended by relating the heating temperature to external conditions, particularly wind speed, which affect the rate of heat loss from heated greenhouses (Bailey, 1986). Hence, heating in periods of the night when wind velocity is low will allow energy saving.

An approach that dynamically controls the climate in a greenhouse that is based on the resources available for photosynthesis (e.g. light) was reported by Ottosen and Rosenqvist (2006). They indicated that experiments in Denmark showed that it is possible to save between 25% and 48% of energy consumption without affecting plant quality and production time by using a control system that regulates temperature and CO_2 concentration according to outdoor Photosynthetic Photon Flux Density and photosynthesis models.

2.2. Heating

To time production for a specific market and to have some control over crop quality and yield, growers need to heat their greenhouse whenever its temperature drops below the recommended temperature for their specific crop. Except of raising the air and crop temperatures to the desired level, heating is also applied in cases where there is a need to reduce air humidity (e.g. to reduce the probability of condensation on plant organs and thus reduce development of fungal diseases). In cold countries greenhouses are heated during most of the year, while in mild climates the heating period is shorter and heating is usually applied during the winter. In countries with a warm climate such as in Israel, heating is mainly applied during winter nights. Greenhouses in the Mediterranean region have much lower energy needs than those in north European countries. According to De Pascale and Maggio (2005) in Southern Italy, one hectare of cut roses requires between 5,200 and 6,800 GJ yr^{-1} vs. 16,000 GJ yr^{-1} required in the Netherlands for cut flower production. However, despite these lower heating requirements, it should be pointed out that the majority of Mediterranean greenhouse systems depend on non-renewable energy sources (fossil fuels) with a high impact on the environment.

Sustainability in cold and warm climates can be improved by using alternative energy sources such as organic waste, geothermal water or renewable energy sources (solar, wind) and through the reuse of energy (Bot, 2004; Short, 2004) and better insulating the greenhouse.

The amount of heat, q_h, required to balance the heat loss from a greenhouse can be estimated by (Bakker et al., 1995):

$$q_h = U A_c \Delta T - (1-\beta)\tau_{solar} S_0 A_f \tag{1}$$

where U is a total heat transfer coefficient which takes into account heat transfer through cladding material by conduction, convection, radiation and also air infiltration, A_c is the cover area of the greenhouse, ΔT is the temperature difference between the greenhouse air and the ambient, β is an evaporation coefficient, τ_{solar} is the transmissivity of the cover, S_0 is the solar radiation outside the greenhouse and A_f is the greenhouse floor area. For a given greenhouse, the maximum required heating capacity is determined according to Eq. (1) by the cover area, the thermal properties and thickness of the cover material, and the difference between the desired greenhouse air temperature and the design outside air temperature, which generally occurs at night.

A heating system is generally made up of a fuel-supply system, fuel burner, heat exchanger, heat distribution system and a control unit. Heating systems are usually classified as central or local. In a central system (Figure 2) the boiler is located in a separate house outside the greenhouse and the heat is distributed to the greenhouses by a distribution system. In a local system the heat is released directly to the greenhouse space since the furnace and thus combustion are within the greenhouse space.

Figure 2. Central heating system with boilers located outside the greenhouse.

The central hot water boiler is the standard for greenhouse heating in the Netherlands (Bakker et al., 1995) and is also very common in other European countries. On the other hand, in warmer countries (e.g. Israel), the hot air furnace is the most common because of its initial lower price in comparison to the hot water heating system. The hot water systems become more economic, in Israel, only in very large structures. There are a number of advantages to the central heating system: 1) a central plant offers greater flexibility to use alternative energy sources; 2) it uses less greenhouse space since the central plant is located in a separate building; 3) partial load performance might be much more efficient; 4) maintenance and control is easier and cheaper and 5) since combustion is done outside the greenhouse, improper combustion does not increase the probability of damaging the crop due to toxic flue gases (e.g. ethylene). Nevertheless, if a grower has a few small greenhouses, a central heating system may be more expensive than placing local systems in each greenhouse because of the need for a distribution system with the central unit.

There are four primary systems for greenhouse heating: 1) steam, 2) hot water, 3) hot air and 4) infrared.

Steam and hot water are usually delivered to the greenhouse by main supply and return system of pipes that are insulated from the surrounding to minimize heat loss. These pipes are connected to a secondary net of pipes (Figure 3) which is installed inside the greenhouse. The water circulates through the secondary net of pipes and heat is delivered to the crop by convection and radiation.

Figure 3. Hot water distribution system.

Air circulation by fans can reduce temperature stratification in the greenhouse during heating and reduce energy loss. Installing horizontal air flow fans that move the air at 0.3 to 0.6 m s^{-1} can limit temperature differences in the growing area.

Floor heating is considered good practice where plant containers can be set directly on the floor (ASABE EP406.4 standard, 2007). Loose gravel, porous concrete, solid concrete or sand can be used for the floor material. Floor heating systems can be either by buried pipes or flooded floor (Aldrich and Bartok, 1992). For floor heating the pipes are usually buried 10 cm in a porous concrete or 30 cm in ground. Floor heating is generally not sufficient for keeping the plants at the desired temperature and additional heat distribution equipment is needed to heat the space.

Floor heating was also described by Kozai (1989) who reported on a system of pipes buried in the greenhouse soil that was used for nocturnal heating. The excess solar heat during the day was stored in the soil by circulating the warm air in the greenhouse through the buried pipes in the greenhouse soil. The stored heat was then released from the soil to air by recirculating the air through the pipes during the night when heating was required.

2.2.1. Combined Heat and Power

Small scale combined heat and power (CHP) systems, also known as co-generation systems, are now quite common in modern large greenhouse structures. They use an internal combustion engine or a gas turbine to drive an electric generator and generate electricity in addition to heat. Such systems have been installed in the last decade in many greenhouses in the Netherlands and the UK (Critten and Bailey, 2002). In most cases the systems were operated to have geographically dispersed electricity generation. The heat produced is supplied to the greenhouse by heating pipes and the engine exhaust gases are distributed in the greenhouse through perforated tubes to provide CO_2 enrichment. Because CO_2 enrichment is beneficial during the day, the CHP systems operate during the day and the heat produced that is in excess of the greenhouse demands is stored in large water tanks and used during night. The electricity produced by the generators is usually used in the greenhouse (e.g. for supplementary lighting) and sold to electricity companies by connecting to the national electric grid. The performance of such a system was studied by Giniger and Mears (1984) who concluded that the optimum matching of the unit's capacity and operating time to the heat and electricity demands of a greenhouse facility are necessary if the most economical possible use is to be made of the unit. To improve the performance of CHP systems, de Zwart (1997) used a simulation model to determine the energy saving obtained by heat storage facilities with different dimensions and demonstrated that the amount of CO_2 supplied to the greenhouse during the day has a significant effect on the optimum storage capacity. Hamer and Langton (2005) carried out simulations to study the efficiency and effect on cost of using micro-turbine CHP units in ornamental production. Their simulations were carried out using an energy balance model for a typical ornamentals lighting installation based on a CHP system comprising a micro-turbine CHP unit, a heat store and a back-up boiler. Energy profiles were compared with those given by a conventional system comprising a boiler to provide the heat, and taking electricity for the lamps from the National Grid. Separate simulations were conducted for four different lighting regimes, each with and without "temperature integration" (an energy-saving protocol). The simulations indicated that CHP can give running cost savings of 30% to 42%, with the higher savings achieved at long operating times. Furthermore, micro-turbine CHP reduced CO_2 emissions by between 25% and 35%. They showed that temperature integration can save energy, particularly for the shorter lighting period. However, they indicated that for the grower the micro-turbine is not a cost-effective means of providing energy unless the existing mains supply is not large enough to meet the power demand. This is because the repayment of the capital investment is large and similar to the running costs. Furthermore the potential benefit of increased availability of CO_2 is not realised because the CHP is frequently not running at times when CO_2 would have benefited production.

2.2.2. Other Concepts of Greenhouse Heating

Bot et al. (2005) developed a "solar greenhouse" for high value crop production without the use of fossil fuels. The main approach was to first design a greenhouse system requiring much less energy, next to balance the availability of natural energy with the system's energy demand, and finally to design control algorithms for dynamic system control. Increasing the insulation value of the greenhouse cover was the first step towards a reduction in energy demand. The challenge was in maintaining a high light transmission at the same time. A first generation of suitable materials was developed. The realizable energy saving was almost 40%. The next reduction in fossil fuel requirement was accomplished by capturing solar energy from the greenhouse air during the summer months with heat exchangers (Figure 4), storing it in an underground aquifer at modest temperatures, and finally using the stored energy during the winter months by using heat pumps. The total realizable energy saving was reported to be more than 60%.

Figure 4. Efficient heat exchangers to collect heat from the greenhouse air during summer. The heat is stored in the aquifer.

A novel model of Latent Heat Convertor (LHC) capable to reduce the air relative humidity in the greenhouse as well as supply energy required for greenhouse heating was developed and presented by Assaf and Zieslin (2003). The principle of LHC is based upon direct contact of air with flowing hygroscopic solution known as brine. Following contact of the humid greenhouse air with the brine the vapour is condensed on the brine. The sensible heat of the condensation heats the brine and the warm brine heats the air which is introduced back with a lower relative humidity into the greenhouse. Such a system was tested in a 3,600 m^2 (120m x 30 m) greenhouse at ambient temperature of 11°C and 90% relative humidity. A continuous maintenance of the greenhouse air at 18°C during 12h night required 963 kWh, and resulted in a relative humidity of 87–88% in comparison to 1,545 kWh and relative humidity of 90–95% in the neighbouring greenhouse with a conventional heating system.

Phase change materials (PCMs) were used by several authors in an attempt to save energy in greenhouse heating. Nishina and Takakura (1984) used a PCM with a melting point around 20°C and a heat of fusion of 56 cal cm^{-3} to store heat from day to night. The greenhouse air was sucked by a fan into the PCM unit, exchanged heat with it and returned into the greenhouse through a polyethylene film duct. Two identical heat storage units were installed in a greenhouse with a total amount of 2.5 tonnes PCM and a potential value of latent heat conversion of 1 x 10^5 kCal. In the daytime, the two fans of the heat storage units were operated to store heat when the inside air temperature was above 22°C. The roof ventilators were opened when the inside air temperature was above 28°C. In the night-time, the fans were operated to deliver heat when the inside air temperature was below the set point. No auxiliary heating system was needed during the experimental period, and tomatoes grew well. The PCM heating method was also investigated by Nishina et al. (1988) who used solar heating during day to store heat and release it during night. They indicated that seventy percent of oil consumption was saved. The PCM method was also applied by Basçetinçelik et al. (1997) for seasonal heat storage.

Geothermal energy has been used most extensively in agriculture for greenhouse heating. According to Popovski (1993) many European countries are experimenting but also regularly using geothermal energy for commercial out of season production of flowers, vegetables and fruits. Worldwide use of geothermal energy in greenhouse heating increased by only 15.7% (or 3.0% annually) during 2000–2005 (Lund et al., 2005), which is slightly higher than during the 1995–2000 period. The installed capacity in 2005 was 1,404 MWt and the annual energy use was 20,661 TJ yr^{-1}. A total of 30 countries report geothermal greenhouse heating, the leading countries being Georgia, Russia, Turkey, Hungary, China and Italy. Most countries did not distinguish between covered (greenhouses) versus uncovered ground heating, and also did not report the area heated. Several countries, such as Macedonia, reported a decrease in geothermal greenhouse use, due to economic problems. Using an average energy requirement, determined for the World Geothermal Congress 2000 data, of 20 TJ yr^{-1} ha^{-1} for greenhouse heating, the 20,661 TJ yr^{-1} corresponds to about 1,000 ha of greenhouse heated worldwide. There are a few problems with geothermal heating as was pointed out by Hanan (1998) and Popovski (1993). The water supply may be highly corrosive, for deep sources there is a cost of drilling a well and attendant piping, pumping may be required which increases cost and the location of the wells may be remote.

2.2.3. Solar Thermal Systems

Solar thermal systems can be used to produce low enthalpy thermal energy for sustainable greenhouse heating systems. Solar thermal systems, based on solar collectors, have higher energy exchange ratio and a better cost-effectiveness with relatively low installation price, in comparison with photovoltaic systems. Common solar collectors consist of a series of copper pipes, which are painted black, sitting inside a thermal insulated box fronted with a glass panel. The fluid to be heated passes through the collector and into a tank for storage, the fluid can be cycled through the tank several times to raise the fluid temperature to the required value.

Due to the intermittent nature of the solar radiation and in relation with the size of the storage tank an auxiliary power supply is often necessary; a burner fed by biomass or fossil fuel can be used as auxiliary power supply; electrical heat pumps fed by wind turbines and/or photovoltaic systems can be used for co-heating as well.

Voulgaraki and Papadakis (2008) simulated a solar heating system with seasonal storage for a 1,000 m^2 greenhouse located in Thessaloniki, Greece, latitude 40° N; the simulation showed that with 900 m^2 of solar collectors and a storage volume of 552 m^3, about 40 % of the total heating load can be provided from the solar energy, while the rest of the energy need must be provided by an auxiliary power supply. The self sufficiency, i.e., when the total heating load is provided by the solar energy, can be obtained with several combinations of collectors area and heat storage volume; the self sufficiency can be reached, for example, with

3,000 m^2 of solar collectors area and 1,200 m^3 of storage volume or with 2,000 m^2 of solar collectors area and 1,840 m^3 of storage volume.

Over the last years experimental tests have been carried out at the University of Bari on the application of solar thermal collectors for greenhouse heating; the tests were performed on a greenhouse located in Southern Italy, latitude 41° N (Vox et al., 2008a). The solar thermal systems consisted of: a boiler for the hot water storage, with a capacity of 1 m^3, and 12 m^2 of solar collectors, positioned on the south-facing greenhouse surface (Figure 5), with an elevation angle of 90° in order to capture more solar radiation in cold than in warm periods. The water heated by the sun in the solar collectors flowed into the hot water tank where it was mixed (direct system) with the water circulating in the plastic pipes used to heat the plants; an electrical heat source was used as auxiliary power supply. Warm water was circulated inside the pipes heating the plants at a temperature of about 40°C. The low enthalpy heating system required a high level of thermal insulation; low tunnels covered with plastic films were mounted over the cultivation area inside the greenhouse and an aluminised thermal screen was used during the night in order to reduce the long wave infrared losses from the greenhouse. The air temperature heating set point inside the heated low tunnels was 14°C. The results of the experimental tests showed that about 34% of the solar energy incident on the thermal collectors was converted into usable thermal energy that was stored and then used for plant heating; about 64% of the total thermal energy heating the plants was provided from the solar energy, while the rest of the required energy was provided by the auxiliary power supply. The tests showed that, in these conditions, 0.15 m^2 of solar thermal collectors and storage of 0.012 m^3 can meet the energy needs of 1 m^2 of greenhouse floor area for a greenhouse located in Southern Italy.

Figure 5. Solar thermal flat collectors mounted on the south-facing greenhouse surface at the experimental farm of the University of Bari, Italy.

2.2.4. Concepts of Energy Savings

Thermal radiation can become the dominant mechanism of night-time heat loss from a greenhouse, particularly when there is a clear sky (Silva and Rosa, 1987). To reduce this heat loss, thermal screens are commonly drawn over the crop at sunset and removed at sunrise; they can reduce the overnight heat loss by 35–60% (Bailey, 1981). In addition to reducing thermal radiation, screens that are impermeable to air decrease the volume of the greenhouse air that needs to be heated and form an extra air gap between the crop and the greenhouse roof (Öztürk and Basçetinçelik, 1997), thereby reducing the heat transfer to the surroundings. Thus, they keep the internal air temperature higher than it would be without a screen (Montero et al., 2005). Furthermore, because screens reduce thermal radiation, heat loss by radiation from the crop is reduced and crop temperature is expected to be raised (Teitel et al., 2009). Kittas et al. (2003) considered the influence of an aluminised thermal screen on greenhouse microclimate and canopy energy balance, and they reported that with a thermal screen the microclimate at crop level was more homogeneous and the average air and canopy temperatures were higher than without a screen.

Another approach for energy saving involves double covers; either double glass with a layer of air between the sheets of glass or a double plastic cover that is inflated with air by a blower. The idea is to increase the heat conduction resistance of the greenhouse cover. Although experiments have shown that it can save as much as 40%, this method was not widely accepted as it resulted in reduction in light level during the days and unacceptable yield loss and crop delay. Other miscellaneous energy conservation methods are given by Hanan (1998).

2.3. Ventilation

The primary purpose of ventilation is to prevent excessive rise of temperature and humidity. This is achieved by replacing the hot and humid air of the greenhouse with ambient cooler and dryer air. In some cases, it is applied to prevent CO_2 depletion in greenhouse air caused by photosynthesis. At the same time, ventilation can reduce the concentration of pollutant gases and during winter, in cases where the heating unit is installed in the greenhouse, keep the combustion of the fuel at high efficiency since the lack of adequate oxygen results in incomplete combustion and carbon monoxide buildup.

In the extreme case, a complete lack of ventilation on a summer day could result total loss of the crop due to excessively high temperatures causing wilting followed by damage to plant tissue. Inadequate ventilation can have an effect on the crop which may not be apparent immediately. For example, the timing of flowering of a carnation crop can be influenced by excessively high temperatures with severe restricted growth delaying the next flush of flowers.

Two types of ventilation can be distinguished: *natural* and *forced*. Natural ventilation is driven by two mechanisms, namely the pressure field induced by the wind around the greenhouse and the buoyancy force induced by the warmer and more humid air in the greenhouse. Forced ventilation is accomplished by fans that are capable to move large quantities of air at relatively low pressure drop. A sustainable greenhouse will heavily rely on natural ventilation as it is driven by renewable energy.

Ventilation rate is specified in the literature as air changes per hour (units of h^{-1}), or flow rate per unit floor area (units of $m^3\ s^{-1}\ m^{-2}$). The former is not an appropriate measure since solar radiation which is causing the heat load on the greenhouse is the same per unit of floor area whether the structure is high or low. For example, if sixty air changes per hour are required for ventilation (one air change per minute) then in a greenhouse with an average height of 3 m, every square meter of floor area which has a column of air of 3 m^3 above it will be ventilated by a flow rate of 3/60 = 0.05 $m^3\ s^{-1}\ m^{-2}$ (floor area). If, however, the average height of the structure is 5 m, then the same flow rate per unit floor area results in only 0.05x3,600/5 = 36 air changes per hour.

By using an energy balance on a greenhouse the flow rate Q required to keep the greenhouse air at a temperature T_i can be calculated, which according to the ASABE EP406.4 standard (2007) is:

$$(1-\beta)\,\tau\, S_0 A_f = U A_c (T_i - T_0) + \left(\frac{Q A_f c_{pex}}{v_{ex}}\right)(T_{ex} - T_{inl}) \qquad (2)$$

Seginer (1997) proposed alternative design formulae for estimating the required ventilation rate of a greenhouse. These formulae refer to canopy rather than to air temperature and can be extended to situations where the Bowen ratio (the ratio of sensible to latent energy fluxes) is negative. One of the formulas proposed by him is:

$$Q = \frac{\alpha \gamma S_0}{\rho c_p \phi \left[\alpha \theta (T_{cr} - T_0) + 1\right]} \qquad (3)$$

By solving an example with $\alpha = 0.25\ K^{-1}$, $\theta = 0.4$, requiring $T_{cr} - T_0 = 5$ K and assuming a positive Bowen ratio he showed that 50% more ventilation is needed than for attaining $T_i - T_0 = 5$ K. On the other hand for a negative Bowen ratio, the opposite is true, namely less ventilation is required to maintain a certain temperature difference relative to T_{cr} than to T_i. He concluded that the larger the humidity gradient between the greenhouse interior and exterior, the less ventilation is required.

2.3.1. Forced Ventilation

The basic requirements of a fan for greenhouse ventilation are that it should be capable of moving large quantities of air at relatively low pressure drops. Of the different types of fan available the most suitable is the axial fan which consists of direct-driven or belt-driven impellers with a varying number of blades. The fans are usually mounted on the sidewalls because of structure limitation and to minimize shading.

Teitel et al. (2004) proposed to use variable speed fans to control the speed of rotation of the fans. They showed that with such control it is possible to save about 25–30% of energy and keep the same microclimate as with ON_OFF control. Similar results were reported by Davies et al. (2008) who reported that reducing the speed can cut the energy usage per volume of air moved by more than 70%. They also indicated that powering a greenhouse fan from a photovoltaic generator is an interesting option. The capital cost of a system that utilizes a photovoltaic generator is high however there are advantage in terms of independence and reliability especially in places such as developing countries where the grid supply may be intermittent. Davies et al. (2008) indicted that currently the availability of energy saving fans using low-speed, sunlight-controlled variable speed or solar-power (e.g., using brushless DC motors) is rather poor.

2.3.2. Natural Ventilation

Natural ventilation can be achieved by opening windows at the top of the greenhouse and/or at the sidewalls. The number and size of the windows and mechanisms for window opening vary. Many different arrangements of opening ventilators have been used in glass and plastic covered houses. Ridge openings can be classified under the type headings of continuous or non-continuous and they are usually on both sides of the ridge though hoses with openings on one side only are also constructed. Roof vents are either fixed or fully automatic (movable roof vents). A fixed overlapping vent on gable ridge provides ventilation while preventing penetration of rain and hail. Movable roof vents are formed by, e.g., film roll-up from gutter to ridge, ridge hinged arched vents, vertical opening at the center of the arc which run the entire length of the roof, vertical roof opening that starts at the gutters and extends to a height of about 1 m, vertical opening at the center of the arched roof which run the entire length of the roof. The position and hinging of the vent at the ridge are the basis of a better evacuation of the hot and humid air which builds up at the top of the greenhouse. In Venlo greenhouses the ventilators in most of the houses are hinged from the ridge and extend half way to the gutter or as far as the gutter. The idea is to provide a large opening area especially in warm and humid areas. Recent greenhouse designs provide retractable roofs. The new designs are traditional A-frame greenhouses with articulating roofs that either hinge at the gutters and open at the peak or hinge at one gutter and the peak while opening at the opposite gutter and moving across the greenhouse bay. Side ventilation is usually achieved by rolling up curtains with central mechanism operated manually or by an electric motor. Mechanisms that open the side vents from bottom to top or vice versa are available, where the most common operate from bottom to top. Side openings with flaps that are hinged from the top are also used however they are more common in glasshouses than in plastic covered greenhouses.

Buoyancy Driven Ventilation

Temperature and humidity differences between the inside and outside of a greenhouse produce forces that drive flow. The natural tendency for hot and humid air to rise and accumulate towards the upper part of a space leads to stable stratification, and this has a significant influence on the flow patterns within the greenhouse. The determining factor in the form of the vertical stratification is the location of the openings. A vertical opening at the top of a single span greenhouse will allow exchange of warm and humid air outwards and cool dryer air inwards. The warm and humid air will flow out through the upper area of the opening and the cool air will enter through the lower area of the opening. The incoming air will descend as a turbulent plume that will tend to mix the air within the space. This type of ventilation is known as mixing ventilation. If two vents are open, one at the top of the greenhouse and the second near the bottom, warm humid air flows out through the upper opening and cool dry air enters through the lower opening. This form of ventilation is known as displacement ventilation. It is characterized by larger temperature gradients with respect to height than those observed with mixing ventilation (Zhao et al., 2001).

Wind Driven Ventilation

Wind effect on greenhouse ventilation is influenced by the shape of the greenhouse and its openings and by the proximity to other structures. Generally speaking, pressures are higher on the windward side of the greenhouse and lower on the leeward side and on the roof. Wind creates a pressure distribution over a greenhouse which is influenced both by the mean wind speed and turbulence.

Combining Wind and Buoyancy Effects

Greenhouses are most of the time subject to both buoyancy and wind-induced pressure forces. The processes are nonlinear and so the combined effects cannot be obtained simply by adding the results of the two different processes acting in isolation. The nonlinearity arises because the flows through openings are a nonlinear function of the pressure drop across them (Hunt and Linden, 1999). The extent to which the wind hinders or enhances the ventilation of the greenhouse depends upon its strength and direction as well as upon the structure of the greenhouse and its openings and the temperature and humidity differences between the internal and external environments. Most authors assume the pressure field on the greenhouse is a sum of the pressure fields due to both wind and buoyancy, i.e., $\Delta P = \Delta P_{w} + \Delta P_{bu}$ and this leads to the following relation:

$$Q = (Q_w^2 + Q_{bu}^2)^{0.5} \tag{4}$$

Boulard and Baille (1995) proposed the following relation for a greenhouse equipped with only roof openings:

$$Q = \frac{A_V}{2} C_d \left(2g \frac{\Delta T}{T_0} \frac{H_V}{4} + C_w w^2\right)^{0.5} \tag{5}$$

For a greenhouse with roof and side openings with areas A_t and A_b, Kittas et al. (1997) suggested the following relation:

$$Q = C_d \left(2g \frac{\Delta T}{T_0} \frac{(A_t A_b)^2}{(A_t^2 + A_b^2)} Z + \left(\frac{A_t + A_b}{2}\right)^2 C_w w^2 \right)^{0.5} \tag{6}$$

Buoyancy driven ventilation is significant only at low wind speeds. The literature indicates that for a wind speed higher than 2 m s^{-1} the buoyancy effect is small and may thus be neglected. Kittas et al. (1997) suggested that for a greenhouse with roof and side vents the buoyancy driven ventilation dominates when $w / \Delta T^{0.5} < 1$.

2.4. Cooling Systems

The large quantity of heat that has to be removed from greenhouses, especially in warm regions, preclude the possibility of using mechanical refrigeration for greenhouse cooling since mechanical refrigeration will require huge capital investment in equipments, operating costs and maintenance. Therefore, all commercial greenhouses that utilize a cooling system use evaporative cooling which is much cheaper. Evaporative cooling is based on the conversion of sensible heat into latent heat. When non-saturated air comes in contact with free moisture and the two are thermally isolated from outside heat source, there is transfer of mass and heat. Because the vapour pressure of the free water is higher than that of the unsaturated air, water transfers in response to the difference in vapour pressure. The transfer involves a change of state from liquid to vapour, requiring heat for vaporization. This heat comes from the sensible heat of the air and the water resulting in a drop of temperature in both of them. Since no outside heat is added during this process, it can be assumed that the total heat (enthalpy) of the air does not change. The process the air undergoes can be described on a psychrometric chart. The lowest temperature the air can get is the wet bulb temperature. Under practical greenhouse conditions, however, the air does not become completely saturated. In this process the wet bulb of the temperature is remained constant, the dry bulb temperature is lowered and the relative humidity is increased. The efficiency of the cooling unit is the ratio between the change in saturation actually achieved to the potential change in saturation. It can be calculated from:

$$\eta = \frac{T_0 - T_p}{T_0 - T_{WB}} \tag{7}$$

The amount of water evaporated in this process can be calculated from:

$$m = \rho Q(\omega_p - \omega_0) \tag{8}$$

Evaporative cooling techniques have recently become more popular in areas like the Mediterranean basin. This new interest is associated with the incorporation of insect proof screens that impede ventilation and increase air temperature (Montero, 2006; Teitel, 2007; Teitel et al., 2005). Evaporative cooling demands high quality water, but water is often a scarce natural resource in horticultural areas. For this reason, it is necessary to know the water consumption of evaporative cooling systems and, more importantly, to understand how evaporative cooling affects plant transpiration in different crops. Montero (2006) indicated that fogging can reduce transpiration by between 12% and 51% depending on the crop leaf area index (LAI). As LAI increased, the fog contribution to transpiration reduction decreased, since the humidity level in a greenhouse with a fully developed crop is higher and also because of the reduced need to artificially add water vapour to the air.

The following lists several systems, which can satisfactorily provide cooling by evaporating water: sprinkling, fan and pad and fogging.

2.4.1. Sprinkling

Spraying water onto a surface of the roof and/or the canopy using sprinklers enlarges the free surface of the water and hence increases the evaporation rate. The evaporation process causes cooling of the canopy and of the air in the immediate vicinity, in accordance with the local microclimate. The advantage lies in the low cost. The main disadvantage of this method is the creation of conditions favourable to the development of fungal diseases. Also, sprinkling usually results in scalding and deposition of precipitates on the surfaces of the leaves and the fruits, especially when water quality is poor. Therefore, sprinkling is inferior in this respect to the fan and pad and fog systems.

2.4.2. Fan and Pad

The currently accepted method is based on placing fans in one wall and the wet pad (Figure 6) in the opposite one. Outside air is sucked into the greenhouse through the wet pad, and is thus humidified and cooled. From the wet pad, this air flows through the greenhouse, absorbing heat and water vapour, and is removed by the fans at the opposite end. Generally the efficiency of a pad is about 80–90 %. The advantages of this method lie in its simplicity of operation and control and also in that it does not entail any risk of wetting the foliage. The main disadvantages are: relatively high cost; lack of uniformity of the climatic conditions, which are characterized by rising temperature and water vapour (due to solar heating and transpiration of the plants) along the length of the structure and in the flow direction; electric power failure transforms the greenhouse into a heat trap; low cooling effect compared with a fogging system; and waste of water—to prevent blockage of the wet pad, water-bleed is necessary. Nearly all fan and pad systems use fresh water which is a drawback in regions with water scarcity. Davies et al. (2006) have shown that effective evaporative cooling can be achieved using seawater in place of fresh water. They claimed that some simple calculations suffice to show that there is in fact little difference in efficacy between using seawater and fresh water. Another system that uses cold seawater to both cool the greenhouse air and provide fresh water was described by Bent (2005).

Figure 6. Vertical pad in a greenhouse cooling system.

Two types of pads are acceptable, the vertical and the horizontal pads. Dripping water onto the upper edge can wet the porous vertically mounted pads. A drip collector and return gutter are mounted at the bottom of the pad and are used to re-circulate the water. In the horizontal pad, loose straw or small pieces of wood are distributed over horizontally supported wire mesh netting. The water is sprayed on the entire surface of the pad. Horizontal pads are more effective than vertical pads regarding pad plugging in dusty areas. The outside air is generally cooled by evaporation to within about 1.5°C of the wet bulb temperature. In regions with very low humidity the outside air temperature can be reduced by as much as 10–25°C cooler than ambient temperature. Temperature differences ranging from 3–7°C between fan and pad are quite common. When the system is operating, overhead ventilators and other openings must be closed. Pads must be continuous to avoid warm areas in the greenhouse. The most common pads are made of aspen wood excelsior, corrugated cellulose, honeycomb paper and polyvinyl chloride (PVC).

2.4.3. Fogging

The fogging method is based on supplying water in the form of the smallest possible drops (in the fog range, diameter 2–60 μm) so as to enhance the heat and mass exchange between the water and the air (Figure 7). This is because (for a given quantity of water) the surface area of the water in contact with the air increases in a direct relationship to the diminution in the diameter of the drops. Also characteristic of drops in this size range is that the frictional forces arising from movement of the drops through the air are relatively large, so that the terminal velocity of the falling drops is low, which results in a long residence time, allowing complete evaporation of the drops. Furthermore, because of their small size these drops are properly carried by the airflow. These combined characteristics ensure highly efficient evaporation of the water, while keeping the foliage dry. The high efficiency is because, in addition to the evaporation of water to cool the air that enters the greenhouse (similarly to the wet pad), it is possible to evaporate water in quantities sufficient to match the energy absorbed in the greenhouse.

Most fogging systems are based on high-pressure nozzles, characterized by low cost and high cooling effect relative to other systems, as discussed by Arbel et al. (1999). In the light of these considerations, the following scheme is recommended, comprising uniform roof openings, fans in all walls and nozzles uniformly distributed at the height of the structure. The air that enters the greenhouse through the roof openings carries the water drops with it, and the water evaporates within the flow. As a result, the air is cooled (by water evaporation), both on its entry into the greenhouse and in the course of its passage among the canopy, and absorbs excess heat.

Arbel et al. (2003) focused on the operational characterization of a fogging system in combination with forced ventilation following the above scheme. The results obtained revealed inside greenhouse air temperature and relative humidity of 28ºC and 80% respectively during the summer at midday when ambient conditions were 36ºC and about 25 % relative humidity. Furthermore, the results obtained revealed generally high uniformity of the climatic conditions, within the greenhouse. Such an arrangement may lead to: uniform climatic conditions within the desired range, even in the summer months; good control over the climatic conditions through reduction of the influence of the wind; operation of the greenhouse by means of a relatively simple control system; the establishment of greenhouses in large units and, consequently, better exploitation of the land area and significant reduction in the cost per unit area of the structure. The main drawback of this method is still the technical problems in preventing nozzle partial or complete clogging and thus formation of large droplets which do not evaporate completely and fall on the foliage and proper control of water spaying and fan operation.

Figure 7. Fogging system for greenhouse cooling. At the top right corner is a close-up of the nozzle.

2.4.4. Other Concepts of Greenhouse Cooling

Heat Exchange with an Underground Aquifer

Bakker et al. (2006) described a greenhouse cooling system with heat storage in an underground water aquifer for a completely closed greenhouse. The cooling system has been designed, based on the use of a fine wire heat exchanger (Figure 4). The performance of the fine wire heat exchangers was tested under laboratory conditions and in a small greenhouse compartment. The effects of the system on the environmental conditions (temperature and humidity distribution) in the greenhouse were simulated to decide on the final lay out of the system.

A sprinkling system that is used to collect energy from the greenhouse cover during periods with a heat surplus was presented by de Zwart (2005) and it showed promising results. He showed that such a system potentially collects more than 500 MJ per m^2 per year, which gives the opportunity to save this amount of fossil fuel (about 16 m^3 of natural gas per m^2 per year).

Shading

The shading (Figure 8) of the crop is also an effective method of high temperature control, as it directly reduces the greenhouse heat load and also reduces the intensity of the solar radiation incident on the crop foliage. Moveable shading screens have the significant advantage of allowing shading to be in place only at the times of high solar intensity. Knowledge of the light requirements of the crop is essential, if shading is to be employed. Shading in combination with medium to high air exchange rates is often an effective approach for many greenhouse situations.

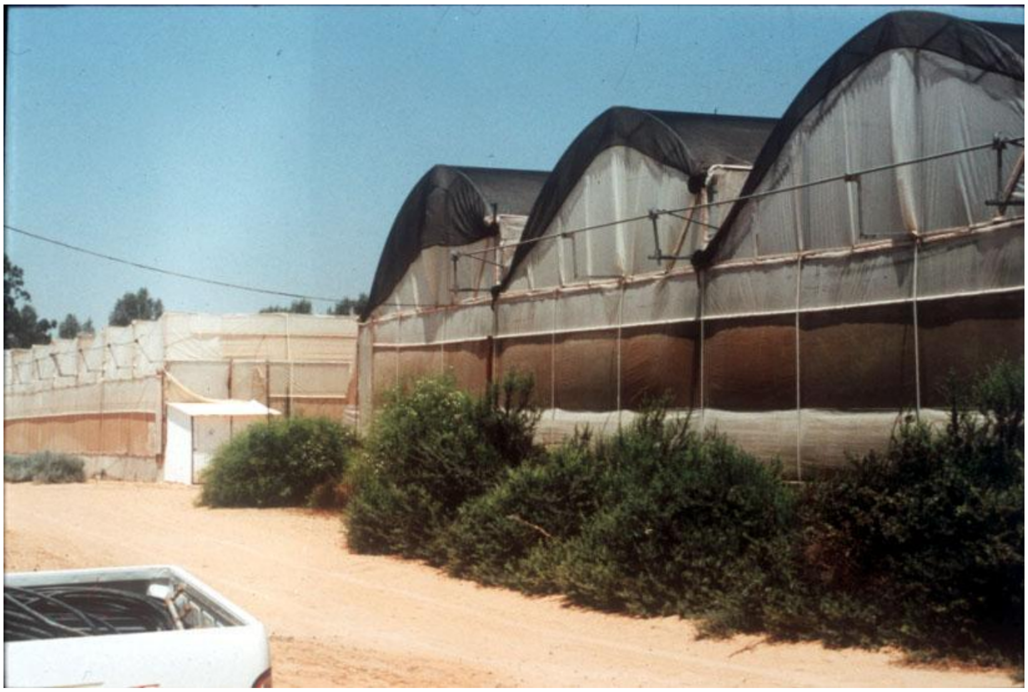

Figure 8. Black shading screens on top of the greenhouse cover.

Whitewashing

Photoselective paints are already common in many countries. The paints are sprayed on the greenhouse roof to reduce the heat load. Compared with 20 years ago whitewash as a shading paint has undergone a technological revolution. Today's shading paints allow a higher percentage of photosynthetically active radiation (PAR) to penetrate the greenhouse and block out the infrared range which cause warming. Whitewash reduces light also in hours when light is not in excess, which reduces growth and production. Therefore it should be used sparsely and mainly on regions of the greenhouse cover that are subject to direct solar radiation. The advantage of the new shading paints is that they can be washed off at the end of the warm season. Furthermore, shading paints that dissolve naturally at the end of the season have been developed, which reduce labour work.

2.5. Energy Sources

2.5.1. Photovoltaics for Greenhouse Systems

Electricity to feed greenhouse equipments such as fans, fertigation and lighting systems can be generated in a sustainable way by means of photovoltaic (PV) systems. The electricity is generated in presence of solar radiation however the greenhouse equipments, for example lighting systems, require the energy also when solar radiation is low, in winter, or absent, during the night. As a consequence PV systems require electricity storage that can be realised by means of batteries in stand alone systems or by means of the public power distribution grid in grid-connected systems.

Stand alone PV systems are suitable in places where electric grid is unavailable and for low power requirements since a high battery capacity needs high investment and maintenance costs, which are not present in grid-connected systems. Energy generated by photovoltaic modules in greenhouse farms that exceeds the equipment energy needs can be inserted into the grid and sold to other utilities. The economic viability of photovoltaic systems, which are grid connected, depends on the produced energy; utilities in Italy and Israel pay approximately 0.40 and 0.35 €, respectively, per kWh produced by the PV generator. Grid connected PV systems in Southern Italy have a financial pay back time between 9 and 10 years with public incentives; in fact the investment cost of a PV system is approximately 5,000-6,000 € per kWp (peak power), the yearly production of electricity in Southern Italy at a latitude of 41° N is 1,300–1,400 kWh kWp^{-1}, the cumulative yearly solar radiation on horizontal surface being more than 5 GJ m^{-2}. The use of PV systems in Northern European countries is less profitable, the yearly production of electricity in the Netherlands at a latitude of 52° N can be estimated in 860 kWh kWp^{-1} (JRC European Commission, 2009).

Tests have been conducted at the experimental farm of the University of Bari, latitude of 41° N, on stand-alone and grid connected PV systems (Figure 9); the electrical energy produced was used for powering 4 fans of the ventilation system of an arched roof greenhouse covered with a plastic film. The electricity obtained during the tests ranged from 2.2 kWh d^{-1} kWp^{-1} in December to 4.9 kWh d^{-1} kWp^{-1} in July.

Figure 9. Photovoltaic modules supplying greenhouse equipment at the experimental farm of the University of Bari, Italy.

The control system was designed to maximise the consumption of the energy at the time of its production, reducing the stored energy. It is a design requirement both for stand alone and for grid connected systems, reducing the battery bank size in stand-alone systems and the losses for electric power transmission for grid connected systems. For this purpose the number of the working fans was correlated both to the greenhouse air temperature and to the level of solar radiation in order to generate and use electricity at the same time; Figure 10 shows the external and greenhouse air temperature, the solar radiation and the power delivered to the fans by the PV system.

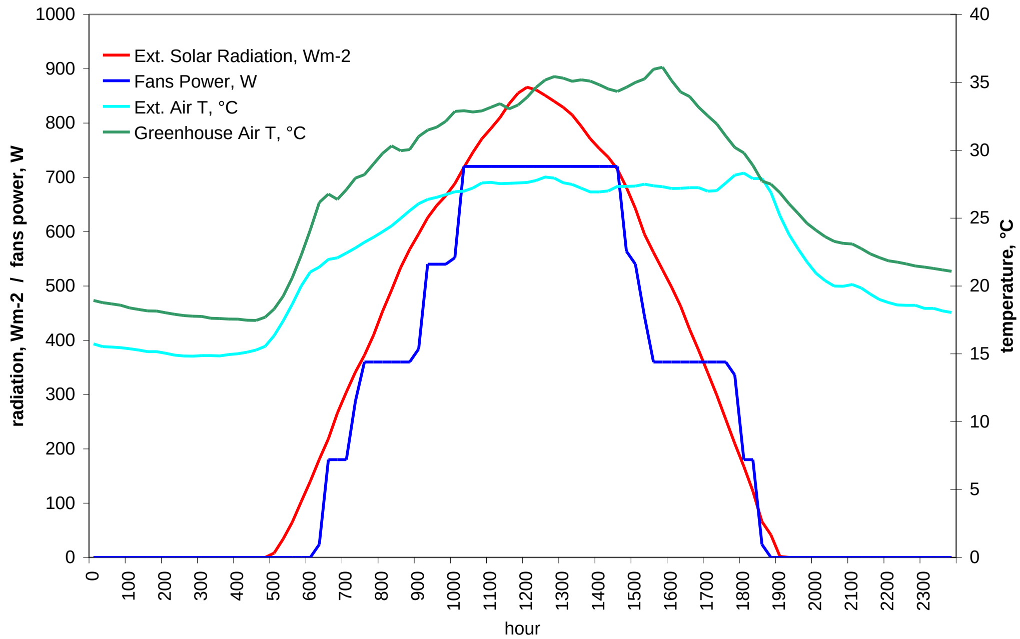

Figure 10. External and greenhouse air temperature (°C), solar radiation (Wm^{-2}) and power delivered to the fans (W) by the photovoltaic system at the experimental farm of the University of Bari, Italy.

Electricity available during the warm season can be used to feed greenhouse cooling systems such as fans, fog and pad evaporative systems, while during cold periods greenhouse heating systems use generally fuels, such as diesel fuel or gas, but rarely electricity. Electrical energy generated by means of renewable sources could be applied to heating systems based on ground-source heat pumps and pond water heat pumps.

The main drawback of photovoltaic systems concerns the high costs related to the poor efficiency of the solar cells. The performance of PV systems can be improved by means of the introduction of photovoltaic concentrators (CPV), which use less expensive lenses or mirrors as receiving surfaces in place of solar cells. With such systems the sun radiation is concentrated on high efficient solar cells of reduced surface (Whitfield et al., 1999). Such systems have high technological complexity requiring accurate tracking to follow the sun in order to maintain the focus of the concentrated incoming radiation on the solar cell. Concentration photovoltaic systems have been developed by utilities for power plants but no application at greenhouse farm level has been tested so far. Greenhouses are suitable for the application of CPV systems because they are characterized by the production of electrical energy combined with heat which should be removed. The produced waste heat could be used as integration of the greenhouse heating system in cold periods and in systems based on absorption chillers for greenhouse cooling in warm periods. Photovoltaic modules as well as concentrating systems can be installed on the ground of the farm outside the greenhouse area, facing south without shading obstacles. Integration of such systems in greenhouse structure is possible however; shadows on the cultivated area inside the greenhouse should be avoided.

Concerning integrated systems in greenhouse structures, Souliotis et al. (2006) proposed the use of transparent glass type Fresnel lenses as greenhouse covering material in order to concentrate the direct fraction of solar radiation on photovoltaic receivers positioned inside the greenhouse and lowering the greenhouse air temperature when necessary. It is an application that requires the study of suitable greenhouse structures and that meets the microclimate requirements of Mediterranean greenhouses.

2.5.2. Wind Turbines for Greenhouse Systems

Wind turbines, which generate electrical energy, can be integrated in a stand-alone system or can be connected to the grid. Today, large wind turbines with a power of 2-3 MW can generate electricity for less than 0.05 € per kWh, a price that is competitive with power plants using fossil fuels, but investment cost and maintenance make large wind turbines suitable more for utilities than for greenhouse farmers.

Figure 11. 1 kW wind turbine at the experimental farm of the University of Bari, Italy.

Small wind turbines with a power of 1–20 kW are less competitive; annual mean wind speed of the site, installation and maintenance costs must be carefully evaluated to assess the economic viability of the installation.

Many small wind turbines start generating energy at wind velocity of 3–4 ms^{-1}, while the maximum energy is obtained with wind velocity of 10–15 ms^{-1}.

Tests carried out at the experimental farm of the University of Bari (Figure 11) showed that 1 kW wind turbine produced an average daily value of 0.53 kWh of electrical energy. The site was characterized by an average yearly wind velocity of 2.6 ms^{-1} and a percentage of wind, occurring over the threshold of 4 ms^{-1}, equal to 17.3 %.

3. COVERING MATERIALS (*E. SCHETTINI AND G. VOX*)

3.1. Introduction

Covering materials, which protect crop from adverse weather conditions, influence the greenhouse microclimate modifying the growing conditions of the crop in comparison with the external climatic conditions. Glass, semi-rigid plastics, plastic films and plastic nets are the most widely used greenhouse covering materials.

The capacity of the covering materials to modify the greenhouse microclimate depends strongly on their radiometric properties, mainly the transmissivity, which is expressed by means of transmissivity coefficients. They are calculated as average values of the spectral transmissivity, $\tau(\lambda)$, over different wavelength intervals, i.e., the solar range, the PAR range and the long wave infrared radiation (LWIR) range, whereas $\tau(\lambda)$ represents the fraction of the incident energy radiant flux that is transmitted at a specific wavelength λ (Papadakis et al., 2000).

For purposes of calculating radiometric coefficients of materials in the solar range, the spectral distribution of solar radiation at the earth's surface must be taken into account as a weighting function. Solar radiation received at the surface of the earth has a spectral distribution so that about 50% of the total energy is emitted in the near infrared radiation (NIR) range (700–2,500 nm) and about 40% in the PAR range (400–700 nm), where the solar radiation has a maximum at a wavelength of about 500 nm (Duffie and Beckman, 1991).

The transmissivity coefficient in the solar wavelength range, τ_{solar}, from 300 nm to 2,500 nm, represents the fraction of the overall solar radiation passing through the material. The higher the value of the solar transmissivity coefficient, the higher is the rise of the air temperature inside the greenhouse. Solar radiation in the PAR wavelength range is necessary for photosynthesis which is the basic process for crop production (Monteith and Unsworth, 1990). The transmissivity coefficient in the PAR range, τ_{PAR}, which expresses the quantity of solar PAR radiation transmitted by the covering material, strongly influences crop growth and yield. Generally, greenhouse covering materials must have high values of the τ_{PAR} coefficient.

Another radiometric property is the reflectivity that also affects the greenhouse microclimate: the higher the reflectivity coefficient of the covering material, the lower is the increase of the temperature inside the greenhouse. Long wave infrared radiation energy losses from a protected volume depend on the transmissivity of the covering material in the LWIR range, which extends for wavelength values higher than 3,000 nm. However, the LWIR transmissivity coefficient, τ_{LWIR}, is defined as the average value of the spectral transmissivity in the range 7,500–12,500 nm, where the bodies at ambient temperature have the maximum energy emission as expressed by Planck's spectral distribution of emissive power (Siegel and

Howell, 1972). The indoor greenhouse air temperature rises with the decrease of the LWIR transmissivity coefficient of the greenhouse covering material.

Greenhouse air temperature is also affected by the emissivity of the material which is a measure of the thermal radiative energy emitted in the LWIR range by the covering material: the higher the emissivity coefficient of the external surface, the higher are the energy losses from the material and from the whole protected volume.

Since energy losses through the covering material are high, the radiometric properties of the greenhouse cover play an important role in reducing energy consumption. Sustainability of greenhouse industry can be increased with innovative covering materials aimed to obtain energy savings in greenhouse heating and cooling together with profitable yield. Besides, covering materials able to modify the spectral distribution of the solar radiation can be used to influence plant growth in place of agro-chemicals. In recent decades research has been addressed to improve the radiometric properties of glasses and more recently of plastic films that are the most widespread greenhouse covering materials. In protected cultivation, the yearly consumption of plastic films as greenhouse coverings and for soil mulching is about 1.3 million tonnes (Jouët, 2001) with the generation of huge quantities of after-use plastic. Such wastes are often heavily contaminated with soil and agro-chemicals making the recycling process time-consuming and expensive so that plastic waste is often burned in uncontrolled conditions or left on the side of the field (Kapanen et al., 2008); the use of biodegradable films that can be disposed of in the field is a sustainable solution to the problem. Biodegradable film can be used in a profitable way also to mulch the growing substrate, which is a practice often applied in greenhouse industry. The main advantages of the mulches are the decrease of the use of chemicals in weed control, the reduction of water consumption, the faster crop development, the improvement of the plants health and of the product quality. Transparent mulching films can be used for soil sterilization by means of solarization practice, heating up the higher layers of the soil in greenhouse to temperatures lethal for a wide range of soil-borne pathogens thus reducing the use of agro-chemicals.

The following paragraphs describe how research has been recently addressed towards sustainable materials aimed to obtain energy savings, plant growth control and to reduce after-use wastes.

3.2. Covering Materials and Energy Saving

Among the greenhouse covering materials glass is characterized by a very low LWIR transmissivity coefficient (Table 1) that strongly reduces the energy radiative transfer from inside to outside the greenhouse. Low transmissivity values imply for glasses high values of emissivity, which causes energy losses due to the high infrared emission from the outside glass surface and partially reduces the advantage related to the low LWIR transmissivity. The use of low-emission glass, which has a coating of low-emissive metal oxide on the external surface, reduces the LWIR radiative thermal losses; it allows higher greenhouse temperatures thus obtaining energy savings in greenhouse heating. Another sustainable solution to reduce energy consumption for heating is the use of double-wall glass, which allows a decrease of the convective energy losses; the drawback of the double-wall glass is the reduction of the transmissivity in the solar range up to 8%–10%; such reduction can be attenuated with the application of anti-reflection coatings, which increase solar transmissivity by 6.8%–7.4% (Hemming et al., 2009).

For purpose of reducing greenhouse temperature during the warm periods, glasses filtering out NIR solar radiation can be used in warm areas, where energy consumption for greenhouse cooling is high.

Shading, which is another method to reduce high air temperatures, is obtained by means of plastic nets that are mounted generally above the greenhouse covering materials or on screen-house structures. Nets, which are permeable to air flow, are generally made with polypropylene (PP) or high density polyethylene (HDPE). Nets are characterized by the shading factor that represents the capacity of the net to reduce the incoming solar radiation and that can range from 10% to 90%. Net mesh size, which is the distance between two threads in warp or weft direction, varies from 0.2 mm to 3.1 mm for insect nets, from 1.7 mm to 7.0 mm for shade nets, from 2.5 mm to 4.0 mm for anti-hail nets, from 1.8 mm to 7.0 mm for windbreak nets, while higher values, 3–4 cm, characterize the anti-birds nets (Briassoulis et al., 2007; Castellano et al., 2008).

Table 1. Transmissivity coefficients of different greenhouse covering materials; PAR, photosynthetically active radiation; LWIR, long wave infrared

Transmissivity coefficients, %		**Glass**	**LDPE**	**EVA**	**ETFE**
	Thickness, mm	4	0.180	0.180	0.100
τ_{solar}		80.4	88.6	89.1	93.1
τ_{PAR}		87.5	91.0	89.7	92.4
τ_{LWIR}		0.0	53.7	25.9	10.9

Unlike glass, plastic films are characterized by low cost and require a lighter and cheaper support frame. They are characterized by good mechanical and thermo-optical properties, chemical resistance, opposition to microbial degradation, as well as by easy processability. Over the last decades several kinds of plastic films for greenhouse covering have been developed using different raw materials and additives. Low density polyethylene (LDPE) based plastic films, which are the most widespread greenhouse covering materials, are characterized by good mechanical and radiometric properties. Figure 12 shows the transmissivity in the solar range of a glass and of a LDPE film, the latter being characterized by higher transmisivity; unfortunately LDPE films have generally high values of the τ_{LWIR} coefficient as well (Table 1). Due to their lower LWIR transmissivity polyethylene-co-vinyl acetate (EVA) films have been introduced as alternative to LDPE films (Figure 13), allowing reductions of the thermal infrared losses with consequent energy savings in greenhouse heating. More recently ethylene–tetrafluoroethylene copolymer (ETFE) films have been developed; such innovative materials are characterized by very good radiometric properties, i.e., high transmissivity in the solar range and low transmissivity in the LWIR range (Figure 13; Table 1). ETFE films have costs higher than LDPE and EVA films and a useful life of 10–15 years longer than the life of LDPE and EVA films, which ranges from some months to 3–4 years.

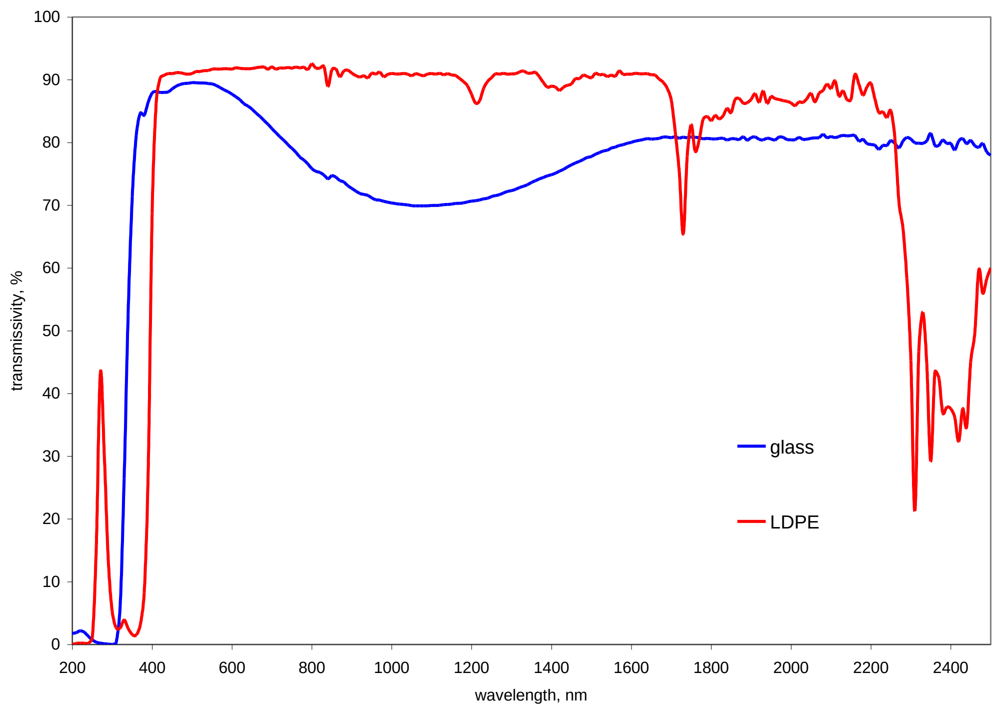

Figure 12. Total transmissivity of a glass (thickness: 4 mm) and of a low density polyethylene (LDPE) film (180 μm), in the wavelength range 200–2,500 nm.

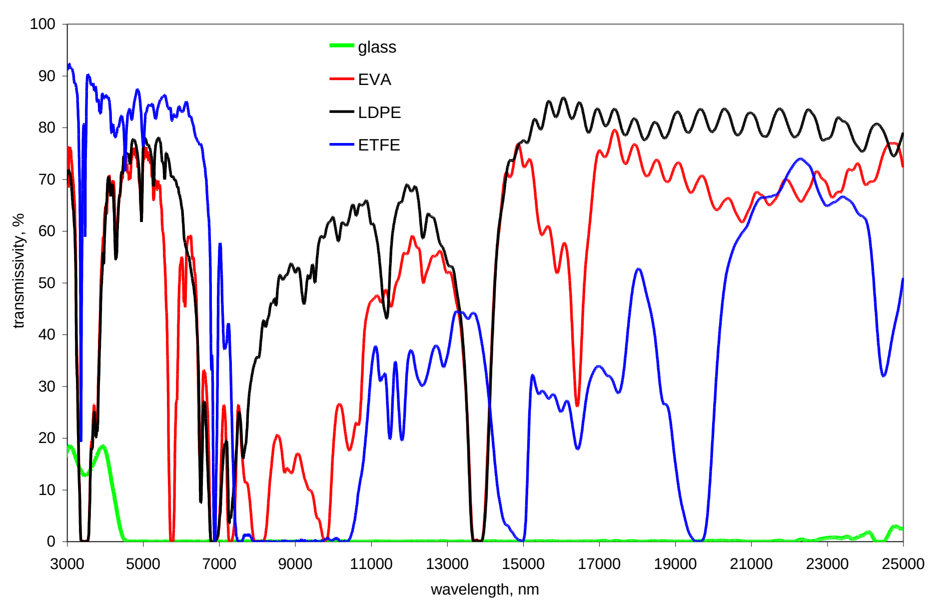

Figure 13. Long wave infrared (LWIR) transmissivity of a glass (thickness: 4 mm), of a low density polyethylene (LDPE) film (180 μm), of a polyethylene-co-vinyl acetate (EVA) film (180 μm) and of an ethylene–tetrafluoroethylene copolymer (ETFE) film (180 μm), in the wavelength range 3,000–25,000 nm.

3.3. Covering Materials as Growth Regulators

Plastic films and nets can be designed with the aim of modifying the spectral distribution of the solar radiation passing through the cover in order to influence plant vegetative and productive activity (Clifford et al., 2004; Rajapakse et al., 1999; Shahak et al., 2004), which is often controlled by means of agro-chemicals (Wilson and Rajapakse, 2001). Greenhouse industry sustainability can be increased using covering materials as plant growth regulators in place of agro-chemicals.

Variations of red (R, 650–670 nm), far-red (FR, 720–740 nm) and blue (B, 400-500 nm) radiation in the growing environment affect plant photomorphogenesis involving the activation of photoreceptors, such as the phytochrome and the cryptochrome. The phytochrome response is characterized in terms of the R/FR ratio of the photon fluence rate in the red to that in the far-red (Kittas and Baille, 1998; Kittas et al., 1999; Murakami et al., 1996; Oren-Shamir et al., 2001; Smith, 1982; Takaichi et al., 2000).

Significant increases of the growth and of the elongation of shoots were pointed out in peach and cherry trees grown under a photoselective film that reduced the R/FR ratio to 0.93, from the value 1.15, which was recorded in open-field at the University of Bari (Italy). Tests carried out on ornamental plants showed that the increase of the R/FR ratio has a dwarfing effect on the plant growth (Smith, 1982). Figure 14 shows the transmissivity of a photoselective film that reduces the R/FR ratio of the photon fluence rate in the red to that in the far-red by means of different values of transmissivity in the red and in the far red wavelength range.

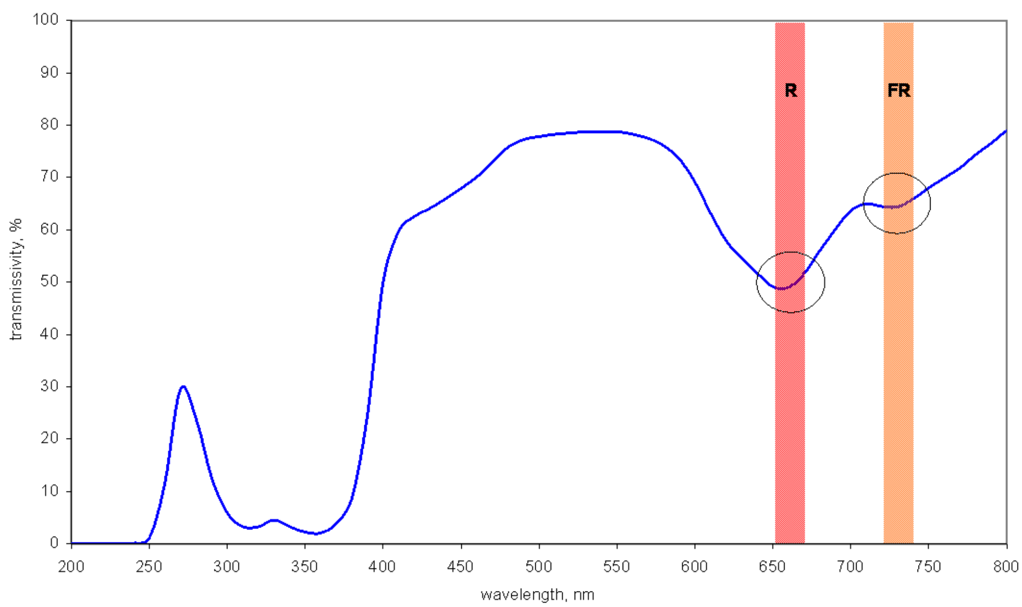

Figure 14. Total transmissivity of a photoselective film that reduces the R/FR ratio of the photon fluence rate in the red (R, 650–670 nm) to that in the far-red (FR, 720–740 nm), in the wavelength range 200–800 nm.

Experimental tests carried out using photoluminescent films at the University of Bari (Italy) and tests performed using coloured nets by Ovadia et al. (2009) showed that an increase of the vegetative activity can be induced under covering materials that increase red radiation in comparison with the other radiation of the solar spectrum, while a dwarfing effect can be obtained under covering materials producing a higher level of blue radiation. Figure 15 shows the transmissivity of a red and of a blue net, filtering out part of the solar spectrum in order to raise the relative level of red (600–700 nm) and blue radiation (400–500 nm), respectively.

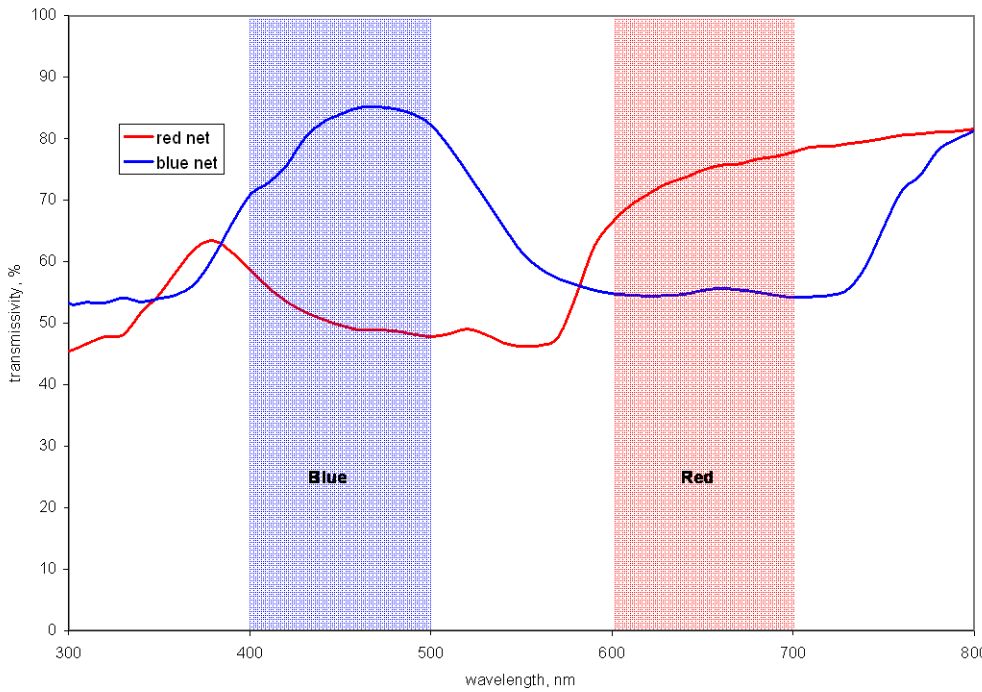

Figure 15. Total transmissivity of a red and of a blue net in the wavelength range 300–800 nm; the nets filter out part of the solar spectrum to raise the relative level of the red (600–700 nm) and blue radiation (400–500 nm), respectively.

3.4. Plastic Films Lifetime

LDPE and EVA film lifetime ranges from some months to 3–4 years as a function of the plastic film thickness and of the additives; the useful life is reduced by the degradation of the polymer induced by the prolonged exposure to solar radiation, wind, high air temperature and relative humidity, and to agro-chemicals used during cultivation (Briassoulis, 2005; Desriac, 1991; Lemaire, 1993; Vox and Schettini, 2007). The plastic film degradation is characterised by discoloration, cracking of surface, stiffening, and a decrease in the physical and mechanical properties up to rupture (Figure 16). The ageing degradation process is caused mainly by the ultra violet (UV) radiation in the solar spectrum, especially by UV-B and UV-A radiation, that occur in the wavelength range from 280 nm to 400 nm (Nijskens et al., 1990). Degradation of the physical and mechanical properties of greenhouse films results in the generation of huge quantities of plastic wastes (Figure 17) that must be removed needing a correct collection, disposal of and recycling process, thus reducing the sustainability of the greenhouse industry.

Figure 16. Rupture of a greenhouse covering film due to the ageing degradation in field.

Figure 17. Post-using plastic waste of greenhouse covering films nearby a greenhouse area in Italy.

Research has been addressed in order to extend the life of the LDPE and EVA films, thus reducing the amount of post-use plastic wastes. In order to extend film lifetime, UV stabilizers, such as UV absorbers, hindered amine light stabilisers (HALS) and nickel quenchers, can be added to mitigate degradation through the prevention of solar radiation absorption as well as minimizing any subsequent radical oxidation reactions (Sanchez-Lopez et al., 1991; Vox et al., 2008b).

3.5. Biodegradable Materials

Petroleum based plastic films are widespreadly used in greenhouse industry as covering materials and for soil mulching. In recent decades, a growing environmental awareness has been prompting research to develop biodegradable materials for agricultural purposes formed with raw materials from renewable origin to be used as environmentally friendly alternatives to synthetic petro-chemical polymers (Avella et al., 2001; Avella et al., 2007; BIO.CO.AGRI., 2005; BIOPLASTICS, 2005; De Prisco et al., 2002; Gáspár et al., 2005; Imam et al., 2005; Immirzi et al., 2003; Kapanen et al., 2008; Kaplan et al., 1993; Kyrikou and Briassoulis, 2007; Lawton, 1996; Malinconico et al., 2008; Russo et al., 2004; Russo et al., 2005; Tzankova Dintcheva and La Mantia, 2007). These materials have to retain their physical and mechanical properties while in use, and at the end of their life they are integrated directly in the soil where bacteria flora transforms them in carbon dioxide or methane, water and biomass; alternatively they can be blended with other organic material, to generate carbon rich composts (Chandra and Rustgi, 1998; Doran, 2002; Kaplan et al., 1994; Malinconico et al., 2002; Narayan, 2001). Thermo-plasticizing, casting and spraying processes have been employed to perform biodegradable materials for agricultural scope. Natural polymers such as starch (Bastioli, 1998; Lawton, 1996; Gáspár et al., 2005; Marques et al., 2006), cellulose (Immirzi et al., 2003), chitosan (Mormile et al., 2007), alginate (Mormile et al., 2007; Russo et al., 2005; Immirzi et al., 2009) and glucomannan (Schettini et al., 2007) have been experimented and tested in the frame of the employment of new eco-sustainable materials for agricultural applications.

Thermoplasticised extruded starch-based films (Mater-Bi, Novamont Co., Novara, Italy) (Bastioli, 1998), tested as low tunnel and soil mulching films within the project "BIOPLASTICS" (BIOPLASTICS, 2005; Briassoulis, 2004a, 2004b and 2006a; Malinconico et al., 2008; Scarascia-Mugnozza et al., 2004; Scarascia-Mugnozza et al., 2006; Vox and Schettini, 2007), were obtained with the same film extrusion line used to extrude and blow commercial LDPE films, with minor modifications (Briassoulis, 2006b and 2007), in this way ensuring economic viability. These biodegradable extruded starch-based films can be installed by means of the same machine used for laying LDPE films, with the same work speed and gear.

An innovative approach, developed within the project "BIO.CO.AGRI." (BIO.CO.AGRI., 2005), consisted of forming mulch coating directly in field by covering the soil with a thin protective geo-membrane obtained by spraying water-based solutions of natural polysaccharides, such as sodium alginate, glucomannan, chitosan and cellulose (Avella et al., 2007; Immirzi et al., 2009; Malinconico et al., 2008; Mormile et al., 2007; Schettini et al., 2007). In the polymeric water solutions natural plasticizers, fillers and coloured pigments can be dispersed to assure the mechanical resistance and suitable radiometric properties of the coating during cultivation (Immirzi et al., 2009; Kamel et al., 2004; Urreaga and de la Orden, 2006). The coatings, able to follow the unevenness of the soil surface, were obtained when the water content of polymeric network was removed through evaporation. The spray technique, used by the farmers to spread agro-chemicals during the cultivation, could be a suitable alternative to the mechanical setting up and removal of plastic pre-formed films, in this way contributing to a reduction of the labour cost.

The biodegradable starch-based films and water-born coatings described in this chapter are materials at an experimental stage so their functionality was investigated by means of several cultivation field tests and laboratory tests. The requirements concerning their mechanical and physical properties have not been defined by international standards so far. The LDPE films currently used for low tunnel covering and soil mulching must satisfy standards such as EN 13206 (EN 13206, 2001) and EN 13655 (EN 13655, 2002).

3.5.1. Thermoplasticised Extruded Starch-Based Films

The research carried out within the project "BIOPLASTICS" (BIOPLASTICS, 2005) showed that the thermoplasticised extruded starch-based biodegradable films had mechanical and radiometric properties and performance in field (Figures 18 and 19) suitable for them to replace LDPE films both as low tunnel and as soil mulching films (Briassoulis, 2004a, 2004b and 2006a; Malinconico et al., 2008; Scarascia-Mugnozza et al., 2004; Scarascia-Mugnozza et al., 2006; Vox and Schettini, 2007). The mechanical and the radiometric behaviour of the biodegradable films were influenced by the film thickness, by the different kind and quantity of biodegradable master batches and of stabilizers used, and, furthermore, by the manufacturing processes (Vox and Schettini, 2007; Briassoulis, 2006a). As happens to LDPE films, the ageing process due to their exposure to atmospheric agents and to agro-chemicals used during cultivation affected the physical and mechanical properties of the biodegradable materials. It has been proven that the mechanical and radiometric properties of the biodegradable films continued to be in the range necessary for agricultural applications during their useful life (Briassoulis 2006a, 2006b and 2007; Malinconico et al., 2008; Scarascia-Mugnozza et al., 2004; Scarascia-Mugnozza et al., 2006; Vox and Schettini, 2007).

Figure 18. Biodegradable melt-extruded mulching film inside the greenhouse at the experimental farm of the University of Bari, Italy.

Figure 19. Biodegradable melt-extruded low tunnel and mulching films at the experimental farm of the University of Bari, Italy.

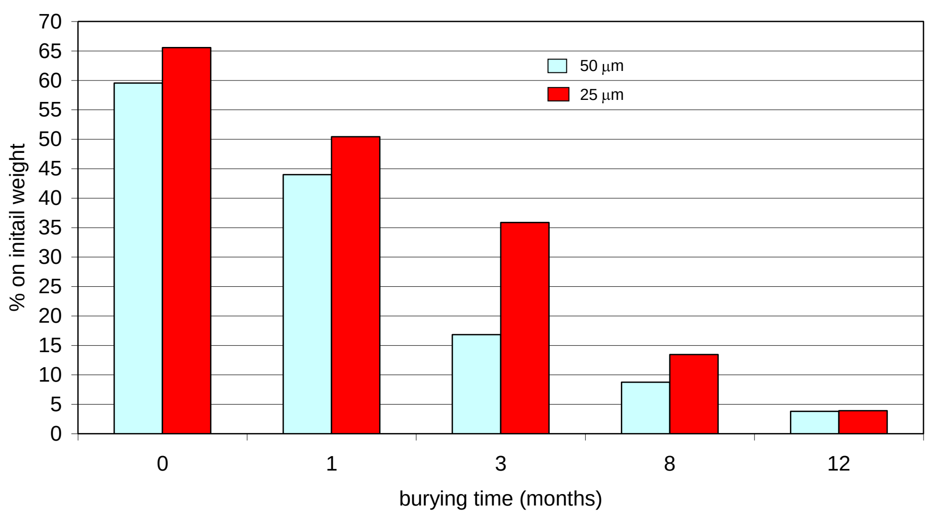

Figure 20. Variation of the residues in the soil of a 50 μm and a 25 μm biodegradable melt-extruded mulching films, as a function of the burying time, recorded at the experimental farm of the University of Bari, Italy.

The biodegradable nature of the raw material indicates that starch-based films can be fully considered for eco-sustainable use in agriculture: these materials degrade to harmless end products in the soil within a reasonable time frame (Kapanen et al., 2007). Figure 20 shows the degradation of the residues of two biodegradable mulching films, characterised by different thickness, buried in the field soil after the tillage performed at the end of the cultivation period: after 12 months the residues were less than 4% of the initial weight of the installed film. The results obtained by Kapanen et al. (2007) showed that the thermoplasticised extruded starch-based biodegradable films did not cause any environmental risk to the agricultural soil.

Low Tunnel Films

The EN 13206 Standard (EN 13206, 2001) establishes for LDPE and EVA films used as greenhouse covering the minimum values of tensile stress and tensile strain at break. The mechanical tests carried out on the biodegradable low tunnel films before the installation in the field showed a comparable or, in some cases, inferior mechanical behaviour to that of the corresponding commercial LDPE low tunnel films in terms of tensile strength in both the directions (Briassoulis, 2006b, 2007). Variability in the thickness was significant so it influenced the mechanical laboratory tests (Briassoulis, 2006a). During the field experiments the biodegradable low tunnel films retained a satisfactory mechanical performance over their useful lifetime (Briassoulis, 2006a, 2006b, 2007; Scarascia-Mugnozza et al., 2004; Vox and Schettini, 2007). The lifetime of the biodegradable low tunnel films ranged from 3 to 9 months as a function of the UV stabilizers and of the thickness (Briassoulis, 2006a); thinner low tunnel films were used for shorter cultivation covering period. Future developments of the research will be addressed on UV stabilizers suitable to extend the film lifetime and to increase the mechanical resistance in order to obtain biodegradable covering films having a roll width up to 8–10 m, useful for covering larger tunnel or greenhouse structures.

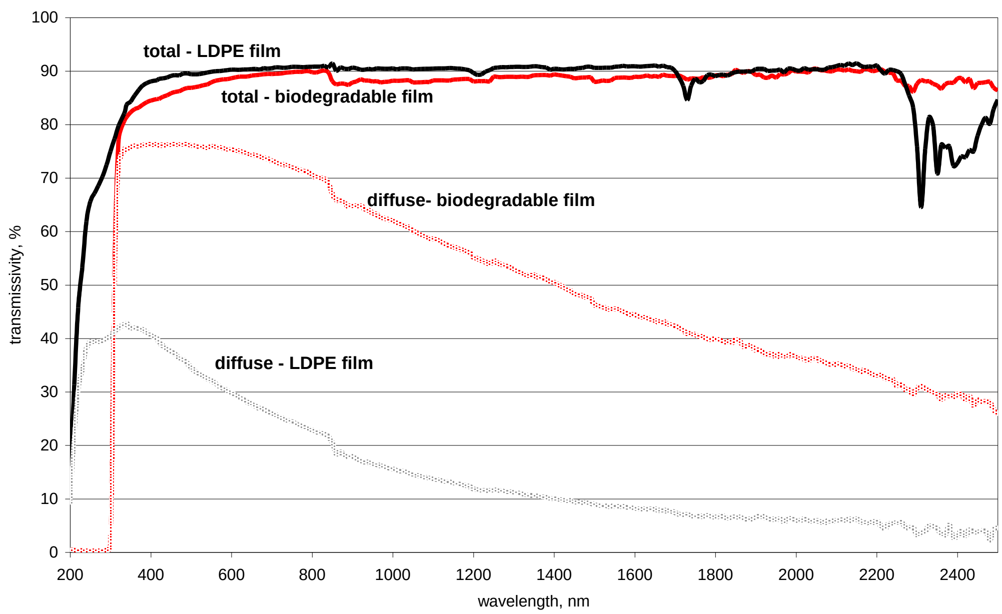

Figure 21. Total and diffuse spectral transmissivity of a low density polyethylene (LDPE) low tunnel film (40 μm) and of a biodegradable melt-extruded low tunnel film (30 μm), in the wavelength range 200–2,500 nm.

Concerning the radiometric properties, the τ_{solar}^{total} coefficient varied from 80.81% to 88.13% (Vox and Schettini, 2007). The biodegradable low tunnel films can be compared to thermic diffusing covering films in accordance with the EN 13206 Standard (EN 13206; 2001) for LDPE and EVA films; moreover these values are comparable with the coefficient of anti-fogging (82.8%) and diffuse (79.8%) LDPE films for greenhouse covering as reported by Pearson et al. (1995). These films are characterised by high radiation scattering capacity like the biodegradable films. Figure 21 shows the total and diffuse transmissivity in the solar range of a LDPE film and of a biodegradable low tunnel film, the latter was characterised by a high capacity to diffuse solar radiation, mainly in the PAR wavelength range. Because of the high $\tau_{solar}^{diffuse}$ coefficients, ranging from 45.13% to 75.51% (Vox and Schettini, 2007), solar radiation was uniformly scattered under the low tunnels covered with the biodegradable films, having a positive effect on plant growth and reducing the incidence of scorch (Pearson et al., 1995).

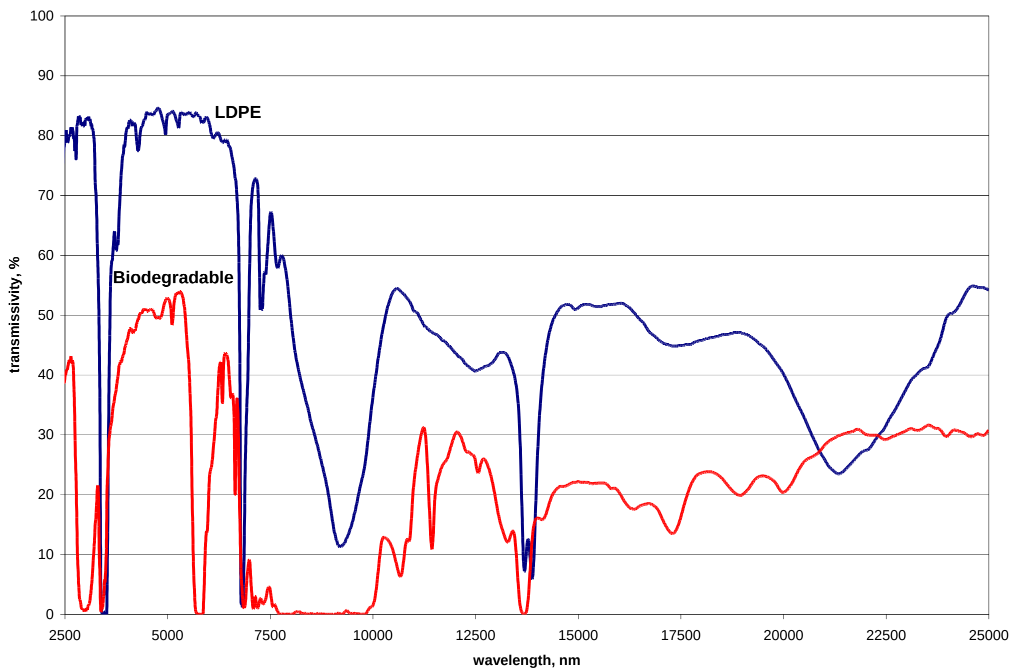

Figure 22. Long wave infrared (LWIR) spectral transmissivity of a low density polyethylene (LDPE) low tunnel film (40 μm) and of a biodegradable melt-extruded low tunnel film (40 μm), in the wavelength range 2,500–25,000 nm.

The biodegradable low tunnel films reduced the radiative energy losses from the enclosed volume in the LWIR range much better than the LDPE films due to their low τ_{LWIR} coefficients (2.98%–31.27%) (Vox and Schettini, 2007). Figure 22 shows the huge differences of the spectral trasmissivity in the LWIR range of a biodegradable low tunnel film compared to a commercial LDPE low tunnel film. The lowest value of the τ_{LWIR} coefficient among the biodegradable low tunnel films (2.98%) was lower than the coefficients of the best thermic LDPE and EVA films (>12%) used for greenhouse covering (Papadakis et al., 2000; von Zabeltitz, 1999). The microclimate under the biodegradable films was positively influenced by the capacity of the biodegradable films to reduce the LWIR energy losses from the low tunnel. During the night when the LWIR radiation energy exchange plays an important role, the air temperature inside the protected volumes with biodegradable materials was always warmer than the air temperature under the low tunnels covered with LDPE films.

Soil Mulching Films

Although the starch-based mulching films tested were characterised by values of tensile stress and strain at break lower than the values required for LDPE films (EN 13655, 2002), their mechanical properties were sufficiently in the range necessary to be used in the period from planting to harvesting, applying the same cultivation techniques currently used for LDPE mulching films (Vox et al., 2005; Briassoulis, 2006a; Malinconico et al., 2008; Scarascia-Mugnozza et al., 2006). In fact, during the crop cycles the edges of the biodegradable mulching films buried continued to satisfy their function to hug the soil bed by stretching the film. The starch-based mulches lasted in the field for a period from 5 to 9 months (Scarascia-Mugnozza et al., 2006; Vox et al., 2005), a lifetime longer than the one of other biodegradable films of similar thickness reported in literature (Halley et al., 2001; Martin-Closas et al., 2002; Novamont, 2009; Shogren, 2000; Tocchetto et al., 2002).

The EN 13655 standard (EN 13655, 2002) states that, independently of their thickness, black LDPE plastic mulching films must have a τ_{PAR}^{total} coefficient less than 0.01 %. The biodegradable black mulching films with a thickness higher than 25 μm met the standard while, for thinner black films, τ_{PAR}^{total} ranged from 0.00% to 0.45% (Vox and Schettini, 2007). All the biodegradable black mulching films, however, inhibited weed growth in the period from planting to harvesting like the black LDPE films did, satisfying in the field one of the main task of mulch.

3.5.2. Water-Born Sprayable Coatings

Innovative sprayable biodegradable water-born solutions were tested as growing media mulching coatings in greenhouse cultivation. Such coatings, developed within the project “BIO.CO.AGRI.” (BIO.CO.AGRI., 2005), were obtained using natural polymers coming both from terrestrial origin, such as cellulose and glucomannan, and from marine origin, such as chitosan and alginate (Avella et al., 2007; Immirzi et al., 2003; Immirzi et al., 2009; Mormile et al., 2007; Malinconico et al., 2008; Russo et al., 2005; Schettini et al., 2007; Schettini et al., 2008). Plasticizing polymers, such as hydroxyethylcellulose, and natural plasticizers, such as glycerol and polyglycerol, were included in the aqueous polymeric blends to improve the mechanical response of the mulching coatings. Carbon black and fillers, such as cellulose fibres, fine bran of wheat and powdered seaweeds, can be used together with the polymeric matrices in order both to improve the mulching function and to increase the tensile strength of the coating formed upon drying.

One polymeric blend consisted of a water mixture of glucomannan (PSS20 Protective Surface System, PSI Polysaccharide Industries AB, Stockholm, Sweden) with the addition of a non-gelling concentration of agarose and of glycerol (Malinconico et al., 2008). This blend was used both as it was (Figure 23) and with carbon black (Figure 24). To the blend used as it was cellulose fibres were added as reinforcing fillers, so the coating was waterproof due the employment of cellulose, a polysaccharide with an enhanced resistance to wet environment (Schettini et al., 2007). As alternative the carbon black was dispersed into the blend in order to make the coating opaque to the PAR solar radiation to prevent the spontaneous weeds growth (Schettini et al., 2008).

Figure 23. Spray biodegradable coating realised on growing media in greenhouse using a transparent polymeric blend at the University of Bari, Italy.

Figure 24. Spray soil mulching performed with a black biodegradable water-born coating inside the greenhouse at the experimental farm of the University of Bari, Italy.

Another polymer selected as the matrix to be sprayed was sodium alginate, a polysaccharide obtained from seaweeds; hydroxyethylcellulose and polyglycerol were added to improve the mechanical behaviour of the coating (Immirzi et al., 2009). This blend was sprayed on the soil previously covered with a pulverized mixture of seaweeds flour and fine bran of wheat to provide a fibrous bed of natural materials (Figure 25**)**.

Figure 25. Spray soil mulching realised with a biodegradable water-born coating inside the greenhouse at the experimental farm of the University of Bari, Italy; the spray was performed on a raised bed covered by fillers.

Quantity of the water-born solution determines coating’s thickness and lifespan from few weeks to few months, as a function of the crop cycle. The solutions can be applied on the soil by means of an airbrush using a spray machine, which is commonly used in agriculture. Soil preparation, such as ploughing and tilling, does not differ from those performed for the installation of extruded films. The soil should be loose and refined and the surface should be as flat as possible in order to prevent holes and cracks of the coatings that can facilitate weed development. The side slope of raised beds should be limited in order to avoid a possible sliding of the water-born coating at the liquid state during the spraying before the dry process. In case of seeds or bulbs sowed before the spraying, buds hole the coatings without any problem (Figure 26) while seedlings transplanting can be performed holing the coating when the drying process of the coating is completed (Figure 27**)**.

Figure 26. Spray mulching coating holed by the bud at the experimental farm of the University of Bari, Italy.

Figure 27. Holing of the coating before seedling transplanting inside the greenhouse at the experimental farm of the University of Bari, Italy.

The biodegradable water-born coatings described in this chapter blocked weeds growth during the crop cycle satisfying the mulching task of weed control such as LDPE and starch-based mulches do; this result was obtained although the τ_{PAR}^{total} coefficient of the sprayed coatings varied from 0.10% to 7.89% while the EN 13655 standard (EN 13655, 2003) states that black LDPE mulching films must have a τ_{PAR}^{total} coefficient less than 0.01% (Schettini et al., 2008; Malinconico et al., 2008). The water-born coatings, characterised by transmissivity coefficients in the LWIR range lower than 1%, can increase the temperature regime of the mulched soil thanks to their high capacity to reduce the radiative LWIR losses (Schettini et al., 2007; Schettini et al., 2008; Malinconico et al., 2008).

Because of their composite nature the water-born coatings were characterised by inhomogeneous surfaces and irregular thickness, which varied from 1.5 to 5 mm. Differently to LDPE and biodegradable extruded films, laboratory mechanical testing methods cannot be applied for the water-born coatings. It was not possible to evaluate the mechanical properties of the water-born coatings by testing the composites obtained spraying the solution onto a model support, since it could not reproduce the interaction between the coating and the soil found in the field. Also, the particular physical structure of the water-born coating did not allow the application of tensile and/or shear tests because these methods are not indicators of the real behaviour of the coating itself. To simulate the mechanical performance in terms of resistance to hail or rain, Malinconico et al. (2008) proposed a new test, called "puncture test". Due to the innovativity of the test, it was not possible to compare the values obtained with the puncture test with the mechanical requirements established by the EN 13655 standard (EN 13655, 2003) and also with the values measured for the biodegradable starch-based extruded mulching films described in this chapter.

The mechanical performance and the radiometric properties of the biodegradable water-born coatings were adequate for their durability and functionality from planting to harvesting and their lifetime was from 3 to 6 months (Immirzi et al., 2009; Malinconico et al., 2008; Schettini et al., 2007; Schettini et al., 2008). The coatings created a physical barrier to prevent airborne weed seeds. The lifetime of the biodegradable mulching coatings decreases if they are used in the open field rather than inside a greenhouse since the life depends on several climatic factors, particularly rainfall, hail and wind. In greenhouse industry, sprayable mulching coatings are particularly suitable for plants grown in pots or trays where the application of extruded films require time and labour cost.

At the end of the crop cycle the biodegradable water-born coatings were fragmented and mixed with plant residue and the soil. Experimental data showed that the time frame necessary for the degradation of the residues disposed of in the soil was at most 1 month (Malinconico et al., 2008; Schettini et al., 2007).

4. HYDROPONIC TECHNOLOGY (*A. PARDOSSI*)

Soilless (hydroponic) culture, which was initially developed for studying plant mineral nutrition (Savvas and Passam, 2002), is thought to be one of the main elements of sustainable cropping systems under greenhouse conditions (Pardossi et al., 2006; Savvas and Passam, 2002). In fact, the implementation of closed hydroponics may reduce drastically the use of water and fertilizers and the environmental pollution associated to over-irrigation, which is quite common in protected horticulture (Pardossi et al., 2006; Thompson et al., 2007).

However, the application of closed-loop hydroponic technology is scarce on a commercial scale (Jouet, 2001; Pardossi et al., 2006) and, with the exception of The Netherlands where closed systems are obligatory, open (free-drain) culture is commonly used in protected horticulture, since its management is much simpler.

Herein the main technical features of hydroponic technology are illustrated and the possible environmental implications associated to its application in commercial greenhouses are discussed.

4.1. Techniques

Hydroponics is a broad term that includes all techniques for growing plants in media other than soil (substrate culture) or in aerated nutrient solution (water culture). The classification of soilless culture considers the type of substrate and container, how the nutrient solution is delivered to the plant (drip irrigation; subirrigation; flowing, stagnant or mist nutrient solution culture) and the fate of the drainage nutrient solution: open (free-drain) or closed (recirculating water) systems.

The most widely used soilless techniques are drain-to-waste substrate cultivation, while water culture systems such nutrient film technique (NFT), floating culture and aeroponics are widely used for research work, but much less on commercial scale.

Table 2 summarizes the main characteristics of different hydroponic techniques, including the growing risk associated to the technical failure of the equipments and to the occurrence of root diseases.

Table 2. Foremost characteristics of various hydroponic techniques

	Substrate and drip irrigation	**Substrate and subirrigation**	**NFT**	**Floating system**	**Aeroponics**
Application for commercial production	Large	Large	Scarce	Increasing	Rare
Type of crops	Fruit vegetables Strawberry Cut flowers	Pot plants	Leafy vegetables	Leafy vegetables Bulb flowers	Vegetables
Growing media	Yes (organic and/or inert)	Yes (organic)	No	No	No
Recirculating solution	Yes/no	Yes	Yes	Stagnant or fairly static	Yes
Investment costs	Moderate/high	High	High	Low	Very high
Running costs	Moderate/high	Moderate/high	Moderate	Low	Fair/high
System’s buffer	High	High	Low	High	Very low
Growing risks	Moderate	Moderate	High	Moderate	Very high

4.1.1. Substrate Culture

Substrate culture is generally used for row crops, such as fruit vegetables (Solanancea, Cucurbits), strawberry and cut flowers (rose, gerbera, anthurium, etc.) (Figure 28). Different containers (banquette, pots, bags, slabs) are used filled with inorganic or organic substrate, or a combination of two or three different materials, such as the peat-perlite or peat-pumice mixture. An excess of nutrient solution (with respect to crop water requirement) is typically supplied to the crop by drip irrigation up. In the cultivation of pot ornamentals, subirrigation is increasingly adopted; the pots are cultivated in gullies with an intermittent flow of nutrient solution or in ebb-and-flow benches. Both open and closed system may be set-up for drip-irrigated substrate culture. In closed systems, the drainage water is captured and reused following the adjustment of pH and nutrient concentration (namely, the electrical conductivity (EC)) and, eventually, disinfection to minimize the risks of root-borne diseases (Figure 29).

Figure 28. Long-cycle tomato culture in perlite bags in a greenhouse in Turkey.

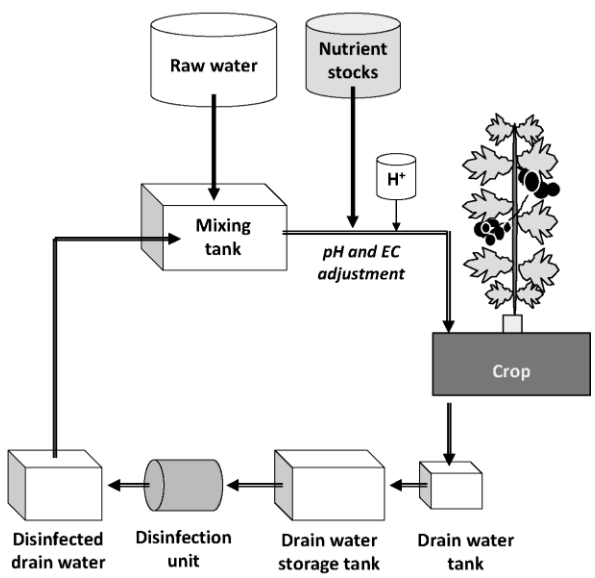

Figure 29. Layout of a closed-loop substrate culture. The nutrient solution is supplied by drip irrigation and the drainage water is recollected and reused after disinfection and the adjustment of pH and electrical conductivity (EC).

Many types of growing media are used. They are generally selected by the growers on the basis of their availability and cost (including shipping), as well as the local experience; however, any media should have the following characteristics: (i) low bulk density to facilitate the installation of otherwise weighty growing systems; high porosity (not less than 75–80%); (ii) a satisfactory distribution of air (oxygen) and water; sub-acid pH or easily adjustable, like sphagnum peat, which is quite acid and is neutralised with calcium carbonate; (iii) low salinity; (iv) chemical inertia, that is the material must not interfere with the nutrient solution by releasing inorganic ions and phytotoxic compounds, or by immobilising nutrients, as it may occur for phosphorus and nitrogen in some substrates (Lemaire, 1995); (v) the ability to maintain the original characteristics during the cultivation, which may be quite long (for instance, in rose culture); and (vi) the absence of pathogens and pests.

Hydraulic properties are of particular relevance, in particular the water retention at container capacity, which is the amount of water and, for difference, of air retained by the container after complete water saturation and free drainage.

While peat is largely used for pot ornamentals, the most popular growing media for growing row crops are perlite and rockwool, which are easy to handle, sterilise and re-use for a few years. In Europe, where soilless culture is more spread compared to other continents, the estimated yearly consumption of rockwool in professional horticulture is about 900,000 m^3 against 140,000 m^3 for perlite and 11.9 millions m^3 for peat (European Commission, 2005).

Mineral wool provides a sort of benchmark for growing media in consideration of their physical and chemical properties (high porosity, for instance) and the standardization of the products on the market. However, this substrate is generally produced (very) far from where greenhouses are concentrated; therefore, market price is high and, moreover, there is the problem originated by the disposal of exhausted material after a reasonable number of growing cycles, since it is not degradable. In some regions recycling or recovery options are not available to the growers, and exhausted slabs must be disposed to landfills.

In Mediterranean countries, perlite, pumice and other volcanic material are widely used in soilless cultivations. Transportation generally represents the most important cost components for the growers; their main disadvantages are the low water holding capacity and the poor stability. The disposal of exhausted perlite seems easier compared to rockwool, since it could be used as soil conditioner. Alternative reuse is the production (close to greenhouse clusters) of blocks for construction industry. A study in this direction is currently carried out in Italy in the framework of a FP7 research project “EUPHOROS” funded by the European Commission (EUPHOROS, 2008).

Peat is appropriate for almost all horticultural crops, but it is used mostly for pot ornamentals and propagation materials (seedlings, cuttings and micro-propagated plantlets). In mixture with perlite, it is largely used also for bag culture of strawberry (Figure 30). Peat is produced primarily in Northern Europe and America. Nevertheless, the price of peat is increasing and in the last ten years an “anti-peat” campaign have been originated in many European countries (Holmes, 2007), which has stimulated the search for alternative substrates. In most cases, these materials are based on industrial or municipal waste by-products. At the moment the most important alternatives to peat are timber industry by-products, coconut coir and high-quality green compost. Coir products are particularly promising.

Figure 30. Suspended bag culture of strawberry. This growing method culture reduces the requirements of hand-labour and make the fruits cleaner and less affected by *Botrytis cinerea* compared to soil culture.

4.1.2. Water Culture

The most used water culture methods are NFT, floating raft systems and aeroponics, which are closed systems.

Figure 31. Floating raft system for producing basil shoots in a plastic tunnel in Italy.

In NFT, a film of nutrient solution is recirculated (in general, intermittently) in light-insulated plastic gullies where bare-rooted plants are planted. The high installation costs, the small buffering capacity and some still unresolved problems, like those related to both non-parasitic (root death; Cooper, 1979; Pardossi et al., 2000) and parasitic diseases of root system, have hampered the commercial application of NFT, which are generally used for short-season crops.

In floating system the plants are grown in styrofoam trays (“rafts”) placed on stagnant or fairly static nutrient solution. The system is mostly used for leafy vegetables, herbs, bulb flowers (especially tulips; James, 2002) (Figure 31).

Aeroponics is another type of water culture technique where the plants are cultivated in holed plastic panels with the roots suspended in the air beneath the panel in the darkness in order to avoid the formation of algae. The roots are misted with nutrient solution very frequently, normally for a few seconds every 5–10 minutes. Aeroponics is an excellent tool for plant scientists; however, its application for commercial production is rare, since it is quite expensive and difficult to manage.

4.2. Water and Nutrient Supply

With the exception of some cultivations of pot ornamentals where the fertilisation is provided by controlled release fertilisers incorporated in the substrate prior to planting, the water and mineral requirements of soilless-grown plant are fulfilled by means of soluble salts dissolved in the irrigation water (fertigation). The nutrient solution used for hydroponic crops contains all macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium and sulphur) and micronutrients (iron, boron copper, manganese, zinc and molybdenum) at concentration of the order of milli-moles (mM) and micro-moles (μM) per liter, respectively. Optimal pH values for the solubility and root uptake of nutrients are between 5.5 and 6.5.

Depending on crop characteristics (e.g., tolerance to salinity) and stage, environmental conditions and hydroponic system, total molar concentration ranges between 20 and 40 mM with nitrate as a dominant ion. Plenty of different nutrient solution formulas have been published, which can be distinguished in two main types (Table 3): the more concentrated nutrient solutions are used for fast-growing crops, such as vegetables, while for ornamental plants and strawberry lower nutrient concentrations are normally used. In general, the same nutrient solution can be used for different crops, and that the same crop can be cultivated successfully with different nutrient solutions.

Table 3. Typical range of macronutrient concentrations (mM) in the hydroponic nutrient solution used for different crop species

	$N\text{-}NO_3^-$	$N\text{-}NH_4^+$	P	K	Ca	Mg	S
Vegetable crops	14.0–15.0	< 1.0	1.5–2.0	7.0–8.0	4.0–5.0	1.0–1.5	2.0–3.0
Ornamentals and strawberry	10.0–11.0	1.0–3.0	1.0–1.2	5.0–5.5	3.0–3.5	1.0–1.2	1.5–2.0

4.2.1. Open Systems

In substrate culture systems an excess of fresh (newly prepared) nutrient solution is generally supplied to overcome the difficulties associated the unequal transpiration of individual plants and to prevent the salt accumulation and the imbalance in the nutrient solution in the root environment. Typically, a drain fraction of at least 25–30% is used in substrate cultivation to prevent root zone salinisation. For this reason, in open soilless systems there is a massive waste of water and nutrients (Table 4), which is responsible for an increase in running costs and in a contamination of deep and surface water bodies.

Table 4. Water and nitrogen balance of open-loop substrate (rockwool) culture (nearly four months under the typical greenhouse growing conditions of Central Italy) of greenhouse tomato

	Supply	**Crop uptake**	**Loss**
Water (m^3 ha^{-1})	2,450	1,840	610
Nitrogen (kg ha^{-1})	510	352	158
Phosphorus (kg ha^{-1})	130	95	35

Accurate irrigation scheduling is a pre-requisite to minimise drainage and runoff. Crop water needs can be estimated on the basis of climatic conditions in the greenhouse. Low-cost devices are now commercially available for irrigation control on the basis of simple measurement of solar radiation, and eventually of air temperature and humidity. Other control systems are based on the measurement of the water content in the substrate by different type of sensors, such as hydraulic tensiometer or dielectric probes (Pardossi et al., 2009a). Irrigation is automatically initiated when the substrate moisture (or tension) content drops below a pre-set value (typically, between 5 and 15 kPa) as moisture tension, which can be modulated according to crop transpiration as assessed through meteorological measurement (Norrie et al., 1994); typically, the moisture content of the substrate is increased with increasing transpiration.

Whatever the approach to estimate the time of irrigation, water supply is normally adjusted on the basis of regular or online measurements of both volume and EC of the drainage solution; more irregularly, the EC of the substrate is also determined.

4.2.2. Closed Systems

In closed systems, the drainage water is collected and re-circulated after proper adjustment of pH and nutrient concentration (as a matter of fact, EC) and, eventually, disinfection in order to prevent the diffusion of root diseases from infected plants.

Closed systems have been developed to avoid the environmental problems related to nutrient runoff of open systems. Unfortunately, the use of closed loop hydroponics is scarce and, with the exception of The Netherlands where closed systems are compulsory, open (free drain) substrate cultures are usually used for greenhouse crops in reason of relatively easy management (Pardossi et al., 2006).

In addition to the possible diffusion of root pathogens, the salinity of irrigation water represents the main difficulty for the management of closed growing systems. When only saline water is available to the grower, there is a more or less rapid accumulation of ballast ions (e.g., sodium and chloride) that are dissolved at concentration higher that the uptake concentration (i.e., the ion to water uptake ratio). Salt accumulation may result in a concomitant increase in the EC of nutrient solution, if the control strategy aims to maintain constant nutrient concentration, or in a parallel depletion of nutrients, if the fertigation is based on a feed-back control of EC. Under these conditions, the nutrient solution is generally recirculated till EC and/or the concentration of some toxic ion remain below an acceptable threshold, afterwards it is replaced, at least partially (the term ‘semi closed’ is used for such systems). In the Netherlands, growers are allowed to flush out the exhausted nutrient solution whenever a crop specific ceiling of Na concentration is reached: for example, 8 mM in tomato and 4 mM in cut roses (Baas and van der Berg, 1999).

Based on a simulation, Stanghellini et al. (2005) concluded that closed systems are not financially viable under stringent environmental rules when the quality of irrigation water is poor and that, under these circumstances, the most valuable strategy is the improvement of water quality by means of desalinization or rainwater collection.

Nevertheless, on species with some salt tolerance (e.g., tomato and melon), the application of particular fertigation procedures may improve both crop sustainability by allowing the growers prolong the recirculation of the same nutrient solution and/or minimize the content of polluting agents, like nitrates and phosphates, in the effluents, when the water is discharged in the end.

Apart from the development of smart, low-cost chemo-sensors for continuous monitoring of the ion concentration, the innovation specific to closed hydroponics concerns the application of procedures for fertigation management that are alternative to the conventional feed-back control of EC and pH.

Indeed, the enthusiasm originated about chemo-sensors has decreased very much and probably in the next future there will be not a real commercial exploitation of these devices, at least for hydroponic management. However, the actual concentration of nutritive and non-nutritive ions in the recycling water could be monitored on a wider time scale (e.g. weekly) by using quantitative or semi-quantitative quick tests, such those employed in environmental or industrial sector, which are easy-to-use and cheap (Thompson et al., 2009).

Both review (Klaring, 2001; Savvas, 2002; Bugbee, 2004; Pardossi et al., 2006) and research papers (Brun et al., 2001; Pardossi et al., 2002) were published on the procedures to control fertigation in closed hydroponic systems. However, only a few works were carried out to develop an appropriate management of nutrient solution recyling in the presence of saline water (Raviv et al., 1998; Bar-Yosef et al., 2001; Pardossi et al., 2002) and, among these, only the papers published by Raviv et al. (1998) and by Pardossi et al. (2002) reported a detailed study on the effect of fertigation procedure on crop yield, water and nutrient use efficiency and the environmental impact associated to the periodical discharge of exhausted nutrient solution.

Other measures to reduce the environmental pollution provoked by nitrogen leaching in open or semi-closed soilless cultures with no important effects on crop yield are the programmed nutrient addition or the use of reduced nutrient concentration in the fertigation water (Maruo et al., 2001; Zheng et al., 2005; Munoz et al., 2008b) or nutrient starvation (Siddiqi et al., 1998; Le Bot et al., 2001; Voogt and Sonneveld, 2004).

Programmed nutrient addition, which has been proposed for both experimental and commercial hydroponics (Ingestad and Lund, 1992), may represent an alternative method to control mineral nutrition of hydroponically-plants. In this case a desired rate of nutrient uptake is maintained, rather than a concentration set-point. In an experiment with NFT-grown melons, Pardossi et al. (2002) compared a conventional control system based on EC adjustment nutrient solution to a nutrient addition based on pre-established weekly supply of macronutrients, without any attempt to maintain constant EC. Compared to the EC control, the second procedure did not affect fruit yield but reduced significantly the use of water and fertilisers, and eliminated nutrient runoff.

In a research conducted in two consecutive years with tomato plants grown in closed-loop rockwool culture and using irrigation water with a NaCl concentration of approx. 9.5 mmol L^{-1}, Pardossi et al. (2009b) tested three different fertigation strategies: (A) crop water uptake was compensated with fresh nutrient solution (EC = 2.5 dS m^{-1}) and recirculating nutrient solution (RNS) was flushed out whenever EC exceeded 4.5 dS m^{-1}; (B) EC was maintained at about 3.0 dS m^{-1} and RNS was flushed out whenever sodium concentration exceeded 20.0 mM and the concentration of nitrate was lower than 1.0 mM, a concentration considered acceptable from the environmental viewpoint (for instance, the maximum acceptable N concentration established by Italian legislation for the disposal of wastewater to surface water is 1.4 mM); and (C) as strategy A, but when the EC of RNS reached 4.5 dS m^{-1}, crop water consumption was compensated with fresh water only in order to take out the nitrates from RNS before discharge. It was found that neither crop water uptake nor fruit yield was affected by the method to manage fertigation. However, the discharges of nutrient solution were much less in strategies A than in strategies B and C and this resulted in increased water and nutrient use as well as a more severe environmental impact due to nitrate leaching.

4.3. Advantages and Disadvantages

Soilless culture may provide conditions for fast plant growth and development and abundant yield irrespective of the type of soil. However, advantages and disadvantages over the conventional soil have to be critically assessed when soilless culture is as a possible option for commercial production.

The first advantage of hydroponic technology is that it eliminates the needs of soil disinfection with steam or pesticides. In this regard, soilless culture is considered one of the most viable alternatives to methyl bromide soil fumigation for greenhouse cultures, which was banned by the end of 2005. Moreover, hydroponic can reduce the crop’s susceptibility to diseases by reducing the humidity inside the greenhouse and increasing the vigour of the plants. For instance, in strawberry, the suspended bag culture reduces considerably the susceptibility to gray mold (*Botrytis cinerea*), in addition reducing hand-labour for planting and harvesting. It is also possible to improve crop’s resistance to some pathogens by specific manipulation of the nutrient solution composition. For instance, Savvas et al. (2009) reported that the supply of at least 1 mM of potassium silicate via the nutrient solution enhanced both tolerance to salinity and powdery mildew (*Sphaerotheca fuliginea*) in zucchini squash (*Cucurbita pepo*).

Generally, the increased production of hydroponics over traditional soil cultures is a consequence of better growing conditions in both the root zone and in the aerial environment. In Italy, where hydroponics is developing slowly, many hydroponic installations failed not due to the scantiness of the greenhouse structure and the poor climate control. As a matter of fact, the occurrence of stressful temperature conditions, reduced CO_2 concentration due to poor ventilation and low light transmission of covering materials cancelled out the stimulating effects on crop yield of hydroponic technology.

As far as produce quality is concerned, the difference between soil culture and hydroponics has been investigated almost exclusively in vegetables. Of course, the vegetables grown hydroponically do not contain the residues of chemicals used for soil disinfection and, usually, they are very clean. This is essential, for instance, in the case of strawberry and of minimally-processed (fresh-cut) leaf and shoots vegetables. Moreover, an appropriate adjustment of the nutrient solution may represent an effective mean to improve crop quality. The removal of nitrogen from the nutrient solution during the last days of culture or the use of appropriate ammonium/nitrate ratio can reduce significantly the nitrate concentration of leafy vegetable that tend to accumulate large amount of these compounds potentially dangerous to human health (Santamaria et al., 2001). In cherry tomato the reduction of nitrogen content along with the use of high EC is the most effective method to reduce vegetative growth and improve the fruit content of sugars and acids.

Soilless culture has also several shortcomings resulting from the low volume of the root zone that increases the risks of management mistake and environmental stress. For instance, high root zone temperature may reduce plant growth during summer and increase crop susceptibility to some root pathogens like *Pythium* (Pardossi et al., 1992). Actually, the heat stress in the root zone during summer is one of the main constraints to the development of hydroponics in the Mediterranean countries. Moreover, in closed systems the recirculating nutrient solution may increase the risk of root-borne diseases. In addition, some pathogens, like *Fusarium oxysporum* f. sp. *radicis-lycopersici* and *Pythium* itself, seem more virulent in soilless culture than in soil (Van Assche and Vaugheel, 1997; Ozbay and Newman, 2004). To avoid the risks of root diseases the nutrient solution can be disinfected by means of pasteurisation, UV light or slow sand filtration (Runia, 1995).

However, the primary obstacle to the implementation of hydroponics in greenhouse industry is the high capital investment costs (Uva et al., 2001). Moreover, the management of soilless culture needs a skilful and highly-trained staff with some basic knowledge of plant physiology and adequate know-how on fertigation and the use of electric devices and electronic instruments. Installation costs range from a few € m^{-2} (floating raft system) to 7–15 € m^{-2} (closed substrate culture, NFT) and up to 50–70 € m^{-2} (movable ebb-and-flow benches for pot ornamentals). If greenhouse and climatic unit are included, capital investment may exceed 700 k€ ha^{-1}. Compared to soil culture, running costs may be lower on account of lower labour requirements, but in general the production costs are higher.

Recently, Papadopoulos et al. (2008) evaluated in terms of investments different hydroponic systems for greenhouse production of both ornamentals and vegetables in Western Macedonia, Greece, and concluded that such an investment is advantageous only with subsidy.

Higher yield and better quality (then higher market price) might compensate higher production costs; however, not necessarily the price for hydroponic products very seldom is higher compared to soil-grown products, also because they are not distinguished by the final consumers. Moreover, hydroponics and, more generally, high-tech cropping systems (as indeed greenhouse crops are) production are not well accepted by an increasing number of green-thinking people. Hydroponic is not compatible with the philosophy and, more practically, with the rules of organic agriculture in Europe (Commission Regulation, 2008) and it is not allowed also by some grower associations (e.g., the consortium for the protection of geographical indication of tomatoes and melons grown in Pachino area in Sicily, Italy). Therefore, effective marketing has to increase the consumer's acceptance of hydroponically-grown products, in particular of vegetables, which not few people still deem without taste and flavour or even dangerous.

4.4. General Remarks

An ideal soilless growing system must be economical, flexible and environmentally safe. Instead, soilless culture is still a capital-intensive technology and, in case of free-drain system, it may results in a huge waste of water and fertilisers. Moreover, it needs a skilful management of both fertigation and climate management to exploit the most of its numerous and undoubted advantages.

Indisputably, the phase out of methyl bromide and other substances for soil disinfection has stimulated the application of soilless culture in greenhouse crops. However, it is difficult to predict to what extent this growing method will develop on a commercial scale, since in many countries protected horticulture is still based on small operations, which use simple, low-cost technologies and for which the investment in hydroponic culture is often risky.

5. Integrated Pest and Disease Management (*A. Minuto and F. Tinivella*)

5.1. Introduction

Pest and disease management in intensive agricultural systems has often been based almost exclusively on the application of pesticides. Recent changes in consumers' needs, who are more keen towards a more sustainable production obtained with a very low use of chemical compounds, has favoured the application of alternative control strategies, and that is valid especially for vegetables grown in greenhouses (Albajes et al., 2000). Vegetable crops have to face many problems: in greenhouses they are characterized by short crop cycles, very narrow rotations and high pest and disease pressure. Damages posed by weeds are not less severe being able to host viruses, pests and diseases too. Their spread can be favoured by cultural practices themselves; moreover, their control throughout the use of herbicides may pose serious problems due to the phytotoxicity risks of a not proper herbicide application or due by residual effects on non target crops. Furthermore, under specific conditions, the application of integrated control strategies is necessary in order to allow the crop to be identified with the label of guaranteed protection (DOP) according to specific production protocols which foresee the use of different strategies and not only the chemical ones. Given these premises, the lack of registered pesticides and the low interest paid by agro-chemical companies towards many vegetables, among which the so called minor crops (Albajes et al., 2000), have made the use of integrated control strategies, which could rationally combine conventional and unconventional chemical (Dayan et al., 2009), genetic, agronomic and biological means (Pilkington et al., 2009), even more necessary. Techniques, which foresee the control and the modification of the environmental parameters within a greenhouse, can be successfully exploited for creating less conductive conditions for pests and diseases (Albajes et al., 2000). Modern control strategies for greenhouse climate control can be used in order to reduce disease infection and to influence plant development and, at this regard, computer-supported anti-botrytis climate control management have been recently developed based on a plant canopy model (Juergen and Lange, 2003) and, in some cases, it is possible to reach an almost complete control effectively interfering with the life cycles of some pests and so avoiding the use of traditional control measures (Albajes et al., 2000).

5.2. Pest and Disease Control Strategies

Different methods are available to put into action an integrated pest management strategy. The use of genetic and agronomic methods is particularly efficient for several pathosystems. Nevertheless, in the vegetable sector the use of certain resistant or tolerant varieties can lapse due to the continuous and quick change in market needs and characteristics. We will try hereby to briefly describe means that can be used and integrated with traditional control strategies and tools.

5.2.1. Biological Control Agents for Pest and Disease Management

Globally, the use of biopesticides is growing annually while the use of traditional pesticides is on the decline. North America uses the largest percentage of the biopesticide market share at 44%, followed by the EU and Oceania with 20% each, South and Latin American countries with 10%, and Asia and India with about 6%. Although biopesticide growth is projected at 10% annually, it is highly variable among the regions constrained by factors such as regulatory hurdles, public and political attitudes, and limitations for market expansion (Bailey et al., 2009). An outstanding example of adoption of non chemical control tools and strategies is represented by Almeria and Murcia greenhouse industry (SE of Spain). In Almeria, where there is the largest greenhouse concentration in the world (about 27,000 ha), protected crops using biocontrol agents have recently increased from 3% in 2006 to 28% in 2007 (Bielza et al., 2008). In order to set up effective disease control strategies with particular regards to minor crops, it is important to remind here that the speed up and the simplification of the registration process of agro-chemicals according with 91/414 CEE regulation would be highly needed in order to face emerging or manage already known pests or diseases. Unfortunately the difficulties related to the registration progress of both traditional and biological means and the low interest shown by agro-chemical companies towards minor crops make the process even more difficult needing the economical support of national and local Government and of grower associations.

Several microorganisms are currently available on the EU market and are registered as biological control means according with EU and national regulations. Among them we remind an *Ampelomyces quisqualis* based formulate, an antagonist fungus specifically developed for the biological control of powdery mildew. It is a specific hyperparasite effective towards more than 60 fungal species causing powdery mildew (Punja and Utkhede, 2003).

Other formulates nowadays commercialized were developed from *Trichoderma asperellum* (formerly *T. harzianum*) and *T. viride* (Punja and Utkhede, 2003). These are antagonistic fungi known and used since a long time for the control of different pathogens such as grey mould (*Botrytis cinerea*) (Figures 32 and 33). Some strains of *T. asperellum* proved to be effective for the control of pathogens which affect the aboveground part of the plant and the underground one (*Fusarium oxysporum* f.sp. *radicis lycopersici; Rhizoctonia solani; Sclerotium rolfsii*) (Howell, 2003).

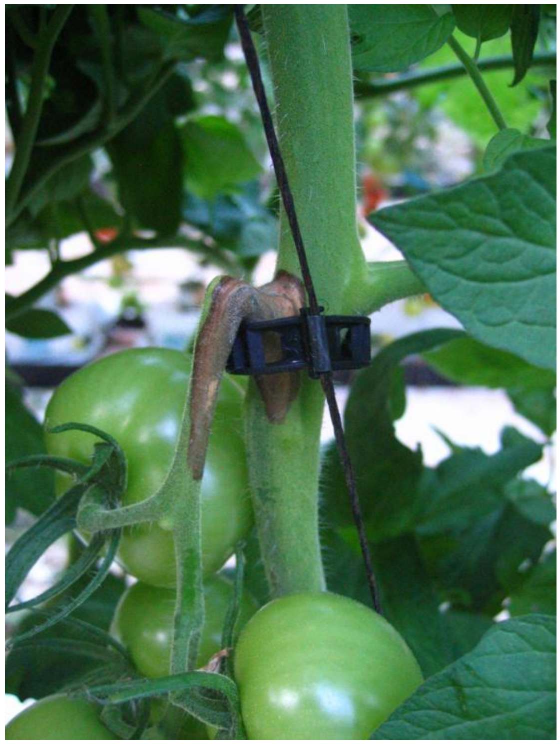

Figure 32. Stem necrosis caused by *Botrytis cinerea* infection on greenhouse tomatoes.

Figure 33. *Botrytis cinerea* infection on eggplant fruits.

A mixture of *Trichoderma asperellum* and *Trichoderma viride* has been recently introduced into the Italian market and registered for the treatment of growing media or soil in nurseries, greenhouses and open field on different vegetables (tomato, pepper, lettuce, radicchio, endive, rocket, melon, fennel, artichoke, basil, celery, bean, French bean, squash, eggplant, cucumber, fresh herbs).

Streptomyces griseoviridis is a bacterium that have been studied and developed as biocontrol agent in Northern Europe for the control of some soilborne pathogens. It acts mainly through competition for nutrients and space and it is effective for the control of root and crown diseases on many vegetables (Minuto et al., 2006a). For instance in Italy the compound is registered on tomato, pepper, eggplant, cucumber, melon, pumpkin, watermelon and basil.

Figure 34. Symptoms caused by infection of *Sclerotinia sclerotiorum* on protected lettuce crop.

Coniothyrium minitans is an antagonist fungus which can be used against root pathogens (Whipps and Gerlagh, 1992): it parasitizes sclerotia belonging to the genus *Sclerotinia.* It should be distributed on the soil preferably on crop debris: in this way mycelium generating from the spores can parasitize sclerotia, devitalizing them in 60–90 days. Temperature and soil moisture influenced both apothecial production of *S. sclerotiorum* and mycoparasitism of *C. minitans* and inoculum concentration of *C. minitans* and time of application appear to be important factors in reducting apothecial production by *S. sclerotiorum* (Jones et al., 2003). However a recent paper has demonstrated the sensitivity of such antagonist to different pesticides such as azoxystrobin, chlorotalonil, fluazinam, pyraclostrobin, tebuconazole and diclosulam, which negatively affected both its mycelial development and conidial germination. *C. minitans* anyway demonstrated to be able to survive and to parasitize sclerotia of *S. minor* even when combined with azoxystrobin, chlorotalonil, diclosulam, fluazinam, flumioxazin, S-metolachlor, pendimethalin, pyraclostrobin and tebuconazole, but only S-metolachlor, an erbicide registered on some open field crops, tomato and bean, had no influence on the ability to parasitize pathogen sclerotia (Partridge et al., 2006). In Italy, for instance, the microorganism is specifically registered on lettuce and on other greenhouse crops and on vegetables, flowers and fruit crops susceptible to *Sclerotinia* spp (Figure 34) for soil application in open field.

Bacillus subtilis is a bacterium which acts preventively controlling or reducing parasitic fungi through competition for nutrients and space and inhibition of germination. It has been developed for disease control on pome fruit and grapevine (Sharma et al., 2009), but it could be useful for the control of grey mould on vegetables too. It proved to be effective for the control of seedborne agents of antrachnose of bean and pea when applied as seed treatment (Tinivella et al., 2008).

Pseudomonas chlororaphis is a rhizobacterium (i.e., isolated from the rizosphere) that produces a fungi-toxic metabolite (2,3-deepoxy-2,3-didehydro-rhizoxin) able to effectively control fungi causing take-all on cereals thanks to antibiosis and competition mechanisms (production of siderophores which make iron unavailable for pathogens) and resistance induction (increased synthesis of phytoalexin, poliphenols and other compounds inside the plant) and it can produce substances similar to hormones. When applied to seeds the bacterium multiplies assuring a long lasting protection on cereals till 5 leaves stage (Johnsson et al., 1998). Experimental trials showed its effectiveness in some pathosystems when applied as seed dressing to control seedborne pathogens (Tinivella et al., 2008).

Biological pest control applied in protected crops has spread as an alternative to chemical application because of the selection of resistant populations of arthropods derived from a too high use of pesticides with a consequent increase in the risk posed to workers (Albajes et al., 2000, Bielza et al., 2008). Success in measuring efficacy of potential biocontrol agents remains somewhat of an art due to the multitude of factors influencing their efficacy, but might be improved by attention to characterization of natural enemy candidates using morphological taxonomy or genetic markers at the onset of a program, climatic matching candidate agents when possible, and evaluations in semi-field or field cage conditions following quarantine evaluations whenever possible before proceeding with widespread releases (Hoelmer and Kirk, 2005).

The good results obtained with natural impollination carried out by bumble bees instead of chemicals applied for setting (up to 80% of total surface of tomato cultivated in greenhouse in some Italian regions) has determined a reduction of treatments together with a more aware choice of selective and less harmful compounds. Moreover the possibility of using honey bees and bumble bees to vector a commercial formulation of *Trichoderma asperellum* for the control of *Botrytis cinerea* on strawberries was demonstated: *T. asperellum* delivered by bumble bees or honey bees provided better *B. cinerea* control than that applied as a spray. In addition, the bee-delivered *T. asperellum* provided the same or a better level of control of *B. cinerea* as commercial fungicides applied at bloom (Kovach et al., 2000).

The environmental isolation of protected crops, the simplicity of such ecosystem, the longer lasting control carried out by beneficials if compared to pesticide treatments has favoured the application of biological control measures. Its spread in Europe is favoured by the commercial availability of beneficials, which can cover the entire spectrum of pests widespread in protected crops (Weintraub and Cheek, 2005) and by costs comparable to pesticides.

Thrips control (i.e., *Thrips tabaci* and *Frankliniella occidentalis*) can be achieved through the introduction of different species of *Orius* (*O. laevigatus* and *O. majusculus*) and of some species of Phytoseid mites belonging to *Amblyseius* genus. Biological control of aphids on nightshades and cucurbits (mainly *Myzus persicae*, *Aphis gossypii*, *Macrosyphum euphorbiae* and *Aulachortum solani*) is based on parasitoids like *Aphidius colemani* and *Lysiphlebus testaceipes* or on predators such as *Adalia bipunctata* and *Chrysoperla carnea* (which is active against thrips and white flies to a lower extent). Against main white flies of vegetables (i.e., *Trialeurodes vaporariorum* and *Bemisia tabaci*) the Aphelinids *Encarsia formosa*, *Eretmocerus mundus* and *E. eremicus* and the predator Myrid *Macrolophus caliginosus* are available. Leafminers *Liriomiza bryoniae*, *L. huidobrensis* and *L. trifolii* can be controlled by Eulophid *Diglyphus isaea.* Against red spider mite *Tetranychus urticae* the Phytoseid *Phytoseiulus persimilis* is used since a long time and, more recently, *Amblyseius californicus* proved to be effective too. Relevant to other pests, such as moths and some spider mite species, biological control based on beneficials has not reached a significant level of application yet. Different effective control measures alternative to chemicals based on microorganisms and on other compounds registered for organic farming are known. Several species which infest greenhouses, such as *Spodoptera littoralis*, *Chrysodeixes chalcites* and *Helicoverpa armigera* (Nottuid moths) and *Ostrinia nubilalis* (Piralyd moth), can be controlled by different strains of *Bacillus thuringiensis* active against moth caterpillars. Sulphur (traditionally effective against powdery mildew) can be used for the control of spider mites, which infest greenhouses located in Southern Italy such as the tarsonemid *Polyphagotarsonemus latus*, harmful to pepper, and the eriophyid *Aculops lycopersici*, harmful to tomato (Figure 35).

Figure 35. Fruit crakings and bronzing caused by *Aculops lycopersici* on tomato fruits.

An important mechanism for insect pest control should be the use of fungal entomopathogens. Even though these organisms have been studied for more than 100 yr, their effective use in the field is not largely adopted. Some entomopathogenic fungi such as *Beauveria bassiana* and *Paecilomyces fumoroseus*, can be effectively used for the control of white flies, thrips and spider mites sometimes in combination with beneficials. Particularly *B. bassiana* have been commercially formulated, distributed and adopted particularly to control pest for minor crop. Recently, however, it has been discovered that many of these entomopathogenic fungi including *Lecanicillium* spp. and *Metarhizium* spp. play additional roles in nature. They are endophytes, antagonists of plant pathogens, associates with the rhizosphere, and possibly even plant growth promoting agents (Vega et al., 2009). These findings indicate that the ecological role of these fungi in the environment is not fully understood and limits our ability to employ them successfully for pest management.

Biological control is a complex technique with application issues that depend on variables which are not always fully understood and which can be biased by operators (Albajes et al., 2000). Crucial factors related to effectiveness are: infestation level and prey/predator ratio; quality of beneficials (sometimes affected by breeding techniques and by storing and shipment conditions); climatic conditions of the greenhouse which often prevent beneficial from fully carrying on its biological activity; cultivation techniques adopted (species and cultivar, transplanting period, crop cycles duration, etc.) with particular regards to some agricultural practices such as leaf removal on tomato plants; control measures adopted (Hoelmer and Kirk, 2005; Pilkington et al., 2009).

The cooling down during winter that can strongly limit the biological activity of entomophagous arthropods represents one of the main issues that affect the good outcome of biological control techniques applied in protected crops in the Mediterranean area. Some beneficials largely used in heated greenhouses in continental Europe showed to be ineffective when applied in the cold ones in Southern areas. For instance, *Encarsia formosa*, which is the most used parasitoid in Europe for the control of white flies, is mostly effective in non-heated greenhouses just since late spring, but often resulted to be ineffective (Albajes et al., 2000).

Even the control of *Frankliniella occidentalis* by *Orius laevigatus* can be difficult since the thrips can mate many times even during the winter time, while the activity of the predator is negatively affected by winter diapause. However *O. laevigatus* can be profitably used only during spring-summer months. Nevertheless, during the last years the introduction of biological agents more active at low temperatures coming from the Mediterranean area increased the effectiveness of such control strategies (Nicoli and Burgio, 1997).

Application of biological control techniques depends even on the other phytosanitary measures undertaken and, above all, on the active ingredients used, the number of treatments, the time of application, etc. in order not to compromise or even neutralise the activity of beneficials. Practical information about toxicity towards beneficials and persistence of main pesticides can be found in the documentation offered by some bio fabrics; this can help in a more proper combination of biological and chemical control means.

In many cases the difficulties met in obtaining robust results using beneficials induced farmers to rely just on chemical control and that is in counter trend compared to what happens in other Mediterranean countries. A very significant example about the application of biological and integrated control strategies is represented by pepper produced in protected environment in Campo de Cartagena (Spain) where, despite the high risk of TSWV (*Tomato* *spotted wilt virus*) incidence transmitted by *Frankliniella occidentalis,* it was possible to nearly eliminate insecticide treatments applying beneficials (Sanchez and Lacasa, 2006).

5.2.2. Use of Suppressive Composts

At the moment composts used as growing media for ornamental and vegetable crops is not as important as other substrates such as peat (Minuto et al., 2006b), but the use of such materials in the nursery sector could lead to the exploitation of interesting mechanisms of disease suppressiveness (Moral et al., 2009). A recent interdisciplinary study allowed researchers to describe, together with the characteristics of some composts deriving from agro-industrial waste materials, the possibility to use such composts for the control of some pathogens which cause crown, root and vascular diseases in different plant species (Minuto et al., 2006b). The greater interest posed at the moment in the exploitation of suppressiveness, a mechanism known since a long time and practically exploited since the sixties (Noble and Coventry, 2005), is mainly due to the possibility to control, although not completely, one or more pathogens even during the cultivation of susceptible hosts and with the presence of pedological and environmental conditions conductive for the disease. The development and use of suppressive substrates against harmful pathogens is an interesting opportunity especially for those crops for which only few pesticides are registered (Moral et al., 2009). Notwithstanding, at the moment, the low uniformity of materials used for compost production can negatively affect its broader use on vegetables (especially in nursery).

5.2.3. Resistance Inducers (SAR Mechanisms)

The possibility to use resistance inducers (which act on SAR mechanisms) could represent an interesting perspective even for disease control on vegetables (Walters, 2009). A pesticide, which has been traditionally exploited for its capacity to induce resistance in the host was Fosetyl-Al. The methilic ester of benzo (1,2,3)-thiadiazole-7-carbothiolic (BTH, acibenzolar-S-methyl) acid is at present available in Italy. It is a particularly effective resistance inducer but application doses must be carefully chosen in order to avoid potential phytotoxic effects (Friedrich et al., 1996). Such compound, currently registered on tomato, has shown some effects against fungal and bacterial diseases. Many other compounds, which can switch SAR mechanisms could be used for the control of plant pathogens; unfortunately for many plant species there are no registered products available at the moment (Gozzo, 2003).

5.3. Case Studies

5.3.1. Integrated Control of Pests and Limitation of Related Virus Damages

Protected crops represent a dynamic system exposed to new and quickly changeable problems can occur. Particularly, the accidental introduction in Italy of *F. occidentalis* (TSWV vector) and of new *Bemisia tabaci* biotypes (vectors of TYLCSV and TYLCV—*Tomato yellow leaf curl Sardinia virus* and *Tomato yellow leaf curl virus*—and of ToCV—*Tomato chlorosis virus*) (Figure 36) has made the disease control based on biological methods much more difficult on some vegetables (especially tomato and pepper). In the Southern Mediterranean countries such as the Southern part of Italy, where climatic conditions enhance the development of such pests and where virus diseases have already been reported, it is necessary to turn to an integrated use of control methods, privileging the preventive ones. Effective management of insect and mite vectors of plant pathogens is of crucial importance to minimize vector-borne diseases in crops. Pesticides play an important role in managing vector populations by reducing the number of individuals that can acquire and transmit a virus, thereby potentially lowering disease incidence. Certain insecticides exhibit properties other than lethal toxicity that affect feeding behaviours or otherwise interfere with virus transmission. Sustainability of insecticides is an important goal of pest management and more specifically resistance management, especially for some of the most notorious vector species such as *B. tabaci* and *Myzus persiscae* that are likely to develop resistance (Castle et al., 2009).

Figure 36. Leaf yellowing and plant stunting caused by infection of TYLCV (tomato yellow leaf curl virus) on protected tomatoes.

Chemical control of these pests is extremely difficult because of their very high reproducing rate and the capacity to quickly differentiate resistant strains (Bielza et al., 2008). Risk related to the transmission of virus diseases, which can be very high even at a very low level of vector population, forces to prefer preventive techniques, which aim at minimizing the contact between vector and host plant. Some agricultural practices proved to be very useful for this purpose: the complete removal of plant debris at the end of crop cycle; the removal of spontaneous plants near the greenhouses which can host vectors of virus diseases; the shift of transplanting time in order to avoid periods when the density of vectors is higher (e.g., July and August and sometimes September relevant to *B. tabaci*); timely uprooting of infected plants. A key control technique against virus vectors is based on the application of adequate screening nets to the lateral opening of greenhouses (Berlinger et al., 2002; Hilije et al., 2001) and on the protection of seedlings during first development stages through tissues realised with a continuous yarn.

Protection of openings through insect-proof nets, although being effective from a phytosanitary point of view, it is not free from drawbacks, such as the change induced to greenhouse inner climate (limited ventilation, increased temperatures, difficult management of relative humidity, etc.). Covering greenhouse roof and lateral firm frames with photoselective UV-absorbing films can reduce infestations of *B. tabaci* and, therefore, the spread of TYLCV (Rapisarda et al., 2005). The reduction of the UV portion of light spectrum alters pest sight capacity and therefore limits crop infestation (Antignus, 2000).

Population of white flies can be reduced adopting yellow traps to catch adults. Yellow coloured, 30 cm high sticky rolls, which can be placed few cm above plants are also available. *F. occidentalis* can be monitored through blue coloured sticky traps which can be triggered with an aggregating pheromone in order to increase their effectiveness (Gomez et al., 2006). Identification and synthesis of such pheromone, which attracts males and females (Hamilton et al., 2005), can lead to the application of control techniques based on mass trapping even for this species.

5.3.2. Tomato: Grey Mould and Climatic Management of Cultivation Environment

The control of *Botrytis cinerea* has always been a key issue for many protected vegetables such as tomato, strawberry, basil and lettuce. On tomato grey mould infections are extremely harmful during autumn, winter and spring time and in all periods characterized by sudden temperature changes between night and day which favour condensation on leaf, flower and fruit surface (Shpialter et al., 2009) (Figure 37).

The most effective control strategy should be based on a correct management of the growing site. It has been demonstrated that the adjustment of the relative humidity through dehumidification can effectively limit damages caused by pathogen infections (Albajes et al., 2000, 1993; Prichard et al., 1999; Sharabani et al., 1999). Particularly, the control technique is based on the possibility to interrupt the infective process. Unfortunately this remedy, relying on heating systems, is not always economically sustainable with the exception of some value crops such as basil and some cut flowers.

Agronomical control techniques, as the one above mentioned, have been combined with pesticide application in order to be more effective (Prichard et al., 1999; Sharabani et al., 1999; Albajes et al., 2000). The combination between biological control and non chemical means was proved to be effective in non heated protected crops by other authors, e.g. a decisional support system suggests the correct application time of *T. harzianum* depending on the evaluation of climatic conditions and infection risk. In this way the rate of application of such compound was reduced by 50% (Shtienberg and Elad, 1997).

Figure 37. Leaf guttation on tomato plants often causes the onset of leaf and fruit rot of protected tomatoes.

5.3.3. Control of Soilborne Pathogens: Solarization, Grafting on Resistant Rootstock, Biofumigation, Soilless Cultivation

Soiborne pathogens can pose big constraints to protected vegetable production because of the recent phase out of methyl bromide, particularly in developed countries where only few critical uses are still allowed. The lack of fumigants characterized by a wide spectrum of activity and effectiveness comparable to methyl bromide imposes the adoption of alternative strategies not only based on chemicals. Relevant to protected crops, solarization and grafting on resistant rootstock represent two of the most important techniques for the control of soilborne pathogens.

Solarization — Different fumigants alternative to methyl bromide and nowadays available can be applied through drip fumigation under plastic films laid down on the soil at least during the hottest months of the year. The same films can be kept for 2–3 weeks exploiting the heating effect due to the solar radiation and enhanced by the application carried out inside a greenhouse. Significant results were obtained for the control of gall nematodes (*Meloidogyne* spp.) (Figure 38) and of pathogens causing root, crown and vascular diseases (Martin, 2003).

Grafting on resistant rootstock — Grafting commercial cultivars susceptible to *Verticillium* onto resistant rootstocks was developed as a replacement for fumigation. However, the practice of growing grafted vegetables started in Japan and Korea in the late 1920s (Lee, 1994). Grafting vegetables onto resistant rootstocks represents a technically and economically feasible alternative particularly in Japan and in Korea where 54% and 81%, respectively, of vegetables grown are grafted (Rivero et al., 2003). In the Mediterranean region, grafting represented an opportunity to maintain productivity of crops such as watermelon, cantaloupe, tomato, pepper, and eggplant (Bletsos et al., 2003; Diánez et al., 2007). It was rapidly adopted and for instance in Greece, 90–95% of watermelon, 40–50% of cantaloupe, 5–8% of tomato and 5–8% and 2–4% of cucumber and eggplant are now grafted (Traka-Mavrona et al., 2000); in Spain 98% of watermelon and 10% of tomato, in Morocco and Netherlands more than 25% and 50% of protected tomatoes and in Cyprus 80% of watermelon (Diánez et al., 2007). Over 5 million eggplants and 5.8 million tomato plants were produced from grafted seedlings in Italy in 2005 (Minuto et al., 2007b).

Figure 38. Galls caused by the heavy infestation of root knot nematodes (*Meloidogyne* sp.) on melon roots.

Formerly quite costly, it can be nowadays considered technically and economically effective as demonstrated by the increasing cultivation of grafted vegetables like melon, watermelon, tomato and eggplant. Grafting vegetables onto resistant rootstocks offers numerous advantages including: resistance to soil pathogens, specifically *Verticillium* and *Fusarium* (Lee, 1994; Bletsos et al., 2003), improved yield in infested soils (Bletsos et al., 2003), greater tolerance against low and high temperatures and salt stress (Rivero et al., 2003) and higher plant vigour that can support longer crop cycles. Bletsos et al. (2003) found that grafted eggplants had not only increased fruit yield of up to 79% over non-grafted plants in *Verticillium*-infested soil (Bletsos et al., 2003) but they also produced fruit a week earlier (Khahm, 2005). Fruits from grafted eggplants contain fewer seeds than from non-grafted plants (Khahm, 2005) and this is regarded as another qualitative benefit to the consumer.

Several rootstocks are available for grafting of tomato and eggplant, the most common being tomato hybrids (“Energy”, “Kyndia”) and interspecific hybrids of *L. esculentum* and *L. hirsutum* (“He Man”, “Beaufort”, “Maxifort”, “Trifort”). For grafted eggplant *Solanum torvum* was introduced and now represents more than the 70% of the total market of eggplant rootstocks in the south Italy (Minuto et al., 2007b). Other *Solanum* species could be adopted for grafting eggplant including *S. sisymbriifolium*, but *S. torvum* guarantees the highest resistance against *Verticillium* wilt (Bletsos et al., 2003) and also carries traits of resistance to the most serious disease of eggplant namely bacterial wilt (*Ralstonia solanacearum*) and nematodes (Gousset et al., 2005).

Among the major constraints and limitations of grafted rootstocks is that resistance may break down under high pathogen population pressure, that new races of the pathogen may evolve, and under some environmental stresses such as high temperature and salinity, the plants may prematurely collapse. Furthermore, pathogens generally considered minor can become major pathogens on the rootstocks in the absence of soil fumigation. As an example, novel root rots caused by *Colletotrichum coccodes* were repeatedly observed on rootstocks currently used for grafting tomatoes and eggplant (Garibaldi and Minuto, 2003). Although *C. coccodes* was previously reported to infect *L. hirsutum* rootstocks, it was never observed on *L. lycopersicum* x *L. hirsutum* hybrids, the most widely used rootstocks.

Grafted hybrids of *L. lycopersicum* x *L. hirsutum* ("Beaufort", "He Man") and of *L. lycopersicum* ("Energy") can be infected by *Phytophthora nicotiane* and *Rhizoctonia solani* accompanied by some plant stunting (Minuto et al., 2007b). Finally, eggplants ("Black Bell", "Mirabell") grafted onto rootstock of *S. torvum* that confer a high degree of nematode tolerance can exhibit a partial tolerance against *Verticllium* wilt (Garibaldi et al., 2005).

Figure 39. Plant wilting caused by *Verticillium dahliae* on *Solanum torvum.*

The relatively low tolerance of *S. torvum* to V. *dahliae* was known (Ginoux and Laterrot, 1991; Gousset et al., 2005). Ginoux and Laterrot (1991) confirmed the resistance of *S. torvum* against *V. dahliae* particularly under mild climate conditions and in sandy soils and when 70–80-day-old grafted plants were transplanted. In trials carried out with 15-day-old *Solanum* spp. seedlings belonging to 14 different species vertical resistance to *V. dahliae* was not found but there was only tolerance to wilt symptoms (Nothamann and Ben-Yephet, 1979). Experiments conducted in highly infested fields confirmed that *S. torvum* conferred only partial wilt resistance (30–50% infection plants compared with non grafted eggplant 80–100% infection), while *L. lycopersicum* x *L. hirsutum* and *L. lycopersicum* hybrid rootstocks always showed low infection (7–10% infected plants) (Minuto et al., 2007b) (Figure 39).

In Northern Italy since 1997, sudden collapse of grafted plants in protected and open field tomatoes ("Cuore di Bue", "Marmande-Raf") grafted on "He-Man" and on "Energy" rootstocks were observed (Garibaldi and Minuto, 2003). The collapse before or after fruit setting during spring and summers was in the 15–70% range. Sudden collapses were also observed on "Iride", "Naomi", "Cuore di Bue" and "Marmande-Raf" grafted on "He-Man", "Energy" and sometimes on "Beaufort", regardless of the season or phenological stage of plants in Southern Italy (Garibaldi and Minuto, 2003). This collapse appears to be a direct consequence of the incompatibility between scion and rootstock or the climatic conditions during fruit setting and ripening.

Similar collapses were observed on eggplant grafted on tomato rootstocks (Ginoux and Laterrot, 1991) demonstrating the importance of rootstock selection. *S. torvum* performs best as an eggplant rootstock during warm seasons, but may reduce plant vigor during other seasons. Tomato rootstocks should be more vigorous and possess cold tolerance, but graft incompatibility may reduce cold tolerance (Minuto et al., 2007b). With tomato rootstocks grafted onto eggplant one often finds that the diameter of the rootstocks is double that of the scion but this is not the main reason for graft incompatibility. This is inferred from the fact that plants with tomato rootstocks transplanted in late spring to early summer do not show signs of damage although the size differences between rootstock and scion are present.

Catara et al. (2001) found a widespread dieback of eggplant ("Mission Bell"), grafted onto the interspecific hybrid ("Beaufort") and on tomato hybrid ("Energy") during winter cultivation. Bacteria isolated from symptomatic tissues were identified as *Pectobacterium carotovorum* subsp. *carotovorum* and *P. carotovorum* subsp. *atrosepticum* and confirmed to be pathogenic. Ginoux and Laterrot (1991) recognized these same symptoms as a graft incompatibility enhanced by low temperature and by heavy leaf guttation and water soaked leaf areas and lesions. Since the wide scale adoption of *S. torvum* for eggplant grafting, this type of plant dieback is no longer considered important.

Biofumigation — Different species belonging to Brassicaceae family can produce metabolites deriving from an enzymatic (myrosinase) degradation of glucosinlates, which accumulate within plant tissues and have biocide properties. Such compounds belong mainly to isothiocyanates and they can act as soil fumigants for the control of different pests and pathogens on semi-intensive crops (Gamliel and Stepleton, 1993; Lazzeri and Manici, 2000). Cultivation and green manuring of brassicas selected for their high content of glucosinolates can bring to the soil compounds characterized by a high fungitoxic activity. For this purpose since 1997 the Istituto Sperimentale per le Colture Industriali in Bologna (Italy) has selected different species of brassicas (*Brassica juncea, Eruca sativa, B. nigra, Rapistrum rugosum, Iberis amara*). Later on the same Institute has set up a procedure for the production of oil-free flours and pellets deriving from different plant portions (Lazzeri et al., 2002).

Soilless cultivation — This technique can be used for the control of soilborne pathogens affecting vegetables through e.g. the exploitation of the suppressiveness related to such cultivation methods without falling back upon expensive procedures such as disinfestation or renewal of growing media.

The possibility to control infections of *Fusarium oxysporum* f.sp. *radicis lycopersici* (agent of crown and root rot of tomato) simply re-using not infected growing media (perlite and rock wool) already used as cultivation substrates has been demonstrated. Such substrates in fact did not induce the disease in the crop even in the presence of artificial infections of the pathogen (Minuto et al., 2007a). This finding is important since the same pathogen, that is often very harmful to crops grown in saline soils or when saline water is used (Triky-Dotan et al., 2005), can easily colonize environments with a poor microflora and therefore settle in soilless cultivation systems (Ozbay and Newman, 2004).

The exploitation of suppressiveness, such as the one above mentioned, can be based on different mechanisms (microbiological, chemical) depending on the growing medium used (perlite, peat, rockwool, pomix, mixtures of different materials) which becomes a key element that must be taken into account (Minuto et al., 2007a; Clematis et al., 2009).

In conclusion the emergence of new pathogens and pests or the fresh outbreak of already known parasites (even if not so harmful in a sector characterized by a high specialization as the intensive horticultural one) complicates the management of disease control strategies. Virus diseases transmitted by pest vectors represent a key issue in vegetable production. Among different control measures that could be easily adopted in this sector, the exploitation of genetic resistance represent the most sustainable choice from an economic and a technical point of view as recently demonstrated for the control of Fusarium wilt of lettuce (Matheron et al., 2005). Moreover the use of genetic means requires an on-going research activity in order to individuate the plant material characterized by a satisfactory level of resistance or tolerance as long as it enters the market. This can be hard especially towards some necrotrophic fungal pathogens. On the contrary, the integration of different control means, although complicating crop management, is the only strategy, which can guarantee the farmers a medium- or long-term application perspective.

6. Summary and Future Perspectives

In recent decades, a growing environmental awareness has prompted the public to ask for environmental protection and nature conservation. This awareness has led, in addition, to the developing of sustainable strategies to meet the needs of the present without compromising the ability of future generations to achieve their own needs. Protected crops are intensive agricultural systems that strongly influence air, soil and water of the agricultural settlement due to their environmental loads, i.e., water, energy and agro-chemical use as well as waste disposal. Thus, a sustainable greenhouse system must reduce environmental degradation, conserve natural resources, maintain a stable rural community, provide a productive agriculture in both the short and the long term, and must be commercially competitive and economically viable. The protection of the natural resources implies innovative solutions concerning greenhouse microclimate control, renewable energy use, covering materials, plant fertigation and pest and disease management. Greenhouse microclimate, in terms of air temperature and relative humidity, carbon dioxide concentration and solar radiation, has an effect on crop growth and on the severity and incidence of pests and diseases. Over the recent decades, several strategies have been developed to improve greenhouse microclimate control; a sustainable approach to microclimate management has the objective to guarantee optimal growing conditions for the plants as well as energy savings. Microclimate control performed by means of temperature integration could lead to a novel procedure that will allow growing greenhouse crops with minimum or even with no fuel consumption for heating. Dynamic control of greenhouse temperature and carbon dioxide concentration, according to photosynthesis models and outdoor available radiation for photosynthesis, permits up to 48% in energy saving for climate control.

Co-generation systems, which generate electricity and heat, are suitable for both greenhouse climate control and geographically dispersed electricity generation, thus increasing the energy efficiency of the systems. An increasing use of renewable energy with a decreasing use of fossil fuel consumption must be achieved for sustainable greenhouse production as soon as possible, especially in light of the increases in fuel prices in recent years.

Among renewable energy sources, geothermal energy, where available, is already used in greenhouse heating. Other renewable energy sources can be applied to the greenhouse industry, even if they require additional reduction in cost of application and further improvements in terms of energy efficiency. Solar thermal systems can be integrated in the existing greenhouse heating systems, which use warm water and are fed by fossil fuels such as diesel fuel or gas. In this case, solar thermal collectors produce a fraction of the thermal energy, allowing the reduction of fossil fuels consumption. Low enthalpy thermal energy produced by means of solar thermal collectors could be integrated with thermal energy produced by means of heat pumps fed by renewable sources such as photovoltaic modules or wind turbines. Photovoltaic systems are easy to install and need low maintenance, but they have a high installation cost. Public incentives have helped to improve the economic viability of photovoltaic systems. Furthermore, increases in cell efficiency and cost reduction are expected over the next years. New techniques could lead to a widespread use of solar photovoltaic systems — for example, concentrating technologies — which could lower installation costs and increase energy efficiency. Besides, concentrating systems could be used for co-generation of heat and power or for tri-generation, i.e., the simultaneous production of cooling, heating and power. The use of wind energy appears cost-effective with large-size high-performance wind turbines in power plants with a size of several MW, but presents high investment costs and maintenance, making large wind turbines more suitable at the moment for electric utilities than for greenhouse farms.

Greenhouse microclimate can be also conditioned and managed by means of covering materials with different properties. Low-emission glass, double-wall glass, and ethylene–tetrafluoroethylene copolymer plastic films can be used to obtain energy savings in greenhouse heating. A sustainable control of plant vegetative activity of vegetable, fruit and ornamental species and a few pests in place of agro-chemicals can be achieved by designing innovative covering materials with specific radiometric properties that alter spectral wavelength distribution of the solar radiation passing through the cover.

Plastic films produced with fossil raw materials are used worldwide in greenhouse industry as covering materials and for soil mulching, and thus huge quantities of plastic wastes that must be disposed of are generated in protected cultivation. Biodegradable materials for agricultural purposes, formed with raw materials from renewable origin, can be used as environmentally friendly alternatives to synthetic petro-chemical polymers. In fact, at the end of their life, biodegradable materials can be integrated directly into the soil where bacterial flora transform them into carbon dioxide or methane, water and biomass; alternatively, they can be blended with other organic material to generate carbon rich composts. Thermo-plasticizing, casting and spraying processes have been employed to perform biodegradable materials for greenhouse applications.

Among possible strategies to achieve effective water and soil protection, soilless culture represents one of the main elements for a sustainable greenhouse cropping system. The implementation of closed hydroponics could drastically reduce the use of water and fertilizers and the environmental pollution associated with over-irrigation, which is quite common in protected horticulture. Hydroponic technology eliminates the need for soil disinfection with steam or pesticides. In this regard, soilless culture is considered one of the most viable alternatives to methyl bromide soil fumigation, particularly in high-tech protected crops. Moreover, hydroponics can reduce a crop’s susceptibility to diseases by reducing the humidity inside the greenhouse, increasing the vigour of the plants and making the root environment more suppressive against soilborne fungi.

Nevertheless, the emergence of new pathogens and pests or the fresh outbreak of already-known parasites complicates the management of pest and disease control strategies. Moreover, the limitation of availability of chemical control strategies, together with the increased demand of fresh and/or processed vegetables with no pesticide residues, encourage the proper adoption of innovative pest and disease management strategies. Among different control measures that could be easily adopted in this sector, the exploitation of genetic resistance represents the most sustainable choice from an economic and a technical point of view. The use of genetic means requires on-going research activity in order to individuate the plant material characterized by a satisfactory level of resistance or tolerance as long as it enters the market. The integration of different control means, although complicating crop management, is the only strategy that can guarantee the farmers a medium- or long-term application perspective.

The application of innovative microclimate control strategies, soilless cropping systems and integrated pest and disease control techniques increases productive costs for greenhouse farmers. Nevertheless, improved plant health and better yield and quality result in a higher value-added production and gross income meeting the end-consumers requirements.

Nowadays, the application of the described sustainable solutions is not as widespread as it should be, because, the exploitation of renewable energy sources requires strong public financial support and the application of innovative biodegradable materials, which are at an experimental stage, needs more research before implementation on a commercial scale for market availability. It is noted that hydroponic systems are applied extensively only in Dutch greenhouse horticulture.

Environmental laws and binding technical standards aimed to push towards environmentally friendly greenhouse systems could encourage a faster application of the described sustainable solutions. Nevertheless, increased operational costs due to the application of innovative and more complex growing methods and strategies have to be shared within all stakeholders and end-consumers, while taking into account the economical support of local and national governments aimed at maintaining, improving, encouraging and sponsoring environmental protection, preservation and renewal.

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LIST OF SYMBOLS

A	area
C_d	discharge coefficient
c_p	specific heat
C_w	wind coefficient
CHP	combined heat and power
CO_2	carbon dioxide
CPV	concentrating photovoltaics
DIF	day time temperature minus night time temperature
EC	electrical conductivity
ETFE	ethylene–tetrafluoroethylene copolymer
EVA	polyethylene-co-vinyl acetate
g	gravitational acceleration
H	height
HALS	hindered amine light stabilisers
HDPE	high density polyethylene
LAI	leaf area index
LCA	life cycle assessment
LDPE	low density polyethylene
LHC	latent heat convertor
LWIR	long wave infrared
m	mass flow rate
NFT	nutrient film technique
NIR	near infrared
PAR	photosynthetically active radiation
PCM	phase change material
PP	polypropylene
PV	photovoltaic
Q	flow rate
q	heat
RNS	recirculating nutrient solution
S	solar radiation
T	temperature
ToCV	tomato chlorosis virus
TSWV	tomato spotted wilt virus
TYLCSV	tomato yellow leaf curl Sardinia virus
TYLCV	tomato yellow leaf curl virus
U	heat transfer coefficient
UV	ultra violet
VPD	vapour pressure deficit
w	wind speed
Z	distance between centers of top and bottom openings

List of Symbols (Continued)

α	coefficient
β	evaporation coefficient
γ	heating coefficient of solar radiation
η	efficiency of a pad
θ	constant
λ	wavelength
ν	specific volume of air
ρ	density
τ	transmissivity of the cover
ϕ	ventilation regime coefficient
ω	humidity ratio

SUBSCRIPTS

b	at the bottom of the greenhouse
bu	buoyancy
c	greenhouse cover
cr	crop
DB	dry bulb
ex	at exit
f	floor
h	heating
i	of air in the greenhouse
inl	at inlet
p	at pad outlet
t	at the top of the greenhouse
v	opening
w	due to wind effect
WB	wet bulb
0	ambient