

Review

Design, Control, and Performance Aspects of Semi-Closed Greenhouses

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Received: 5 October 2020; Accepted: 6 November 2020; Published: 8 November 2020



Abstract: Several greenhouse energy saving technologies and management strategies have been developed in order to meet the needs for implementation of production systems with low and efficient energy use and low CO₂ emissions. Towards this aim, a number of greenhouse concepts that make use of these technologies have been developed and tested, such as the closed greenhouse, the solar greenhouse, the energy-producing greenhouse, and others. The closed or semi-closed greenhouse concept is widely accepted as a concept to achieve the targets for energy saving and low CO₂ emissions. A major difference of this concept to a conventional greenhouse is that climate control by window ventilation is partially or completely replaced by systems that treat the air, regulate the air exchange between inside and outside, and in few cases collect and store the excess heat load in order to be reused at a later time. A semi-closed greenhouse allows temperature, humidity, and CO₂ concentration to be controlled independently, during heating as well as cooling mode function. Among others, semi-closed greenhouses offer possibilities for better control of greenhouse environment, for increasing water use efficiency by decreasing the evaporation losses via ventilation and for reducing the pesticide use by decreasing the entry of insects and fungal spores in the greenhouse through the ventilation openings. The aim of this review is to focus on the design, control, and performance aspects of semi-closed greenhouse systems which use either (a) an air treatment corridor with evaporative cooling pad connected with an air distribution system with perforated polyethylene tubes or (b) decentralized air treatment units distributed inside the greenhouse. It gives an overview of the principles of the semi-closed greenhouse, the potential energy consumption and the expected savings. Additionally, it gives insight into the climate conditions in relation to the conventional greenhouse, crop growth, water consumption, and pest control.

Keywords: decoupling; ventilation; cooling; dehumidification; energy saving; CO₂ supply

1. Introduction

The implementation of Kyoto Protocol [1] agreement in European Union was made with the well-known “EU Climate and Energy Package”, a set of binding legislation, which ensures that EU meets its climate and energy targets for the year 2020. Following this agreement, the greenhouse horticulture must contribute to a reduction in CO₂ emissions, which can be realized by reducing fossil fuel consumption. To meet the climate and energy targets towards 2020, several countries developed plans towards this aim. For the Dutch greenhouse industry the target of CO₂ emissions was set to 4.6 megatons CO₂ for 2020, which corresponds to a reduction of 32% compared to 1990 levels [2,3].

Researchers and SMEs working in the greenhouse sector targeted the development of greenhouse energy saving technologies and management. Thus, during the last decades, technological developments in the greenhouse industry have focused on decreasing use of resources, mainly energy and water and increasing yield and quality of products. A number of relevant technologies and greenhouse concepts have been developed and tested towards this aim, such as the closed greenhouse [3,4], the solar greenhouse [5], the Watergy [6], the energy-producing greenhouse [7], the sunergy greenhouse [8], the low energy greenhouse [9], and others. A major difference of these concepts to a conventional greenhouse is that climate control by window ventilation was partially or completely replaced by mechanical systems which have two common characteristics, an air-processing system and a distribution system of the treated air within the greenhouse. That is why the authors of [4] indicated that the trends in greenhouse developments related to energy saving and environmental protection, would be mainly related to the ventilation process, which reflects in the use of window and mechanical air treatment. Of these systems, only one operates a seasonal heat storage and can store excess thermal energy during summer in an underground aquifer. Thermal energy is used in winter, and the relatively cold water stored in winter is used for cooling in summer [10].

The closed or semi-closed greenhouse concept is widely accepted as a concept to achieve the above-mentioned targets for energy saving and for reducing CO₂ emissions. The energy saving is achieved by reduction of losses mainly due to less ventilation, due to partly diurnal and partly seasonal-phase shift of heating (or cooling) usage and heat (or cold) storage (if a seasonal storage is used) and due to additional use of technical equipment (humidifiers, air conditioners, heat exchangers, fans, etc.) [11]. It also allows temperature, humidity, and CO₂ concentration to be controlled independently for different control modes (e.g., during heating, cooling, dehumidification, etc.). This makes it possible to achieve different combinations of climatic conditions that were not possible until now in conventional greenhouses. For example, conditions of high light intensity plus high CO₂ concentration, and a low rate of CO₂ supply are possible only in a closed or semi-closed greenhouse [12,13].

There are additional potential benefits of semi-closed greenhouses, such as better control of the greenhouse environment, reduced water consumption due to reduced water vapor loss through ventilation, and reduced entry of insects and fungal spores into the greenhouse, resulting in reduced use of pesticides. Several studies have been carried out during the last 15–20 years investigating the effects of the implementation of this concept on the inputs and outputs of the greenhouse system. The aim of this review is to focus on semi-closed greenhouse systems which consist of either (a) an air treatment corridor with an air distribution system of perforated polyethylene tubes or (b) decentralized air treatment units distributed inside the greenhouse. These two versions of the semi-closed greenhouse differ from each other in two fundamental technical characteristics, first in whether some kind of outside air treatment is done and second in the way the treated air is distributed in the greenhouse environment.

The manuscript is formed with the following structure: an overview of the principles of the semi-closed greenhouse is initially presented and the main system variations are presented and discussed. Then, the measurements needed for the control of semi-closed greenhouses are revised. The next part of the review presents data related to the performance evaluation of semi-closed greenhouses such as the microclimate conditions created in the greenhouse, the water saving obtained, and the effects on pest control. Finally, the manuscript closes with a general discussion and conclusion section. The manuscript does not focus on other technologies that have been developed related to the semi-closed greenhouse concept (e.g., seasonal heat storage).

2. Principles, Design, and Control of a Semi-Closed Greenhouse

2.1. Degree of Coupling of Semi-Closed Greenhouses to Outside Climate

The main difference between a conventional and a semi-closed greenhouse equipped with an air treatment corridor and an air distribution system, is the method of creating the appropriate climatic conditions inside the greenhouse and how this is achieved by controlling the different processes related

to heat and mass transfer, mainly the ventilation. In a conventional greenhouse, roof vents (i.e., natural ventilation) are used to exchange air between inside and outside for air temperature, relative humidity, and CO₂ concentration control. On the other hand, in a semi-closed greenhouse, the climate control is realized by actively controlling the physical properties of the air that enters the greenhouse, the air exchange between inside and outside, the treatment of the inside air via recirculation, and the air flow within the greenhouse.

When an air treatment corridor with air distribution system is used, the greenhouse climate is controlled, for heating, cooling, and dehumidification, either by adding fresh treated air from outside to the greenhouse, or by recirculating the greenhouse air via the air treatment corridor or by mixing outside with inside air. In all control modes the air temperature, the air vapor content, and the air flow (i.e., ventilation rate) are controlled. The same air physical properties are controlled also when decentralized air treatment units are used, however in this case the greenhouse air is treated in situ by these units depending on the climate requirements. While outside treated air is blown to the greenhouse, the latest remains under positive pressure (overpressure until a certain limit) which helps to keep the pests out of the greenhouse.

Taking into account the above control modes and natural processes, mainly that of air exchange, we can say that a semi-closed greenhouse is less dependent-coupled to outside climate than a conventional greenhouse. This correlation between the greenhouse and outside climate has been expressed by the coupling factor ($1-\Omega$) [14]. Values of the coupling factor $1-\Omega$ close to 1 indicate a completely coupled greenhouse to outside air and close to 0 a fully decoupled greenhouse (e.g., a complete closed greenhouse). The authors of [15] calculated that while a conventional (without an active cooling system) greenhouse in Greece and in Algeria has a degree of coupling around 0.27, a conventional greenhouse in The Netherlands has a degree of coupling of 0.12. Clearly, the climate conditions in The Netherlands lead to lower ventilation needs, which results in a low degree of coupling compared to Mediterranean regions. The above study showed that the $1-\Omega$ values estimated for non-cooled semi-closed greenhouses equipped with dehumidification system, located in Greece and in The Netherlands, are about 0.20 and 0.07, respectively. Thus, compared to a conventional greenhouse, dehumidification alone in semi-closed greenhouses considerably reduces coupling. The same work studied the effect of the capacity of the cooling system of a semi-closed greenhouse on $1-\Omega$ and showed that a greenhouse with a cooling system capacity of 170 W m⁻² is enough to half daytime ventilation requirements and significantly reduce $1-\Omega$ in the three regions studied (Figure 1).

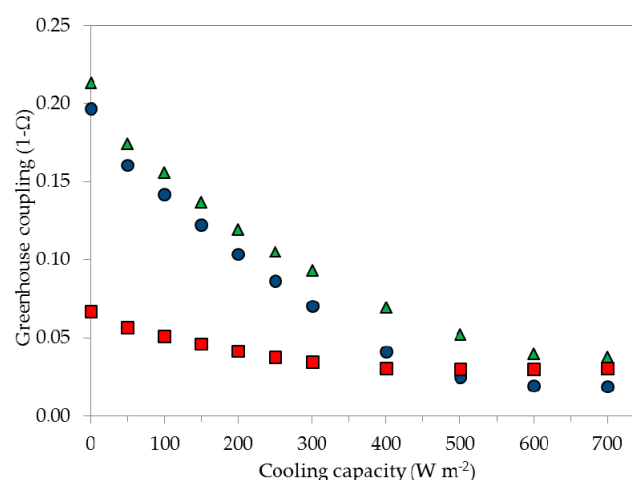


Figure 1. Coupling factor ($1-\Omega$), as affected by the capacity of the cooling system. The simulations were done for a greenhouse with a dehumidification system with tomato cultivation all year round for three areas. Triangles: Algeria; circles: Greece; squares: The Netherlands [15].

2.2. Main Design and Control Variations of Semi-Closed Greenhouse

In semi-closed greenhouses, the treated air is supplied either in situ, when heat exchangers are used or via an air-distribution system. Thus, in relation to the air treatment and distribution inside the greenhouse, two main semi-closed greenhouse types could be distinguished: (a) semi-closed greenhouses with an air treatment corridor where the air is treated in one side of the greenhouse and after is distributed via perforated tubes usually installed below the crop gutters or below the benches and (b) semi-closed greenhouses with decentralized fan coil units, usually used in greenhouses with cultivation benches for pot plants.

Except for the above (a) and (b) systems, the equipment of a semi-closed greenhouse includes roof vents and a pipe rail and a grow pipe or other heating system. In addition, it may also include a shading and an energy saving screen and a fog system.

2.2.1. Air Treatment Corridor and Air Distribution System

The main components of a semi-closed greenhouse with air treatment corridor and air distribution system are presented in Figure 2.

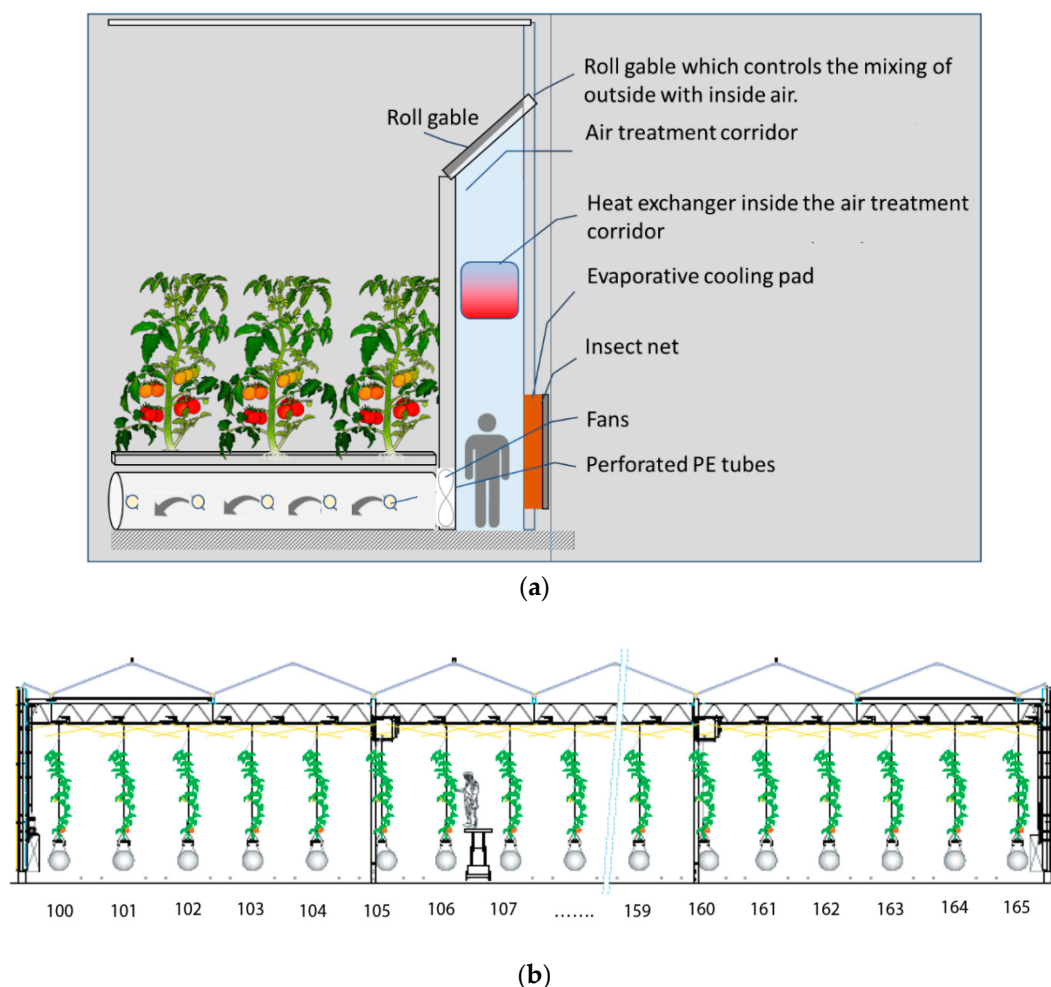


Figure 2. Main components of a semi-closed greenhouse equipped with air treatment corridor and perforated tubes: (a) 2D graphical presentation of the air treatment corridor and perforated tubes, (b) vertical cross section of greenhouse equipped with perforated tubes below the crop gutters. The numbers indicate the row number parallel to plant width [16].

The air enters the greenhouse through an evaporative cooling pad. In order to prevent insects' intrusion in the greenhouse, an insect proof screen is placed at the outside segment of the evaporative cooling pad and in the roof vents of the greenhouse. After passing the cooling pad, the air does not directly enter in the crop section, as it would be the case for a conventional greenhouse, but in a separate section/compartment that is named air treatment or air exchange corridor.

The air treatment corridor is the part of the greenhouse where the air is treated before it is distributed inside the greenhouse. It is a separate compartment located on the outer gable end walls of the greenhouse, usually to the direction of the ridge, with length of around 1.5–2.0 m and width equal to the width of the greenhouse. The air is moved by means of fan-blowers installed in the air treatment corridor, connected to the air distribution system i.e., one per polyethylene perforated tube. The air treatment corridor can be also equipped with a roll gable, to control the air flow; heat exchangers, which allow to further regulate the temperature of the air distributed to the greenhouse; a misting system for humidification and a CO₂ injection system (e.g., see [17,18]).

Since the air is being treated in the air treatment corridor and the properties of the air that flows in the greenhouse are defined in this section, its construction and operating characteristics have a decisive influence on the overall performance of the semi-closed greenhouse. The air flow characteristics may be affected by different parameters such as the air pressure profile of the porosity of the insect proof screen, the pad surface characteristics [19], the fan speed, and the position of the roll gable. These parameters, together with physical properties of outside air, finally determine the amount of the internal greenhouse air that will enter the air treatment corridor and get mixed with the outside air (that enters the greenhouse passing through the evaporative pad). The efficiency of a semi-closed greenhouse equipped with air treatment corridor in reaching the air temperature, humidity, and CO₂ concentration set-point values inside the greenhouse is influenced by three groups of factors related to the air treatment corridor: (a) the design of the air treatment corridor, (b) the type of the systems installed in the air treatment corridor, the overall control and efficiency of the systems installed in the air treatment corridor, and (c) the outside climate.

The air, after its treatment in the treatment corridor, is distributed inside the greenhouse via perforated tubes. The amount of treated air discharging from any opening in a pipe is dependent on the discharge coefficient of the opening and the static pressure difference across the opening. If both of these quantities remain constant along the perforated tube, then uniform discharge will result. In order to achieve this, the cross-sectional area of the pipe has to be so large so that it acts as a plenum chamber. In practice the static pressure difference is varying, due to [20]:

- the friction of the air with the tube wall, which causes a decrease of pressure to the direction of flow and is characterized by the friction factor;
- the reduction of the air momentum in the tube as the air is discharged at the openings, which results in an increase of pressure in the tube across each opening. This has been named the 'diffusion', 'inertia', and 'static regain' effect, and is characterized by the static regain coefficient, which is the change in static pressure expressed as a decimal part of the velocity pressure change.

The relative magnitudes of these processes determine whether over any section of tube there is a net increase or decrease in the static pressure. Obviously, the uniformity of the air pressure between different tubes of the same greenhouse compartment is important for the proper operation of the system. However, while this is considered to be the case, it is not always true. The static pressure measured in the center of the cross section of perforated tubes, one meter before their end in several rows in a tomato greenhouse is presented in Figure 3 [16], indicating that differences can occur in commercial greenhouses.

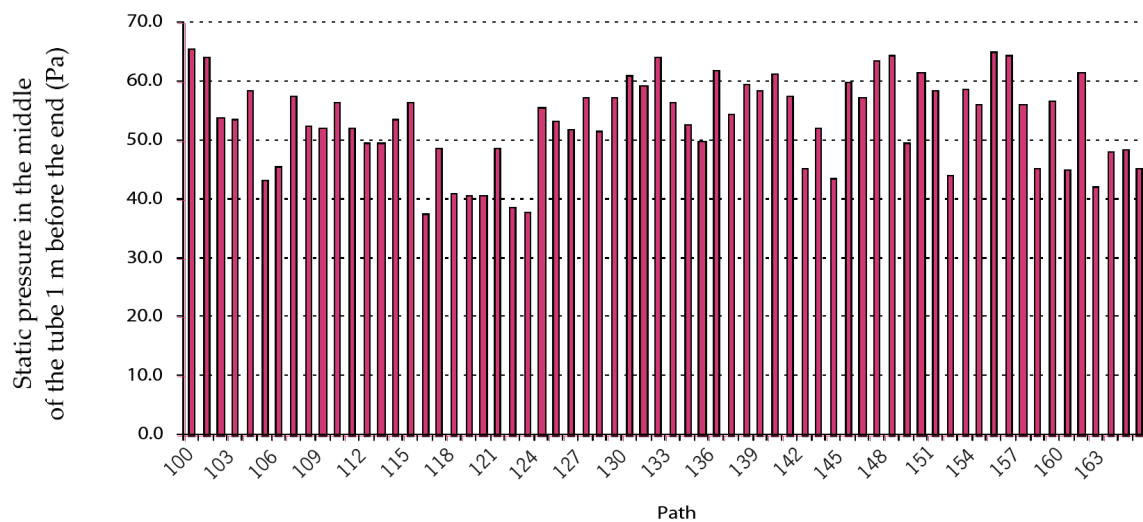


Figure 3. Static pressure (Pa) values measured in the center of the cross section of perforated tubes, one meter before their end in several rows in a commercial greenhouse with tomato crop [16].

The performance of the air distribution system is crucial for the overall performance of the semi-closed greenhouse, because it should be able to uniformly distribute the air inside the greenhouse under different ventilation rates. This is the reason why different hole patterns and diameters of the perforated tubes should be designed considering: the length of the tube, the range of the ventilation rate that should be achieved, and the operational characteristics of the fans.

How it works (Figure 4): as long as the capacity of the coolers and dehumidifiers of the greenhouse is enough to maintain the set point air temperature and relative humidity, the greenhouse is closed and no air is entering the greenhouse. The greenhouse air is entering the air treatment corridor, is dehumidified, heated enriched in CO_2 , and then distributed again inside the greenhouse by means of the perforated tubes. The pipe rail and grow pipe heating system of the greenhouse may be used during this period to maintain the set point air temperature inside the greenhouse while the thermal screen may be also used for energy saving (Figure 4a). In the case where there is a heat exchanger in the air treatment corridor, then this is also used to control the greenhouse air temperature.

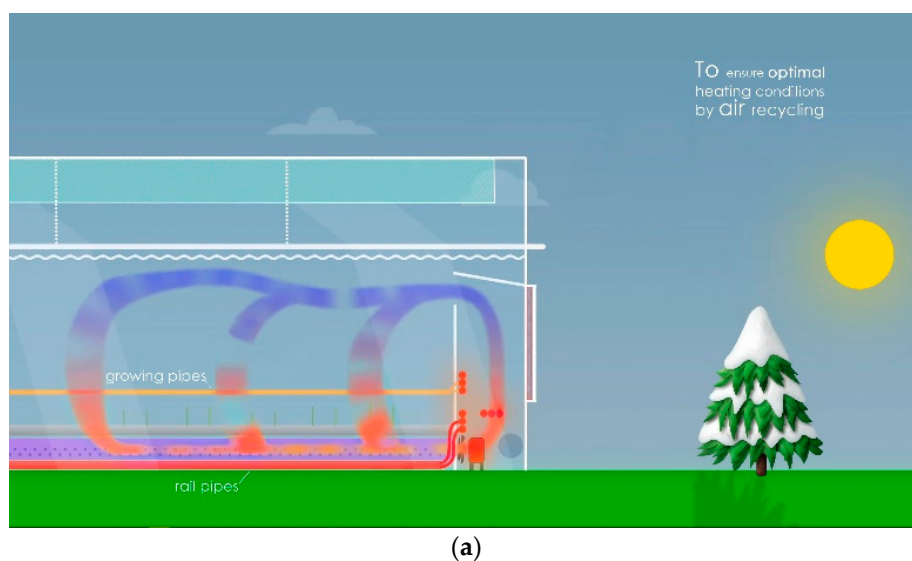


Figure 4. Cont.

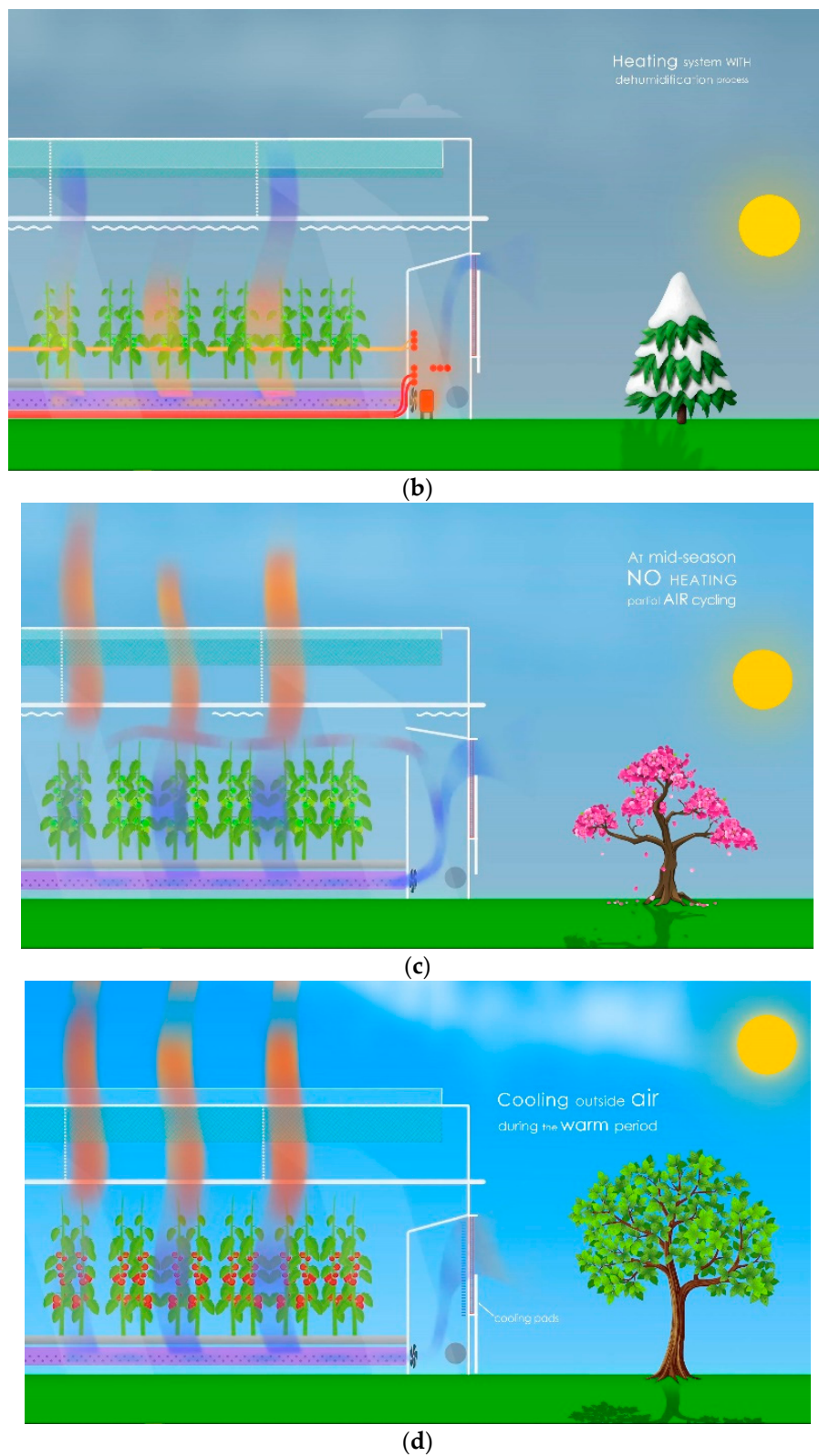


Figure 4. Graphical presentation of the semi-closed greenhouse with an air treatment corridor functioning under different climate conditions and modes. (a) Dehumidification and heating of internal air, (b) dehumidification and heating of outside air, (c) mixture of internal and outside air, (d) cooling of outside air.

In cases where outside air temperature and relative humidity levels are appropriate to lead, after some air treatment, to optimal conditions inside the greenhouse, avoiding the dehumidification of the greenhouse air, the pad gable is opened, and outside air is entering the greenhouse air treatment corridor. Then, after heating, dehumidification, and CO₂ enrichment, the air is distributed inside the greenhouse (Figure 4b). An overpressure is created inside the greenhouse and the roof vents are opened to release the air outside the greenhouse. The above takes place when the cost for the treatment of the outside air is lower than keeping the greenhouse completely closed.

During periods when no heating is needed, a mixture of internal and outside air may be created in the air treatment corridor. Then, after CO₂ enrichment, the mixture is distributed inside the greenhouse through the perforated tubes and exits the greenhouse through the roof vents (Figure 4c).

During warm periods, the evaporative cooling pad is used to cool the outside air before its entrance to the air treatment corridor. Then, after CO₂ enrichment, the air is distributed inside the greenhouse through the perforated tubes and exits the greenhouse through the roof vents (Figure 4c).

It has to be noted that several greenhouse companies have been working on the development of semi-closed greenhouses around the world and that is why the systems developed may have some or many differences from what is presented above. Nevertheless, to the best of the authors' knowledge, the above operation concept gives an average presentation of the variations available. Although it is not possible to present all the available designs, Figure 5 shows two design types of air treatment corridors in semi-closed greenhouses [21]. The ventilation unit at Figure 5a greenhouse has three intake ducts while that presented in Figure 5b has two intake ducts. This difference makes possible the mixing three or two air streams, by controlling the valves of the inlet air ducts to regulate the air supplied in the greenhouse. In the case of Figure 5a, one inlet is positioned outside of the greenhouse, allowing outside air to enter the greenhouse when dehumidification or cooling is required. The other two air inlets are positioned inside, below and above the thermal screen. The lower air inlet (below the thermal screen and the anticondensation foil) is used for recirculation, while the upper one (above the thermal screen) can supply dry air for dehumidification, as the air above the screen is less humid due to condensation on the cold greenhouse cover (especially during winter), [16]. In the case of Figure 5b, the first inlet is installed inside of the greenhouse below the thermal screen and the second one at the outside, supplying outdoor air. The unit is equipped with an air-to-air heat exchanger, which is used to recover heat from the outgoing indoor airstream and to deliver it to the incoming cold outdoor air airstream. In both systems, the air supplied to the greenhouse will flow along a low temperature heat exchanger before entering the ventilator.

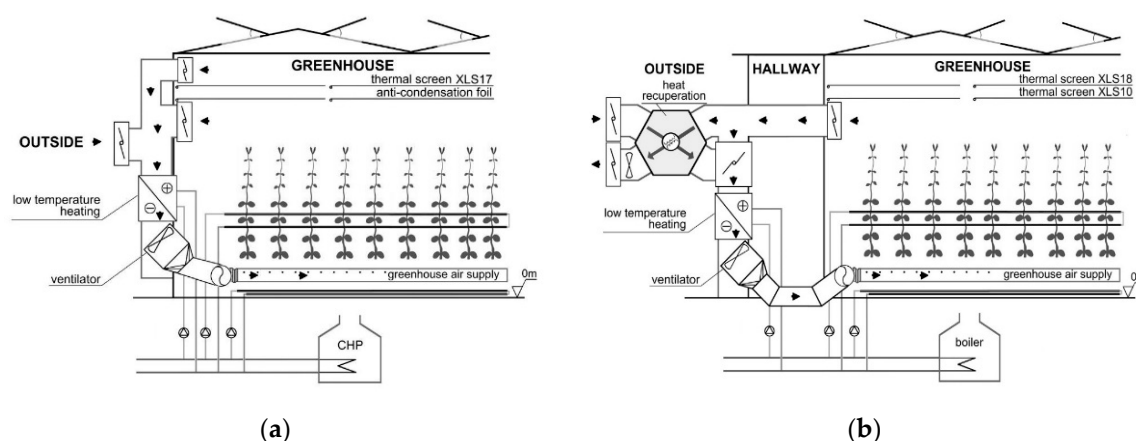


Figure 5. Different design types of air treatment corridors in semi-closed greenhouses. System with (a) three intake ducts, and (b) two intake ducts [21].

2.2.2. Decentralized Air Treatment Units

In the case of the semi-closed greenhouses with decentralized air treatment systems, there is no air treatment corridor and central cooling system but only air coolers/dehumidifiers distributed inside the greenhouse (Figure 6). The distributed air treatment units may be located above or below the crop. When the crop is cultivated on benches, the air treatment units are usually located below the crop, while for the rest of the cases they are usually located above the crop. The distributed air treatment units cool, dehumidify, and redistribute the air locally without using an air distribution system. In the case of semi-closed greenhouses with distributed air treatment units, the greenhouse has no evaporative cooling system and the cooling needs are completely covered by conventional coolers. In addition, compared to the case of a semi-closed greenhouse with air treatment corridor, no overpressure can be created inside a semi-closed greenhouse with distributed air treatment units.

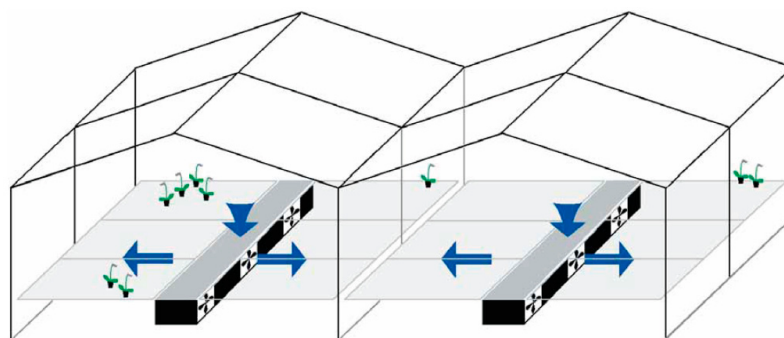


Figure 6. Semi-closed greenhouses with decentralized air treatment units [16].

How it works: as long as the capacity of the coolers and dehumidifiers of the greenhouse is enough to maintain the set point air temperature and relative humidity values inside the greenhouse, the greenhouse vents are closed and no ventilation is performed. An independent heating system (e.g., pipe heating) of the greenhouse may be used during this period to maintain the set point air temperature inside the greenhouse while the thermal screen may be also used for energy saving. During warm periods, when the cooling needs cannot be covered by the conventional coolers and as long as the outside air is colder than the greenhouse air, the greenhouse vents are opened in addition to the functioning of the air treatment units. When the outside air temperature is higher than the greenhouse air, the vents are opened and the coolers are not used. CO₂ enrichment is applied together with cooling.

2.3. Measurements and Control of a Semi-Closed Greenhouse

In principle, in all controlled greenhouses the ultimate target is to achieve the desirable climate conditions of the grower. Assuming that there is not any limitation related to the capacity of the systems (e.g., heating, cooling, fogging, etc.) the ‘controller-climate computer’ should be able to achieve the target values set by the grower. The greenhouse control systems of semi-closed greenhouses may use almost all the relevant control modes (heating, cooling, dehumidification, and humidification) together. In addition, although in most of the systems it is possible to have recirculation of inside air via the air treatment corridor, however, from practical experience, inside recirculation rarely occurs alone, because almost always a certain amount of capacity for heating, cooling, dehumidification, or humidification is needed. It has to be noted that different climate strategies may be implemented in semi-closed greenhouses compared to the conventional ones. This was, for instance, the objective of the study of [22] who showed the importance of dynamic adjustment of the set-points for precise climate control in closed greenhouses. Their study mentioned that to attain all the advantages of semi-closed greenhouse systems, the growers have to reduce the frequency of the ventilation and to accept higher mean air temperature and relative humidity levels during summer.

In relation to the control functions, in most of the cases the user/grower can define his strategy for few (e.g., up to six) time periods per day and most of the growers use all of them. For each time period it is possible to define the time and the set points related to the four control modes mentioned above. Obviously for each control mode and for each control parameter there is a set point value, the calculated value by the climate computer and the measured one (e.g., by the temperature (T)/Relative Humidity (RH) ventilated box inside the greenhouse, or by an encoder used for windows and screens, etc.).

Another important difference between open and semi-closed greenhouses is the control of the roof vents, which in the case of semi-closed greenhouses are controlled by the overpressure created by blowing outside air into the greenhouse. Usually the overpressure is measured by a sensor. When the pressure exceeds a certain threshold (set point) the roof vents are opened for a certain percent. However, there are systems which use a model based control of the roof vents. In this case the climate computer calculates the amount of air that has been blown into the greenhouse and the resulted overpressure. Then the controller opens the roof vents and after the PID (Proportional–Integral–Derivative) controller tries to keep the windows in a position to fulfil the set point for overpressure.

Controlling a semi-enclosed greenhouse requires more measurements than controlling a conventional greenhouse. This is due to the fact that the greenhouse is equipped with more technical systems for climate control (e.g., fans, air vents, exhaust, heat exchangers, etc.) and because the control of these systems in many cases requires measurements that related to the spatial distribution of climatic parameters. Except the obvious measurements related to outside and inside climate conditions, most of the systems also measure the T and RH of the greenhouse air which returns to the air treatment corridor, the T and RH of the mixing air, where the greenhouse air is mixed with the air that enters from the evaporative cooling pad and the T and RH of the air just before the fan-blowers. In this particular area the impact of other systems used such as heat exchangers and/or fogging can also be measured.

The air velocity of the air entering the air treatment corridor from the evaporative cooling pad may not be always uniform, due to not uniform pressure profile created by the fans on the inside surface of the pad. This will result in air temperature gradients just after the pad. That is why in many systems the T and RH of the air just after the pad is measured in different vertical positions and the grower can decide which one should be used by the climate computer. Usually the average value of these measurements is used. In a few systems, the amount of water used to wet the evaporative cooling pad is also controlled. In this case a model calculates the wet bulb temperature required to fulfil the cooling requirements as they are determined by the desired greenhouse air temperature. Finally, the model calculates the amount of water needed to create this wet bulb temperature via the evaporative cooling process and in this way the pump that supplies water to the evaporative pad is controlled.

The air distribution system is used to uniformly distribute the air treated in the air treatment corridor inside the greenhouse. The control of the system aims to distribute the correct amount of air in order to achieve certain climate conditions. This is done by changing the speed of the fan-blowers which means by changing the ventilation rate of the system. The control systems may also measure the pressure of the air in different positions inside the tube to the direction of the air flow. This approach is not common because by using even one pressure sensor per tube, the number of required inputs for the controller will be dramatically increased, which increases also the cost and the complexity of the system. However, from the technical point of view it is possible to control the fan-blower speed by measuring either the pressure difference occurring inside the tube or the air temperature difference.

Usually, the fan-blowers operate at 50% of their capacity when the system operates in the heating mode or when there is a mixing with outside air. Higher than 50% fan speed is used mainly during the summer when the system is running in the cooling mode. The proper choice of the fan speed is crucial for saving energy. In order for the air to be uniformly distributed inside the greenhouse it is important that the perforated polyethylene tubes keep their cylindrical shape and for this a minimum required pressure must always be taken into account. The minimum or initial pressure must be kept at the beginning of the tube and it is actually the pressure created by the operation of the fans. This pressure is different for different systems, but is roughly in the range of 30–40 Pa. Although the grower must

know which is the minimum fan speed that ensures a tube's cylindrical shape, sometimes the growers prefer to run the system with lower than minimum fan speed (low pressure), but in this case the air tubes are not cylindrical and well shaped. There is not any knowledge about the influence of this low pressure on the uniformity of the air flow that exits from the air tubes. The air velocity and the velocity vectors of the air exiting the tubes are also important. It is preferable that the air exits the tube perpendicular to the tube surface with velocity that does not create any venturi effect. The electrical energy consumption of the fan-blowers is dependent on the fan speed and their capacity and on the efficiency of the electrical motor.

The ventilation capacity of the semi-closed system usually installed ranges from 30 to 120 m³ m⁻² h⁻¹. Obviously by using high ventilation capacity there is no need for using the roof vents for ventilation. The control system can calculate the desired ratio between the roll gable and the vent attached to the evaporative cooling pad and control them properly. In most of the systems, the roll gable, which controls the greenhouse air returning to the air treatment corridor and the vent attached to the pad, is controlled as one vent or as one 'mixing valve'. This means that when one of them opens the other closes. When the roll gable opens, allowing more greenhouse air to return to the air treatment corridor, the vent attached to the pad closes allowing less outside air to enter the air treatment corridor.

Regarding the dehumidification mode, usually the priority is given to the semi-closed system but the grower has also the option to use the roof vents for ventilation and dehumidification.

3. Performance Evaluation of Semi-Closed Greenhouses

3.1. Climatic Conditions

3.1.1. Air Temperature, Humidity, and Velocity

Although a semi-closed greenhouse gives the opportunity of a better control of the air exchange between the greenhouse and the outside, this does not necessarily mean that the climate conditions in a semi-closed greenhouse are always optimal and better than in conventional greenhouses. The main reason for that is the existence of the air treatment and air distribution system, which under certain conditions can create high air temperature and humidity heterogeneity inside the greenhouse. The degree and type of heterogeneity (vertical, horizontal, and temporal) depends on the type and power of the air distribution system.

Decentralized air treatment units such as fan coils, which heat and cool the air from above, result in a better homogeneity, especially in the longer term. It was found that the horizontal air temperature may show instantaneous differences of around 2 °C, but since the warm and cold spots were observed not only in a particular part of the greenhouse but in different spots at different times, on longer term (e.g., one week), structural temperature differences can drop below 1 °C [23], which is not expected to influence the crop growth. However, the vertical air temperature, relative humidity, and vapor pressure deficit gradients in this type of systems are usually high [11,23,24] (Figure 7). A better uniformity typically occurs during the cooling process and therefore the system should be optimized, in order to create a balanced indoor climate mainly for heating mode operation. Aspects such as the capacity of the heat exchanger, the location of the air treatment units, and the airflow characteristics are crucial and influence the overall performance of the system.

In semi-closed greenhouses heated with central air treatment units and air distribution with perforated tubes, the horizontal air temperature differences may be up to 2 °C along the length of the perforated tubes. In addition, lower temperatures are usually observed near the sides of the greenhouse in comparison to the central region, which increases the risk of botrytis [23]. When the above system is functioning in cooling mode, the horizontal temperature distribution is rather homogenous. Furthermore, in cooling mode, distributing the cool air below the gutters results in vertical air temperature gradients of up to 6 °C [23]. This is the reason why more and more often, in addition to the central air distribution systems, vertical ventilation fans are used to create a constant airflow at plant level and mixes the warm air from the top of the greenhouse with cold lower air. It has to

be noted that low air temperature values at the lower levels of the crop may delay fruit ripening and result in non-favorable low temperatures in the root zone.

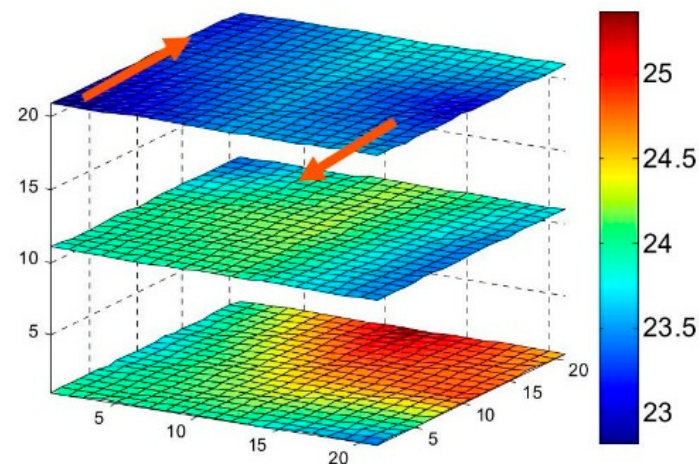


Figure 7. Temperature (°C) map during cooling periods. Measurements recorded for a repeatable section of a greenhouse at three heights where top coolers were used to condition the air. The arrows in the figure indicate the direction of the air as it flows from the heat exchanger [23].

Depending on the degree of climate control and the equipment used, the microclimate inside a conventional, naturally ventilated greenhouse is affected by the greenhouse structure and vent configuration and many other factors such as the outside air velocity, temperature, and humidity [25,26]. On the other side, by principle, in a semi-closed greenhouse the natural ventilation is limited, and a conventional cooling system is used in order to keep the greenhouse as much as possible ‘closed’ and decoupled from the outside environment. By increasing the capacity of the cooling system, the greenhouse microclimate becomes less dependent on outside climate and more similar to what is required (control set-points) and the ‘region’ effect disappears [15], however energy consumption increases with cooling capacity increase. Comparison of the daily average air temperature inside a semi-closed and a conventional greenhouse (Figure 8) shows that the microclimate inside a semi-closed greenhouse is less dependent on the outside climate and more stable than in the conventional greenhouse [27].

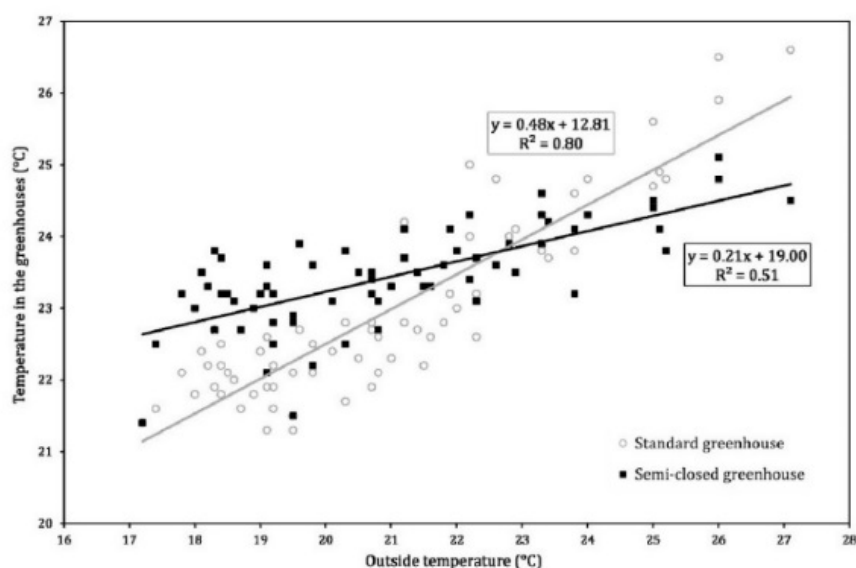


Figure 8. Average air temperature (°C) of a semi-closed greenhouse compared to a conventional one. Both greenhouses were cultivated with soilless tomato crop the same time period in 2014 [27].

The observed air velocities inside a conventional greenhouse may range depending on the ventilation rate, from 0.1 m s^{-1} (when the windows are closed) to 0.4 m s^{-1} (when the windows are open) [28]. Although a semi-closed greenhouse is ventilated much less via the roof vents, the air velocity inside may be higher than in a conventional greenhouse. This air movement is related to the ventilation rate of the air distribution systems. An experimental study conducted in a closed *Phalaenopsis* greenhouse showed that the air movement was turbulent, even when the air velocity was low ($<0.4 \text{ m s}^{-1}$) [29].

Several physical dynamic models have been developed to simulate the microclimate in semi-closed greenhouses [15,30–33]. The authors of [15] simulated the effect of the cooling system capacity of a semi-closed greenhouse on the greenhouse and crop microclimate in Central Europe (The Netherlands) and in Mediterranean (Greece and Algeria) regions. They found that increasing the capacity does decrease the number of hours and days with supra-optimal greenhouse air temperatures compared to a non-cooled greenhouse. In addition, they indicated that a cooling capacity of 300 W m^{-2} could decrease the daytime mean values of air temperature during May and June in the semi-closed greenhouse of about 2°C , compared to a conventional one.

Partial closure of the greenhouse may lead to high humidity levels inside the greenhouse and thus control of closed or semi-closed greenhouses is crucial, since not all crops can be grown under high humidity conditions. The authors of [24] evaluated the microclimate at four commercial tomato growers in The Netherlands and reported that all semi-closed greenhouses had a higher humidity than in the monitored conventional greenhouses. They also noted that in semi-closed greenhouses where the air was conditioned by a heat exchanger and cold water, a higher humidity was observed in the lower section of the greenhouse, compared to semi-closed greenhouses where the air was coming from outside. In [11,34] the authors observed that compared to a conventional greenhouse, the daytime vapor pressure deficit (VPD) was about 30–33% lower in semi-closed greenhouses in The Netherlands. In addition, the authors of [27] reported an about 44% lower VPD in a semi-closed greenhouse in France than in a conventional one. Furthermore, other studies [21,22] reported that the average relative humidity values observed in the semi-closed greenhouses studied were only 2–3% (in absolute relative humidity values) lower than in the conventional ones. The above results reported in different semi-closed greenhouses and locations indicate that the degree of greenhouse control and of ventilation of a semi-closed greenhouse may be a significant factor affecting the resulting microclimate.

To provide references for improving greenhouse climate management, the authors of [35] developed a humidity model for a semi-closed greenhouse working in completely closed or semi-closed mode. In [30], the authors simulated the influence of the flow rate ($Q = 7.6 \text{ m s}^{-1}$, $2Q$ and $3Q$) produced by the air treatment unit, on the inside temperature and water vapor concentration of a semi-closed greenhouse (Figure 9). They found that when Q increases, its influence on the climate parameters increases too. A higher air flow rate of the cooling system leads to a more constant temperature and vapor pressure deficit values, especially during the period that the greenhouse vents are open. However, they concluded that an important increase of the airflow rate does not bring a significant modification of the inside climate.

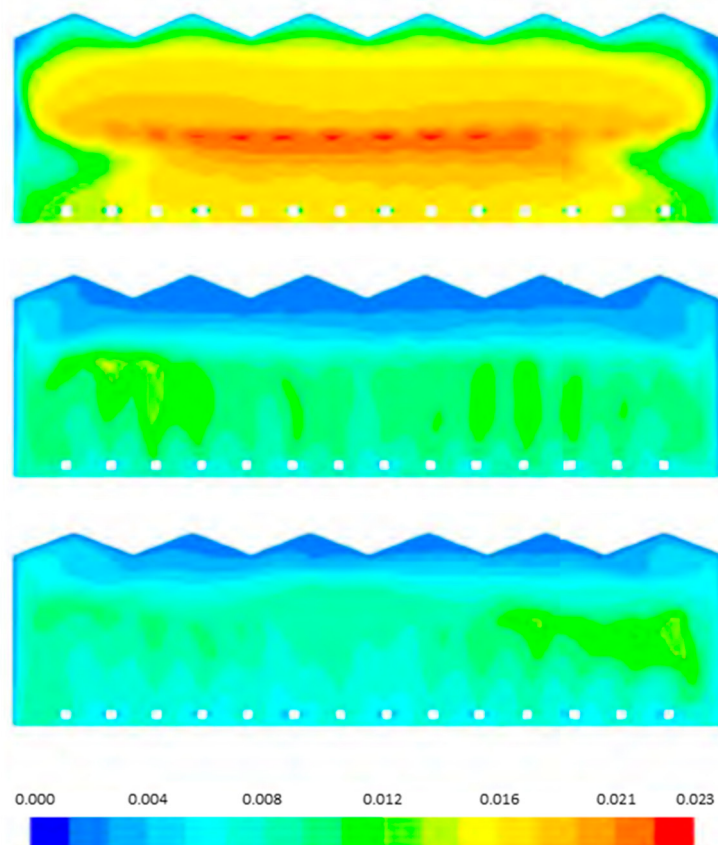


Figure 9. Simulated water vapor concentration (kg kg^{-1}) in a median plane at 4:00 pm for airflow rates in the ducts equal to Q ($=7.6 \text{ m s}^{-1}$) (top), $2Q$ (middle), and $3Q$ (bottom) [31], (the legend has been adjusted based on the manuscript of [31]).

3.1.2. CO_2 Concentration

One of the main reasons for reducing (at a cost) the need for ventilation has been mainly to lengthen the period when CO_2 enrichment of the greenhouse air can be used to increase crop yield [35]. The authors of [36] compared the performance of an open (conventional) greenhouse to that of two semi-closed greenhouses with cooling capacity of 150 W m^{-2} and 350 W m^{-2} and to that of a closed greenhouse (cooling capacity of 700 W m^{-2}). The results of the study showed in both semi-closed greenhouses and in the open one, that the CO_2 concentration was decreased by increasing solar radiation. In the closed greenhouse there was no effect of the outside climate on the CO_2 concentration of the greenhouse air [36].

In [11], the authors monitored the microclimate variables in open and closed greenhouses and showed that for the region of The Netherlands, the difference of the CO_2 levels (as well as the microclimate differences in general) between an open and a closed greenhouse during winter were small. However, in summer time, the differences observed are larger (Figure 10) due to the higher ventilation rate in the conventional greenhouse and the limitations in CO_2 availability because of the low heat demand. The highest overall CO_2 levels were observed in the completely closed greenhouse [11].

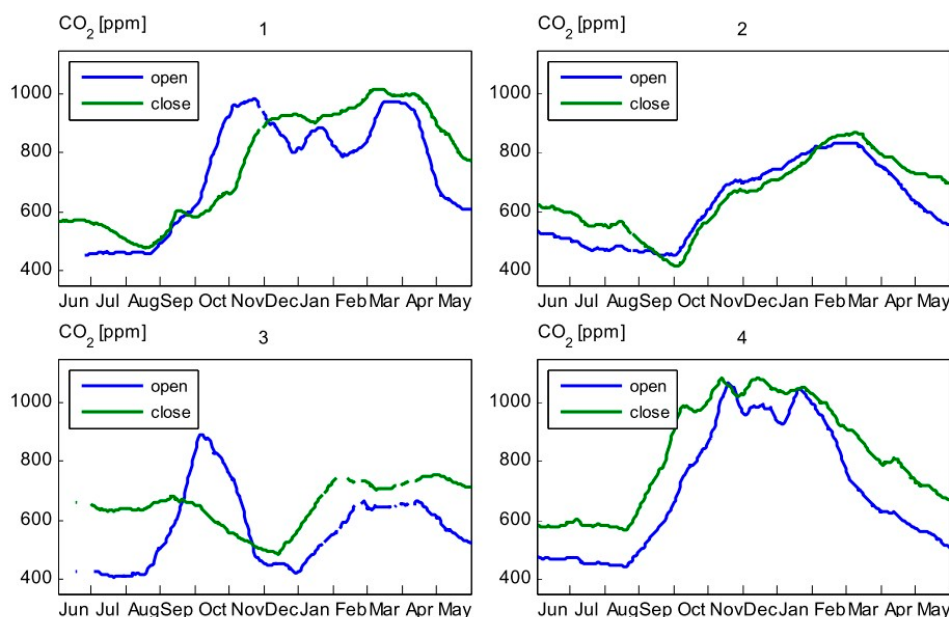


Figure 10. Daily average CO₂ level during daylight for open and closed greenhouses of four tomato growers in The Netherlands during a year-round period [11].

In [13], it was shown that in a closed greenhouse in the Netherlands, 14 kg m⁻² CO₂ were required to maintain a year-round average CO₂ concentration of >1000 ppm, while in an open greenhouse, 55 kg m⁻² CO₂ were required to maintain an average daytime CO₂ concentration of about 600 ppm. In addition, the authors of [15] calculated the amount of CO₂ needed to maintain 1000 ppm in three different greenhouses in The Netherlands, (a) a non-cooled greenhouse, (b) a greenhouse with cooling capacity of 150 W m⁻², and (c) a greenhouse with cooling capacity of 350 W m⁻². They found that the CO₂ required for the enrichment in these cases was (a) 42.8 kg m⁻² yr⁻¹, (b) 28.5 kg m⁻² yr⁻¹, and (c) 21.4 kg m⁻² yr⁻¹, respectively. They also noted that the CO₂ supplied to maintain a CO₂ concentration of 420 ppm in a greenhouse with cooling system capacity of 400 W m⁻² was about 12.0 kg m⁻² yr⁻¹ for a greenhouse in the Mediterranean region and 8.0 kg m⁻² yr⁻¹ for a greenhouse located in Central Europe and attributed these differences to the different solar radiation levels between these regions that led to different ventilation needs.

3.2. Energy Consumption and Saving

The semi-closed greenhouse is supposed to be in general more energy efficient than a conventional greenhouse where a lot of energy is lost due to ventilation for dehumidification. However, given that electricity consumption is higher in semi-closed greenhouses, a comparison of energy consumption between conventional and semi-closed greenhouses is needed.

In [27], the authors compared the energy consumption of a semi-closed greenhouse (with central air treatment corridor and perforated tubes under the crop gutters) with a conventional one in the West of France. The study found that while the gas consumption was lower for the case of the semi-closed greenhouse, the electricity consumption was lower in the case of the conventional greenhouse during both periods (Table 1). The average gas energy saving observed in the semi-closed greenhouse compared to the conventional one was about 10%. The considerably higher electricity consumption in the semi-closed greenhouse (about 510%) compared to the conventional one during the autumn period was due to the fact that the chosen fan speed was 80% of max fan speed, which was out of the optimal range (30–65%) of electricity efficiency for these types of fans. This indicates the importance of the control system used in semi-closed greenhouses and the proper choice of set points related to fan speed.

Table 1. Energy consumption of a conventional and a semi-closed greenhouse compartment in France during a summer and an autumn day. Data from [27].

Greenhouse	Summer 2015		Autumn 2014	
	Gas	Electricity	Gas	Electricity
	kWh m ⁻²			
Conventional	253	3.5	322	5.2
Semi-closed	217	11.3	307	31.9

An average energy saving of about 20% was reported in a similar study in two semi-closed greenhouses in Belgium [21] observing that the larger part of heating energy saving was obtained in the first half of the growing period. The significant energy savings were achieved mainly due to dehumidification control by mechanical ventilation. In the same work it was observed that it is beneficial to control dehumidification by using mechanical ventilation during spring and autumn, as closing of the greenhouse windows in combination with recuperation of indoor heat leads to an enormous reduction of heat loss. The authors of [22] also compared the energy performance of a semi-closed greenhouse with that of a conventional one in Germany, observing that the energy use efficiency of the semi-closed greenhouse was improved by 43%. To achieve this high energy saving the above authors used the stored energy and the energy saving screens indicating that a semi-closed greenhouse should be also well equipped/insulated in order to achieve high energy saving. Their data showed that the energy required to produce 1 kg of tomatoes was 39.49 and 57.27 MJ, for the case of the semi-closed and the conventional greenhouse, respectively [22].

In [37], the authors used a simulation model to compare the energy performance of a semi-closed greenhouse with that of a conventional and a closed one. Their results showed that, compared to the conventional one, the energy consumption for heating was almost half in both closed and semi-closed greenhouse (reduction of 53% and 48%, respectively, Table 2). Regarding the energy demand for cooling, they showed that the closed greenhouse requires almost four times more than the semi-closed one. In the same study a feasibility study was carried out considering the annual fixed and variable costs and profit. The study concluded that in the area of Almeria, a semi-enclosed greenhouse may be more economically viable than a greenhouse where a common production system is used. This can be achieved by extending the production period over the summer, as a result of using the climate control options that a semi-closed greenhouse offers.

Table 2. Comparison of annual energy demand of a conventional, closed, and semi-closed greenhouse. Data from [37].

Process	Conventional	Closed	Semi-Closed
Heating (MJ m ⁻² y ⁻¹)	1182	557	620
Cooling (MJ m ⁻² y ⁻¹)	0	530	134

3.3. Irrigation and Water Saving

The authors of [27] observed that the tomato crop water consumption was about 13% higher in the semi-closed greenhouse than in the conventional one, due to the upper air circulation. In [15], the authors estimated the product water use (PWU) by means of the amount of water liters needed to produce 1 kg of tomato and correlated PWU with the ‘coupling factor’, which indicates the level of ventilation via roof vents, or on which level a greenhouse is ‘coupled’ with the outside climate. Their results showed that the amount of water needed to produce 1 kg of tomato decreased as the cooling capacity increased (Figure 11). Their results are consistent with the results presented by [38], which showed that a cooling system capacity of 325 W m⁻² could increase the water use efficiency (WUE) by up to 71%, compared to a conventional greenhouse. The above authors reported that the

plant transpiration rate in the semi-closed greenhouse studied was about 58% lower than that observed in the conventional greenhouse.

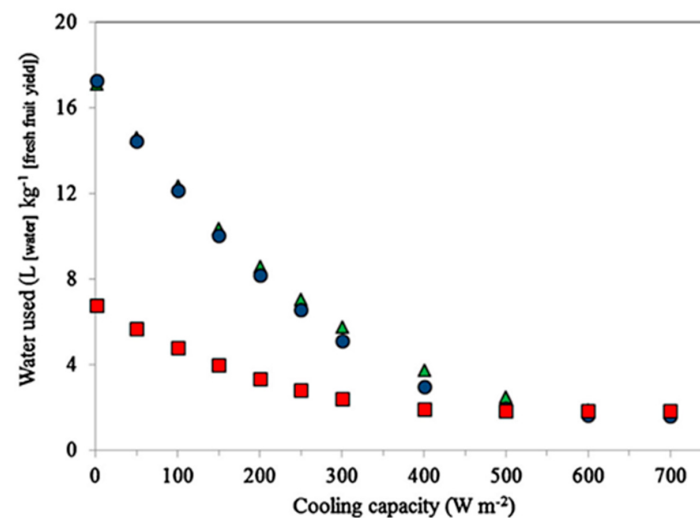


Figure 11. Water used (L of water per kg fruit yield) estimated for year-round tomato cultivation vs. greenhouse cooling system capacity. Triangles: Algeria; circles: Greece; squares: The Netherlands [15].

In the study of [15], the differences calculated regarding the greenhouse WUE in the different regions were eliminated only when the capacity of the cooling system was higher than about 450 W m^{-2} . For cooling system capacity lower than 400 W m^{-2} , the WUE in The Netherlands was almost double than the WUE of the greenhouses in Algeria and in Greece. When the capacity of the cooling system was lower than 300 W m^{-2} the effect of cooling capacity increase to the WUE was higher in The Netherlands, whereas a significant effect of cooling on WUE is attained in the Mediterranean region only at capacities exceeding this value. Apparently, quality of equipment of a greenhouse and the grower's crop-management skills may significantly affect the water use efficiency. However, the ventilation process (greenhouse coupling), in different climates is probably the largest single cause of differences related to water use efficiency [15]. The higher WUE observed with confined ventilation is due to the higher crop production (better microclimate of the semi-closed greenhouse) and the lower transpiration rate observed in the semi-closed greenhouses, especially in northern latitudes [15,22], and also due to the option offered in the semi-closed greenhouse to collect and reuse the transpired water condensing at the cooling element [15]. The second is the most important process by far, since potentially it allows to dispose of the innately low transpiration efficiency of crops [39].

3.4. Pest Control

Greenhouse climate influences not only plant growth and productivity, but also the development, behavior, and interactions among pest and beneficial arthropods present in the greenhouse growing system [40]. The authors of [4] described the perspectives of a closed greenhouse to crop and pest management. Reduced pesticide use is among the main benefits of semi-closed greenhouses [7,41]. In [42], two identical experimental greenhouses with tomato crop were compared, one with a positive-pressure forced ventilation system and one with natural ventilation system, in order to investigate their effect on insect invasion. They found that the positive pressure was highly effective at preventing invasion by leafminers, but less effective for preventing invasion by whiteflies, and not at all effective for preventing invasion by thrips. The reason for these differences was the mesh size of the screens used in the greenhouse. Although the use of insect net in front of the evaporative pad prevents insects entering the air treatment corridor, the type of the insect net is important.

The higher air humidity levels usually observed in closed greenhouses may lead to condensation on the crop, which is known to increase the incidence of fungal diseases such as *Botrytis* [43]. Therefore,

special attention should be given to humidity control, in order to avoid fungi infections [44]. In [27], the authors reported no significant differences between the crop protection needs of the semi-closed and conventional greenhouse compartments studied but only some symptoms of *Botrytis cinerea* appeared in the semi-closed greenhouse due to difficulties in controlling the increase of humidity during the night.

3.5. Crop Growth and Yield

In [45], the authors studied the yield performance of a tomato crop grown under semi-closed and conventional greenhouse compartments. They found that the tomato fruit production was higher in the semi-closed greenhouse compartments due to higher dry matter production i.e., higher total crop photosynthesis. As the fruit partitioning was almost the same, the yield differences were explained by the differences in CO₂ concentration between the semi-closed and conventional greenhouses. They also noted that in the semi-closed greenhouse with cooling from below the crop the fruit fresh weight was about 6% higher than in the semi-closed greenhouse with cooling from above.

In [11], an average tomato yield production increase of 5.5% in semi-closed greenhouses compared to conventional ones was reported. The higher yields observed in closed and semi-closed greenhouses compared to the conventional ones are mainly due to the higher CO₂ concentration that can be maintained in semi-closed greenhouses [36] (Table 3). This is in agreement with the results reported in [22] where, compared to a conventional greenhouse, the photosynthesis expressed as CO₂ uptake was 21% higher in the semi-closed greenhouse, mainly due to 25% higher CO₂. This resulted to 28% more fruits which had also higher fruit mass by 8%.

Table 3. Cumulative fruit production in week 29 after planting, final cumulative production in week 48 after planting, and total amount of supplied CO₂ in semi-closed greenhouses with different cooling capacities and in an open greenhouse. The values between brackets indicate increase compared to open greenhouses [36].

Treatment	Early Production	Final Production	Supplied CO ₂
Conventional	24	55	55
Semi-closed (cooling 150 W m ⁻²)	26	59	46
Semi-closed (cooling 350 W m ⁻²)	27	61	30
Semi-closed (cooling 700 W m ⁻²)	28	57	14

In [36], by comparing the yield performance of a tomato crop grown in a semi-closed greenhouse (with a cooling capacity of 350 W m⁻²) with that in a conventional one, the authors reported that photosynthetic acclimation as a result of higher CO₂ concentration, only occurred when the number of fruits was considerably reduced. The increase of dry matter production in a semi-closed greenhouse compared to an open one was mainly explained by the higher CO₂ concentration. The researcher noticed that in high producing crops in a semi-closed greenhouse, elevated CO₂ concentrations do not cause feedback inhibition, because the plants have sufficient sink organs (fruits) to utilize the extra assimilates [36]. In the same study, the final measured production was higher than 55 kg m⁻² of the reference-open greenhouse, in all compartments equipped with cooling system. In particular, the production was higher for 6%, 10%, and 4% in the compartments with cooling capacities of 150, 350, and 700 W m⁻², respectively. Their results are in agreement with those presented in [21] where the average height and leaf area of tomato plants grown in a semi-closed greenhouse with cooling capacity of 325 W m⁻² was significantly increased when compared to those grown in conventional greenhouses (Figure 12).

In [46], the authors developed a Dynamic Artificial Neural Network (DANN) to explain the weekly fluctuations of tomato yield observed in a semi-closed greenhouse and in a conventional one. They noted that although a gradual reduction in yield capacity with crop age was observed in both

greenhouses the total yield was bigger in the semi-closed greenhouse than in the conventional one, due to higher CO₂ assimilation.

In relation to the effect of the microclimate conditions of semi-closed greenhouses to fruit quality, the authors of [22] also showed that the quality characteristics such as soluble solid content (SSC), lycopene, β -carotene, phenolic compounds, and lipophilic antioxidant activity (LAA) in tomatoes grown under a semi-closed greenhouse were significantly increased by 9%, 22%, 21%, 8%, and 26%, respectively, compared to those ripened in a conventional greenhouse.

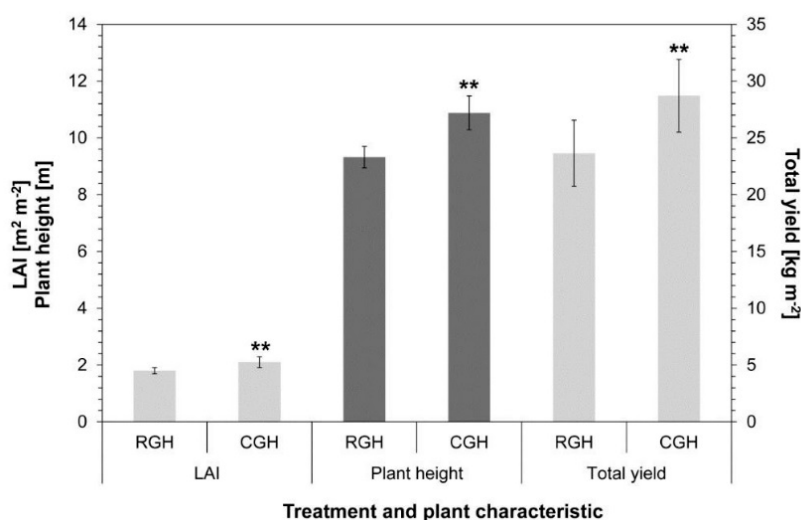


Figure 12. Growth and total yield of a tomato crop grown under a conventional (RGH) and a semi-closed (CGH) greenhouse [22] (bars mean standard deviations and asterisks significant differences according to the *t*-test procedure at a significance level $\alpha = 0.05$ and ** $\alpha = 0.01$).

4. General Discussion and Conclusions

The semi-closed greenhouse concept has been extensively investigated by many researchers. Many experiments and model studies have been carried out. The concept has been tested in practice in commercial greenhouses in the last 10–15 years and more and more greenhouse projects are realized all over the world by using technologies related to semi-closed greenhouses.

The semi-closed greenhouse has certain advantages related to the increase of production, particularly for vegetable crops which require high CO₂ concentrations, especially in the summer months when solar radiation is high, and cooling is required. It is obvious that the availability of CO₂ is influencing the performance of the semi-closed greenhouse. CO₂ is required to enhance the photosynthetic activity and the loss of CO₂ via ventilation is limited.

Regarding the inside climate, the existence of the air treatment corridor provides more flexibility of controlling the air that enters the greenhouse and finally the inside climate. However, this does not necessarily mean that the uniformity of the inside climate can be improved compared to a conventional greenhouse. An air distribution system below the crop gutters can create a more uniform horizontal temperature distribution especially when it is used for heating, but when the same system is used for cooling, unfavorable vertical gradients can be created.

A semi-closed greenhouse has also a positive effect on water use efficiency since the loss of vapor via ventilation is reduced. The amount of water that can be saved is almost linearly related to the cooling capacity of the system installed. This technology is very promising, especially for areas with limited water resources.

In semi-closed greenhouses the overpressure created by the air blown inside the greenhouse can reduce the pressure of pests, as the overpressure occurred at the area of roof vents does not allow insects to enter into the greenhouse. However, if the insect net installed at the outside of the

evaporative cooling pad is not the proper one (e.g., big openings for given pests), the pest population might increase, as outside air is blown into the greenhouse.

After more than 10 years of experience with commercial semi-closed greenhouses, we can say that the technology has reached the maturity level, has proven the possibilities that they offer, especially related to the increase of production, and the potential drawbacks related to spatial climate distribution during cooling and high electricity consumption. However, the good performance of semi-closed greenhouses does not necessarily mean that this concept should be used in any case, as at the end, it is mainly the product price which determines the level of technology that should be used. Investments in semi-closed greenhouses are high and the potential higher profit should justify the use of this technology. The concept of the semi-closed greenhouse is expected to be adopted mainly in large greenhouse projects where the high investment cost can be compensated by the need for high production and for minimizing risk.

A semi-closed greenhouse offers more potential options for control of the greenhouse environment. The reason is that the processes of air treatment and air distribution within the greenhouse are separate. In contrast, these processes are unified when it comes to natural ventilation which is regulated only by the roof vents, while we cannot change the properties of the air exchanged via these vents. By analyzing these processes separately, but also in the context of a greenhouse project as a whole, we can investigate the possibilities of further developing the semi-closed concept mainly to the following directions:

- Improve the design and operation of the air treatment corridor (e.g., reduce the pressure loss, optimize the air flow via the pad and heat exchangers, use fans with high efficiency at wide range of ventilation rates, etc.).
- Improve the design and operation of the air distribution system (e.g., by using better perforated tubes, by using sensors to identify the spatial climate distribution and its correlation to the operation of the fans, etc.).
- Integrate different technologies and systems mainly in air treatment corridor in order to change the properties of the air distributed in the greenhouse such as use of desiccant materials for dehumidification or misting for humidification, capture, and reuse water from transpiration or water condensed at the cold surface of heat exchangers, integrate systems based on use of sustainable energy or on district heating and cooling systems, etc.
- Develop greenhouse concepts for different areas in the world in order to address challenges related to extreme climatic conditions such as those occurring in tropical areas, in deserts, or water scarcity areas, etc.
- Develop the semi-closed concept for agroparks or greenhouse clusters by decoupling the air treatment corridor from the air distribution system and developing systems where one air treatment area serves more than one air distribution system with different requirements and priorities.

By watching the evolution of the semi-closed greenhouse, we can safely say that the more this concept is applied, the more technological solutions will be developed to address specific challenges.

Author Contributions: Conceptualization, A.S. and N.K.; writing—original draft preparation, A.S. and N.K.; writing—review and editing, A.S., N.K., B.S., R.B., and C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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