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Review

Comprehensive Review on Climate Control and Cooling Systems in Greenhouses under Hot and Arid Conditions

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Abstract: This work is motivated by the difficulty of cultivating crops in horticulture greenhouses under hot and arid climate conditions. The main challenge is to provide a suitable greenhouse indoor environment, with sufficiently low costs and low environmental impacts. The climate control inside the greenhouse constitutes an efficient methodology for maintaining a satisfactory environment that fulfills the requirements of high-yield crops and reduced energy and water resource consumption. In hot climates, the cooling systems, which are assisted by an effective control technique, constitute a suitable path for maintaining an appropriate climate inside the greenhouse, where the required temperature and humidity distribution is maintained. Nevertheless, most of the commonly used systems are either highly energy or water consuming. Hence, the main objective of this work is to provide a detailed review of the research studies that have been carried out during the last few years, with a specific focus on the technologies that allow for the enhancement of the system effectiveness under hot and arid conditions, and that decrease the energy and water consumption. Climate control processes in the greenhouse by means of manual and smart control systems are investigated first. Subsequently, the different cooling technologies that provide the required ranges of temperature and humidity inside the greenhouse are detailed, namely, the systems using heat exchangers, ventilation, evaporation, and desiccants. Finally, the recommended energy-efficient approaches of the desiccant dehumidification systems for greenhouse farming are pointed out, and the future trends in cooling systems, which include water recovery using the method of combined evaporation–condensation, as well as the opportunities for further research and development, are identified as a contribution to future research work.

Keywords: greenhouse; control methods; cooling; dehumidification; energy consumption; water recovery; arid areas

Citation: Soussi, M.; Chaibi, M.T.; Buchholz, M.; Saghrouni, Z. Comprehensive Review on Climate Control and Cooling Systems in Greenhouses under Hot and Arid Conditions. *Agronomy* **2022**, *12*, 626. https://doi.org/10.3390/agronomy12030626

Academic Editor: Carmine Guarino

Received: 8 January 2022
Accepted: 24 February 2022
Published: 3 March 2022

1. Introduction

Protected agriculture is a growing activity that is spreading throughout all the world continents, and that covers an area that was estimated to be 5.2 million ha in 2014 [1]. Greenhouses that are covered either by plastic films in mild climates, or by glass or rigid plastic in temperate and cold climates, extend over an area that averages 4.7 million ha in the temperate regions of Europe, Asia, and America, and over an area that averages 364,000 ha in the Mediterranean, as well as over an area that averages 156,000 ha in the tropical and subtropical regions [1].

Hot and dry areas are characterized by hot summers, with high solar radiation and air temperatures. The protected agriculture in these areas has important economic value. The greenhouse sector is also considered to be the highest fossil energy consumer among the agricultural activities, as well as the highest consumer of water, especially if it uses evaporative cooling. Therefore, the increasing limits on the supply of conventional energy sources, the fading groundwater stocks, and the groundwater salinization, show the vulnerability of this economic sector.

In hot climate regions, such as in the Middle East and North African (MENA) regions, and the Gulf Cooperation Countries (GCC), where the protected crop areas reached 13,000 ha and 71,297 ha, respectively, in 2014 [1], efficient greenhouse cooling is required during the hot seasons to bring the internal temperature to levels that are suitable for crop growth. Hence, traditional cooling systems in greenhouse agriculture have been adopted in regions of harsh and variable weather conditions, and they have improved the related climatic greenhouse parameters. Nonetheless, the traditional cooling processes, which involve natural ventilation and passive cooling techniques, were difficult to control, and no ideal climate conditions were guaranteed for the crops, which prohibited the cultivation of many crops, especially those that were not resistant to the high levels of temperature [2,3]. Similarly, at high levels of relative humidity, which are commonly occurring inside greenhouses in hot countries, especially during the night period, the risk for condensation on the leaves is high, and, therefore, the risk of botrytis and fungal and bacterial diseases is increased.

The transpiration rate of plants is affected by the amount of moisture in the air, which inhibits plant health, growth, and development. A relative humidity ranging between 80 and 90% during the day, and between 65 and 75% during the night, is generally recommended, but is difficult to reach technically [4]. The climate control of greenhouses refers to the regulation of the main environmental parameters inside the greenhouse in all growing climates in order to meet the crop's growth requirements, which provides growers with the chance to enhance the crop quality and to increase the yield. In the last few years, numerous research works have been focused on the climate control inside greenhouses, which is assisted by computing technology via control hardware, such as sensors, controllers, and actuators, which allow for the monitoring of the temperature, the relative humidity, the solar radiation, and the carbon dioxide (CO_2) concentration [5], as well as for the coordination of the equipment operation [5–7].

The cooling and heating processes, which aim to maintain the greenhouse environment under optimal conditions, and which are suitable for crop growth, have the highest share of energy consumption, at about 65 to 85% [8]. The cooling energy consumption in the Mediterranean region is about 100,000 kWh/ha per year [1], while no numerical estimate for the hot regions is available in the existing literature; however, the amount of energy consumed definitely reaches much higher values in the hot countries. For instance, the cooling energy consumption for protected crops in the United Arab Emirates ranged from 10.43 to 14.67 kWh/m^2 during the production cycle, while the water consumption for the evaporative cooling ranged from 2.6 to 3.5 times the amount of water that is required for irrigation [9,10].

This energy consumption is mainly based on electric power, which is essentially produced from fossil energy, which is increasingly being depleted, which threatens the energy supply. Consequently, selecting and developing appropriate climate control techniques and more efficient cooling systems that aim to decrease the high amounts of energy and water consumption is considered to be the major challenge in the upcoming years, particularly in hot and arid countries.

As the existing literature on protected cropping fields lacks sufficient focus on greenhouse climate control and the investigation of cooling systems in hot and arid regions, the present work attempts to address this gap by providing a thorough review of the climate control methods, as well as the cooling techniques, on the basis of the humidification and dehumidification of greenhouses under these environmental conditions. A detailed review of the research studies carried out during the last few years is provided, with a specific focus on the emerging technologies that have been proposed and the experiments in horticulture under hot and arid conditions. The main scope of this review is to support decisions according to the use of humidification/dehumidification and climate control practices, and to ensure that the technologies advance in the right direction by promoting reliable and relevant solutions for the needs of the greenhouse farming communities in hot and arid countries. Hence, this paper discusses the several cooling processes that allow for taking advantage of the great potential of renewable energies, which are mostly unexploited in arid areas. Finally, the future trends in cooling systems are presented, and the opportunities for further research and development are identified as a contribution to future research.

2. Control of Greenhouse Operation

The climate management of the greenhouse environment depends on many parameters, such as the solar radiation, the air temperature (T), the relative humidity (RH), and the carbon dioxide (CO_2) concentration. By controlling and regulating these parameters, the growing conditions for the crop, as well as valuable energy savings and water use regulation, could be achieved. However, the interaction of the parameters that affect each other, and their dependance on the changing ambient climate, makes the monitoring and the climate control complex. For instance, the relative humidity is dependent on the amount of moisture that is continuously being released by the plants, on the soil evaporation, as well as on the temperature, which is, in turn, reliant on the solar radiation and the meteorological conditions. Hence, monitoring such parameters is a real challenge in greenhouse climate control.

2.1. Control Parameters

2.1.1. Temperature

The temperature and relative humidity are interdependent parameters that should be controlled simultaneously. These two parameters strongly affect the growth of crops. The main role of the temperature is to ensure the expansion of the leaves of the crops at a young age [11]. Young crops are more affected by heat, as the leaf area and the root development are insufficient for high evaporation as a reaction to heat stress. With a continuous growth system, and by using the permanent presence of mature and younger crop stands, this problem might be resolved. Increased humidity in closed greenhouses can relieve the problem of evaporation for the insufficient roots of young crops.

According to Nelson [12], the healthy growth of most plants is observed for temperatures ranging between 10 and 24 °C, and the ideal growth for greenhouse plants is observed for temperatures varying between 15 and 30 °C [13]. Nelson [12] found that, under sunny conditions, the difference in the temperature that is needed for crop growth between the day and night times should be around 8 to 10 °C. The optimum temperature growth levels vary according to the plant species. Table 1 summarizes the temperature requirements for selected greenhouse crops in hot and arid climates.

Heat stress is always related to the overall climate conditions, as well as to the water availability and to the means of the CO_2 and nutrient concentrations in the air and water. By this standard, the terminus of an optimum growth temperature is a fluctuating term. Cooling is the most expensive and most energy-consuming intervention, and it is ahead of all the other solutions. Accordingly, the provision of a level for good growth at high temperatures must be considered in all stages of growth, before considering the technical measures of space cooling.

2.1.2. Humidity

The relative humidity control inside the greenhouse is vital to the maintenance of an optimal climate for crop growth, especially in closed greenhouses, where the water vapor has to be withdrawn by condensation or absorption processes in order to maintain healthy conditions. This is considered to be the most complicated climatic parameter to be controlled. The relative humidity also triggers the air indoor temperature, as the self-cooling evaporation of the vegetation is dependent on the vapor pressure deficit in the air. Amani et al. [5] found that the optimal relative humidity inside the greenhouse should range between 60 and 80%.

Table 1. Climate requirements for selected greenhouse crops in hot and arid regions.

	Optimal T (°C)		Optimal RH (%)	Optimal DLI ($mol\ m^{-2}\ d^{-1}$)	Reference
	Day	Night			
Tomato	23–27	13–16	50–80	15–53	[14–17]
Pepper	22–30	14–16	50–70	20–30	[18–21]
Cucumber	25–30	16–18	70–90	20–53	[17,19,21]
Lettuce	24–28	13–16	60–80	16–40	[17,21,22]
Aubergine	25–28	14–16	50–60	40–55	[17–19,21,23]
Cabbage	15–16	2	70–80	42	[21,24]
Courgettes	20–22	17–18	65–80	NA	[19]
Beans	22–26	16–18	70–80	19–24	[19]
Peas	25–30	16–18	70–80	42	[21]
Strawberry	20–26	13–16	50–65	17–20	[25–27]
Melon	32	14–20	65–75	58–64	[17,21,28,29]

Vadiee and Martin [30] analyzed the influence of the humidity rate on the crop growth. A lower relative humidity rate inhibits the crop growth, induces water stress in the crops, and reduces the stem length and leaf sizes. In climates with high moisture levels, the vapor condensation on the greenhouse cover increases and condensate decreases cause a decrease in the transmittance of the normal incident radiation of the covering materials, which reaches 23% [31]. Moreover, the excess of the moisture in the greenhouse is considered to be one of the main factors that causes the fungi's appearance, as well as other serious crop diseases [4,32]. On the other hand, the problem of the condensation droplets from the roof might be solved by the provision of a modified greenhouse shape, with an increased slope for droplet removal, especially if higher amounts of humidity can be tolerated in order to reduce the complexity of the control. The use of a covering material with a high drip resistance can also provide an effective solution to condensation dripping, as it contains special additives that prevent the formation of small water droplets, and it makes the condensate stream down in a continuous thin layer onto the sides of the greenhouse [4,33,34]. During the night, the roof temperature is lower than the leaf temperature, and condensation mainly appears on the roof. The removal of condensate can be considered an easy method of air dehumidification.

It is important to stipulate that the ideal humidity levels for a plant are highly dependent on the water stresses, extreme weather conditions, the danger of fungus/pest/insect attack, the maturity stage, and the plant growth stage [5,13]. Hence, the ideal growth of a plant requires ideal humidity levels, which are reported in terms of the vapor pressure deficit (VPD), which is defined as the difference between the water vapor pressure at saturation (P_{sat}), and the actual water vapor pressure at the temperature of the greenhouse (P) [5]. The relationship between the temperature and humidity always has to be reflected. For example, a 20°/80% relative humidity means that another 3 g of water can be absorbed by one m^3 of air, while, at 30°/80%, it is 5.5 g, and, at 40°, it is already 11.2 g, and at this increased level, it is much more apart from the saturation.

A high vapor pressure deficit increases for low humidity and high temperature values, which, in turn, increase the plant transpiration and vice versa. As is shown in Figure 1, the VPD that is required for greenhouse plant growth ranges from 0.45 to 1.25 kPa, and it ideally varies from 0.8 to 0.9 kPa [13]. Therefore, it is extremely important to use the appropriate technology to control the relative humidity, the temperature, and the resulting VPD, especially inside a closed greenhouse, in order to avoid crop damage and to guarantee their proliferation.

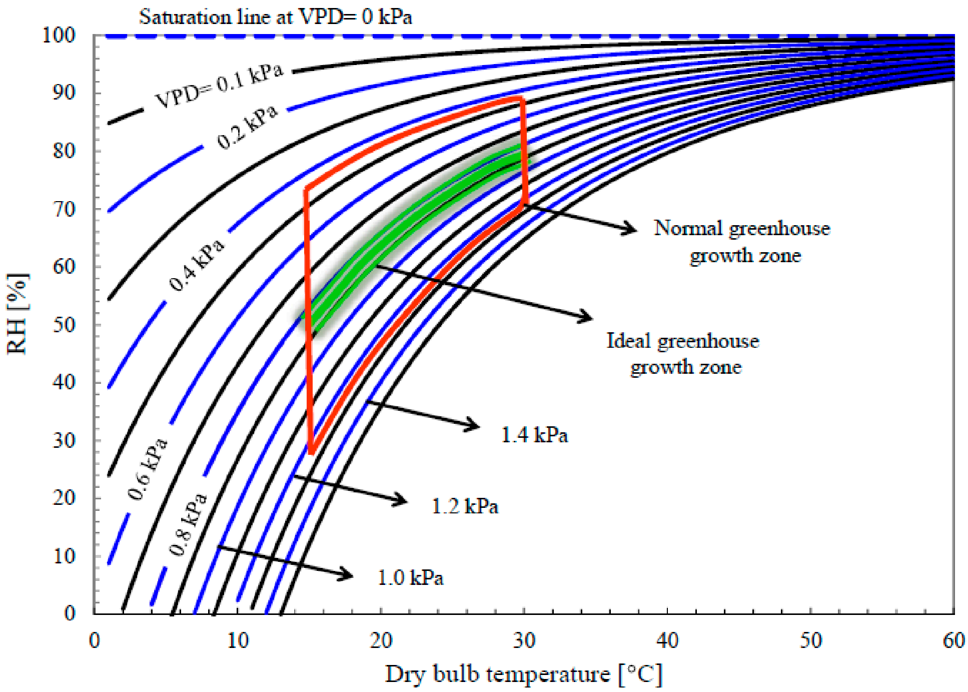

Figure 1. Normal and ideal greenhouse growth zones according to vapor pressure deficit levels. Reprinted with permission from Ref. [13]. Copyright 2016 Elsevier.

2.1.3. Carbon Dioxide Concentration

The CO_2 enrichment in the greenhouse is a crucial parameter since it has a positive effect on the crop growth, provided that other growth factors, such as the water supply, the nutrient supply, and especially the sunlight exposure, are sufficiently satisfied. Better control of the required CO_2 concentration is beneficial to increasing crop growth rates and to enhancing the production quality [35,36]. The CO_2 amounts should be supplied to the greenhouse crops to compensate for the strong reduction in the CO_2 by photosynthesis, especially when good ventilation measures are lacking.

The benefit of the CO_2 enrichment is reflected mainly in the higher crop production through photosynthesis enhancement. Kirschbaum [35] states that, under elevated CO_2 concentrations, the photosynthetic rate increase can exceed 50%, when compared to plants grown under normal CO_2 concentrations. Drake et al. [37] proved, through 60 experiments that were performed under a CO_2 enrichment of around 700 µmol mol^{-1}, that the increase in the photosynthesis of plants reaches 58%, compared to plants under ambient conditions.

Several previous studies have quantified the CO_2 amount to supply in greenhouses, and they have proven that the economic-based optimal CO_2 concentration for healthy crop growth ranges between 700 and 900 µmol mol^{-1}, depending on the plant species [34,35,38,39]. At CO_2 concentrations higher than 1000 µmol mol^{-1}, growth reduction and leaf injuries can occur for some species [35]. Under increased CO_2 concentrations, multiple positive effects on plants have been reported in the literature, such as increased numbers of leaves, lateral branching, and plant heights, and advanced flowering dates and high fruit yields of good quality [35,40–42]. Even crops with partially closed stomata can uptake sufficient amounts of CO_2, and can thereby provide considerable growth rates, even under increased temperatures or reduced water availability.

Sanchez-Guerrero et al. [43] studied the effect of CO_2 enrichment on cucumber culture in a greenhouse during the autumn/winter of the Mediterranean climate. A CO_2 enrichment was applied to the greenhouse to maintain a CO_2 concentration ranging between 600 and 700 µmol mol^{-1} when the vents were closed, and of 350 µmol mol^{-1} when the vents were open. The mean daytime values averaged between 400 and 500 µmol mol^{-1}, while, in the nonenriched greenhouse, they ranged between 285 and 300 µmol mol^{-1} [43,44]. Sanchez-Guerrero et al. found that the dynamic control strategy of the CO_2 enrichment of the greenhouse culture permits an increase in the fresh yield of up 19%, compared to the nonenriched one. Ohyama et al. [45] mention that, in European countries, the CO_2 concentrations are controlled in order to maintain the equilibrium between the CO_2 content inside the greenhouse and the atmosphere. However, the control of the CO_2 concentration is not usually set in hot climates, where systems with high ventilation rates are employed. Very high levels of CO_2 (>1000 ppm) are only feasible in closed greenhouses. Even in semiclosed greenhouses, the ventilation losses are high, and the supply of CO_2 at this level is uneconomical. Furthermore, given the close relationship between the ventilation rate and the CO_2 concentration inside the greenhouse, it is strongly recommended that these two parameters should be controlled simultaneously [30].

2.1.4. Solar Radiation

Solar radiation is the first and main climate parameter for evaluating the suitability of a region for protected cropping [4]. Direct solar radiation that is intercepted in the greenhouse is the first source of heat gain, and it makes the highest contribution to the increase in the daytime temperature of the protected cropping environment. Moreover, important amounts of solar radiation are intercepted and stored in the soil that are to be released during the night [9]. Inside greenhouses in dry climates, the solar radiation passing beside the leaf area is directly transferred into sensible heat, and it heats up the air surrounding the soil. The solar radiation that is intercepted is also the driving force behind the photosynthesis process, and it harnesses the solar radiation energy and turns it into the chemical energy that is necessary for plant metabolism, growth, and development. The part of electromagnetic radiation that can be used as the source of energy for photosynthesis by green plants is the photosynthetically active radiation (PAR). It is expressed either in terms of the photosynthetic photon flux density (PPFD) (mmol photons, m^{-2} s^{-1}), or in photosynthetically active radiation (PAR) (mmol m^{-2} s^{-1} or W/m^2) [46]. PAR irradiance depends upon several factors, such as the meteorological seasonal conditions, the geographical conditions, and the conceptual greenhouse characteristics. The cumulative daily PAR radiation incident of the plants is known as the daily light integral (DLI) (mol m^{-2} d^{-1}). The typical indoor greenhouse DLI values that are required for different crops in hot and arid zones under periods of long daylight (16 h) are presented in Table 1.

2.2. Greenhouse Climate Control Methods

The climate control in the greenhouse is mainly used to guarantee the optimal environmental conditions for crop growth, and to minimize the water and energy consumption. There are different types of control systems (manual, automatic, or intelligent control), where the greenhouse is equipped with Internet data monitoring [47,48]. The hardware of the control system involves sensors, controllers, and actuators. The controlled parameters, namely, the T°, RH, CO_2 concentration, and the air flowrate, are measured by multiple sensors that are placed inside and outside the greenhouse at different positions, including at the planting level, as well as at the inlets and the outlets of the control components. The control components are mainly the cooling, heating, and ventilation systems, as well as the shading and fogging systems.

Detailed studies have been carried out to investigate the coupling characteristics between the environmental parameters, and they show that, in order to enhance the accuracy of the control strategy for low-energy greenhouses, it is necessary to study the multiparameter coupling [47,49]. Several control algorithms and numerical models have been performed to simulate the complexity of the control of the greenhouse environment. The accuracy of these models ensures the control management and minimizes the energy consumption whilst providing a pleasant environment for the plants. Beveren et al. [50] found that by using the optimal control method, the cooling energy consumption and the CO_2 injection could be reduced by up 15% and 10%, respectively.

Hence, effective control methods, particularly smart greenhouse monitoring, have become a new trend for ensuring clean crop production. With these advanced control methods, which are integrated into the greenhouse and combined with renewable resources, the energy consumption in the greenhouse will be negligible.

3. Cooling Systems in Greenhouses

The temperature and relative humidity control inside the greenhouse are operated by different cooling technologies, such as ventilation, external cooling systems using heat exchangers, and evaporative and desiccant systems. The cooling processes can be classified into two main categories: "passive" and "active" systems. "Passive" cooling in the greenhouse mainly refers to the design approach (shape, covering materials, openings, passive night cooling of the soil) to reducing the temperature inside the greenhouse without the consumption of additional water or power. "Active" cooling refers to all the cooling systems that use electrical equipment, such as pumps, fans, and heat pumps. The integration of passive cooling techniques followed by active cooling could simultaneously ensure adequate conditions for crop growth and a decline in the energy consumption.

3.1. Passive Cooling Systems

Several design features strongly contribute to the decrease in the cooling requirements, namely, the shape and the geometry of the greenhouse, its location and orientation, the covering materiel, and the pattern of the openings. According to Choab et al. [51] and Sethi [52], independently of the considered location, the Quonset form corresponds to the minimal values of the temperature and solar collection, as opposed to the uneven-span shape, which allows for maximum solar capture, as well as high heat records. As for the orientation, it is concluded in many comparative studies that the E-W orientation is more convenient at all latitudes, except near the equator, where summer is weakly insolated compared to winter. Stanciu et al. [53] studied the effect of the greenhouse orientation, with respect to the E-W axis, on its required heating and cooling loads for an even-span greenhouse of 180 m^2 at 44.25° N latitude. They found that, for the E-W orientation, the cooling and heating requirements were reduced by 125 kWh/day in June, and by 87 kWh/day in January, respectively. These energy savings for the E-W orientation, with respect to the N-S axis, in both the summer and winter periods, has been confirmed by many previous studies [52,54–56]. Other directions have been proven to be more appropriate when the wind direction to avoid storm losses is considered. For instance, in southern Algeria, greenhouses are S–N oriented because of the direction of stormy winds.

In hot and arid regions, greenhouses have several cladding material types, such as glass, fiberglass, polyethylene, and polycarbonate, with various optical and thermal performances. Shading and reflection are the basic concepts in the reduction and avoidance of intense solar radiation, and they therefore reduce the cooling requirements. A reduction in the greenhouse air temperature of 10% is guaranteed by a 50% shaded roof [57]. Several shading methods have been used and investigated, such as roof shading, external shading, and different material shading nets. It was proven that external shading is more effective in radiation control than under-roof and side-wall placements [58]. For hot climates, white painted roofs that are alternatively combined with external black shading nets, or internal aluminized screens, can guarantee the necessary shading [59]. Painting or spraying the greenhouse with white paint, which is known as "whitewashing", is also a common shading practice for regulating the greenhouse climate in hot and arid regions, and even in cold regions with periods of intense heat [59–61]. At the start of the hot season, lime or white painting cover is sprayed onto the external surface of the glass or plastic-covered greenhouse, which allows for a general level of shading. Whitewashing is, therefore, a passive and low-cost shading technique that reduces the indoor temperature, the VPD, and the light supply [62]. The resulting minimized photosynthesis is accepted, as overheating is the more stressful problem during heat waves.

Specific covering materials can also provide the appropriate shading/reflection effect, namely, colored plastic films [62,63], and near infrared radiation (NIR)-filtering plastic films. The selection of the appropriate covering material is realized on the basis of the amount of intercepted radiation, as well as the type of crops. The minimum transmissivity of the covering material is about 0.7 [64]. Al-Amri [65] demonstrated that the thickness of the covering materials ranges between 0.1 and 0.2 mm for ultraviolet-stabilized polyethylene, between 6 and 10 mm for polycarbonate sheets, and 4 mm for glass. Several covering materials are also under experimentation in order to prove their optical performances. NIR-filtering films are recommended for harsh climates since they reflect the near infrared radiation without affecting the crop photosynthesis or the plant growth. As a result, the air temperature inside the greenhouse is lowered by 5 °C, and the energy requirements for cooling are reduced by 8% [66,67]. However, the use of movable NIR reflectors during wintertime is recommended to prevent increases in the heating requirements [66,67].

Applying passive cooling strategies at the greenhouse design step helps the growers to reduce the cooling requirements and provides more suitable operating conditions for active cooling systems.

3.2. Ventilation Systems

Ventilation systems are commonly used to maintain a suitable environment inside the greenhouse, especially for air dehumidification and for decreasing the temperature. Two types of ventilation systems are used in greenhouses: natural ventilation and forced ventilation. Natural ventilation is carried out mainly via the roof or the side-wall openings, without any external input. Hence, it is the simplest and most cost-effective ventilation technique for controlling the humidity and temperature. However, in greenhouse environments with high humidity levels, in certain conditions, forced ventilation is required and can be carried out using air fans.

3.2.1. Natural Ventilation

Natural ventilation inside the greenhouse is driven by the wind and the internal buoyancy that is created by the air density gradient. The air density gradient is created by increasing the temperature and moisture values. Natural ventilation can be considered as a passive cooling system since it is based on a greenhouse design that does not resort to the use of equipment. Many works have been carried out on natural greenhouse ventilation systems, which are controlled by the window openings at the side-wall and roof levels [68–72]. The researchers found that the climate of greenhouses is highly impacted by the rate of the air exchange through natural convection, which mainly depends on the area of the openings. Therefore, the total area of the vents should be 15 to 30% of the ground area [72], with simultaneously different types of openings (side, ridge, roof), rather than one unique type of vent (Figure 2).

Figure 2. Different types of greenhouse openings: (**a**) roof vents; (**b**) ridge vents; (**c**) side vents.

The indoor climate conditions also depend on many factors, such as the greenhouse design and direction, the wind direction and speed, the solar radiation, the temperature gradient between the inside and outside air, and the plant evapotranspiration. Accordingly, natural ventilation is not sufficient to maintain the desired climate and it becomes more energy intensive, especially in cold periods [5]. For instance, in Sweden and Spain, the energy consumption designed for greenhouse dehumidification via natural ventilation is estimated to be between 20 and 30% of the total energy consumption [5,71,73].

3.2.2. Forced Ventilation

Forced ventilation is ensured by fans or ventilators that are used for heat removal and for the relative humidity control (Figure 3). According to A. Santosh et al. [74], maintaining a suitable rate of ventilation is also essential to avoiding the inequitable CO_2 distribution, and to equalizing the inside greenhouse temperature to the outside temperature. The forced ventilation can ensure a homogeneous air distribution inside the greenhouse better than natural ventilation can [75]. It is commonly used on summer days in hot areas to dehumidify and cool the greenhouse. Forced ventilation ensures the control of the indoor environment to prevent overheating in greenhouse growing environments, and it can either replace other common cooling systems, for instance, fans and pad systems, or contribute to lowering their energy consumption [76,77]. According to Flores-Velazquez et al. [78], maintaining a comfortable climate inside the greenhouse is induced by combining the roof opening and the ventilators, which is better than using forced ventilators only.

Figure 3. A greenhouse equipped with forced ventilation devices at the Institute of Arid Regions (Kebili, Tunisia).

3.3. Heat Exchangers

The heat transfer is one of the most influential driving processes of the cooling systems in greenhouses, especially in hot climates, where the heat flow received by the greenhouse is highly prominent. In cooling systems, the heat transfer occurs between the greenhouse inner air and a second fluid at a lower temperature, which is the cold source of the exchange. This can be not only ambient air, but also cooling water, e.g., from deep ocean water, or water that is cooled within an external cooling tower.

3.3.1. Air-to-Air Heat Exchangers

An air-to-air heat exchanger is recognized as a heat recovery ventilator (HRV), and it constitutes an alternative technique to the condensation mechanism, and it is preferably used in cold or mild climates. Many works have considered that HRVs are an efficient technique for the dehumidification of the greenhouse, particularly during cold periods. Moreover, the air-to-to-air heat exchange process is more valuable in closed greenhouses, where the energy inside the greenhouse is extracted and replaced by the incoming cool air. Air-to-air heat exchangers are usually made up of plastic or metallic plates, and they operate either in the crossflow or the counterflow mode. Furthermore, the air stream circulation and the turbulence require additional ventilation, specifically in no-wind conditions. Hence, this cooling process entails heat exchanger costs, as well as ventilation equipment and the related energy costs [79].

Numerous studies have dealt with the effectiveness of heat exchangers. For instance, Campen et al. [80] investigated the effect of using the exchanger in the greenhouse on economic incomes. According to Amani et al. [5], operating the air-to-air exchanger during the early morning and in the summertime becomes more economically relevant, as it requires more ventilation input to increase the dehumidification capacity. A rotary air-to-air exchanger, which was modeled by Maslak and Nimmermark [71] and was intended for greenhouse dehumidification, exhibits around a 70% effectiveness. They found that, compared to natural ventilation, this process leads to a reduction of up to 17% of the overall energy consumption. Thus, the air-to-air heat exchanger is an efficient way to maintain a comfortable climate in greenhouses in cold and hot climates. This exchanger could also be coupled with another cooling process to cover the cost and to achieve valuable results.

3.3.2. Air-to-Liquid Heat Exchangers

Cooling systems that involve air-to-liquid heat exchangers generally use cold water as the cooling medium, such as seawater, or cooled water that is circulated from a compression or an absorption chiller, or day-to-night cold storage.

Several theoretical and experimental studies have been carried out to investigate the various cooling mediums and their operational limits. For instance, in India, Sethi and Sharma [62,81] performed an experiment on a cooling and heating system using the aquifer water at 24 °C as the heat transfer fluid in the air-to-liquid heat exchanger to ensure the greenhouse heating on winter nights and cooling during summer days. The aquifer coupled with the cavity flow heat exchanger system successfully maintained the greenhouse air temperature at between 7 and 9 °C above the outside air temperature during winter nights, and between 6 and 7 °C below the outside air temperature during extreme summer days. The relative humidity was also decreased by 10–12% in the winter, and it averaged 60% during extreme summer days, while it was about 25% on the outside.

Albright and Behler [82] modeled and performed an experiment on two air-to-liquid heat exchangers that were joined as an air liquid-to-air heat exchanger in a 240 m^2 greenhouse in the United States. The experimented liquid was a mixture of 50% water and a common automotive antifreeze, with a specific heat of 3140 J/kg K. The achieved heat exchanger effectiveness values ranged between 0.4 and 0.5. According to Buchholz [79], the greenhouses cooling systems that use air-to-cold-water heat exchangers require 50 L h^{-1} m^{-2} at a temperature difference of 20 °C. This is traduced by 0.5 m^3 day^{-1} m^{-2} of cold water for 10 h of the cooling operation. Hence, the energy required for pumping this amount of cold water is huge, particularly in the case of noncoastal regions. An important fact is also to be taken into consideration in hot and arid conditions, which is, namely, the heat loss in the piping that supplies the heat exchanger by the liquid cooling medium, especially in extremely hot temperatures. Consequently, emphasis should be placed on the nature and the cost of the piping material and insulation.

3.4. Heat Pump Cooling Systems

Heat pumps, or mechanical refrigeration systems, are electrically driven units that operate according to the vapor compression process for either heating or cooling purposes. Thus, controlled condensation on a cold surface that causes air dehumidification is guaranteed by mechanical cooling units. The main disadvantage of these electrically driven units is the significant amount of energy that they consume. In fact, condensation is initiated when the warm indoor air is cooled down to its dew point. Consequently, the amount of energy consumption consists of the energy needed for cooling the air, plus the energy needed for the phase change from vapor to liquid water, which corresponds to 680 kWh/m^3 [79]. The majority of the research agrees that, although mechanical cooling is efficient at controlling the temperature, humidity, and CO_2 levels, particularly in closed greenhouses, the energy consumption remains intensive and also uneconomical, except if the heat pumps are operated in the heating mode too, or if the heat released during the cooling mode is also used, e.g., for hot water production for domestic or industrial use [73,83–86].

Absorption heat pumps, which are commonly known as “absorption chillers”, are also used for cooling, either in buildings or in greenhouses. Absorption chillers are thermally driven units compared to electric heat pumps. Depending on the energy source, several types of absorption chillers are distinguished, such as: direct-fired, hot water, steam, and exhaust gas chillers. Absorption chillers have expansive integration in the industrial and buildings fields, but few research cases have been performed on the integration of this process in greenhouse cooling. For instance, Campiotti et al. [87] studied an absorption plant that consisted of a single-effect water/lithium bromide absorption chiller, which was coupled to evacuated tube solar collectors that were used for cooling a 300 m^2 greenhouse in Italy. Campiotti et al. [87] found that this system provided satisfactory results when considering the achieved energy savings. It is important to note that the absorption system was performed to cover solely the cooling of the air volume surrounding the crop, and not the entire greenhouse.

According to several experimental and numerical studies, the main advantage of absorption chillers is their capability to be coupled with solar thermal collectors (Figure 4). However, the adoption of solar collectors to generate high temperatures and to operate the system efficiently, particularly for agriculture use, is often constrained by economic and technical barriers [79,88,89].

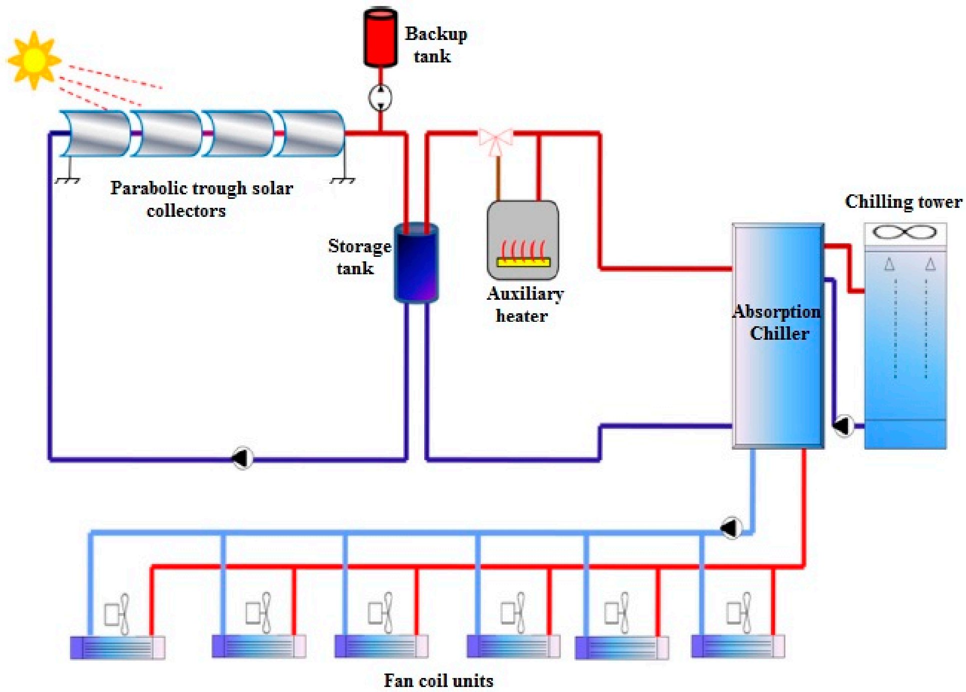

Figure 4. An absorption cooling system coupled with parabolic trough solar collectors. Reprinted with permission from Ref. [88]. Copyright 2013 Elsevier.

3.5. Evaporative Cooling

Evaporative cooling systems, which are based on the conversion of sensible heat into latent heat by means of water evaporation, are commonly used to maintain a comfortable climate for crop growth in hot and dry areas. There are many types of evaporative cooling systems that are used to cool greenhouses, such as fan and pad systems, fogging systems, and roof evaporation cooling systems. According to Ganguly et al. [90], the integration of an evaporative cooling system with natural and forced ventilations, shading, and dehumidification, provided a favorable climate for better crop yields. Ghani et al. [64] confirm that the evaporative cooling coupled with ventilation devices (fans, roof openings) is more efficient for climate control in greenhouse in hot climates [91]. Table 2 summarizes the performances of the different types of evaporative cooling systems that are used in greenhouses under hot and arid climate conditions. Different systems permit a decrease in the temperature and contribute to the energy efficiency.

Table 2. Evaporative cooling systems used in greenhouses in arid and hot regions.

Types	Locations	Advantages	Limitation	Performance
Indirect–direct evaporative cooling (IDEC) unit using groundwater	Baghdad, Iraq [60]	Water saving	Dependent on the groundwater availability	Higher cooling efficiency as compared to the direct evaporative cooler
Fan and pad evaporative cooling system	Khartoum, Sudan [92]	Low energy consumption	Short life cycle of the pads	Cooling efficiency up to 90%
Fan and pad systems	Shanghai [93]	Energy saving and easily adjustable	Not sufficient in humid climates, and it is necessary to add shading	Decrease in temperature to 27–29 °C
Fan and pad systems	Oman [94]	Energy saving and fresh water production		Decrease in water temperature of 3 °C, and increase in the RH to 100%

3.5.1. Fan and Pad Systems

The fan and pad evaporative cooling system is considered to be an efficient control and cooling method for greenhouse climates where the temperature exceeds 40 °C. Its principle is to place a wet pad and fans in opposite positions in the greenhouse (Figure 5). The water evaporation through the wet pad material leads to a decrease in the temperature, and to the humidification of the air inside the greenhouse [64]. There are two types of evaporative cooling systems: direct and indirect. Indeed, a direct evaporative cooling effect is obtained through a crossflow water-to-air heat exchanger. The air that is ventilated by the fans circulates through a porous material, and the surface is humidified by a water drip that is pumped vertically via a hydraulic pump. However, the indirect evaporative cooler is a heat exchanger that decreases the temperature while maintaining a constant humidity level.

Figure 5. Fan and pad cooling systems for greenhouses at the Institute of Arid Regions (Kebili, Tunisia).

Rafique et al. [95] report that the use of only an indirect evaporative cooler in hot and humid climates is not sufficient, and that the use of only a direct evaporative cooler is not economical. For this reason, they propose a combination of the two configurations. Hui and Cheung [96] found that this combination led to the attainment of cool air better than using one type of evaporative cooler only. The cooling system parameters, such as the pad area, the fan power, the flowrates, the distribution system, and the pump capacity, should be rigorously calculated and selected in order to guarantee the sufficient humidification of the pad, and to avoid pad clogging. For instance, according to Kittas et al. [34], it is recommended that the pad area correspond to 1 m^2 per 20–30 m^2 of the greenhouse area, and that the air flowrate range from 120 to 150 m^3 per m^2 of the greenhouse area per hour.

3.5.2. Roof Evaporative Systems

Roof evaporative cooling is performed by circulating a thin film of water throughout the greenhouse roof surface (Figure 6). The solar thermal energy, which is absorbed through the external surface, is therefore reduced, and the roof, and the surrounding air under the roof, are cooled. As a result, the air temperatures are lowered, and the humidity increases inside the greenhouse. Hence, this system operates with high effectiveness under hot and dry conditions [34].

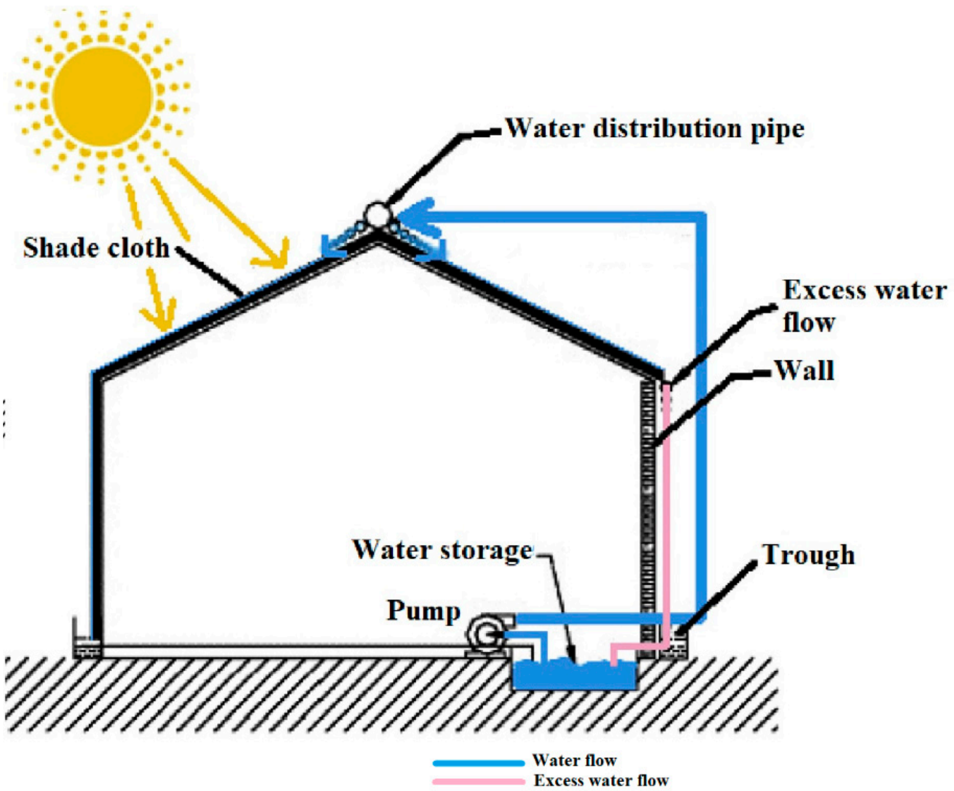

Figure 6. Schematic of cooling by roof evaporative system. Reprinted with permission from Ref. [97]. Copyright 2019 Elsevier.

All of the numerical and experimental studies that have been performed on roof evaporative systems assert that using this system efficiently could be a cost-effective solution to improving climate conditions for greenhouse cooling under hot and arid climate conditions [98–100]. Limited studies have been conducted to investigate the performance of roof evaporative cooling for greenhouses in hot and dry regions. The reported results show that the addition of the roof water flow over the greenhouse roof can lower the greenhouse inner temperature by up to 6 °C [98,101]. Willits and Peet [102] found that the application of a film of water under an external black shade cloth significantly improved the cooling performance, compared to an unshaded greenhouse. Their results reveal that the energy gain reached 15.9 kW, that the greenhouse temperatures were lowered by 2.6 °C, and that the electricity consumption was reduced by 157 Wh. However, an important constraint of this system is its relatively high water consumption, which could reach about 67% of the greenhouse water needs, which is beyond the irrigation requirements [103]. Therefore, using nonconventional water, such as pretreated wastewater or sea water, could be considered to compensate for the water consumption excess.

3.5.3. Fogging Systems

Fogging is a simple and common cooling method that is used mainly in commercial greenhouses. This system provides cooling by humidifying the ambient air inside the greenhouse that is to be conditioned by pressurizing and spraying water through small nozzles in the fogging pipe that is mounted at a high level in the greenhouse (Figure 7). The fogging systems are usually applied as a complementary system to the principal cooling process, especially during the summer season, and they show better results in hot and dry climate conditions [104]. The fogging systems could operate at a high pressure (40 bars), propelling droplets of 10–30 µm, or at a low pressure (5 bars), propelling droplets with minimum diameters of 200 µm [34].

Figure 7. Schematic of cooling by a fogging system. Reprinted with permission from Ref. [97]. Copyright 2019 Elsevier.

Several studies were performed on the distribution of the spray nozzles, their optimal diameter, and the length of the spray cycles and flowrates, as well as on the feasibility of applying a water recovery process. Perdigones et al. [105] proved that at equal spray cycle duration, and mounting the fogging pipe below the shading screens, allowed for higher values of relative humidity (71.8%) than mounting it above the shading device (58.59%). Tiny water droplets of 2–60 µm were recommended by Ohyama et al. [106] to avoid the water droplets dripping off of the plant leaves. Many researchers [33,104–107] agree that fogging systems provide an efficient cooling process that allows for adequate climate control and that prevents the plant dehydration and heat stress caused by high temperatures. Moreover, compared to fan and pad systems, the main advantage of the fogging systems is the uniformity of the climate conditions that they generate inside the greenhouse, without requiring forced ventilation [34]. However, as it is a fresh-water-consuming technology, it is not highly recommended in countries that suffer from water scarcity. Perdigones et al. [105] propose a pulse-width modulation (PWM) method to lower the water consumption. PWM allows for fogging control by varying the cycle duration as a function of the inner temperature. This method can reduce the water consumption by 8–15%, compared to fogging systems with fixed cycle durations. A.M., Abdel-Ghany, and Kozai [33,107] compared three fogging cycles, with fixed fogging rates of 10 g/s, and fixed fogging spans of 30, 60, and 90 s, which were separated with time intervals of 90, 180, and 270 s, respectively. The experiments show that using a fogging cycle of 60 s on/180 s off provided a higher cooling efficiency. Nevertheless, the main disadvantages of fogging systems that should be considered are, on the one hand, the high-quality water they require in order to prevent the clogging of the spray nozzles, which leads to higher costs, especially in water-scarce countries. On the other hand, the pressure that is required for the fog system requires a higher rate of pumping energy compared to droplet evaporators. The time that it is in contact with the air is also shorter, compared to good evaporators, which also results in higher pumping costs.

3.6. Desiccant Systems

Desiccant cooling systems are effective for applications in multiple climates, including in hot and arid regions. The main principle of these systems is based on the combination of the cooling and the dehumidification of the ambient air by using desiccant materials that could be solid or liquid. The commonly used cooling-based dehumidification systems have very high energy consumptions, depending on the design of the structure and the systems, the local climate, the temperature settings, the controls, and the growing strategies [5,8,51]. Therefore, using desiccant systems coupled to solar devices is an effective and energy-saving process. In fact, solar thermal collectors coupled with desiccant systems are largely used in building and agriculture sectors as an alternative to conventional air dehumidification and cooling systems [108–110].

The solar desiccant concept was first proposed by Lof [111]. The two system phenomena, which characterize the reaction between the vapor reaction and the desiccant solution, are based on either the absorption or adsorption processes. The absorption is a chemical reaction between the humidity and the liquid solution, while the adsorption phenomena, which uses a solid desiccant, occurs on the desiccant surface, without any chemical reaction. For the regeneration, a low-energy level is required to regenerate the absorbed humidity.

Liquid desiccant is widely used for dehumidification and cooling purposes as an alternative to conventional vapor compression systems. Moreover, most of the research deals with the performance of liquid rather than solid desiccants, given the ability of liquid-desiccant systems to be more easily integrated into the greenhouse roof.

A comparison between desiccant and conventional vapor compression systems is presented in Table 3. Conventional vapor compression systems cool the air below its dew point in order to condensate the water vapor and remove the moisture. The dehumidified greenhouse air is then heated to the setpoint temperature. These deep cooling and reheating electrically driven processes are energy consuming compared to desiccant processes, which can be driven by low-grade thermal energy. Desiccant systems are considered to be an environmentally friendly technology, as they can be operated by solar energy or waste heat, and they restrict the use of hazardous refrigerants, which are widely used in vapor compression systems [108,112–115]. Moreover, these systems are able to remove all of the airborne contaminants (dust, spores, bacteria, viruses) because of the direct contact between the air and the highly concentrated desiccant solution. Therefore, high indoor air quality is reached, compared to the vapor compression systems that generate large humid surfaces that breed bacteria [108].

Liquid desiccant dehumidification technology has been shown to be very effective in controlling the humidity level, but it is often more complex to operate and control compared to conventional systems [108,113,115,116]. The evaluation of the installation cost is also still under debate. Some researchers have concluded that the vapor compression installation cost is higher than that of desiccant systems [117,118], and others have found that vapor compression systems have the lowest installation costs [112,116]. Thus, reducing the initial costs should be considered in order to achieve the economic benefits of desiccant cooling applications in hot climate regions.

Table 3. Comparison between desiccant and conventional systems [113,116,119].

Parameter	Conventional Vapor Compression System	Desiccant System
Performance	High	Low
Operation cost	High	Low
Energy source	Mainly electricity	Low-grade thermal energy
Environmental safety	Low	High
Control over humidity	Average	Accurate
Indoor air quality	Average	Good
System control	Average	Complicated

Ghoulem et al. [97] were motivated to use a solar regenerator combined with a desiccant to dehumidify and cool the climate inside the greenhouse to ensure crop growth for the humid and hot regions by dehumidifying and cooling (Figure 8). Ghosh and Ganguly [120] numerically investigated desiccant evaporative cooling for agricultural greenhouse applications to be used in humid and hot regions. They modeled a partially closed loop with a recirculation of a partial quantity of the return air, and the desiccant regeneration was realized by a solar roof. The results show that the coefficient of performance (COP) of the system, which is defined as the ratio between the refrigerating power delivered by the system and the heating power required [120], ranges between 0.64 and 0.74 during the most humid periods while maintaining a required temperature for the growth of lettuce crops.

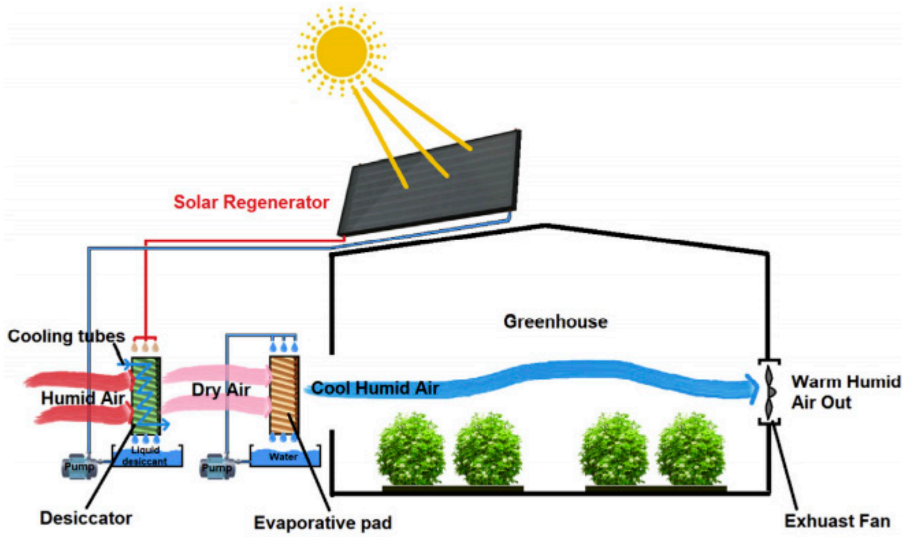

Figure 8. Schematic of solar-assisted desiccant cooling system. Reprinted with permission from Ref. [97]. Copyright 2019 Elsevier.

Davies [2] studied the coupling of the incoming air desiccation to the evaporative cooling in a greenhouse under hot climate conditions in the Gulf state of Abu Dhabi. The proposed arrangement consists of adding a desiccant pad that is placed immediately upstream of the first evaporator pad of an evaporative cooling system. The system is also powered by solar energy, which ensures the regeneration of the desiccant solution. Davies [2] claims to have reduced the greenhouse summer temperature by 5 °C. Thus, the generated climate was suitable for the cultivation of lettuce between 3 and 6 months, and for the cultivation of tomatoes and cucumbers for about 7 months during the whole year.

In Saudi Arabia, Abu-Hamdeh and Almitani [121] studied the performance of coupling desiccation with evaporative cooling, and of integrating different nanofluids with various concentrations in the cooling system. The nanofluid pipes were embedded in the desiccant pad to improve the heat exchange process of the cooling system. They found that the energy effectiveness of the enhanced desiccant evaporative system, which was expressed through the NTU method, reached 50.10%. The daily maximum temperature inside the greenhouse was reduced by about 6 °C, compared to a conventional evaporative cooling system.

Table 4 summarizes the main research carried out on desiccant systems for greenhouse cooling [108–110,122].

Table 4. Summary of studies of desiccant systems in greenhouses.

Locations	System Characteristics	Desiccant	Greenhouse Area (m^2)	Performance
Saudi Arabia [121]	Solar-assisted desiccant-evaporative system; liquid desiccant.	Liquid desiccant nanofluids	300	A decrease of 6 °C of the maximum indoor temperature compared to a conventional evaporative cooler. The energy effectiveness reaches 50.10%.
The Gulf, Abu Dhabi [3]	Solar regeneration desiccant-evaporative system.	Liquid desiccant, $CaCl_2$ LiCl	250	A decrease of 5 °C of the maximum indoor temperature; increase in crop yield; extension of the growing season.
Australia [123]	Solar-assisted desiccant system.	Liquid desiccant	-	Good agreement between experimental and numerical results; satisfactory performance.
India, Bangladesh, Italy Cuba [124]	Solar-powered desiccant system.	Liquid desiccant, $MgCl_2$	1000	A reduction of 5.5–7.5 °C of the indoor temperature; extension of the growing season.
Netherlands [125]	Desiccant system.	Liquid desiccant, $CaCl_2$ LiCl	40	RH is maintained between 75% and 85%.
India [120]	Solar-powered desiccant evaporative system.	Liquid desiccant, LiCl	224	Indoor temperature is maintained below 27 °C; optimum growing conditions for crops.
Greece [126]	Hybrid system: air–air heat pump and desiccant	Liquid desiccant, $CaCl_2$	63	RH is maintained below 80%; increase in total water losses.

4. Innovations and Emerging Technologies for Greenhouses

The emerging technologies consist of innovative systems, renewable energy processes, and coupled systems that aim to allow for and control suitable indoor conditions for crop growth in greenhouses, the production of fresh water, and, mainly, a reduction in the water and energy consumption.

4.1. Water Recovery in Greenhouses

Agriculture is the largest water-consuming sector, with a rate of 70% of the global fresh water [127]. Furthermore, given the relevant decreases in the groundwater reserves because of high consumption rates and the warranty of water availability in the face of climate change, the development and improvement of irrigation water management techniques has become a major priority in agriculture development, particularly in arid areas. Protected cultivation has contributed significantly to the enhancement of water efficiency, as it produces higher yields with reduced water consumption, as well as the efficient use of other resources, such as fertilizers, pesticides, and labor, compared to open-field cultivation [4,128,129]. Water management, which is correlated with issues such as the limitation of freshwater resources, efficient water use, and water desalination, consists of water recovery monitoring techniques that apply closed, or semiclosed, air cycles in the greenhouse design. Another source of the water supply consists of recovering the wastewater that is treated and recycled. Wastewater can be collected from any water-consuming process, such as industrial processes or those of households. Hence, converting wastewater or the loss of water by evapotranspiration into irrigation water could be an ideal strategy for transforming crop agriculture from its status as the greatest water consumer, to the status of water producer.

4.1.1. Condensation on a Cold Surface

This technology is based mainly on collecting the condensate of humid air. The existing systems of water recovery are based on the following two conditions: taking advantage of the high values of the air humidity that are achieved in greenhouses, especially in closed ones; and decreasing the greenhouse temperature by cooling processes. Actually, condensation occurs when the humid air of the greenhouse comes into contact with a surface that is at a temperature that is lower than its dew point. The water content of the air is thus removed by means of condensation. The relative humidity of the air in a closed greenhouse is mainly affected by the ventilation and the evapotranspiration of the plants. Hence, it remains a great challenge to apply humidification with the aim of collecting more droplets, without causing crop damage. Indeed, water recovery could be achieved by coupling a condensation process to the natural convection or mechanical cooling systems, or even to air-to-air heat exchangers. On the basis of the developed dynamic model for predicting the energy and mass exchanges in a greenhouse as a function of the dynamic environmental factor, Yildiz and Stombaugh [83] prove that condensation, in the case of a closed heat pump system that was used for greenhouse cooling in the United States, could ensure a water recovery reaching 1.17 kg of water day^{-1} m^{-2} during the summer season, which is the same amount as the daily water transpiration. They found that the closed loop system was the most water-conserving system, since all the transpired water could be recovered on the coils, making the overall water consumption in this system null. Moreover, the cooling process maintained the greenhouse temperature at 20 °C during the day, and at 18 °C during the night, with an energy consumption of 0.69 kWh day^{-1} m^{-2}. In the arid region of Oman [94], the performance of an evaporative cooling system for the recovery of freshwater was investigated by utilizing two condensers placed after the second pad of the system (Figure 9). Perret et al. [94] found that the relative humidity often reached 100%, and that the water temperature was reduced by 3 °C through the two cooling pads. The dew point temperature was higher than the temperature of the condensers, by about 4 °C, and condensation was therefore observed on the dehumidifier, but the amount of condensate was negligible, and was not measurable. This was justified by the high air flowrate through the condensers, and improvements in the condenser design were, thus, highly recommended.

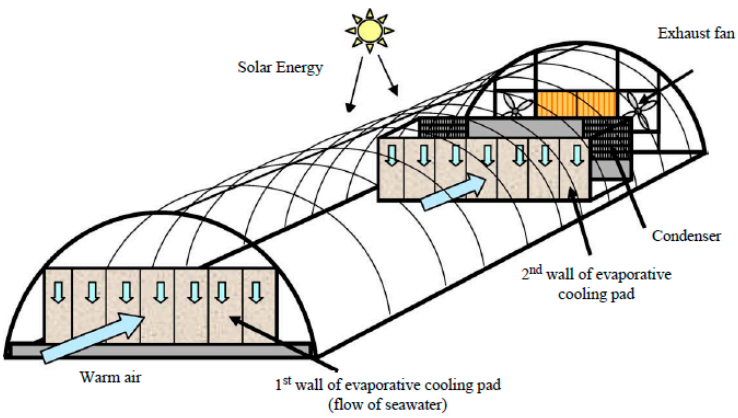

Figure 9. Water recovery in the evaporative cooling system of a seawater greenhouse in Oman. Reprinted with permission from Ref. [94]. Copyright 2005 Elsevier.

4.1.2. Advanced Desalination Processes

Several studies have focused on desalination in greenhouses as a key process of water management, and they have investigated several techniques to improve its efficiency and sustainability, particularly in the water-scarce countries [130]. Desalination processes are generally coupled to solar processes in order to guarantee low costs and zero-energy integrated systems. Buchholz et al. [131] and Zaragoza et al. [132] performed an experimental study in Spain under the Watergy project, which achieved a controlled indoor climate and water recovery. The solar-assisted system is based on water and air cycles, with the additional usage of a heat exchanger that harnesses the temperature difference between the night cooling and the indoor air to condensate the water vapor on the envelope surface. The 200 m^2 closed greenhouse ensured thermal energy capture, water recycling, water desalination, and advanced horticultural use. The greenhouse control climate allowed for a 75% savings in the water consumption. El-Awady et al. [133] performed an experimental investigation of an integrated solar greenhouse that combined the methods of desalination and wastewater treatment, along with water condensation harvesting, in the arid area of Giza in Egypt. The proposed prototype showed satisfying results for the zones suffering from water shortages, given that the greenhouse that was studied provided a low-cost solution, on the one hand, for indoor climate control, and, on the other hand, for the production of freshwater that was suitable either for drinking or irrigation purposes. In Muscat, Oman, the seawater greenhouse studied by Al-Ismaili and Jayasuriya [134] combined humidification–dehumidification and solar desalination processes. The freshwater production is about half of the irrigation demands: 300–600 L day^{-1} of a salinity lower than 0.020 $dS{\cdot}m^{-1}$. Furthermore, multiple studies have aimed to integrate the desalination system into the roof of the greenhouse. Chaibi and Jilar [135] demonstrated that this technique aims to maximize the grower economic return, and they proved that a roof-integrated desalination system in Tunisia guaranteed the plant water supply, with a rate that ranged from 1 to 1.6 kg day^{-1} m^{-2}, and a system efficiency of about 40% [136]. Davies and Paton [2] studied the temperature variation trends in a seawater greenhouse in Dubai, where the cooling was achieved by an evaporative system that was equipped with fans and two cooling pads. An array of plastic pipes, which were used for the greenhouse shading, provided the back evaporative pad with hot seawater to boost the freshwater production, and the condenser was fed with cooled seawater from the front pad. The greenhouse mean temperature and the radiant temperature were decreased, respectively, by 1 °C and 7 °C. Moreover, the freshwater production was enhanced by 63% [2]. In conclusion, water production is a necessary design objective, especially in hot and arid countries, where water scarcity is increasing.

4.2. Advanced Cooling Systems

4.2.1. Renewable-Energy-Powered Cooling Systems

(i) Solar Thermal systems

Solar thermal applications in agriculture have the advantage of the heat being generated by solar radiation. They include desalination processes, crop drying, greenhouse heating, as well as solar cooling, which is the most promising technology, given that the peaks of the cooling requirements in greenhouses match the solar radiation peaks. Solar cooling thermal systems use the thermal energy of the sun as an energy source to generate coolness. They have been widespread in protected cropping agriculture for years since they offer a zero-impact technology. Their performance has been consistently investigated and improved by coupling solar collectors to different cooling processes [4,108,109]. As was detailed in the previous sections, several experimental and numerical studies were performed on solar systems that were based on the evaporative or desiccation cooling processes [3,121,123,124,133,137]. The results show that solar cooling systems that are adapted for greenhouse units are showing satisfactory results in terms of the efficiency and the economic income. Furthermore, the reviews of the research that focus on the solar cooling processes in greenhouses [5,64,138–141] point out that these systems enhance the greenhouse energy efficiency and reduce their dependence on the grid electricity supply. High-performance solar thermal plants, which reach up to 40% [8], consist of integrating concentrating solar collectors (CSCs) into greenhouse cooling systems. The main CSCs that are integrated into protected faming fields are linear Fresnel collectors and parabolic trough solar collectors, which are usually coupled to an absorption chiller. Sonneveld et al. [103] performed an experiment on linear Fresnel collectors combined with PV cells to provide the greenhouse with hot water and electric power to be used for cooling and lighting purposes. The linear Fresnel lenses were integrated between the double glass of the southerly oriented roof cover (Figure 10). The Fresnel system splits direct radiation from diffuse radiation, and it concentrates it on the PV modules that are mounted within the focal line of the Fresnel lenses. As a result, the amount of solar energy that is blocked reaches 77%, which leads to a reduction in the greenhouse cooling requirements by about a factor of 4. The Fresnel system also generated 143.89 kWh m^{-2} of thermal energy, and 29 kWh m^{-2} of electrical energy, which can be exploited for further cooling by means of an evaporative system.

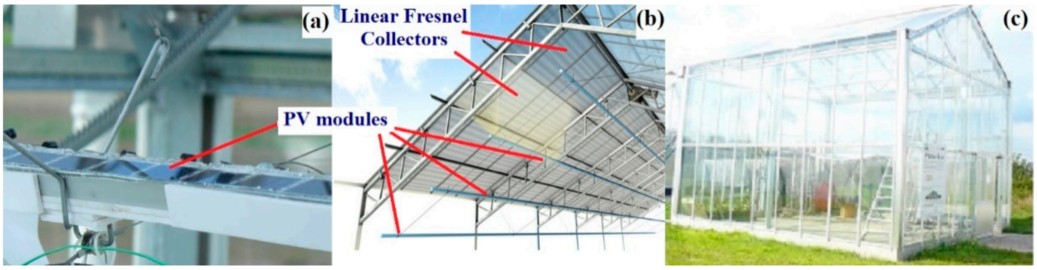

Figure 10. (**a**) The PV modules of the system; (**b**) the linear Fresnel collectors of the system; (**c**) the Fresnel greenhouse (The Netherlands). Reprinted with permission from Ref. [103]. Copyright 2011 Elsevier.

CSCs are usually mounted with solar tracking systems to collect the maximum radiation, and they are coupled to solar cooling processes, particularly in hot desert locations or rural areas, where electrification is difficult and expensive, and where solar resources are abundant [8]. CSCs remain particularly expensive, compared to conventional thermal power generation, and further research and development is needed on this emerging technology for power cooling systems. Alternative ways of improving the operations could be considered and applied, either for the component materials, or for the whole design, in order to enhance the system effectiveness.

(ii) PV Solar systems

Contrary to solar thermal energy, photovoltaics enable sunlight to be directly converted into electrical power for use in cooling systems, or any other electric equipment, such as pumps, heat pumps, dryers, and artificial lighting. Ghoulem et al. [97] demonstrated that a solar cooling system, which was based on a heat pump coupled with PV panels, covered 33.2 to 67.2% of the greenhouse demand in the summer periods. Carlini et al. [142] affirm that the efficiency of PV cooling systems ranges between 30% in the summer and 11% in the winter. Actually, the capacity generated by PV cooling systems is dependent on different factors, namely, the location of the panels and their areas, as well as the greenhouse requirements.

The selection of the appropriate panel area and characteristics should accord with the energy demand and the load profile [143]. Moreover, the structure and the covering of the greenhouse with large PV panels causes extensive shading, which may contribute to a reduction in the greenhouse temperature and to plant stress in hot climates. This affects the plant growth and productivity [144,145], as light is considered to be one of the most important sources for photosynthesis.

PV panels, when installed properly and when coupled with cooling systems, show satisfying results, as was demonstrated by Al-Ibrahim et al. [146], who experimented with the use of PV panels of 14.72 kW to cover the electrical needs of a 9 × 39 m greenhouse, which was, namely, an evaporative cooling system. The PV cooling system performance was satisfactorily established since it met the required load of the greenhouse under the hot and arid conditions of Saudi Arabia. As for Ganguly et al. [90], they proved that the cooling solar plant that was tested in India, which combined a fan and pad evaporative system and PV panels, provided the coolness required for a 90 m^2 greenhouse. According to them, the PV cooling system constitutes a viable option for powering stand-alone greenhouses in a self-sustained manner. The use of PV systems has expanded in recent years thanks to the decrease in the photovoltaic equipment costs [90]. The satisfactory performances of the PV cooling systems will allow this sustainable technology to be promptly implemented worldwide, and specifically in hot and rural locations.

(iii) Geothermal cooling systems

Geothermal cooling systems, which are often referred to as "shallow geothermal systems", consist of a ground pipe that is implanted at a depth that is inferior to 100 m, and that exploits the relatively stable low-temperature earth surface to exchange heat and deliver cooling in warm and hot climates [147]. Ground heat exchangers are mainly classified into three types: vertical, horizontal, and basket.

The earth–air heat exchanger systems have been studied and tested in several countries, and usually with satisfactory results, such as in Thailand [148], where the cooling performance and condensation impact of a horizontal earth tube system, at a depth of 1 m, was investigated. During the summer season, the generated cooling capacity of the system was about 74.84%, and the COP, which is defined as the ratio of the cooling power to the electrical input power, reached 3.56 [148]. In Kuwait [149], the greenhouse temperature reduction was about 2.8 °C for a 1.7 m ground-buried heat exchanger. Several studies also focus on geothermal heat pumps, which are vapor compression systems that use the relatively stable earth surface temperature as the heat exchange medium, instead of the outside air temperature, in order to produce either cooling or heating power. Rabbi et al. [18] show that geothermal heat pumps outperformed all the other heating methods, except for natural gas. Sanaye and Niroomand [150] performed an optimization study of a ground heat pump in Iran, which reached a capacity of 8 to 32 kW, and a coefficient of performance (COP) that varied from 3.9 to 5.4. Boughanmi et al. [151] studied the thermal performance of a conic basket heat exchanger, which was implanted at a 3 m depth and coupled to a geothermal heat pump for greenhouse cooling in the Tunisian climate.

The heat pump COP is defined as the ratio of the amount of heat extracted from the greenhouse by the compressor input power. The overall process COP is defined as the ratio between the amount of heat absorbed from the greenhouse and the total electric input power (to the compressor and the pumps). An evaluation of the thermal performance of the system shows that the heat pump COP varied from 3.9 to 4.7, and that the overall process COP ranged between 2.82 and 3.25. The maximum average temperature difference between the inlet and outlet of the geothermal process system was approximately 30 °C. Hence, the greenhouse temperature was decreased by about 12 °C.

4.2.2. Future Trends in Cooling Systems

(i) Day-to-night thermal storage

During the last few years, several types of thermal storage have been exploited in greenhouses, which aim to take advantage of the available heat sources (solar gain, ground heat, exhaust heat, etc.). The thermal storage achieved by means of storage mediums, namely, water, rock bed, soil, and phase change materials (PCMs) (Figure 11), enhanced the overall thermal performance of the greenhouse [8].

Day-to-night thermal storage is an innovative recovery process that extracts heat during the day for the purpose of using it at night. It consists of a passive system that stores the rising water that is to be served for cooling the air flow that falls through a heat exchanger during the day. The stored heat is released back inside the greenhouse during the night by the buffered water that flows in the opposite direction of the water loop (back to cold storage). As a result, the thermal storage is cooled, and the cooling capacity for the next day is recharged. As for diurnal cooling, this is achieved by naturally low air temperatures inside the closed greenhouse, as well as by plant evaporation. A first prototype of the day-to-night storage concept was reported by Buchholz et al. [131] and Zaragoza et al. [132] in Almeria, Spain (Figure 12), and it showed satisfactory results. Under the hot climate conditions of the region, the day-to-night storage system succeeded, without any extra energy to maintain the temperature during the day between 20 and 35 °C, which is a suitable range for crop growth. The water consumption was also reduced by 75%. Accordingly, day-to-night thermal storage constitutes a basic innovative device that can be mounted in any cooling system and that can generate important energy savings.

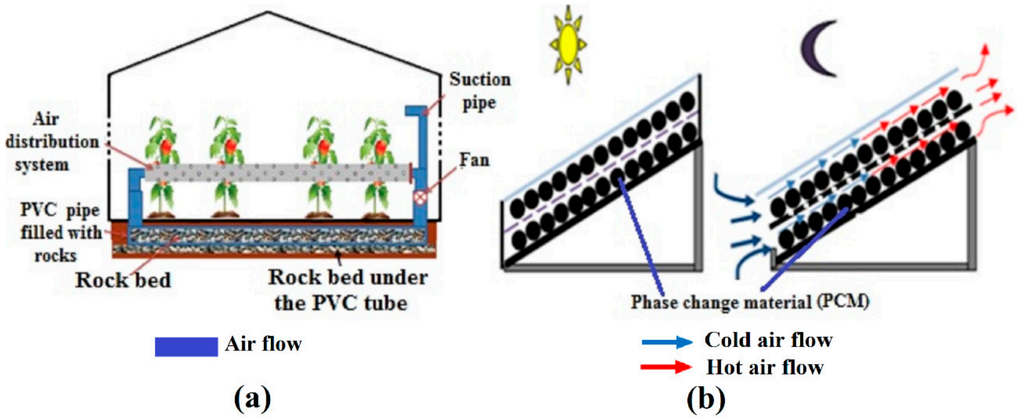

Figure 11. Thermal-storage-based systems used in greenhouses: (**a**) rock bed storage; (**b**) PCM storage. Reprinted with permission from Ref. [152]. Copyright 2018 Elsevier.

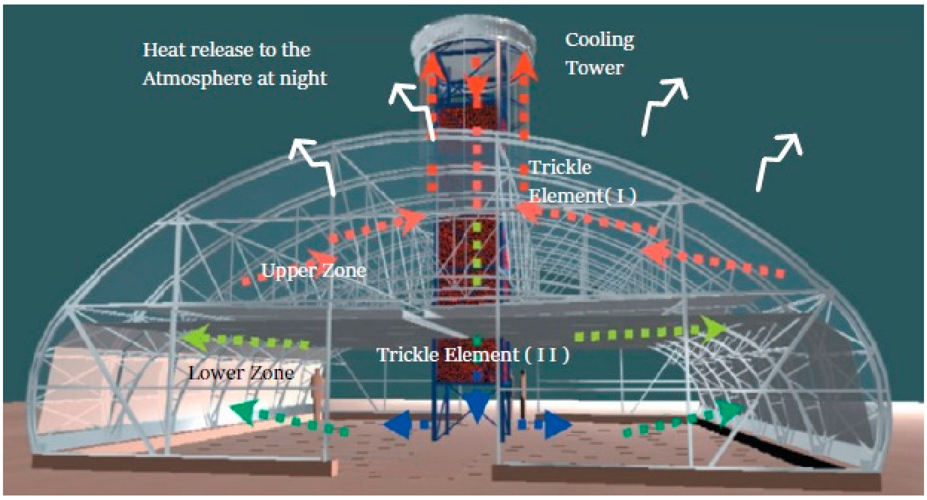

Figure 12. Air circulation in the greenhouse cooled by the day-to-night thermal storage system. Adapted from [131].

(ii) Closed Desiccant Greenhouses

In a closed desiccant greenhouse (Figure 13), the humidity is consistently withdrawn from the hot air by a fluid desiccant that allows for the regulation of the humidity and the temperature, and for the recovery of the heat. A particular surface covering material and design can also be applied in closed desiccant greenhouses in order to guarantee condensation and the recovery of the water vapor that is evaporated by the plants.

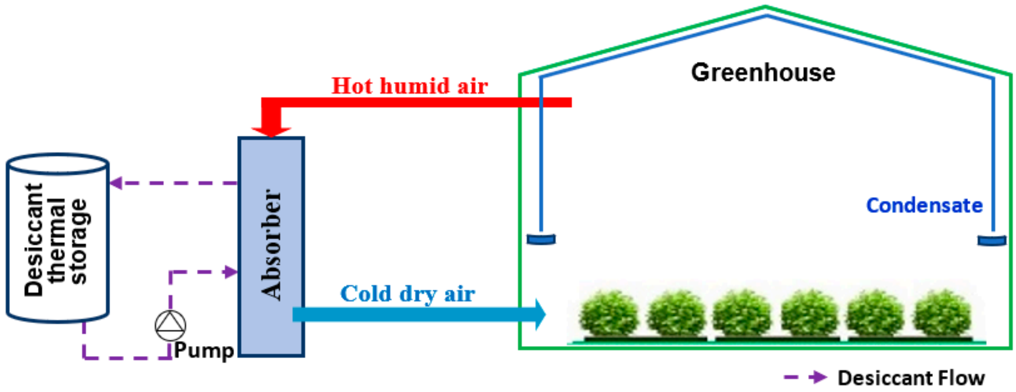

Figure 13. Closed desiccant greenhouse (daytime operation).

During the day, the hot humid air in the greenhouse drops in the counterflow with the cold dry fluid desiccant. Then, it reaches the crop zone as cold dry air, while the hot diluted desiccant solution is buffered in the thermal storage. Air cooling is also achieved by means of the evapotranspiration of plants. During the night, the amount of heat stored is used for the desiccant regeneration, as well as for greenhouse heating, and, hence, the evaporation process drags the humid air up into the covering surface, where it condensates and can be recovered. The main advantage of this technology is that it is independent of the air humidity [9,153,154]. Hence, its implementation is suitable either for hot arid or humid climates. In fact, the first prototype of a desiccant greenhouse, which is mounted in Cairo, Egypt, is under experimentation [137]. This emerging technology offers the substitution of energy-intensive mechanical cooling units by a low-cost and economical heat-driven solution.

The thermal energy required for a closed desiccant greenhouse is provided either by the solar thermal energy or the residual heat. The source of the residual heat can be either the return air of the heating loop, or the unexploited heat of an industrial process, or an air-to-air heat exchanger or ground heat exchanger (Figure 14). A desiccant greenhouse that is coupled to an air-to-air heat exchanger requires less mechanical ventilation, and important heat transfer occurs without resorting to water use. In addition, this system guarantees lower temperature and humidity levels than desiccant greenhouses [84]. Actually, this system is being installed at the National Research Institute for Rural Engineering, Water, and Forestry (INRGREF) in Tunisia in order to test its performance and operational capabilities.

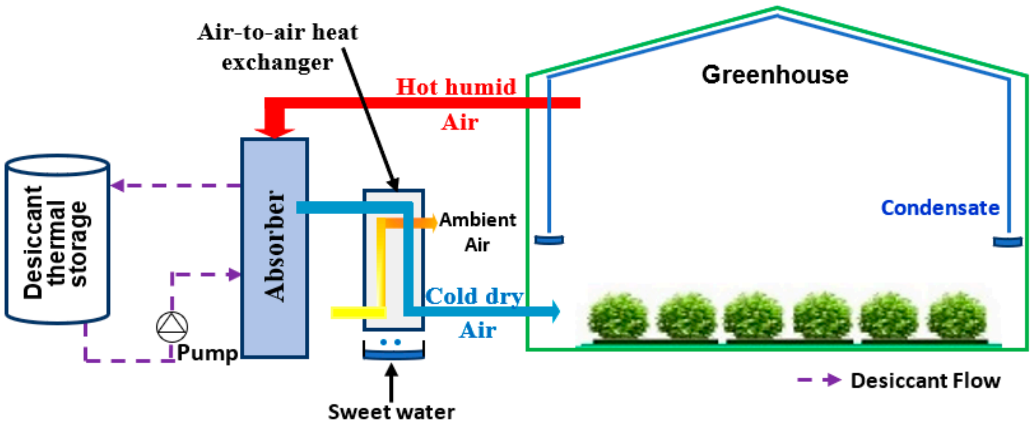

Figure 14. Desiccant greenhouse with use of additional residual heat (daytime operation).

Closed desiccant greenhouses can also be coupled to a solar thermal source, such as solar ponds or solar thermal collectors, namely, concentrating solar collector systems that generate high temperatures, such as parabolic trough collectors (PTC) or Fresnel collectors [8]. Closed desiccant greenhouses also offer the opportunity of being mounted onto several existing and emerging systems, for instance, CSP plants. The waste heat of the

CSP plant is harnessed into the desiccant regeneration, and the cooling energy is transferred to the CSP plant; hence, the coupling of these two technologies could be very effective if the ventilation electricity consumption is lowered. Nonetheless, it is worth developing closed desiccant greenhouse technology in a cost-effective way. For instance, coupling desiccant greenhouses to simple plastic solar absorbers, which are two magnitudes lower in cost than concentrating solar collectors, makes this technology more profitable and convenient for growers. Consequently, this technology is considered to be among the most promising future trends in greenhouses, particularly in hot and arid climates. To this end, the INRGREF has planned to continue future work on testing desiccant systems in a prototype closed greenhouse in Tunisia, using calcium chloride and magnesium chloride desiccants, with relatively low solution concentrations that do not require high temperatures for regeneration.

5. Conclusions and Recommendations

The present paper provides an updated literature review of the climate control methods and cooling systems, with a particular focus on their reliability under hot and arid climate conditions. The main criteria of the performance evaluation are the effectiveness of these systems in generating suitable climate conditions for crops, and the decline in the energy and water consumption.

In the greenhouse conception, particular attention must be paid to the shape, orientation, covering materials, and the opening patterns, in accordance with the geographical location. For hot and arid climates, the E-W orientation is the most recommended at all latitudes, as the greenhouse receives higher radiation in winter than in summer. However, other directions can be proven more appropriate when the stormy wind direction is considered.

The climate management of the greenhouse environment is crucial to guaranteeing suitable growing conditions for the crop. The climate control passes through the monitoring of the solar radiation, air temperature, relative humidity, and carbon dioxide concentration inside the greenhouse, either manually or automatically, or via smart methods that guarantee advanced remote control. The use of a basic or a smart greenhouse monitoring system depends on the aimed accuracy and effectiveness. Advanced control methods that are integrated into the greenhouse with effective cooling systems guarantee valuable energy savings and water use regulation.

The outcomes of our review on the cooling systems that are used in greenhouses under hot and arid climates show that the cooling effect of ventilation systems is more effective when mechanical ventilation is used with the appropriate monitoring of the greenhouse openings in terms of choosing the adequate areas and positions of the openings, and also in controlling the time and duration of the opening, depending on the outside ambient temperature conditions.

The performance of cool roof and fan and pad systems, which are widely used techniques in hot and arid regions, can be enhanced by the use of saline water under the use of techniques that prevent clogging. The use of a second pad, or a condenser, in the fan and pad system, as well as coupling the evaporative system to a desiccant system, offers the opportunity to achieve a higher cooling efficiency and lower energy consumption than when using only a desiccant or an evaporative system, particularly if a solar loop is applied for the desiccant regeneration.

The progress in achieving the high energy and cost efficiency of cooling could be made by improving the heat transfer processes, the heat storage methods, and the water recovery techniques. Multiple advanced cooling systems are emerging as viable solutions for hot and arid regions, particularly when they are powered by renewable resources, such as solar collectors, PV modules, concentrating collectors, or geothermal systems.

The adoption of the day-to-night thermal storage concept in greenhouses by means of water, rock bed, soil, or PCMs reduces the climate control energy demands and, consequently, enhances the overall thermal performance of the greenhouse.

The implementation of closed desiccant greenhouses in hot regions is proposed as a low-cost and economical heat-driven solution that can replace energy-intensive mechanical cooling units. This emerging technology can be coupled to a solar thermal source, an air-to-air heat exchanger, or a ground heat exchanger, in order to achieve maximum energy efficiency.

With consideration to the improved water efficiency in protected cultivation, further research efforts continue to be performed, with a specific focus on the advanced processes of combined evaporation–condensation, which is aimed at the recovery of the irrigation water in greenhouses. The development of these technologies, which are closely linked to modified or advanced cooling systems, will lead to energy-efficient and cost-effective protected agriculture systems.

Author Contributions: Conceptualization, M.S., M.T.C. and M.B.; investigation, M.S. and Z.S.; methodology, M.T.C. and M.S.; writing—original draft preparation, M.S. and Z.S.; writing—review and editing, M.T.C. and M.B.; supervision, M.T.C. and M.B.; project administration, M.T.C. and M.S.; funding acquisition, M.T.C. All authors have read and agreed to the published version of the manuscript.

Funding: The project leading to this work received funding from the European Union's Horizon 2020 research and innovation program, under grant agreement No. 101000801 (Project LC-FNR-06-2020 TheGreeFa, G.A. 101000801). The authors acknowledge the funding from the Tunisian Ministry of High Education and Scientific Research, under the support of the PRIMA program (CONSIRS project).

Informed Consent Statement: Not applicable.

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

Abbreviations

COP	Coefficient of performance
DLI	Daily light integral (mol m^{-2} d^{-1})
NTU	Number of transfer units
P_{sat}	Vapor pressure at saturation (Pa)
PAR	Photosynthetically active radiation (W/m^2)
PPFD	Photosynthetic photon flux density (μmol m^{-2} s^{-1})
RH	Relative humidity (%)
T	Temperature (°C)
VPD	Vapor pressure deficit (Pa)
CSC	Concentrating solar collectors
CSP	Concentrating solar power
E-W	East-West
GCC	Gulf Cooperation Countries
HRV	Heat recovery ventilator
INRGREF	National Research Institute for Rural Engineering: Water and Forestry
MENA	Middle East and North African area
NIR	Near infrared radiation
N-S	North-South
PTC	Parabolic trough collectors
PV	Photovoltaic

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