Chapter

Temperature and Humidity Control for the Next Generation Greenhouses: Overview of Desiccant and Evaporative Cooling Systems

Muhammad Sultan, Hadeed Ashraf, Takahiko Miyazaki, Redmond R. Shamshiri and Ibrahim A. Hameed

Abstract

Temperature and humidity control are crucial in next generation greenhouses. Plants require optimum temperature/humidity and vapor pressure deficit conditions inside the greenhouse for optimum yield. In this regard, an air-conditioning system could provide the required conditions in harsh climatic regions. In this study, the authors have summarized their published work on different desiccant and evaporative cooling options for greenhouse air-conditioning. The direct, indirect, and Maisotsenko cycle evaporative cooling systems, and multi-stage evaporative cooling systems have been summarized in this study. Different desiccant materials i.e., silica-gels, activated carbons (powder and fiber), polymer sorbents, and metal organic frameworks have also been summarized in this study along with different desiccant air-conditioning options. However, different high-performance zeolites and molecular sieves are extensively studied in literature. The authors conclude that solar operated desiccant based evaporative cooling systems could be an alternate option for next generation greenhouse air-conditioning.

Keywords: desiccant dehumidification, evaporative cooling, temperature and humidity control, next generation greenhouse

1. Introduction

Plants are highly sensitive to a specified temperature and humidity range inside a greenhouse. Higher than normal humidity level inside a greenhouse can be fatal for plant growth which leaves the plants open to fungus/pests' attacks, and causes dripping due to condensation. Humidity inside a greenhouse is contributed through photosynthesis and evapotranspiration. Photosynthesis is a natural phenomenon inside plants (which occurs due to chlorophyll) during daytime which results in carbohydrates in plants using carbon dioxide and photons. As a result of this process, plants' leaves generate water vapors into the surroundings contributing to the humidity of the air signified by Eq. (1) and **Figure 1**. Additionally, air temperature inside greenhouse is also impacted by incident solar radiations/sunlight.

$$2nCO_2 + 4n(H_2O)_{xylem} \overset{sunlight}{\rightarrow} 2(CH_2O)_n + 2nO_2\uparrow + 2n(H_2O)\uparrow$$

Furthermore, evapotranspiration or ET is combined process of evaporation and transpiration. Evaporation of water vapors occurs from the soil inside the greenhouse and transpiration of water vapors occurs from stomata (i.e., small openings underside the plant leaves). It concludes that moisture is added into the surrounding air inside the greenhouse at night (through evapotranspiration) as well as at daytime (through photosynthesis). **Figure 1a** and **Figure 1b** show the addition of moisture into the air through evapotranspiration and photosynthesis processes, respectively. Optimum growth and flowering stages of plants is highly impacted by the level of carbon dioxide (CO_2) and relative humidity (RH) inside a greenhouse [1, 2]. Photosynthesis process requires some amount of CO_2 from the air whereas the RH is dependent on the vapor pressure deficit (VPD) inside the greenhouse. The VPD inside the greenhouse is impacted by the plant growth stage, climatic conditions, temperature of plant leaf, and temperature of the inside air (i.e., microclimate) [3, 4]. **Figure 2** shows the impact of different humidity levels inside next generation greenhouses.

In this study, the authors summarize their previously published studies on temperature and humidity control options in next generation greenhouses. Optimum temperature/humidity levels, vapor pressure deficit (VPD) inside the greenhouse, evaporative cooling systems, desiccant air-conditioning systems and different desiccant materials for greenhouse air-conditioning are reviewed in this study.

1.1 Optimum temperature/humidity in greenhouse

As established earlier, optimum temperature/ humidity conditions are required inside the greenhouse optimum functioning of plants. Different plants require specific ranges of temperature and humidity at different stages of their growth. **Figure 3** shows a desiccant dehumidification-based temperature/humidity control system for agricultural greenhouse air-conditioning. **Figure 3** shows the psychrometric representation of the desiccant air-conditioning system for greenhouse air-conditioning. Outdoor air is cooled using direct evaporative cooling (which increases the humidity ratio of the air), further cooled using a sensible heat exchanger before passing through a low-grade heating source (i.e., solar thermal, or biogas), which passes through the desiccant material for regeneration purpose. Whereas on the other side, process air from the system outlet is used for greenhouse

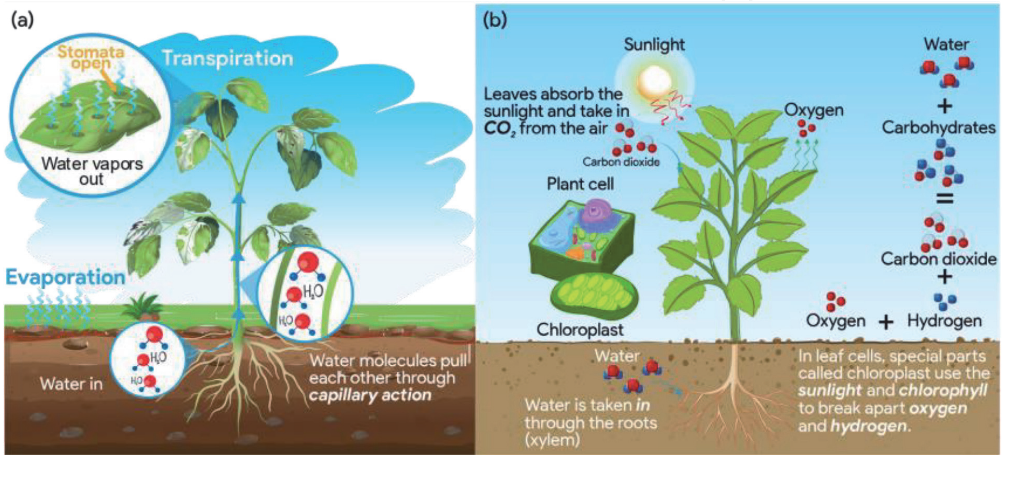

Figure 1.
Illustrations of (a) evapotranspiration (ET) process, and (b) photosynthesis process.

air-conditioning purpose on a simple recirculation mode using the MEC or IEC system for additional cooling.

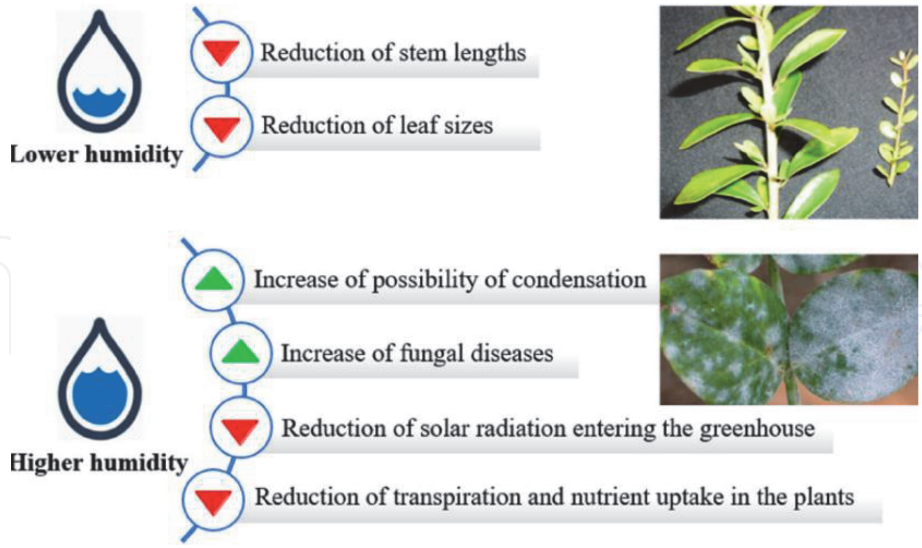

Figure 2.
Impact of different humidity level inside next generation greenhouses [5].

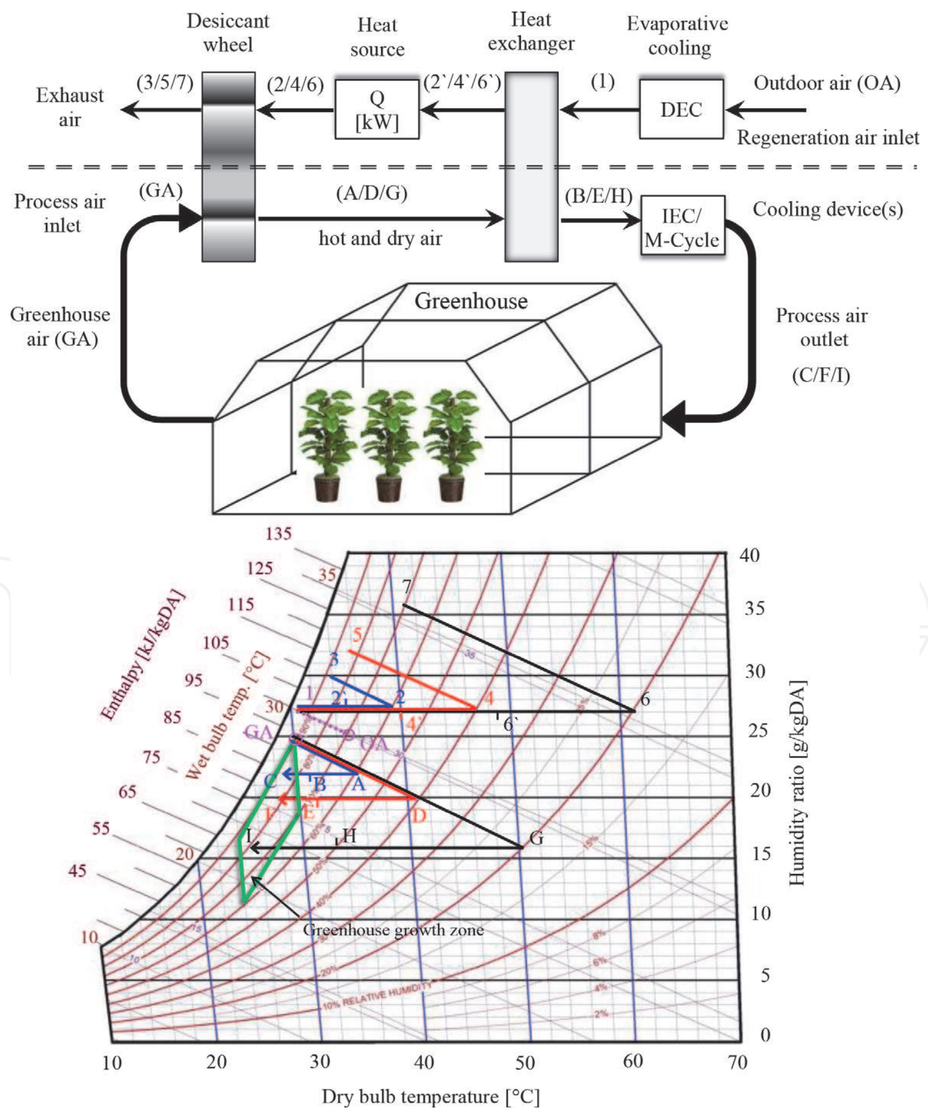

Figure 3.
(above) schematic representation of desiccant air-conditioning system, and (below) psychrometric working of the desiccant air-conditioning system, for next generation agricultural greenhouses [1].

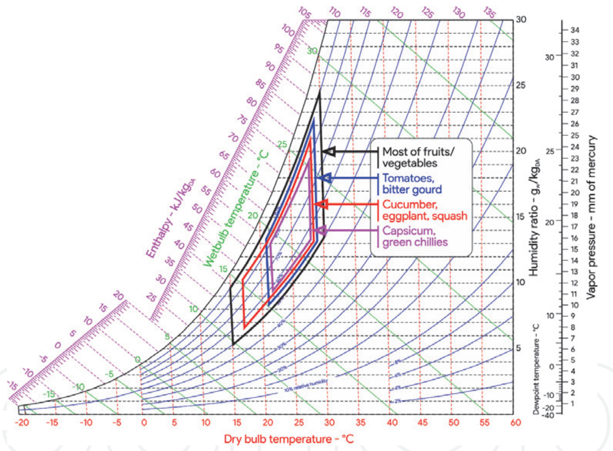

Figure 4.
Optimum temperature/humidity conditions for various fruits and vegetables inside an agricultural greenhouse.

Figure 4 shows the temperature and relative humidity range for optimum growth of various fruits and vegetable plants inside a typical next generation greenhouse. Most of the fruits and vegetable plants require 15 to 30°C temperature with 50 to 90% relative humidity for optimum growth inside an agricultural greenhouse. The most important parameter to address inside an agricultural greenhouse is vapor pressure deficit (VPD), which could be defined as a function of temperature of air, temperature of leaf, and relative humidity of the air. VPD changes with change in plant growth stage as well. Therefore, it is of paramount importance to address the vapor pressure deficit inside the greenhouse before designing a greenhouse air-conditioning system.

1.2 Vapor pressure deficit (VPD)

Vapor pressure deficit is a function of leaf temperature, air temperature, and relative humidity of the air. Vapor pressure deficit inside the greenhouse also varies with different growth stages, regions, and the plant being cultivated for crop. **Figure 5** shows the spatiotemporal profile of vapor pressure deficit across Pakistan. According to **Figure 5**, regions with higher relative humidity and lower temperature (i.e., Northern and North-Western regions of the country) tend to have relatively lesser vapor pressure deficit throughout the year. However, plain areas of the country with relatively higher temperature and drier climate tend to have peaks of vapor pressure deficit as high as 1.52 kPa for the month of June, which demands an air-conditioning system to regulate the temperature/humidity inside the greenhouse for optimum plant growth. The spatiotemporal profile (**Figure 5**) shows that air-conditioning is required inside an agricultural greenhouse in the plain areas (i.e., South, South-Eastern, and South-Western regions) of the country through April to September.

Additionally, **Figure 6** shows the correlation of vapor pressure deficit against dry bulb temperature and relative humidity of the air. According to **Figure 6**, most of the plants (fruits and vegetables) require a vapor pressure deficit of 0.45 kPa to 1.25 kPa for their normal growth throughout their different growth stages. However, for optimum growth of most fruits and vegetables, plants require a vapor pressure deficit of 0.8 to 0.9 kPa. **Figure 7** shows the experimental results of vapor pressure deficit of a next generation agricultural greenhouse. According to **Figure 7**, the vapor pressure deficit inside an agricultural greenhouse was comparatively higher than the outside conditions throughout the day. The study concluded that the developed evaporative fan/pad cooling systems were most feasible for regions with relative humidity lesser than 65% from the viewpoint of vapor pressure deficit.

Moreover, studies show that fungi diseases survive below 0.4 kPa vapor pressure deficit therefore an appropriate air-conditioning system is required for maintaining

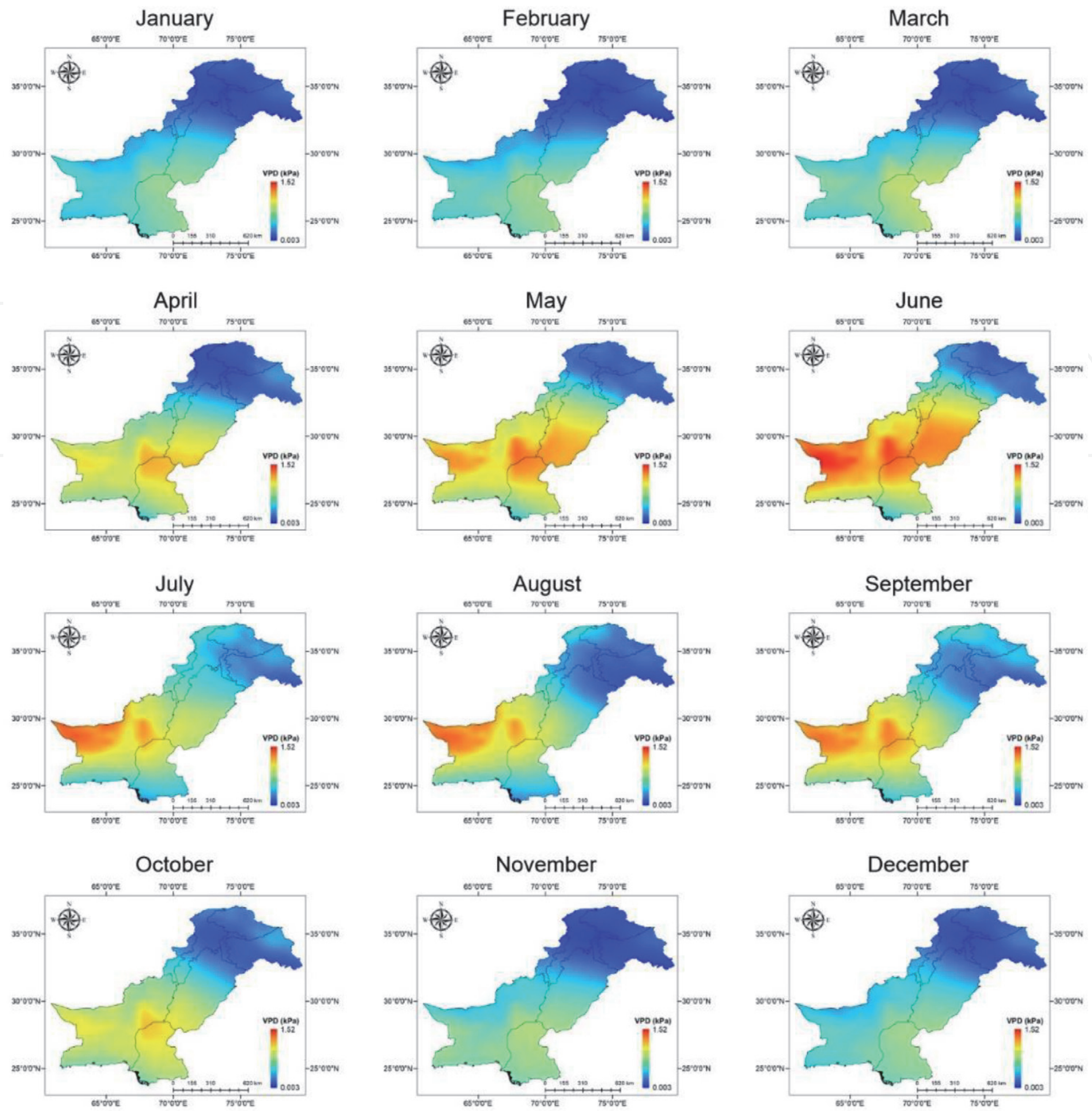

Figure 5.
Spatiotemporal profile of vapor pressure deficit (VPD) across Pakistan [6].

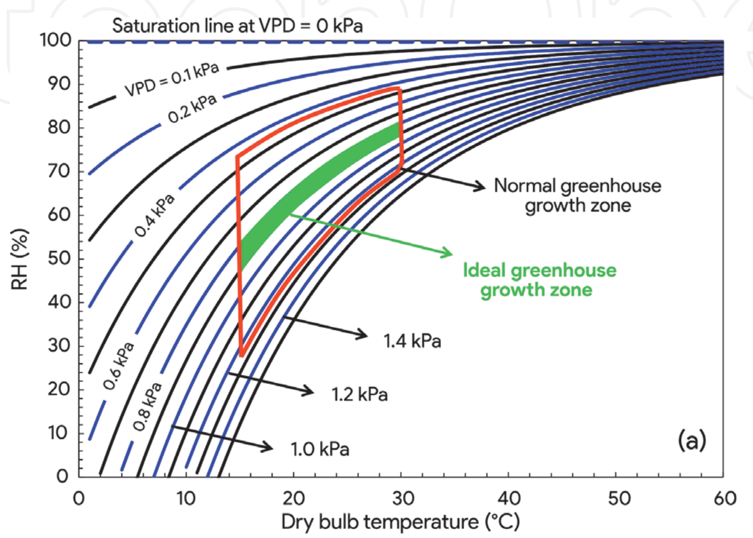

Figure 6.
Identifying the normal and ideal greenhouse growth zones for agricultural products on the basis of water vapor pressure deficit, reproduced from [1].

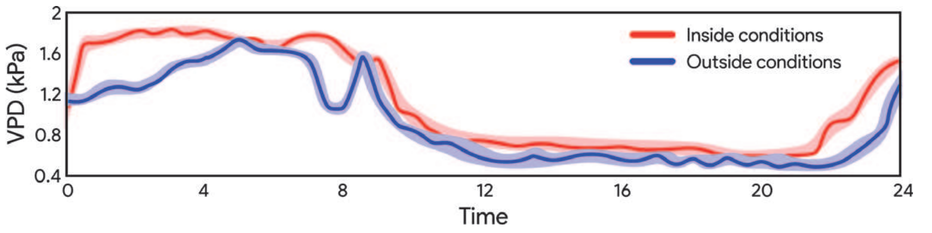

Figure 7.
Vapor pressure deficit (VPD) inside a next generation greenhouse for tomato case study, reproduced from [7].

Optimum ranges			Marginal ranges			Ref.
VPD (kPa)	T (°C)	RH (%)	VPD (kPa)	T (°C)	RH (%)	
0.75–1.06	15–34	40–85	0.45–1.25	15–34	35–85	[2]
0.5–1.2	15–35	35–90	0.4–1.37	17–34	35–90	[8]
0.4–0.79	15–30	55–90	—	—	—	[9]
0.47–1.27	15–30	60–85	—	—	—	[10]

Table 1.
Optimum and marginal ranges of vapor pressure deficit (VPD), temperature (T), and relative humidity (RH) inside next generation greenhouses.

the humidity inside greenhouses. **Table 1** shows optimum and marginal ranges of vapor pressure deficit, temperature, and relative humidity inside next generation greenhouses from different sources. Some of the case studies (presented in Section 1.3) show the variation in vapor pressure deficit, air temperature, relative humidity and solar irradiance being received for different crops at different growth stages.

1.3 Case studies

Numerous next generation greenhouses have been studied for different plant/crops under controlled climate environment (i.e., microclimate) in literature. Shamshiri R. R. et al. [4] evaluated IoT sensors inside two different types (i.e., screenhouse and Polycarbonate sheet greenhouse) next generation greenhouses for energy efficient crop production of tomato plant. The authors studied different growth stage requirements of tomato crop and developed a novel comfort ratio model (i.e., *Cft* model) which was further validated using MATLAB Simulink. **Figure 8** shows the dynamic inputs/outputs of the study on tomato crop.

Moreover, **Figure 9** shows the difference in air temperature, relative humidity, vapor pressure deficit, and irradiance, between the two studied greenhouses (i.e., naturally ventilated screenhouse and energy efficient Polycarbonate sheet evaporative cooling-based greenhouse). The results indicate that the comfort ratio index (which takes into account dynamic assessment of each input parameter i.e., air temperature, relative humidity, vapor pressure deficit, and irradiance, at different timeframes) could be more insightful parameter for comparing the energy efficient crop production between any two studied greenhouses. **Figure 9** shows the raw data used for the IoT sensor-based modeling for two next greenhouses. From the studied literature, it can be concluded that typically naturally ventilated screenhouses and evaporative cooling-based energy efficient greenhouses are in practice for enhanced crop production. However, evaporative cooling systems fail to perform optimally under certain high humidity conditions. In this regard, thermally driven dehumidification based evaporative cooling systems could be an option for additional humidity control in such regions.

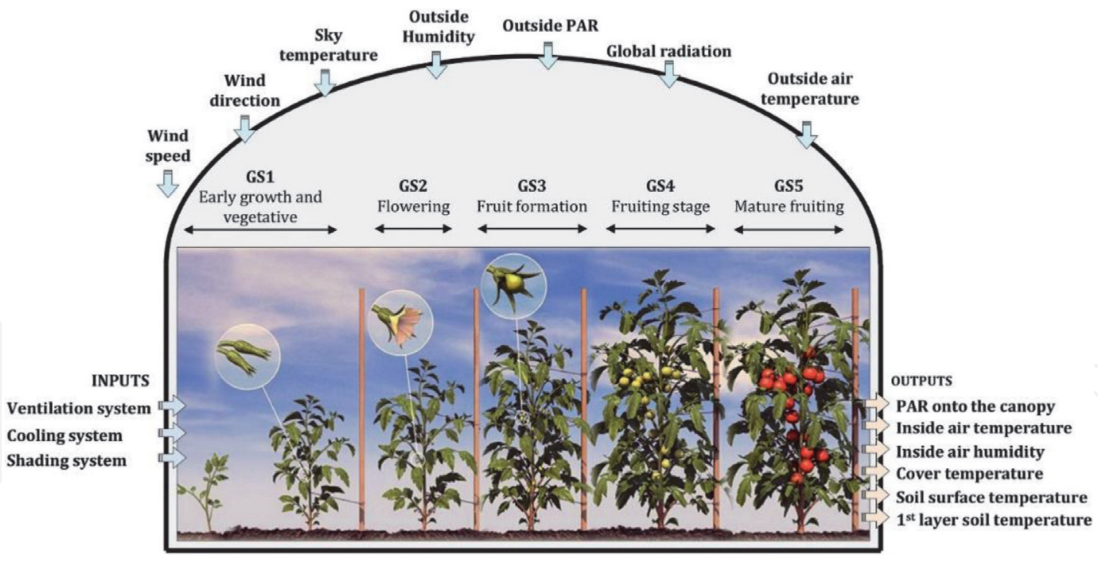

Figure 8.
Illustration of stages of tomato growth inside next generation greenhouses [4].

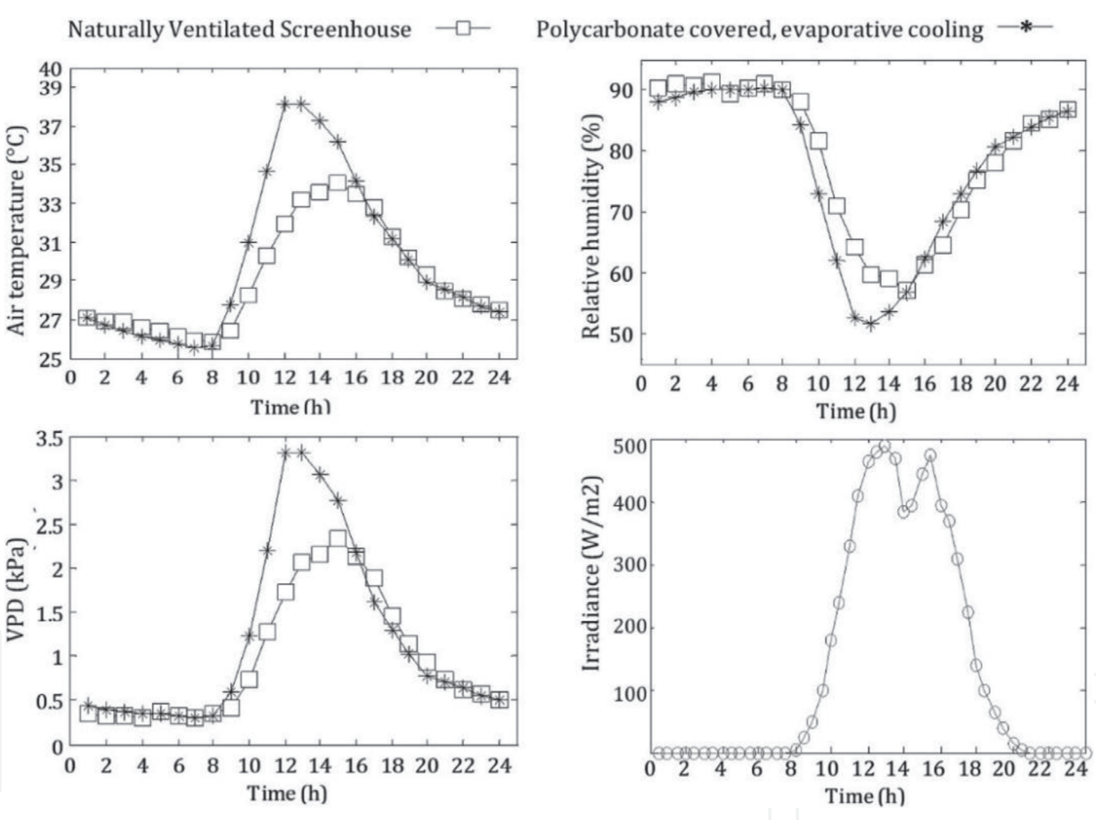

Figure 9.
Experimental results profile of the microclimate inside a next generation greenhouse [4].

2. Evaporative cooling systems

2.1 Evaporative cooling options

Evaporative cooling (EC) is a traditional cooling technique which utilizes endothermic energy from the phase change of water from liquid into water vapors. This phase change mostly occurs due to a current of air using the heat energy present in air for the phase change. Typically, regions with higher temperatures, evaporative cooling is preferred as a low-cost option for air-conditioning, however it does have its drawbacks. Too high temperature can sometimes result in failure of EC systems.

Moreover, humidity present in air also presents a limitation on the performance of the EC systems. The EC systems are, as a thumb rule, suitable for regions with high temperatures and relatively lesser humidity in the air [11]. The authors have thermodynamically, experimentally, and numerically investigated mainly three types of EC systems (i.e., direct evaporative cooling (DEC), indirect evaporative cooling (IEC), and Maisotsenko cycle evaporative cooling (MEC)) for various climatic conditions and air-conditioning applications [11–15]. In direct evaporative cooling (DEC) system, inlet air is in direct contact with wet channels (wet medium usually water with honeycomb/*khas*) which causes cooling due to evaporation but also increases the humidity of the ambient/inlet air at the outlet. On the other hand, in the IEC system, inlet air is in indirect contact with wet channels (wet medium usually water with aluminum channel walls). It causes cooling due to evaporation in the wet channel, conducts the cooling through the channel walls into the inlet air flowing in dry channel. Both the DEC and IEC systems are psychrometrically limited to the wet bulb temperature of the inlet/ambient air however, the MEC can create a temperature gradient of below wet bulb temperature up to dewpoint temperature of the inlet/ambient air. The MEC system is an advanced form of the IEC system with slight modification. Some portion of the outlet air from dry channel is diverted into the wet channel which ultimately results in temperature gradient lower than wet bulb temperature of the ambient/inlet air. **Figure 10(a)** shows the schematic diagram and psychrometric working principle of traditional MEC system. Another modification in the traditional MEC system is shown in **Figure 10(b)**. Mahmood et al. studied the MEC system for various air-conditioning applications [16]. **Figure 11** shows the experimental setup of the developed IEC and MEC systems. The authors concluded that the standalone MEC system was only able to achieve the required temperature/ humidity conditions when the humidity ratio of the ambient air was ≤11 g/kgDA. In other words, in humid regions with humidity ratio higher than 11 g/kgDA, the standalone MEC system failed to produce the optimum temperature/ humidity conditions as the temperature increased. Higher humidity ratio in the air resulted in relatively higher temperature gradient (i.e., according to **Figure 12**, the

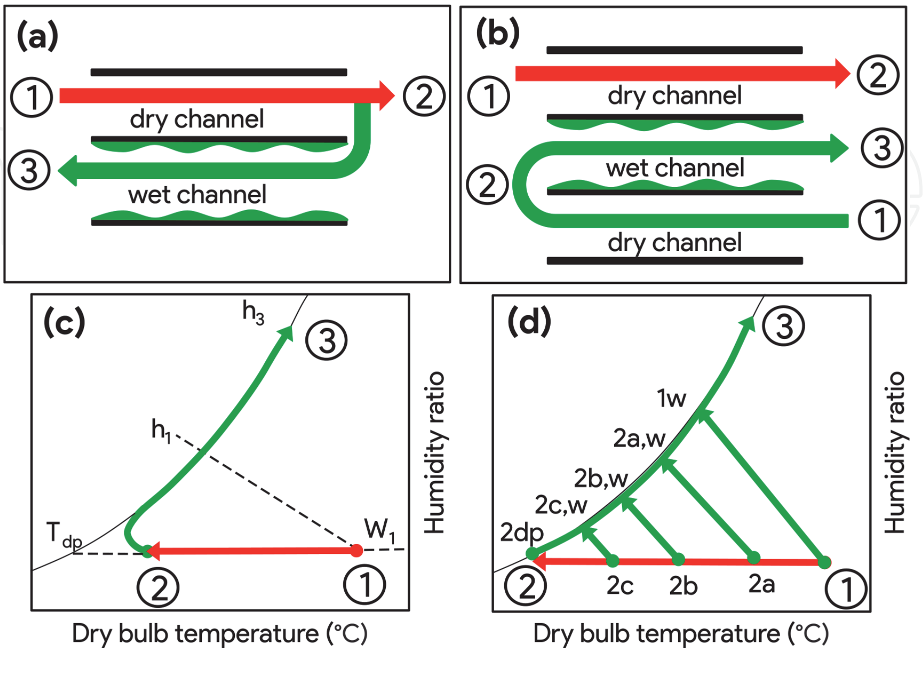

Figure 10.
Schematic illustrations (a,b) and psychrometric representations (c,d) of traditional Maisotsenko cycle evaporative cooling (MEC) system, and modified Maisotsenko cycle evaporative cooling system, respectively, reproduced from [16].

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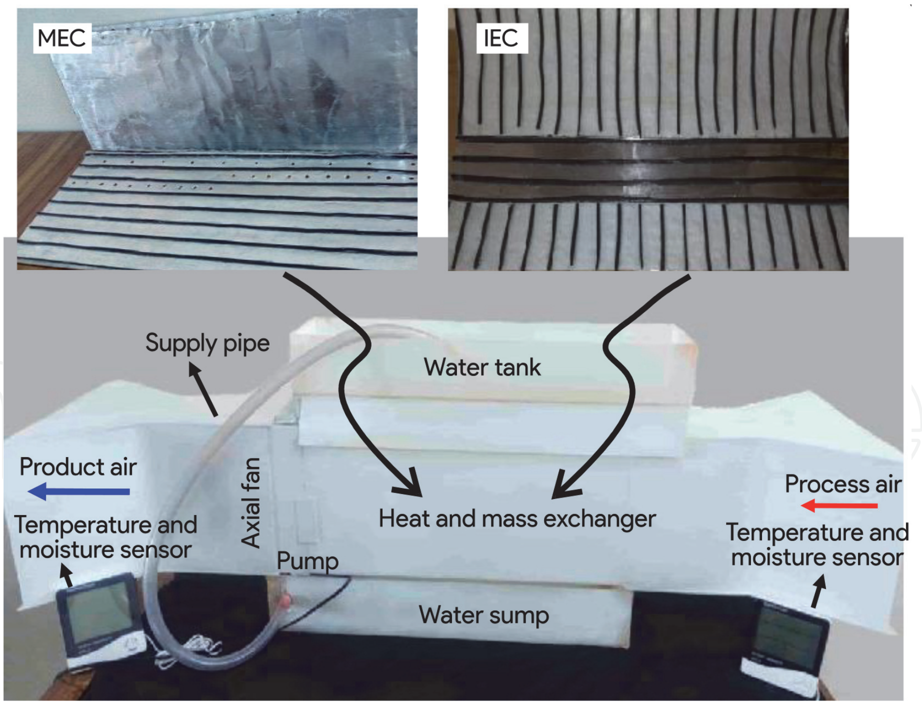

Figure 11.
Experimental setup of the IEC and MEC systems, developed by the authors, reproduced from [17].

MEC system cooled the ambient air with 25 g/kgDA humidity down to 27°C, whereas 20°C in case of 11.2 g/kgDA humidity ratio).

In conclusion, the DEC system creates an addition of moisture into the supply air; increasing its humidity ratio in an uncontrolled fashion which psychrometrically limits the evaporative cooling potential, is undesirable in next generation greenhouses. Whereas the IEC system offers a solution for the uncontrolled humidity problem faced in the DEC system. However, the IEC system is psychrometrically limited to the wet bulb temperature of the ambient air which results in lower temperature gradient, unsuitable for next generation greenhouses. In this regard, an advanced IEC system or the MEC system proves to be effective which is theoretically psychrometrically limited to the dewpoint temperature of the ambient air which results in relatively more temperature gradient, suitable for next generation greenhouses. However, the MEC system is not feasible for regions where humidity in air is ≤11 g/kgDA. In such regions, multi-staging of evaporative cooling systems could an appropriate option for various air-conditioning applications.

2.2 Multi-staging of evaporative cooling systems

Psychrometrics limits the evaporative cooling of the air to its wet bulb temperature (in case of direct evaporative cooling) and dewpoint temperature (in case of Maisotsenko cycle evaporative cooling). However, multi-staging of evaporative cooling systems with other types of evaporative cooling systems or vapor compression air-conditioning (VCAC) systems can break above mentioned conventional bonds of psychrometrics and achieve below wet bulb temperature and effectiveness. Authors have previously worked on multi-staging numerical analysis of evaporative cooling coupled with vapor compression air-conditioning systems and their possible combinations. Noor et al. studied DEC, IEC, and VCAC systems and their possible combinations for building air-conditioning and concluded that multi-stage IEC-DEC-VCAC achieved maximum temperature gradient of ~21°C and wet bulb effectiveness of 1.4 for the summer conditions of Multan [11]. **Figure 12** shows the illustrations and

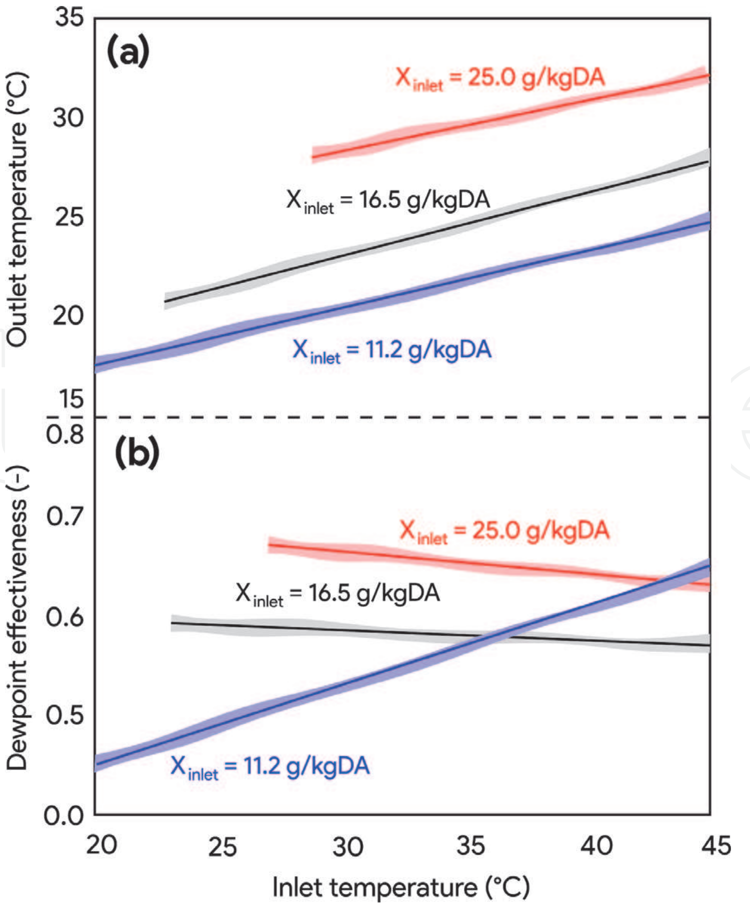

Figure 12.
Effect of inlet temperature on (a) outlet temperature, reproduced from [18], and (b) dewpoint effectiveness of MEC, reproduced from [18].

psychrometric representations of multi-staging of DEC, IEC, and VCAC systems for building air-conditioning application. **Figure 13** shows the temperature gradient profile of the DEC, IEC, and VCAC systems and their possible combinations. As can be seen from **Figure 13**, the IEC-DEC-VCAC created a maximum temperature gradient (i.e., ~21°C), whereas the IEC system created the least temperature gradient (i.e., ~10°C) for summer conditions of Multan (Pakistan). Moreover, the IEC-DEC-VCAC system consumed relatively less power as compared to standalone VCAC system. Additionally, the IEC-DEC-VCAC system had a carbon dioxide release equivalent of 241,134 kg/CO_2/year which is relatively lesser than the standalone VCAC system (i.e., 274,883 kg/CO_2/year). Moreover, the IEC-DEC-VCAC created maximum cooling capacity (i.e., 184 kW) and its work input was ~100 kW. However, maximum COP of the IEC-DEC-VCAC was 2.1, which is relatively lesser as compared to the standalone DEC system (i.e., 4.5) due to higher work input at VCAC stage. Thus, the authors concluded that the IEC-DEC-VCAC system could potentially achieve the desired conditions of any environment including building air-conditioning and other air-conditioning applications at a relatively lower cost (**Figure 14**).

2.3 Evaporative cooling for greenhouse temperature/humidity control

Evaporative cooling could be an energy efficient option for greenhouse air-conditioning in regions where ambient conditions are not feasible for naturally ventilated screenhouses. Noor et al. [6] investigated the thermodynamic performance of direct, indirect and Maisotsenko cycle evaporative cooling systems for greenhouse air-conditioning under the climatic conditions of Multan (Pakistan). The authors took into account the air temperature, relative humidity, vapor pressure deficit, and wet

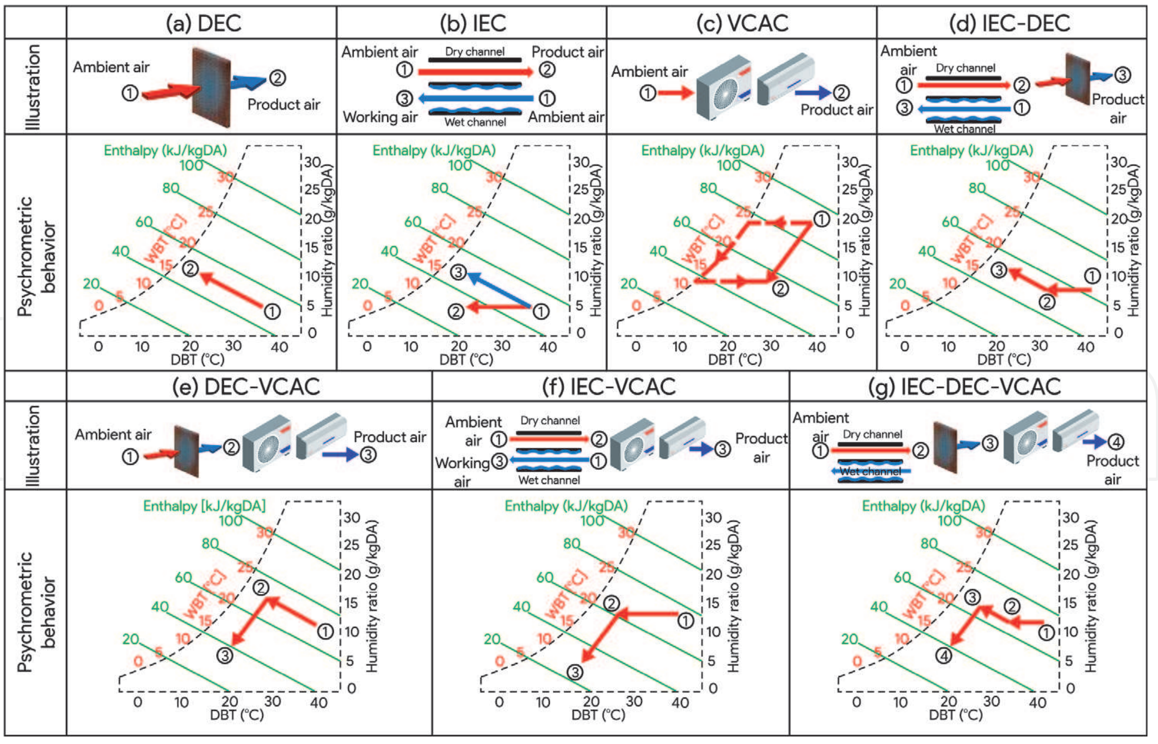

Figure 13.
Schematic illustration and psychrometric working of all possible multi-stages of the direct evaporative cooling (DEC), indirect evaporative cooling (IEC), and vapor compression air-conditioning (VCAC) systems [11].

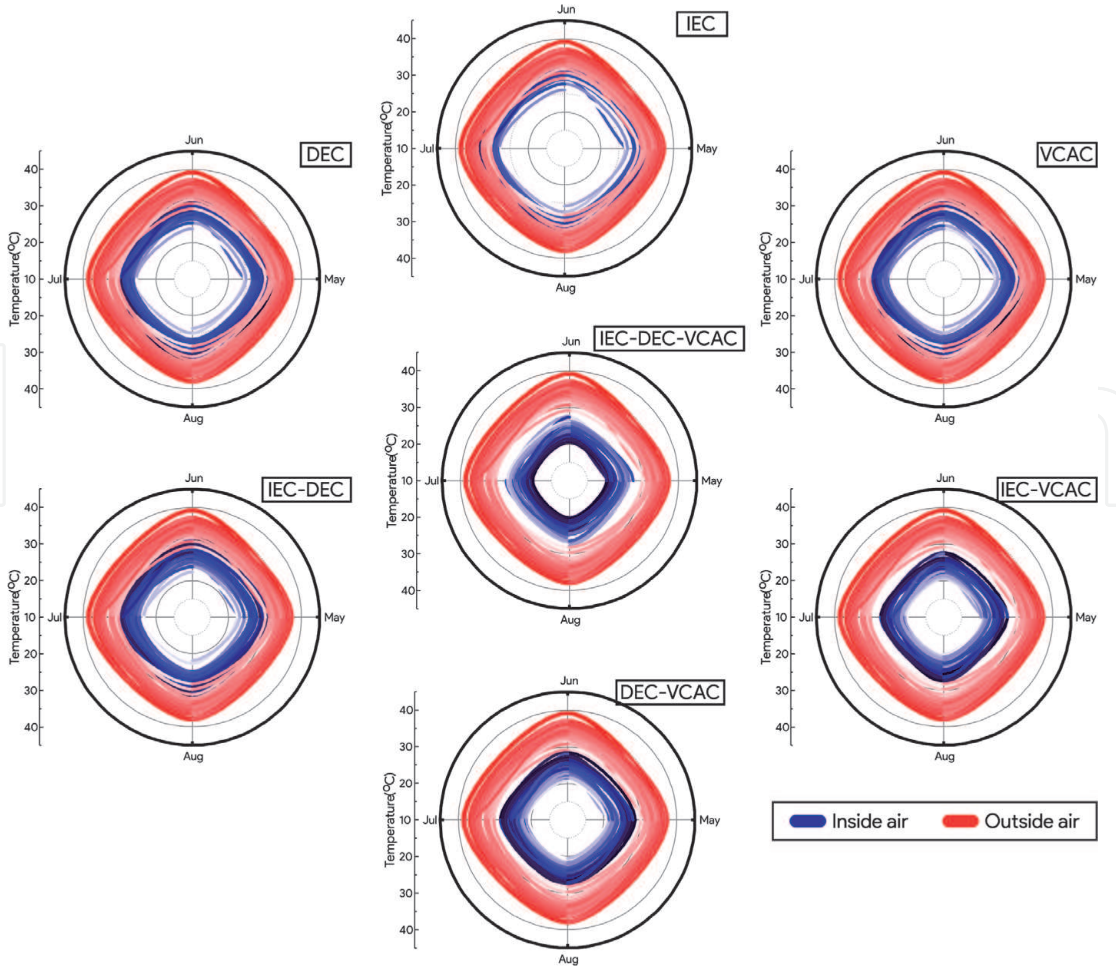

Figure 14.
Temperature gradient profile of the DEC, IEC, and VCAC systems and their possible combinations [11].

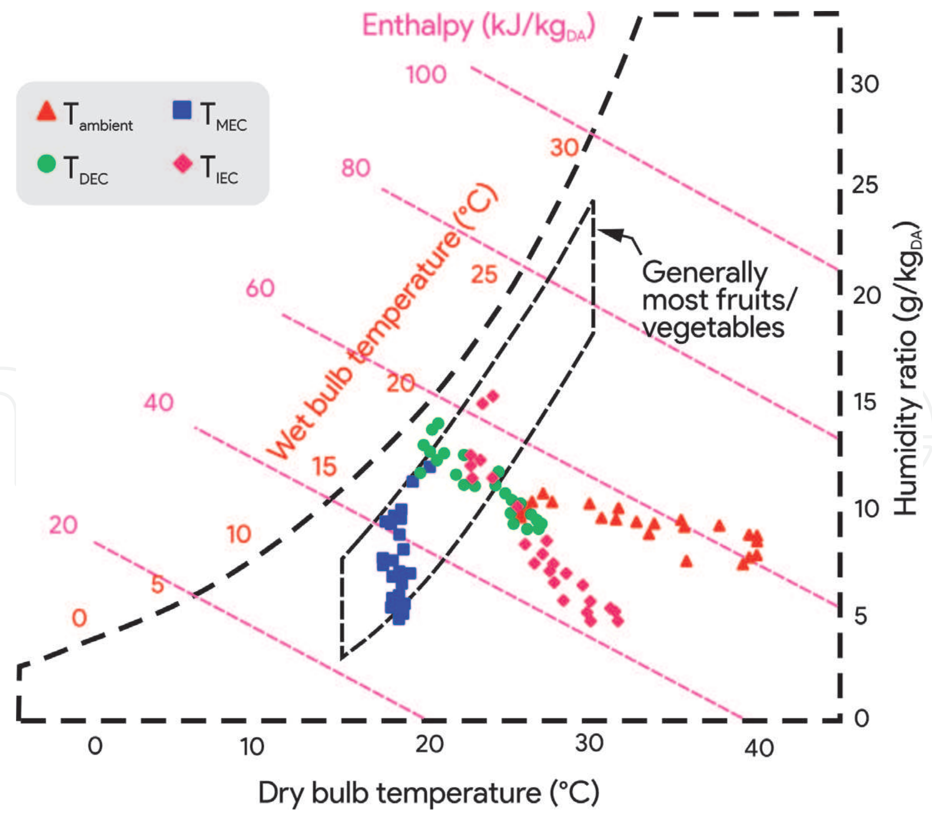

Figure 15.
Psychrometric performance of direct (DEC), indirect (IEC), and Maisotsenko (MEC) cycle evaporative cooling systems for greenhouse air-conditioning (15th may) for Multan (Pakistan), reproduced from [6].

bulb and dewpoint effectiveness of the systems. The authors concluded that the ambient conditions of the study area were not feasible for greenhouse temperature/ humidity requirements, and only the MEC system were able to achieve the desired temperature/ humidity conditions. Moreover, the DEC system was partially able to achieve the required temperature/humidity conditions inside next generation greenhouse. However, the IEC system failed to achieve the required conditions. The authors also concluded that the DEC system achieved the maximum wet bulb effectiveness of 0.9, whereas the MEC system was able to achieve maximum dewpoint effectiveness of 0.5 to 0.6. However, the DEC system was not feasible for greenhouse air-conditioning due to high humidity ratio in the product air throughout the year which indicates that more feasible energy efficient option could be explored (**Figure 15**).

In this regard, the MEC system could be a suitable option for greenhouse air-conditioning. However, performance of the MEC system is also limited to ambient air-conditions (see Section 2.1 in this Chapter, **Figure 12**) which essentially indicates that MEC system fails to perform in too high humidity conditions. Therefore, desiccant dehumidification based evaporative cooling options could be an alternative option for next generation greenhouse air-conditioning in regions with higher humidity ratio.

3. Desiccant air-conditioning systems

3.1 Desiccant materials

3.1.1 Silica-gels

Desiccant air-conditioning has been extensively studied in literature for various applications including next generation greenhouse air-conditioning. Performance of any desiccant air-conditioning system is still somewhat limited to the surrounding conditions however these systems performs admirably well in humid climates unlike the conventional evaporative cooling system which cap at wet bulb temperature of the ambient air. Performance of the desiccant air-conditioning system varies with the desiccant material being used for adsorption of moisture and regeneration temperature for desorption of the material. Silica-gels serve as a viable, cost effective solution for moisture uptake as opposed to expensive, high efficiency experimental polymers, activated carbons, metal organic frameworks, zeolites, and molecular sieves. Sultan et al. [1] investigated the experimental performance of silica-gel based desiccant air-conditioning system for greenhouse air-conditioning at different regeneration temperatures. The experimental results were validated through modeling. **Figure 16** shows the adsorption uptake performance of the silica-gel at 20, 30, and 50°C regeneration temperatures against pressure. According to **Figure 16**, silica-gel adsorption uptake is relatively equal at lower regeneration temperature and pressure as compared to high temperature and pressure, which makes it economically feasible and viable in regions with harsh conditions. However, the underlying fact cannot be denied that performance of other desiccant materials (discussed in coming Sections) is relatively higher than the silica-gels.

3.1.2 Activated carbons

Activated carbons (i.e., powder (ACP) and fiber (ACF)) relatively adsorb higher amount of moisture as compared to conventionally used, easily available silica-gel. Sultan et al. [1] experimentally investigated the adsorption uptake onto the activated carbon powder (Maxsorb-III) and activated carbon fiber (A-20) for next generation solar operated greenhouse air-conditioning. The aim of the study was to investigate the performance of different desiccant materials at different regeneration temperatures. The authors concluded that at 30°C regeneration temperature, the activated carbon powder adsorption uptake was 3 times higher as compared to conventionally used silica-gel whereas it was 1.5 times higher in case of activated carbon fiber vs. silica-gel. **Figure 17** shows the adsorption uptake performance of the activated carbon powder (Maxsorb-III) at 20, 30, and 50°C against different pressures. According to **Figure 17**, the adsorption uptake in case of ACP at 50°C regeneration temperature was 1.4 kg/kg whereas it was 1.25 kg/kg and 1.2 kg/kg at 20 and 30°C, respectively.

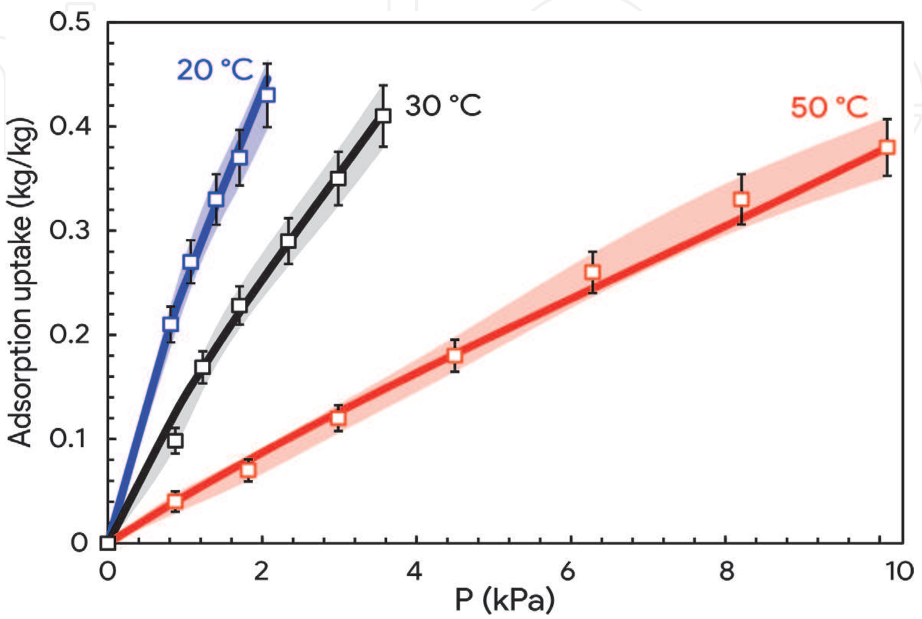

Figure 16.
Adsorption of water vapor onto silica-gel at different temperature, reproduced from [1].

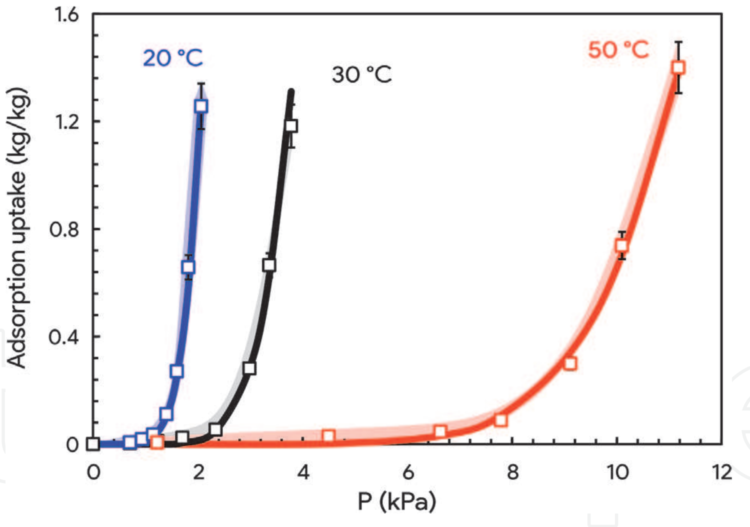

Figure 17.
Adsorption of water vapor onto activated carbon powder (ACP) at different temperature, reproduced from [1].

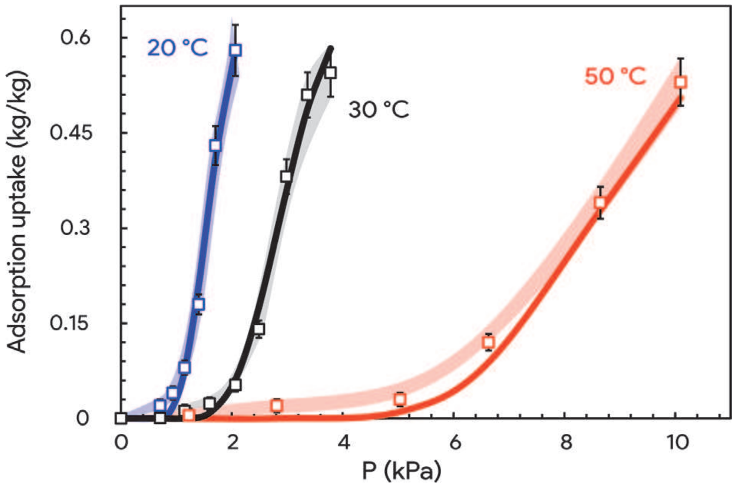

Figure 18.
Adsorption of water vapor onto activated carbon fiber (ACF) at different temperature, reproduced from [1].

Whereas **Figure 18** shows the adsorption uptake performance of the activated carbon fiber (A-20) at 20, 30, and 50°C against pressure. According to **Figure 18**, the adsorption uptake in case of ACF at 50°C regeneration temperature was 0.47 kg/kg whereas it was 0.6 kg/kg and 0.5 kg/kg at 20 and 30°C, respectively.

Figure 19 shows the Polanyi's adsorption potential of the activated carbon powder and activated carbon fiber against conventionally used silica-gel. According to **Figure 19**, the activated carbon powder and activated carbon fiber have higher adsorption uptake as compared to conventionally used silica-gel when the adsorption uptake potential is lower than 50 kJ/kg, which could be considered as the threshold limit for greenhouse air-conditioning [1]. **Figure 20** shows the mass fraction of the adsorbent material per mass of air required for dehumidifying the air. According to **Figure 20**, the activated carbon powder was able to produce the best results for demand category-I with the least amount of mass fraction of adsorbent required. All three materials, silica-gel, ACP, and ACF were able to satisfy the demand category-I whereas only ACF and the conventionally used silica-gel was able to achieve the required output conditions of demand category-II. However, neither ACF nor ACP were able to satisfy the demand category-III which has the maximum humidity gradient (i.e., difference between inlet and outlet humidity) which makes silica-gel more suitable in case of demand category-III.

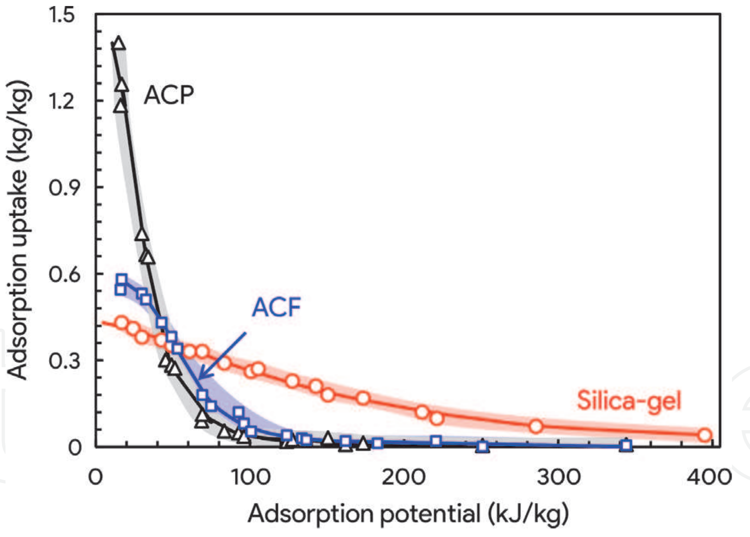

Figure 19.
Profile of adsorption uptake equilibrium against different adsorption potential for silica gel, ACP, and ACF. Points: Experiment; lines: General trend, reproduced from [1].

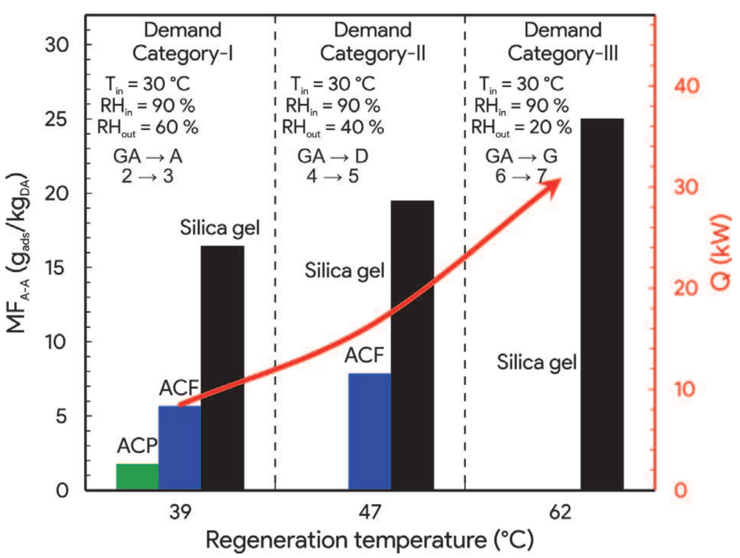

Figure 20.
Profile of regeneration temperature and heating energy using silica-gel, ACP and ACF for different next generation greenhouses' humidity demand, reproduced from [1].

3.1.3 Polymer sorbents

In this study, experimental performance of two polymeric sorbents i.e., PS-I and PS-II has been investigated from authors' previous work [19]. Sultan et al. [19] investigated the experimental performance of moisture uptake onto the PS-I/water and PS-II/water pairs for desiccant air-conditioning applications. **Figure 21(a)** shows the adsorption uptake isotherms of PS-I and PS-II at 30°C adsorption temperature. According to **Figure 21(a)**, PS-II type polymeric sorbent has higher adsorption uptake (i.e., 0.9 kg/kg) at 30°C adsorption temperature whereas it was 0.6 in case of PS-I. **Figure 21(b)** shows the adsorption kinetics of the PS-I and PS-II water adsorption uptake. The authors concluded that PS-I was able to achieve higher rate of adsorption uptake/dehumidification at relatively low regeneration temperature (i.e., 50°C) as compared to PS-II. Although PS-II was able to produce better steady state adsorption kinetics, however it did not have an impact on the overall performance of the system.

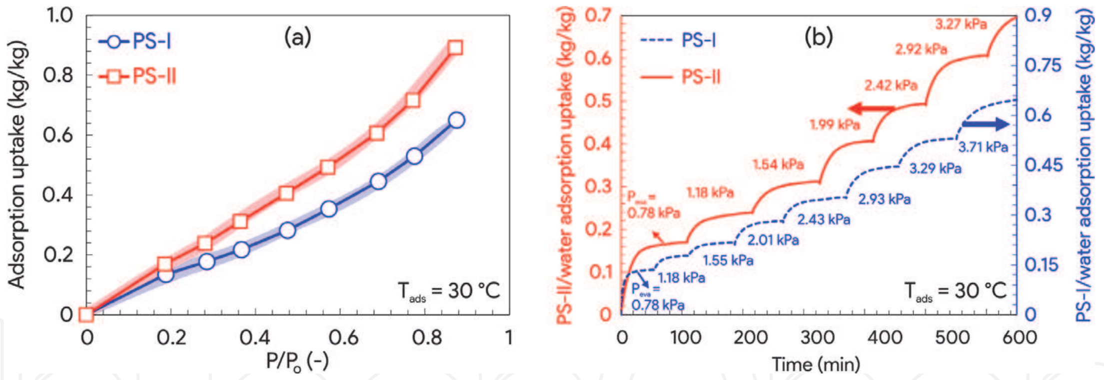

Figure 21.
Performance profile of PS-I and PS-II at T_{ads} = 30, (a) isotherms for PS-I and PS-II, points: Experiments; lines: General trend; fill area: Experimental uncertainty, reproduced from [20], and (b) adsorption kinetics for PS-I and PS-II, reproduced from [20].

3.1.4 Metal organic frameworks (MOFs)

Figure 22 shows the adsorption uptake performance of four different metal organic frameworks reviewed from literature. According to **Figure 22(a)** and **(c)**, MIL-101(Cr) and HKUST-1 produced the highest adsorption uptake i.e., 1.45 kg/kg and 0.50 kg/kg, at 25°C adsorption temperature, respectively. Whereas CPO-27(Ni) and MIL-53 produced the highest adsorption uptake i.e., 0.45 kg/kg and 0.90 kg/kg, at 30°C adsorption temperature, respectively. HKUST-1 shows more degree of stability at low pressure. Whereas adsorption uptake performance of the MIL-53 was negatively impacted by increase in adsorption temperature. However, CPO-25 (Ni) produced relatively same adsorption uptake performance throughout the variation in pressure due to all particle sizes.

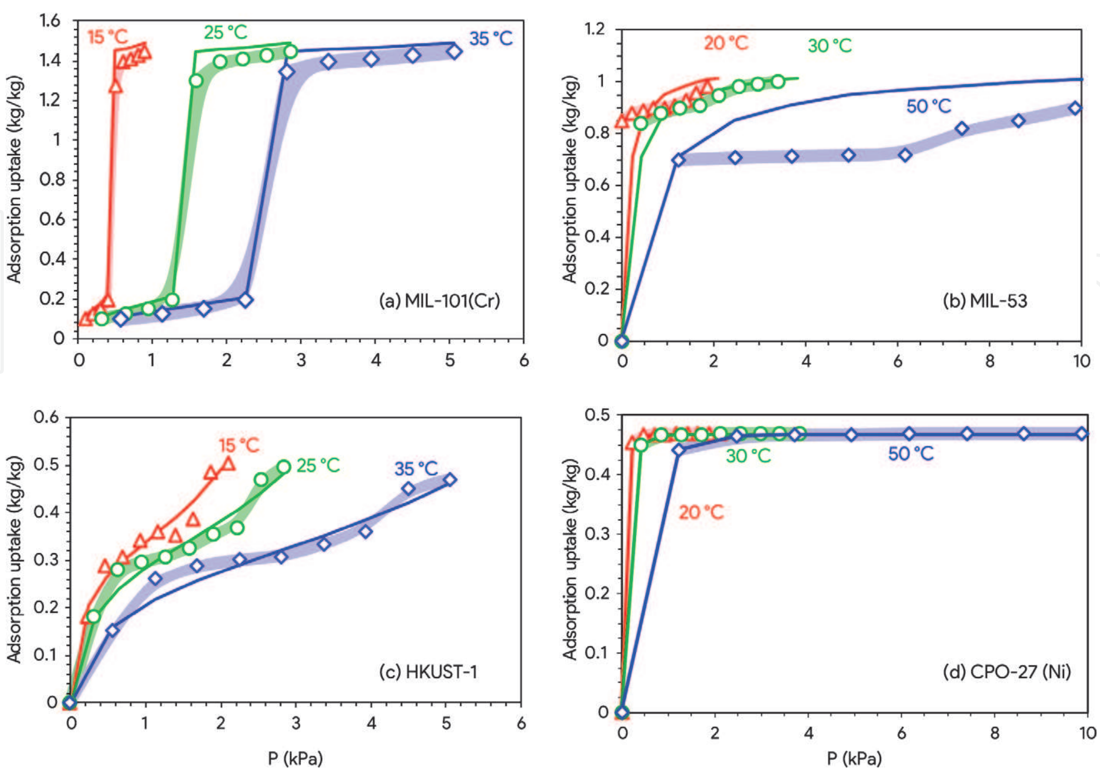

Figure 22.
Adsorption uptake for (a) MIL-101(Cr) [21, 22], (b) MIL-53 [23, 24], (c) HKUST-1 [25, 26], and (d) CPO-27(Ni) [27, 28], reproduced from [29].

3.1.5 Others

Apart from the silica-gels, activated carbons (powder or otherwise fiber), polymer sorbents, and metal organic frameworks, different types of zeolites, and molecular sieves have been investigated in literature whose adsorption uptake performance relative to the studied materials could be higher but for the sake of simplicity and ease, only few materials i.e., silica-gels, activated carbons, polymer sorbents, and metal organic frameworks have been accounted for in this study.

3.2 Desiccant air-conditioning options

Desiccant air-conditioning for different air-conditioning options has been extensively studied in literature. Niaz et al. [30] investigated silica-gel desiccant dehumidification based Maisotsenko cycle evaporative cooling system for livestock thermal comfort. **Figure 23** shows the performance of the studied standalone desiccant and evaporative cooling based desiccant air-conditioning options for livestock thermal comfort for climatic conditions of Multan (Pakistan). The authors concluded that only the desiccant dehumidification based Maisotsenko cycle evaporative cooling system was able to achieve the desired temperature/humidity conditions for livestock thermal comfort. Whereas the ambient and standalone desiccant air-conditioning system conditions were unfavorable for livestock thermal comfort. Moreover, Aleem et al. [31] investigated the experimental performance of sieve/layers type orientation of silica-gel beads and compared it with polymeric sorbents. The authors concluded that polymeric sorbent had higher adsorption uptake as compared to the silica-gel. **Figure 24** shows the experimental setup, and the schematic diagram of the developed desiccant air-conditioning system.

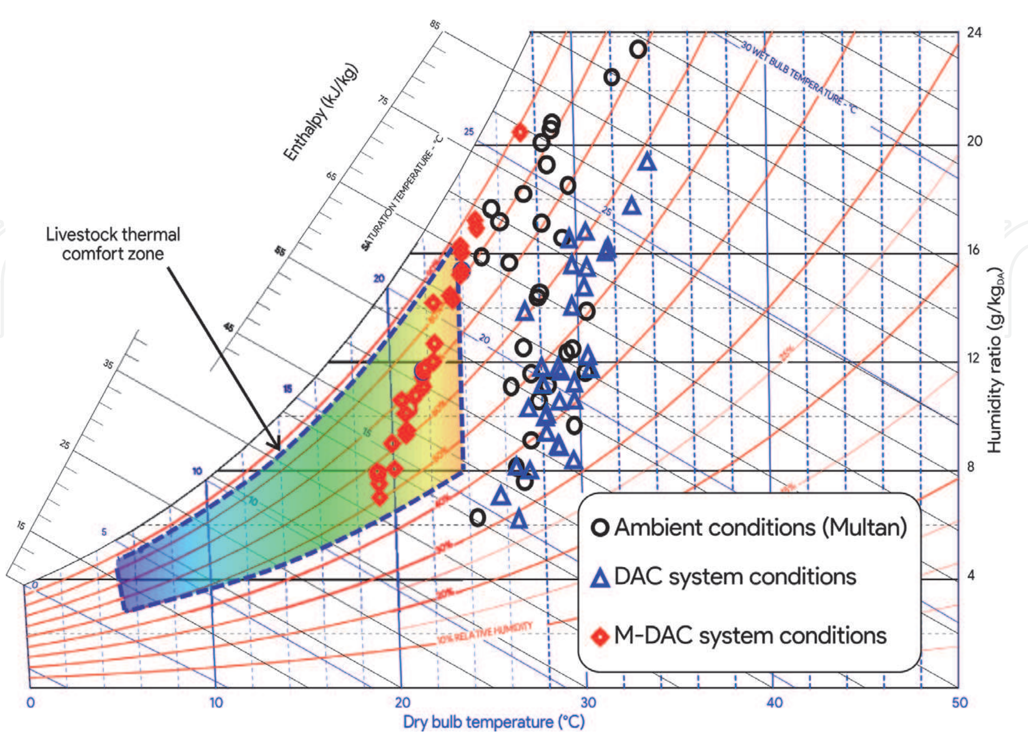

Figure 23.
Thermodynamic performance of desiccant dehumidification based Maisotsenko cycle evaporative cooling system for livestock thermal comfort for Multan (Pakistan), reproduced from [30].

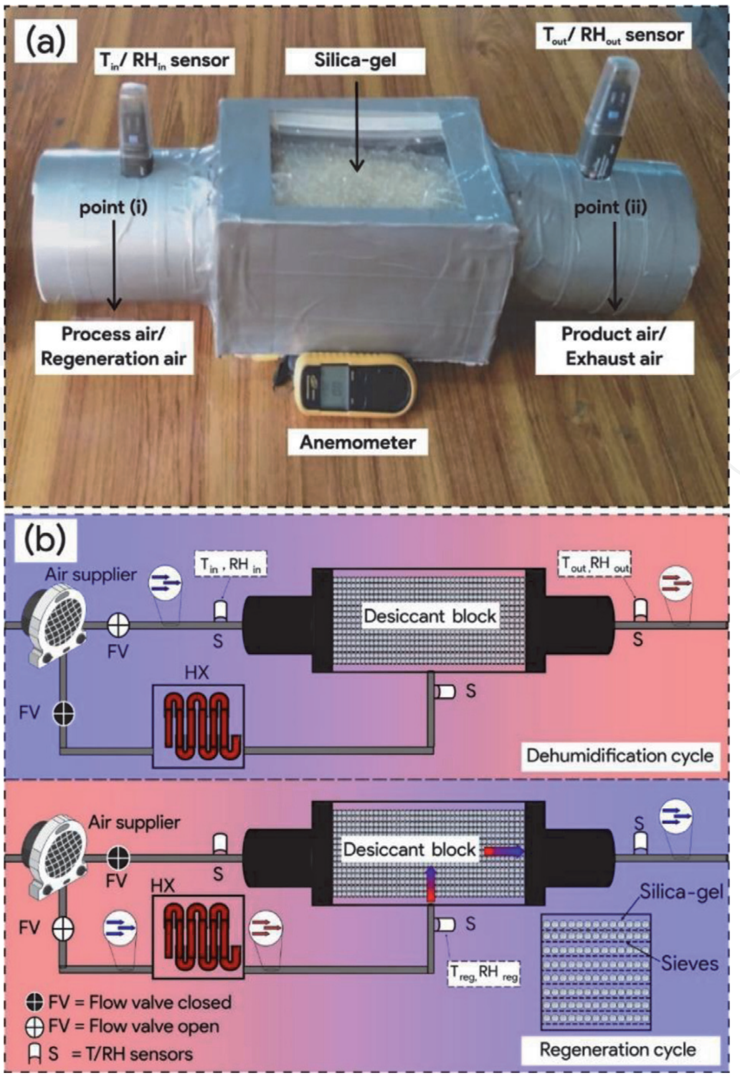

Figure 24.
Illustration of the experimental silica-gel desiccant dehumidification system, (a) snapshot of the developed system, and (b) schematic illustration of the developed system, reproduced from [31].

3.3 Desiccant air-conditioning for greenhouse temperature/humidity control

Authors have extensively studied desiccant air-conditioning options for the next generation greenhouse air-conditioning in literature [1, 3, 4, 14, 32–35]. Ashraf et al. [33] studied silica-gel desiccant dehumidification based Maisotsenko cycle evaporative cooling system for the next generation agricultural greenhouse. **Figure 25(a)** shows the schematic diagram of the investigated desiccant air-conditioning system. **Figure 25(b)** shows the annual performance profile of the desiccant dehumidification based Maisotsenko cycle evaporative cooling system for the climatic conditions of Multan (Pakistan) for next generation greenhouse air-conditioning. According to **Figure 25(b)**, the evaporative cooling enhanced desiccant air-conditioning system achieved the required conditions of greenhouse air-conditioning in the lower limit. However, the standalone desiccant and the ambient conditions were not feasible through most of the year for next generation greenhouse. The authors concluded that solar operated silica-gel desiccant based Maisotsenko cycle evaporative cooling system could be an alternate low cost, energy efficient, feasible solution for greenhouse air-conditioning.

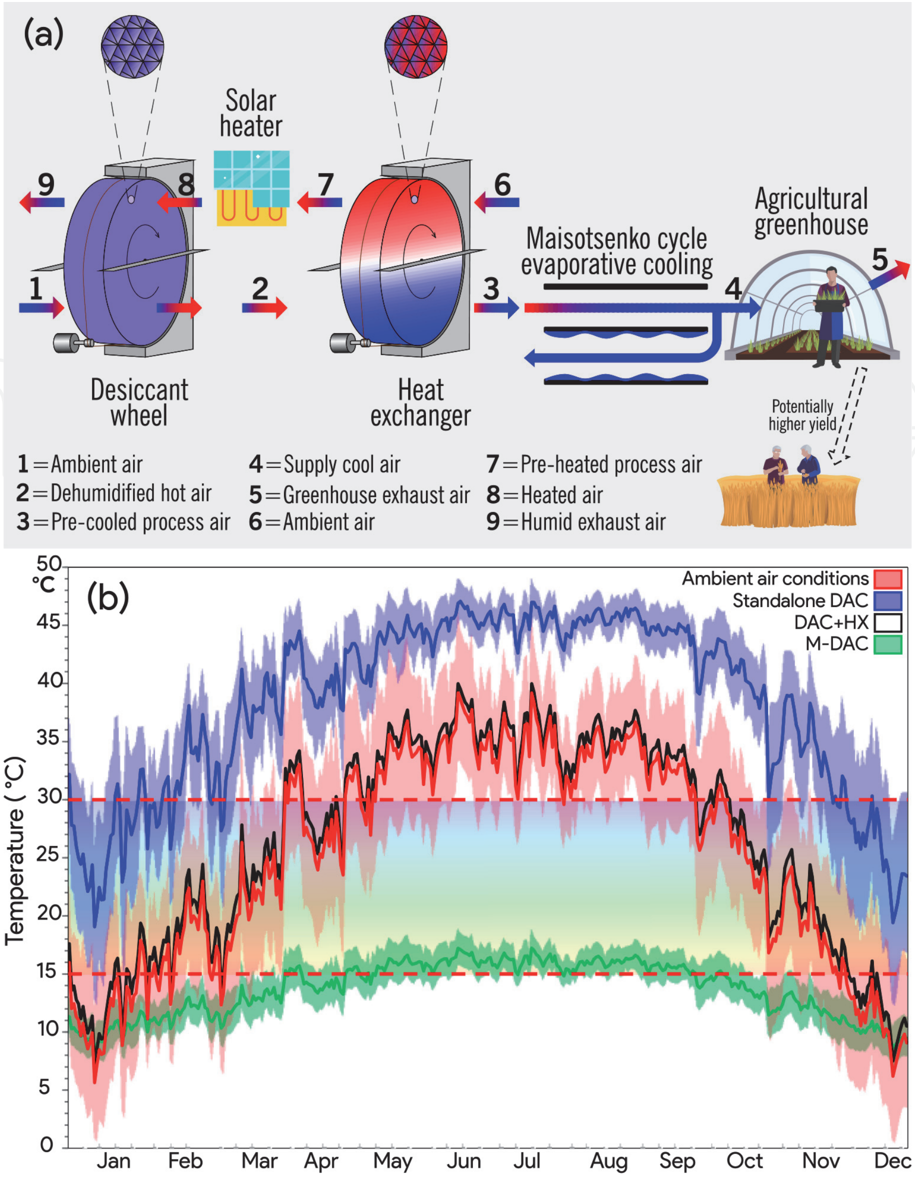

Figure 25.
(a) Schematic diagram of desiccant based Maisotsenko cycle evaporative cooling system, and (b) performance profile of standalone DAC and M-DAC systems for greenhouse air-conditioning in Multan (Pakistan), reproduced from [33].

4. Conclusions and summary

In this study, the authors summarized different evaporative cooling and desiccant air-conditioning options for next generation greenhouses. The authors summarized direct, indirect, and Maisotsenko cycle evaporative cooling options for different air-conditioning options including next generation greenhouses from the point of view of optimum temperature/humidity conditions and vapor pressure deficit inside the greenhouse. The authors concluded that only Maisotsenko cycle evaporative cooling system was able to achieve the required conditions under limited climatic applicability. However, performance of the Maisotsenko cycle evaporative cooling system could be enhanced using desiccant dehumidification. The authors summarized different desiccant materials (i.e., silica-gels, activated carbons, polymer sorbents, and metal organic frameworks) and impact of desiccant material and adsorption temperature on adsorption uptake. The authors concluded that each of the studied desiccant material somewhat achieved the required conditions. However, polymer sorbents and metal organic frameworks had relatively the highest adsorption uptake as compared to other materials. However, silica-gel based desiccant dehumidification system was able to achieve relatively more humidity gradient (i.e., difference between inlet and outlet humidity) for more adsorbent material to air mass fraction.

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Conflict of interest

The authors declare no conflict of interest.

Author details

Muhammad Sultan[1*†], Hadeed Ashraf[1†], Takahiko Miyazaki[2,3], Redmond R. Shamshiri[4] and Ibrahim A. Hameed[5]

1 Department of Agricultural Engineering, Bahauddin Zakariya University, Multan, Pakistan

2 Faculty of Engineering Sciences, Kyushu University, Fukuoka, Japan

3 International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Kyushu University, Fukuoka, Japan

4 Department of Engineering for Crop Production, Leibniz Institute for Agricultural Engineering and Bioeconomy, Potsdam-Bornim, Germany

5 Department of ICT and Natural Sciences, Faculty of Information Technology and Electrical Engineering, Norwegian University of Science and Technology (NTNU), Ålesund, Norway

*Address all correspondence to: muhammadsultan@bzu.edu.pk

† These authors contributed equally to this work.

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