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Comprehensive review on dehumidification strategies for agricultural greenhouse applications

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HIGHLIGHTS

- A review on the different dehumidification methods in the agricultural industry.
- Main dehumidification methods are ventilation, condensation, and adsorption.
- Discussion on the advantages and disadvantages of various dehumidification methods.
- Analyzing energy consumption and operating cost of dehumidification methods.
- Identifying opportunities for further research and development in this area.

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ABSTRACT

Humidity is one of the important climate parameters in greenhouse food production. Maintaining humidity levels within the optimal growth range enhances yield. Moreover, excessively high relative humidity leads to diseases and deterioration of the crops. This paper presents a state-of-the-art review of the various dehumidification technologies available in the agricultural industry. Several novel conceptual designs from the literature are also discussed. The principal humidity control approaches utilized in greenhouses are ventilation (natural and forced), maintaining a high temperature, condensation on a cold surface, and adsorption by hygroscopic materials. The most common method for dehumidification is ventilation due to its minimal infrastructure. Although this method is considered the simplest, it causes additional sensible heating loads, particularly in colder climates. The added heating load can be reduced, ideally eliminated, by employing heat recovery systems. Furthermore, dehumidification by controlled condensation on a cold surface enables the capture and re-use of the latent energy released in condensation. By adsorption of water vapor using hygroscopic material, the latent heat of condensation is converted to sensible heat, which can be used for space heating in the greenhouse. Such a system can reduce the greenhouse humidity while maintaining a more uniform temperature profile over the crop canopy and reducing energy consumption. Finally, it is essential to emphasize that an appropriate dehumidification method should prevent condensation on plant surfaces, and also its operational cost should be as low as reasonably achievable to remain beneficial for growers.

1. Introduction

Climate control plays a vital role in high-yield greenhouse food production [1]. The most essential climatic parameters to be controlled are temperature, humidity, CO_2 concentration, and supplemental lighting. An optimum crop growth condition is crucial to increase crop quality and yield. Several researchers concentrated on the climate control of greenhouses. Hand [2] reported that physiological disorders and plant diseases occurred for vapor pressure deficit (VPD) of less than 0.2 kPa. Shamshiri et al. [3] provided a detailed summary of optimal temperatures, relative humidity (RH), and VPD for the greenhouse cultivation of tomato. Cuce et al. [4] reviewed various environmentally-friendly, energy-efficient, and cost-effective innovations for potential use in greenhouses to reduce the emission levels and energy consumption. Li et al. [5] discussed the crucial parameters affecting the greenhouse performance and reported that the inside flow pattern, thermal characterizes, total solar radiation, wind velocity and direction, and the greenhouse shape and its orientation had a significant impact

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Nomenclature

c_p	specific heat (J/kg K)
COP	coefficient of performance
h	enthalpy (kJ/kg)
HRV	heat recovery ventilator
L_v	heat of vaporization (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
MRR	moisture removal rate (kg/s)
p	pressure (Pa)
$\dot{Q}$	heat transfer rate (W)
RH	relative humidity (%)
T	temperature (°C)
V	volumetric flow rate (m^3/s)
VPD	vapor pressure deficit
$\dot{W}_{comp}$	compressor power (W)

Greek letters

ρ	density (kg/m^3)
ω	humidity ratio (kg/kg)
ε_s	sensible effectiveness

Subscripts

cond	condenser
eva	evaporator
sat	saturation
w	water

on the greenhouse performance. Singh et al. [6] reviewed studies of natural ventilation, shading, and evaporative cooling to control the inside climate of the greenhouse in the summer. Torre-Gea et al. [7] summarized the state-of-the-art computational fluid dynamics studies on the climatic conditions of greenhouses.

Humidity is the most complicated climatic parameter to control in the horticulture industry. Maintaining set points for the moisture is a challenge for control and monitoring devices. Relative humidity varies with air temperature and plants continuously release moisture to the air. Additionally, humidity control is vital for the health of the crops and the prevention of diseases. Fig. 1 demonstrates that humidity in the horticulture industry is a big challenge. Too dry of an environment slows down the plant growth, while excessive moisture causes plant diseases [8]. Moreover, humidity control is rather energy-intensive, especially in colder climates. Therefore, humidity control plays a vital role in climate control of greenhouses.

Several researchers summarized the studies on the indoor climate control of agricultural greenhouses. Singh et al. [6] reviewed natural ventilation, shading, and evaporative cooling techniques for controlling the microclimate of greenhouses. Syed and Hachem [9] and Li et al. [5] discussed the influential parameters affecting the heating, ventilation, and air-conditioning of a greenhouse. Ghani et al. [10] highlighted the merits of energy-efficient cooling methods implemented in modern greenhouses in the hot and arid environments. While climate control in greenhouse horticulture has been the subject of numerous studies, an energy-focused review and assessment of the humidity control methodologies is missing from the literature. The present paper is an attempt to address that gap by providing an overview of the general approaches to humidity control in greenhouses, namely conventional natural ventilation, forced ventilation, maintaining a high temperature, condensation on a cold surface by using refrigeration-based systems or heat exchangers, and adsorption by a hygroscopic material such as various types of desiccants. A detailed review of the corresponding research studies, with a focus on energy consumption, is presented. Opportunities for further research and development in this area have been identified in the hope that they will guide future research efforts.

2. Why dehumidification is needed?

Humidity in greenhouses is monitored and controlled for different reasons. The humidity of air can be quantified in terms of the humidity ratio, defined as the mass ratio of water vapor and dry air, as shown in Eq. (1) [11].

$$\omega = \frac{m_{\mathrm{vapor}}}{m_{\mathrm{air}}}[\mathrm{kg/kg}] \tag{1}$$

Another standard parameter to quantify the humidity content of air is relative humidity (RH), which is defined as the ratio of the partial water vapor pressure in moist air to the saturation pressure at the air temperature (see Eq. (2)) [11].

$$\mathrm{RH} = \frac{p_{\mathrm{vapor}}}{p_{\mathrm{sat}}}[\%] \tag{2}$$

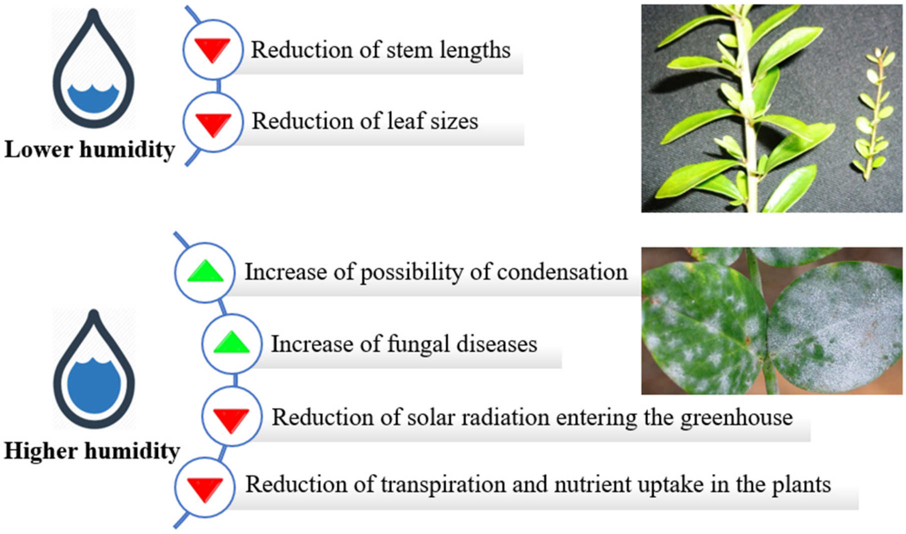

Fig. 1. Effects of lower and higher humidity levels in greenhouses.

While the air temperature varies throughout the greenhouse as dictated by various factors such as solar radiation, transpiration by crops, heating, and ventilation [12], the absolute humidity (humidity ratio) is generally uniform [13]. Therefore, RH can be taken as a function of the temperature distribution. Where the temperature is lower, RH is larger, increasing the chance of condensation.

Generally, it is suggested that greenhouse air RH should be kept in the range of 60–80% for healthy growth. Low humidity leads to reduced stem lengths and leaf sizes, which inhibit plant growth [14]. Also, few fungi develop in low RH. On the other hand, higher humidity levels increment the possibility of condensation on leaves, especially at night, which results in developing Botrytis and other fungal diseases. At high humidity levels, plants cannot evaporate water from their leaves, so the uptake of nutrients such as boron and calcium may be limited. Moreover, condensation on the greenhouse cover can reduce the solar radiation entering the greenhouse by as much as 23% [15]. Bakker [16], for instance, has reported that high humidity in greenhouses has a significant influence on light interception which leads to the decrement of photosynthesis and leaf area index (calcium deficiency), an increase in the number of the leaves, and growth of fungi [17]. The principal sources of moisture in greenhouses are plant transpiration and the evaporation of water from the soil. The combination of transpiration from plant and evaporation from the soil is referred to as evapotranspiration. It must be noted that preventing excessive humidity levels is particularly challenging in closed greenhouses which are gaining popularity in colder climates [18].

The ideal humidity levels for a plant are usually determined based on water stresses, extreme weather conditions, danger of fungus/pest/insect attack, maturity stage, and plant growth stage [19,20] and reported in terms of VPD, defined as the difference between the absolute humidity of the air and the absolute humidity of saturated air at the temperature of the greenhouse (see Eq. (1)) [21].

$$VPD = p_{\mathrm{sat}} - p_{\mathrm{vapor}}\,[kPa] \tag{3}$$

Fig. 2 illustrates the ideal and typical greenhouse growth zones for horticultural crops: VPDs in the range of 0.45–1.25 kPa are usually suitable for greenhouse crops with 0.8–0.9 kPa being the ideal range [22].

3. Dehumidification methods

The methods used to dehumidify greenhouses can be categorized into four groups based on their working principle: ventilation (natural and forced), maintaining a high temperature, condensation on a cold surface, and adsorption by hygroscopic materials. In the following, these categories and their application in greenhouses are discussed, and a review of the relevant literature is presented.

3.1. Ventilation

Ventilation is the most prevalent method for climate control in greenhouses, specifically for dehumidification and sensible cooling [24]. Kacira et al. [25] have proposed that the ratio of the opening area to the ground area of the greenhouse must be in the range 0.15–0.25 to ensure adequate ventilation in the greenhouse. Ventilation achieved by merely opening the vents, without active pressurization, is referred to as natural or passive [26]. When fans are used to augment air exchange, ventilation is referred to as forced [27].

3.1.1. Natural ventilation

Natural ventilation does not create additional heating demand when used to reduce the greenhouse temperature while excess heat is available in the greenhouse. If the need for ventilation to remove moisture from the greenhouse is larger than the need for sensible cooling (reducing the temperature), ventilation leads to additional heating loads. The warm, humid greenhouse air is replaced by cold, dry outdoor air, lowering the temperature inside the greenhouse. The sensible heat loss in the greenhouse is given by [11]:

$$\dot{Q}_{sensible} = c_p \rho_{air} V_{vent}\,(T_i - T_o)[\mathrm{W}] \tag{4}$$

where ρ_{air} is the density of air, c_p is the specific heat of air, V_{vent} is the air exchange rate through the vent (window), and T_i and T_o are the temperatures of the air inside and outside of the greenhouse.

In addition to sensible heat, latent heat is also removed through ventilation [11]:

$$\dot{Q}_{latent} = L_v \rho_{air} V_{vent}\,(w_i - w_o)[\mathrm{W}] \tag{5}$$

where w_i and w_o are the humidity ratio of indoor and outdoor air

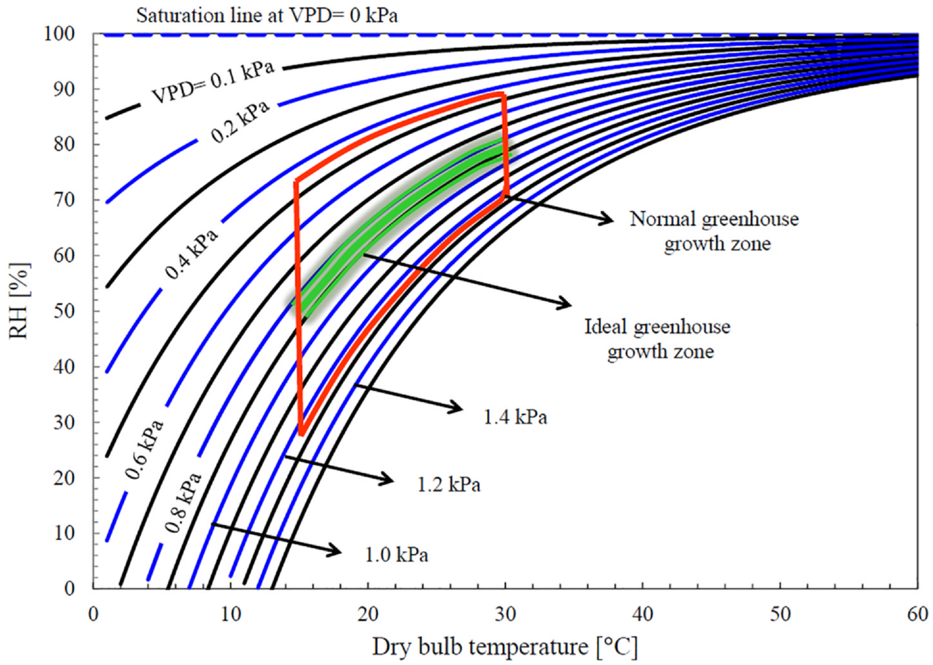

Fig. 2. Typical and ideal greenhouse growth conditions based on VPD [23].

respectively, and L_v is the latent heat of vaporization.

The air exchange rate $V_{dehumid}$ needed to maintain the humidity ratio set point w_i in the greenhouse is calculated by

$$V_{dehumid} = \frac{\phi_{trans} - \phi_{cond}}{w_i - w_o}[m^3/s] \quad (6)$$

where ϕ_{trans} and ϕ_{cond} are the vapor mass fluxes due to transpiration and condensation. The desirable air exchange rate is the larger of the ventilation rates required for humidity and temperature control.

Natural ventilation is driven by a difference in the pressure of greenhouse indoor and outdoor. This pressure difference depends on many factors, e.g., temperature, size, and location of the openings, wind

Table 1
Summary of studies conducted on the natural ventilation in greenhouses.

Author	Ventilation	Analysis	Location of greenhouse	Area of greenhouse (m^2)	Crop	Studied parameters
Baptista et al. [24]	Wind-driven	Experimental & Theoretical	United Kingdom	205	Tomato	● wind speed ● wind direction ● in/out temperature difference ● ventilator aperture
Kacira et al. [25]	Wind-driven	Numerical	Japan	2400	–	● wind speed ● side ventilators ● greenhouse span numbers
Papadakis et al. [28]	Wind-driven	Experimental	Greece	384	–	● wind speed ● wind direction ● ventilator opening area
Boulard and Baille [29]	Wind-driven	Theoretical	France	416	–	● wind speed ● wind direction ● opening angle
Bartzanas et al. [30]	Wind-driven	Numerical	Greece	160	Tomato	● vents configuration
Rico-Garcia et al. [31]	Buoyancy-driven	Numerical	Mexico	1872	–	● inside temperature
Benni et al. [32]	Wind-driven	Numerical	Italy	307	–	● wind direction ● roof opening configuration
Boulard and Draoui [33]	Wind-driven	Theoretical	France	416	–	● wind speed ● wind direction ● opening angle
Boulard et al. [34]	Wind-driven	Experimental & Theoretical	France	200–400	Tomato	● opening position and type ● wind speed
Boulard et al. [35]	Wind-driven	Experimental & Theoretical	France	368	Tomato	● wind speed ● vent opening rate
Bournet et al. [36,37]	Wind-driven	Numerical	France	2500	Ornamental plants	● vents configuration
Campen and Bot [38]	Wind-driven	Numerical	Spain	881	No crop	● wind speed ● wind direction ● roof openings configuration
Fernandez and Bailey [39,40]	Wind-driven	Experimental	United Kingdom	422	Tomato	● wind speed ● wind direction ● in/out temperature difference ● ventilator aperture
Boulard et al. [41]	Buoyancy-driven	Numerical	–	3.3	–	● vent arrangement
Ganguly and Ghosh [42]	Wind-driven	Numerical	India	90	Flowers	● wind speed ● solar radiation ● greenhouse dimension
De Halleux and Gauthier [43]	Wind-driven	Simulation	Canada	10,000	Tomato	● mode of ventilation
Harmanto et al. [44]	Wind-driven	Experimental	Thailand	200	Tomato	● size of ventilation opening area
He et al. [45]	Wind-driven	Numerical	China	1980	Lettuce	● vents configuration ● vent opening size
Montero et al. [46]	Wind-driven	Experimental	United Kingdom	0.8	No crop	● vents configuration
Ould Khaoua et al. [47]	Wind-driven	Numerical	France	2600	Ornamental plants	● wind speed ● roof opening configuration
Roy and Boulard [48]	Wind-driven	Numerical	France	176	Tomato	● wind direction
Shklyar and Arbel [49]	Wind-driven	Numerical	Israel	10,200	No crop	● wind direction ● opening angle of the vent
Baeza et al. [50]	Buoyancy-driven	Numerical	Spain	881	No crop	● vents arrangement ● greenhouse dimensions ● anti-insect screen
Short and Lee [51]	Wind-driven	Numerical	–	–	–	● wind speed ● wind direction ● side opening size and location
Teitel and Tanny [52]	Wind-driven	Experimental & Theoretical	Israel	960	Pepper	● opening of roof windows ● height of window opening ● wind speed ● solar radiation
Teitel et al. [53]	Wind-driven	Experimental & Numerical	Israel	960	Pepper	● wind direction
Teitel et al. [54]	Wind-driven	Theoretical	Israel	69	Rose	● wind speed
Kittas et al. [27]	Wind-driven	Experimental	France	179	–	● wind speed ● wind direction ● opening angle

velocity and direction, making the characterization and modeling of ventilation complicated. A summary of research studies investigating the effects of wind and buoyancy forces on natural ventilation in greenhouses is presented in Table 1.

There are two fundamental driving forces causing pressure difference, hence inducing natural ventilation: the wind and the buoyancy force created by gradients in the density of air. The density is affected by the temperature and the moisture content of air, which are most importantly influenced by the solar heat gain, envelope heat losses, transpiration, and photosynthesis. Ventilation in a greenhouse is usually caused by a combination of wind and buoyancy effects. Mistriotis et al. [26,55] reported that for wind speeds in the range of 0.5–2 m/s, the main driving force for ventilation was wind, and the buoyancy effects remained remarkable and cannot be neglected. However, Boulard et al. [56], Kittas et al. [57], Papadakis et al. [28], and Boulard and Baille [29] concluded that the wind forces overcome the buoyancy forces when the wind speed exceeds 1.8–2 m/s. Nevertheless, Boulard and Baille [29] have shown that the wind speed threshold is dependent on some factors, including the temperature difference between the indoor and outdoor air, greenhouse geometry, opening positions, and height of the equivalent chimney.

Some studies have shown the buoyancy effect to be the dominant driving force in greenhouses when the wind speed is low. Boulard et al. [41] observed some air loops between the roof openings and the greenhouse warm floor and Rico-Garcia et al. [31] reported a stagnant effect in the center of the greenhouse. Baeza et al. [50] concluded that employing roof and sidewall openings leads to improved ventilation rates. Additionally, Fernandez and Bailey [39,40] and Baptista et al. [24] reported that the inside-outside temperature difference affected ventilation rate under low wind speeds and has no influence on the ventilation rate of the greenhouse located in a windy area.

In the case of prevailing wind effect, most of the studies concluded that the air exchange rate in greenhouses is linearly dependent on the wind speed [24,28,33,35,39,40,47,54]. Boulard et al. [34], Kacira et al. [25], and Campen and Bot [38] have presented linear correlations between the air exchange rate and wind speed only in case of negligible buoyancy effects. In contrast, Boulard and Baille [29] have reported that the dependency of the ventilation rate on the wind speed slightly decreases as the wind speed increases. In addition to the wind speed, the effect of wind direction on the ventilation has been the subject of several studies. In some studies, the wind direction has been reported to have no significant influence on the ventilation rate in greenhouses [24,28,29,33,39,40]. In contrast, several other studies have reported considerable effects on the air velocity, temperature, and humidity inside the greenhouse [32,38,48,49,53]. For example, Campen and Bot [38] observed a 50% increase in the ventilation rate by only 10° change in the wind direction. Since the wind is never constant in speed and direction, climate differences in the greenhouse are never constant, which could be the reason for the discrepancy of the reported results. Therefore, it would be desirable to carry out more studies on the effect of the wind direction.

The effects of the opening arrangement on natural ventilation in greenhouses have also been the subject of several studies. The majority of studies showed that the maximum greenhouse ventilation rate is achieved when both sidewall and roof vents are used [25,28,36,37,45]. For instance, He et al. [45] demonstrated that the sidewall plus roof openings are 1.2–6.4 times more efficient than roof or sidewall openings alone, respectively. Ganguly and Ghosh [42] revealed that the distance between the roof and side openings significantly influences greenhouse ventilation. Simulations by Bournet et al. [36,37] showed that sidewall openings at the lowest parts of the wall must be avoided as they cause a jet stream directly impinging on the crop. However, Short and Lee [51] revealed that by embedding the sidewall opening in the lower section of the greenhouse wall, the air mixing is enhanced, and the temperature at the canopy level becomes more uniform. Bartzanas et al. [30] showed that the replacement of roll-up openings with pivoting openings creates a distinct airflow pattern where the flow along the roof was intensified. At the same time, in the rest of the greenhouse, the flow patterns was more homogeneous. Similar observations have been reported by Montero et al. [46], while conflicting results were obtained by Campen and Bot [38], who found the roll-up opening to have higher ventilation rates than the pivoting type.

3.1.2. Forced ventilation

Forced ventilation by fans or blowers expedites air exchange and the removal of the excess moisture. It is noteworthy that forced ventilation offers more control over the ventilation rate, which is essential because “incomplete” ventilation can lead to uneven CO_2 distribution, low greenhouse VPD, and high temperature [58]. In this approach, the intake air can be mixed and distributed more homogeneously inside the greenhouse [59]. Moreover, unlike natural ventilation, forced ventilation is notdependent on the buoyancy or wind forces [60].

Forced ventilation is a common practice for greenhouse dehumidification in the summertime and in tropical areas [61]. In cold climates, forced ventilation causes heat loss from the greenhouse, resulting in a higher heating requirement, which makes it uneconomical [62]. Kittas et al. [27] showed that forced ventilation reduces overheating in the greenhouse and is a beneficial tool for reducing solar irradiation and improving the greenhouse climate conditions. In another study, Flores-Velazquez et al. [63] concluded that, due to better mixing, the combination of roof openings and fan-induced ventilators improves the climate conditions in comparison with fan ventilation only. Campen et al. [64] developed an air distributor to adjust air exchange with the cold outdoor air (see Fig. 3). The return air passed through thermal screens and went back to ventilators. They concluded that this system is easily controllable and increased the ventilation efficiency of the greenhouse. Therefore, the humidity set points could be adjusted more strictly, thereby saving energy.

3.2. Maintaining a high temperature

The RH inside the greenhouse tends to increase during the night due to lower temperatures in the greenhouse, while the humidity ratio is almost the same as in the daytime. As the greenhouse gets colder at night, the RH increases and may reach saturation levels, resulting in condensation on the greenhouse envelope and plants. Thus, maintaining a high temperature inside a greenhouse in the evening can be an effective method to reduce RH without reducing the humidity ratio [62]. For this purpose, supplemental heating or extra thermal insulation, e.g. through thermal screens, are required. Since air temperature should be maintained at an optimum level in greenhouses, this method is useful only for reducing the RH in the evenings. It is not helpful for

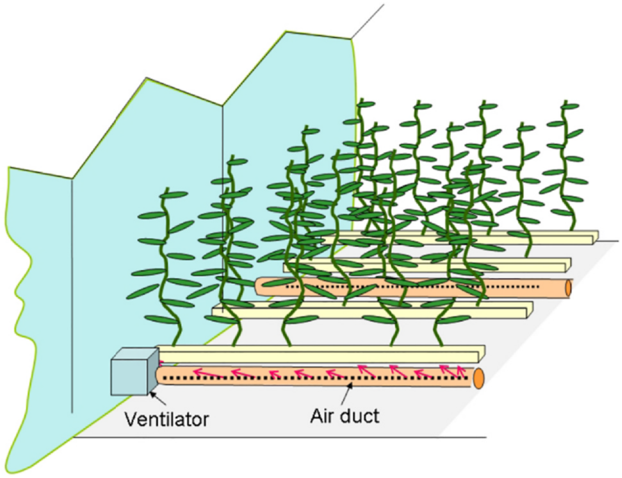

Fig. 3. A schematic of a forced ventilation system by mechanical devices [64].

regular daytime or nighttime temperature and RH management.

3.3. Condensation on a cold surface

Moisture can be removed from the air through condensation. Once the humid air in the greenhouse comes in contact with an object with a lower temperature than its dew point, the water content of the air condenses and is removed from the air. In this approach, the humid air inside the greenhouse is cooled down to saturation, for example, by using chilled water or air. The actual moisture removal rate (MRR) from the greenhouse by condensation on a cold surface can be calculated using Eq. (5) [11]:

$$MRR = \rho_{air} V_{air} (\omega_i - \omega_o) [\mathrm{kg/s}] \tag{7}$$

where V_{air} is the volumetric flow rate of the air passing over the cold surface.

Condensation on a cold surface can occur by utilizing natural convection condensation, mechanical refrigeration with controlled condensation, and air-to-air heat exchangers. Table 2 summarizes studies of dehumidification using this approach.

3.3.1. Natural convection condensation

Water vapor can be removed by natural convection condenstaion on cold surfaces, e.g. finned tubes cooled by chilled water or air. Campen and Bot [65] devised a low-energy buoyancy-driven dehumidification approach for greenhouses consisting of cold and hot surfaces for condensation and heating. Their experimental results showed that the prototype of 1 m length of the finned tube could remove 50–65 ml/h of water vapor from the greenhouse air. The system has been reported to be scalable [65]. In another study, they examined finned tubes with chilled water flowing through them for dehumidification of a greenhouse [66]. Fig. 4 shows the finned tubes and their location under the gutter. The humid air moved across the fins by natural convection. They have reported 40 g/(hm^2) moisture removal from the moist air with 80% RH and a temperature of 20°C during the heating periods. Fig. 5 illustrates the latent heat removal in terms of a temperature difference for greenhouse air with various RH. As can be seen from the figure, less than 40, 30, and 25% of total heat removal by finned tubes were associated with the latent heat for the air with RH of 90, 80, and 70%, respectively. The capital and energy cost were not taken into account in their study.

3.3.2. Mechanical refrigeration with controlled condensation

Mechanical refrigeration systems can provide controlled condensation on a cold surface. Controlled condensation is typically achieved through heat pumps where an electrically-driven refrigeration cycle removes water vapor from the air. There is excellent potential in employing a heat pump system for greenhouse air-conditioning based on its ability to perform the functions of heating, cooling, and dehumidification. The energy extracted during condensation can be re-used to reduce the net energy consumption. In a survey of the energy-saving options for greenhouses in the Netherlands, Saye et al. [67] have pointed out the high energy saving potentials of recirculating the heat absorbed by the heat pump dehumidifier back to the greenhouse. A schematic view of a dehumidifying heat pump is illustrated in Fig. 6. As shown in this figure, the heat pump operates in a closed cycle with a refrigerant. The refrigerant in the evaporator is at temperatures below the dew point of the air stream. As the humid air from the greenhouse passes through the evaporator, the temperature drops below the dew point and the moisture in the air undergoes a phase change. As a result, the air becomes dryer and colder. The heat exchange at the evaporator $\dot{Q}_{eva}$ and the condensed water mass was then defined as [11]:

$$\dot{Q}_{eva} = \rho_{air} V_{air} (h_1 - h_2) [\mathrm{W}] \tag{8}$$

$$\dot{m}_w = \rho_{air} V_{air} (\omega_1 - \omega_2) [\mathrm{kg/s}] \tag{9}$$

where h_1 and h_2 are the air enthalpies at the inlet and outlet of the evaporator, respectively. In the next step, the air passes through the condenser, absorbs heat, and as a result, becomes warmer. Latent heat released during moisture condensation is used as additional sensible heat for the greenhouse. The power exchange at the condenser $\dot{Q}_{cond}$ may be written as [11]:

Table 2
Summary of studies conducted on the dehumidification of greenhouses by using condensation on a cold surface.

Author	Dehumidification	Analysis	Location of greenhouse	Area of greenhouse (m^2)	Crop
Campen and Bot [65]	Natural convection condensation	CFD & Experimental	Netherlands	–	Cucumber
Campen and Bot [66]	Condensation on finned tubes	Experimental & CFD	Netherlands	160	Cucumber
Saye et al. [67]	Heat pump	Theoretical	Netherlands	–	–
Yildiz and Stombaugh [68]	Heat pump	Simulation	USA	244	Cucumber
Gilli et al. [69]	Heat pump	Experimental	Switzerland	358	Tomato
Han et al. [70]	Heat pump	Experimental	Canada	843	Tomato
Chantoiseau et al. [71]	Heat pump	Experimental	France	2350	Flower
Migeon et al. [72]	Heat pump	Experimental	France	2350	Potted plants
Lycoskoufis and Mavrogianopoulos [73]	Heat pump	Experimental	Greece	63 135	Cucumber
Arbel et al. [74]	Heat pump	Experimental	Israel	1100	Pepper
De Zwart [75]	Heat pump	Experimental	Netherlands	500	Tomato
Cámara-Zapata et al. [76]	Heat pump	Experimental	Spain	877	Tomato
Chasseriaux [77]	Heat pump	Theoretical	France	3000	Rose
Boulard et al. [78]	Heat pump	Experimental & Theoretical	France	400	Tomato
Chassériaux and Gaschet [79]	Heat pump	Theoretical	France	2340	Flower
Han et al. [80]	Heat pump Air-to-air heat exchanger	Experimental	Canada	266	Tomato
Campen et al. [81]	Heat pump Air-to-air heat exchanger	Simulation	Netherlands	–	Tomato Pepper Rose Cucumber
Rousse et al. [82]	Air-to-air heat exchanger	Experimental	Canada	220	Tomato, Cucumber
Albright and Behler [83]	Air-liquid–air heat exchanger	Experimental & Theoretical	USA	240	–
De Halleux and Gauthier [43]	Air-to-air heat exchanger	Simulation	Canada	10,000	Tomato
Han et al. [84]	Air-to-air heat exchanger	Experimental	Canada	843	Tomato
Maslak and Nimmermark [85]	Air-to-air heat exchanger	Simulation	Sweden	80,000	Tomato
Zhou et al. [86]	Active heat storage release	Experimental	China	264	Tomato

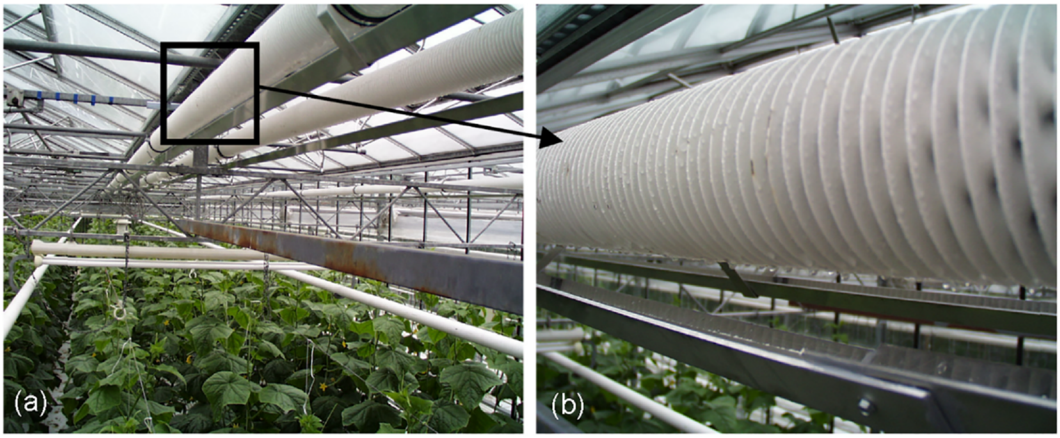

Fig. 4. Photo of the greenhouse dehumidification by condensation on finned pipes [66]. The humid air moves across the fins by natural convection.

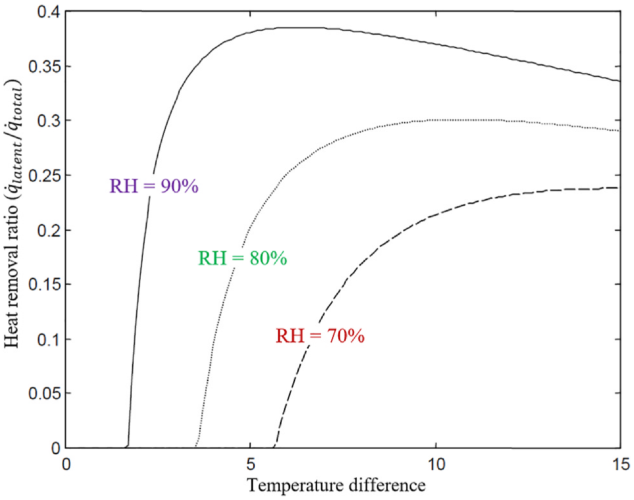

Fig. 5. Heat removal ratio versus temperature difference for different RHs [66].

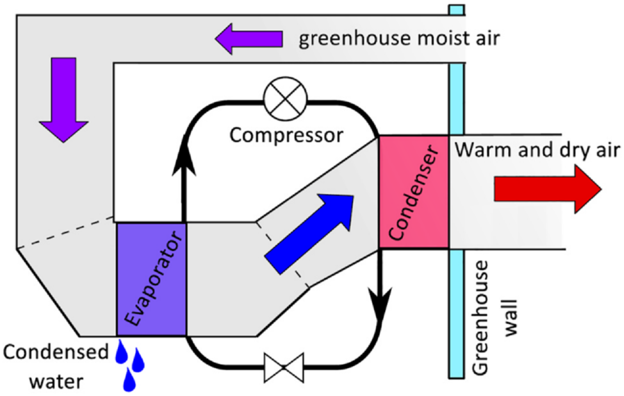

Fig. 6. Airflow in a heat pump dehumidifier [71].

$$\dot{Q}_{cond} = \rho_{air} V_{air} (h_3 - h_2)[\mathrm{W}] \tag{10}$$

where h_2 and h_3 are the air enthalpies at the inlet and outlet of a condenser, respectively.

The efficiency of a heat pump can be expressed in terms of the coefficient of performance (COP), determined by dividing the desirable effect of the heat pump by the electrical power needed to run the heat pump (Compressor energy consumption ($\dot{W}_{comp}$) and the energy need for the defrost of the evaporator ($\dot{Q}_{defrost}$)), at a specific temperature. The higher the COP, the more efficient the heat pump. See Eq. (11) [11]:

$$COP = \frac{\dot{Q}_{cond}}{\dot{W}_{comp} + \dot{Q}_{defrost}} \tag{11}$$

Although dehumidification using heat pumps is very useful, it is also energy-intensive. For example, for a greenhouse at 22°C and 80% RH, cooled to 5°C and 100% RH, the absorbed sensible and latent heats are nearly equal. Thus, only 50% of the power consumption of a heat pump goes toward dehumidification; the rest results in a cooling effect,which is not desirable, but unavoidable [65].

Most studies have shown that heat pump dehumidifiers are a promising option with excellent water and energy savings. This method is especially attractive for closed greenhouses, facilitating the control of CO_2 and humidity levels [68,69]. Han et al. [70,80] compared dehumidification options using a heat pump dehumidifier, an air–to–air heat exchanger, and an exhaust fan system in a commercial tomato greenhouse in Saskatchewan, Canada and showed the heat pump system to have the lowest overall energy consumption. At the same time, it was the most expensive approach due to its high electricity consumption. Campen et al. [81] concluded that heat pump dehumidifiers are not economical, unless used for space heating too. Chantoiseau et al. [71] and Migeon et al. [72] observed no sign of plant diseases by using a heat pump dehumidifier with 4 W/m^2 energy consumption and found that the energy consumption was 3–8 times less than in the case of dehumidification through natural ventilation, depending on the outdoor conditions. In another study, Arbel et al. [74] indicated that the heat pump system was capable of energy savings of about 80% compared to natural ventilation. Cámara-Zapata et al. [76] employed a heat pump with a COP of 2.5 and water removal of 16.2 g/(hm^2) and concluded that it would be beneficial for temperatures higher than 15°C and RH's of 84–88%. Chasseriaux [77], Boulard et al. [78], and Chassériaux and Gaschet [79] concluded that the system could remove the excess moisture to avoid condensation on the roof and dripping on the plants. At the same time, it could not decrease the humidity level of air, notably if the system was not powerful enough. De Zwart [75] proposed an internal heat pump dehumidification system, as shown in Fig. 7. The greenhouse air is cooled to around 14°C to condense some of the water vapor; then, using a second heat exchanger, the air is heated back to its original temperature. The results revealed that the heat exchanger required 2.2 times the latent heat extraction as cooling power. In other words, on average, condensing 20 g/(hm^2) of water vapor content requires 30 W/m^2 for cooling and 16 W/m^2 for reheating the air that is inevitably cooled down during condensation.

3.3.3. Air-to-air heat exchangers

Air-to-air heat exchangers are an alternative controlled condensation mechanism, preferable in cold climates. These heat exchangers, known as heat recovery ventilators (HRVs), are designed to extract the

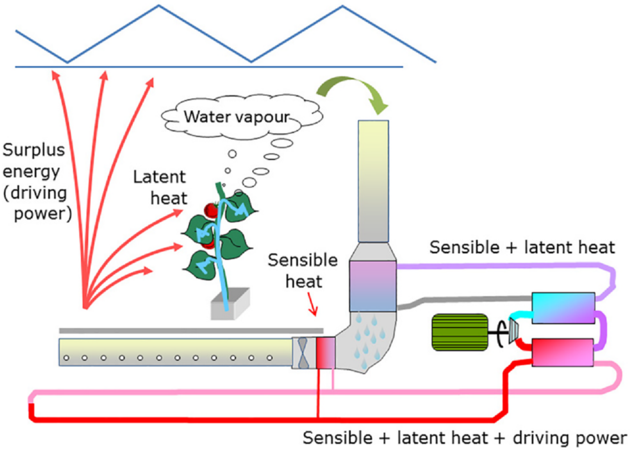

Fig. 7. A sketch of the internal heat pump dehumidification system proposed in Ref. [75].

heat from the exhaust air and heat the incoming fresh outdoor air. In the winter, the warm indoor air is often cooled down to its dew point to initiate condensation. Fig. 8 shows a schematic view of HRV units.

Heat recovery systems are evaluated based on effectiveness, defined as the ratio of the actual sensible heat recovered to the maximum sensible heat that could be recovered by the unit, according to Eq. (10) [88].

$$\varepsilon_s = \frac{\dot{m}_{air} c_{p,air} (T_2 - T_1)}{(\dot{m}_{air} c_{p,air})_{min} (T_3 - T_1)} \tag{12}$$

where T_1 and T_2 are the temperature of supply air stream before and after the heat recovery system, while T_3 is the temperature of exhaust air stream before the heat recovery system.

Some studies have considered air-to-air heat exchangers for dehumidifying greenhouses. The majority of studies proved air-to-air heat exchangers to be the most efficient approach, especially during cold seasons. De Hallaux and Gauthier [43] and Campen et al. [81] concluded that using heat exchangers could lower the energy consumption and that their benefits depend on the energy consumption and the effectiveness of the heat exchanger. Campen et al. [81] reported savings of 0.31–0.84 €/m^2 for various crops by using air-to-air heat exchangers. Rousse et al. [82] and Albright and Behler [83] reported that condensation plays a significant role in the overall heat exchange and that only about one-third of the enthalpy could be recovered from the exhaust air. Han et al. [84] employed an air-to-air heat exchanger to provide dehumidification for a commercial tomato greenhouse located west of Saskatoon, Canada, in cold weather conditions, which is illustrated in Fig. 9. They concluded that while the heat exchanger was beneficial during cold and mild weather conditions, it did not meet the ventilation requirements and was less effective during early mornings and nights in summer. Increasing the dehumidification capacity of the heat exchangers to meet the requirements proved to be too costly. Maslak and Nimmermark [85] modeled a rotary air–to–air heat exchanger for dehumidifying a greenhouse, as shown in Fig. 10. The rotary heat exchanger transfers energy in the form of both latent and sensible heat. The effectiveness of the heat exchanger was reported 70%. The overall energy consumption was reduced by up to 17% compared to natural ventilation.

3.4. Adsorption by hygroscopic materials

Adsorption of water vapor by hygroscopic materials can be used to remove moisture from the air and decrease the humidity. Desiccants are hygroscopic materials that adsorb moisture and are commonly used for humidity management. Desiccant systems are categorized, based on the sorbent material, into two types: liquid and solid. Liquid desiccant systems act based on an open-loop chemical absorption cycle and a low-grade heat source (see Fig. 11(a)). The moist air is brought in contact with a rich desiccant solution. The water content of air is absorbed due to the VPD difference, resulting in dehumidification and dilution of the desiccant solution. In regeneration, low-grade heat is employed to desorb the water to an air stream and regenerate the desiccant solution. Calcium chloride, lithium bromide, and lithium chloride are commonly-used liquid desiccants [89,90]. Solid desiccants are environmentally-friendly, non-corrosive, non-flammable, and less expensive than liquid desiccants. Furthermore, solid desiccants are not chemically reactive with moist air. Solid desiccant dehumidifier is generally a slowly rotating desiccant wheel or a periodically regenerated adsorbent bed [91]. Fig. 11(b) illustrates a desiccant wheel dehumidifier consisting of adsorption and desorption sections. In the adsorption section, the moist air moves through the desiccant for dehumidification. In the desorption section, the adsorbed water is removed from the desiccant by a stream of hot air. Zeolite, titanium silicates, and activated silica gel are typical solid desiccants [89,90]. Table 3 presents a summary of the studies of sorption for dehumidifying greenhouses.

As seen in Table 3, most studies focused on the application of liquid-desiccant dehumidifiers, rather than solid ones, likely due to the possibility of liquid-desiccant systems to be more easily integrated on the greenhouse roof. Liquid-desiccant systems are also reported to successfully reduce greenhouse humidity and maintain a uniform vertical temperature distribution over the crop canopy [94,95,100]. On the other hand, the complexity of the system, the heat required for the regeneration of the material, and its costly installation pose practical challenges to the application of hygroscopic dehumidifiers [81]. In addition, it has been reported that liquid-desiccant systems are only able to meet 30–50% of the dehumidification load [73,97]. Longo and

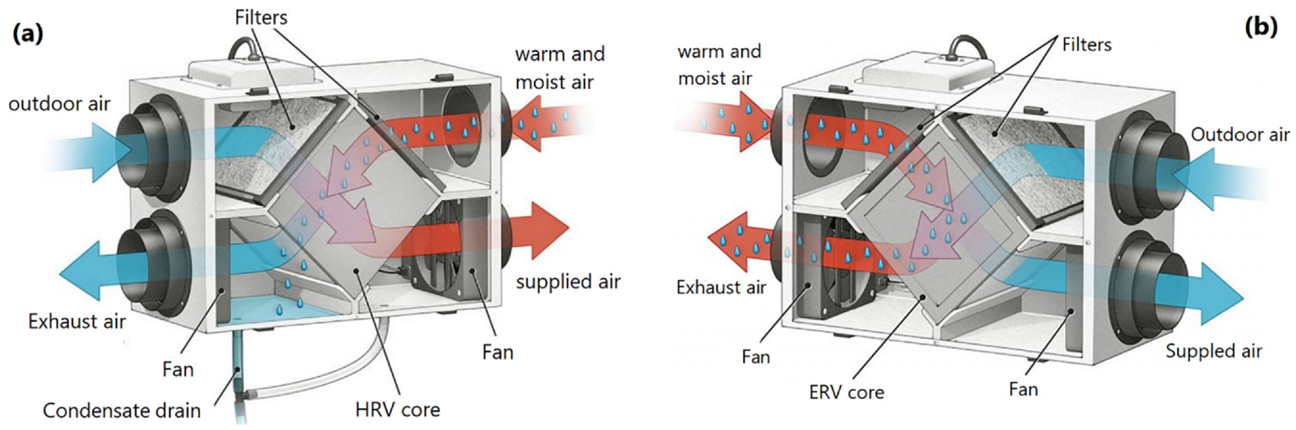

Fig. 8. Schematic view of HRV systems [87].

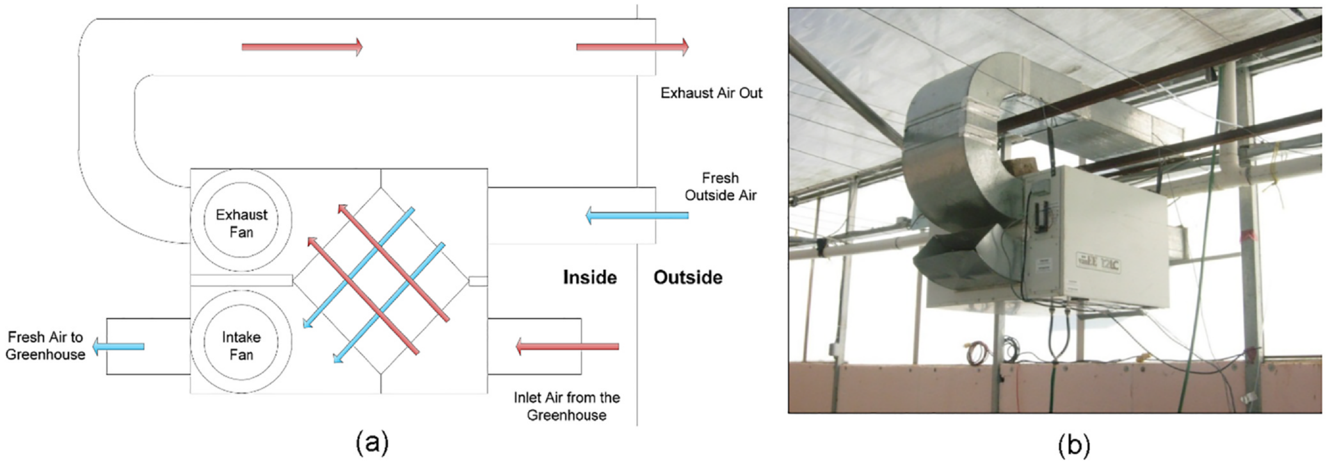

Fig. 9. An air-to-air heat exchanger used in the study of Han et al. [84]. It was located west of Saskatoon, Canada under cold weather conditions. (a) Schematic view and (b) image of the setup.

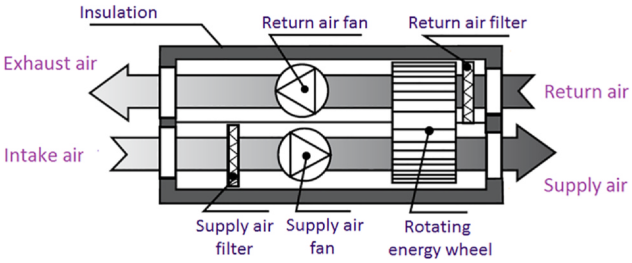

Fig. 10. Schematic view of a rotary heat exchanger used in the study of Ref. [85]. The rotary heat exchanger transfers energy in the form of both latent and sensible heat.

Gasparella [96] presented an innovative LiCl desiccant-based dehumidification system for a flower greenhouse (see Fig. 12). The vapor in the air is absorbed by the hygroscopic solution, while the heat of condensation raises the solution temperature above the air temperature. The desiccant is then heated for regeneration in a hot water coil, connected to a dedicated water heater system. The vapor released from the heated brine condenses on the inner side of a desiccant solution-vapor heat exchanger. The heat absorbed by the desiccant is recovered as sensible heat and transferred to the dehumidified air. The proposed system was able to remove around 13–20 kg/h of water when the regeneration water was supplied at 70–85°C. Moreover, 10% energy saving in the winter season as well as a consistent reduction of Botrytis and the associated economic and environmental advantages were reported.

There are very few studies conducted on the application of solid-desiccant dehumidifiers in the agriculture industry. A solid-desiccant block system was considered by Sultan et al. [23,101], which is reproduced in Fig. 13. They analyzed the water uptake of various desiccant materials, including activated carbon fiber (ACF), activated carbon powder (ACP), and silica-gel in the greenhouse. It was shown that the ACF and ACP dehumidified the greenhouse notably for RH > 40% and RH > 60%, respectively. Silica gel, on the other hand, can dehumidify the greenhouse at any RH. Nevertheless, according to the results in [23,101], activated carbons were more efficient, in terms of the mass of adsorbent required to drive the desiccant. Mahmood et al. [102] evaluated a desiccant dehumidifier, shown in Fig. 14, for the storage of agricultural products. They have reported that longer dehumidification time is required for higher process air RH's. Moreover, higher COP was observed at a low regeneration temperature, which was nevertheless not useful for higher latent loads. Rjibi et al. [103] simulated the performance of a desiccant wheel under greenhouse condition using the TRNSYS software. It was concluded that by increasing the regeneration air temperature from 60 to 90°C, the humidity ratio can be decreased from 0.0043 to 0.0007 kg/kg. They reported that a high regeneration temperature permits better moisture removal during the adsorptive process.

The heating and dehumidification of desiccants by humidity swing adsorption is an innovative approach for applications with restricted heat sources [104,105]. Tsujiguchi et al. [106] evaluated the feasibility of simultaneous heating and dehumidification by employing a silica gel-based desiccant. Their experimental setup is shown in Fig. 15. They have reported successful dehumidification with increased temperature. By increasing the rotation speed, the amount of water uptake increased regardless of the air velocity ratios. It was unlikely that the highest

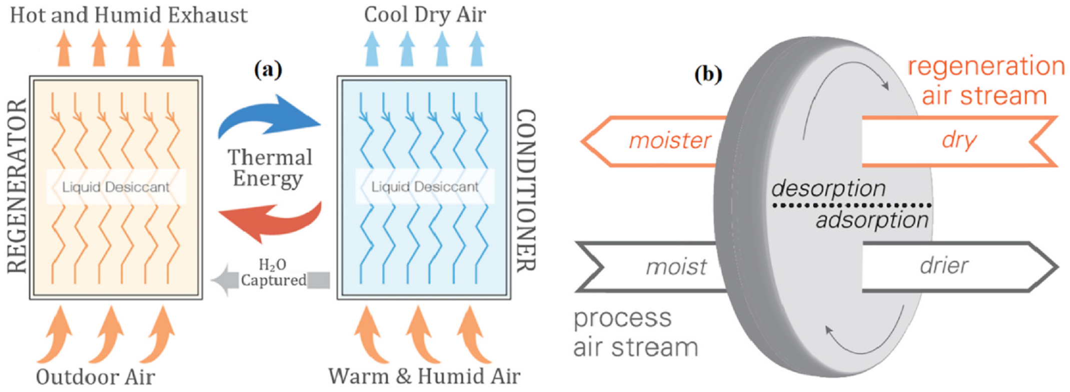

Fig. 11. A schematic of (a) a liquid desiccant [92] and (b) a solid desiccant [93].

Table 3
Summary of studies conducted on the use of sorption system in greenhouses.

Author	Dehumidification method	Analysis	Desiccant	Location of greenhouse	Area of greenhouse (m^2)	Crop
Lycoskoufis and Mavrogianopoulos [73]	Liquid desiccant	Experimental	$CaCl_2$	Greece	63	Cucumber
Campen et al. [81]	Liquid desiccant	Simulation	–	Netherlands	–	Tomato Pepper Rose Cucumber
Ali et al. [94]	Liquid desiccant	Simulation	$CaCl_2$ LiCl	Netherlands	40	–
Hao et al. [95]	Liquid desiccant	Experimental	–	Canada	45	Cucumber
Longo and Gasparella [96]	Liquid desiccant	Experimental	LiCl LiBr KCOOH	Italy	–	Flower
Longo and Gasparella [97]	Liquid desiccant	Experimental & Simulation	LiCl	Italy	1500	Flower
Abu-Hamdeh and Almitani [98]	Liquid desiccant	Experimental	CaCl	Saudi Arabia	300	Cucumber Lettuce
Ghosh and Ganguly [99]	Liquid desiccant	Experimental	LiCl	India	224	Lettuce
Lychnos and Davies [100]	Liquid desiccant	Experimental & Theoretical	$MgCl_2$	India Bangladesh Italy Cuba	1000	Lettuce Soy Bean Tomato Cucumber
Sultan et al. [23,101]	Solid desiccant	Experimental	Silica-gel ACP ACF	–	–	–

temperature increment was obtained at a lower rotation speed. They also observed that increasing the regeneration temperature improves both dehumidification and heating. It was concluded that in order to gain heating effects, the regeneration temperature must be above 13°C.

4. Employment of renewable energy sources

Dehumidification driven by renewable energy sources (RES) is generally economically competitive compared to the conventional processes powered by fossil energy. Many researchers have investigated the applicability of RES for dehumidification purposes. Lychnos and Davies [100] evaluated the performance of a solar-powered liquid desiccant system using $MgCl_2$ desiccant for greenhouse food production in hot climates. Their results revealed that this concept is technically viable and could enable year-round cultivation of all the crops and at all the locations studied. Bouadila et al. [107] employed a solar air heater collector using a latent heat system. They observed that the system was able to dehumidify the greenhouse at night and decrease the RH by 10–17%. Moreover, it has been reported that using geothermal energy systems could decrease the greenhouse energy consumption by 20–70% at various locations [108]. Ozgener and Hepbasli [109,110] investigated the performance of a solar-assisted ground-source heat pump system for heating, cooling, and dehumidifying greenhouses. They revealed that this system is economically preferable to the conventional heating/cooling systems in the Mediterranean and Aegean regions of Turkey. Effective use of ground source heat pump systems with suitable technology in modern greenhouses could play a leading role in sustainable environment control of greenhouses.

5. Summary and discussion

Some growers seek to decrease moisture generation in the greenhouse by upgrading the methods of irrigation and culture media. Still, the effectiveness of such methods is limited because plant transpiration is the main source of moisture generation. Currently, ventilation is the most common and simplest dehumidification method in agricultural greenhouses due to its minimal infrastructure. However, its appropriateness depends on the ambient conditions and the fine climatic control needed for the greenhouse plant. A major problem with this method is the corresponding heat loss during the cold season, which increases the heating costs. To illustrate this, Maslak and Nimmermark [85] and Campen and Bot [38] reported that 20–30% of the total use of thermal energy for climate control of greenhouses located in Sweden and Spain is dedicated to natural ventilation for dehumidification depending on the crop transpiration level. In order to overcome this challenge, the employment of heat recovery by using air-to-air heat exchangers could be a promising option to save energy. An air-to-air heat exchanger is an excellent choice for greenhouse dehumidification in cold regions because it can be applicable usually year around.

Controlled condensation on a cold surface by using heat pump systems offers a much larger energy-saving potential than heat recovery exchangers. Heat pumps limit the energy consumption by recycling the inside air instead of heating the cold outside air. They supply the energy retrieved from water vapor condensation back to the greenhouse. Consequently, the main advantage of such a device is to minimize energy losses by re-using the energy extracted through condensation. In addition, heat pumps are easy to set up, operate, and maintain, and their effectiveness in controlling the humidity is independent of the external air conditions, making them suitable for high humidity greenhouses in the heating season. The main challenge in using heat pumps to replace natural ventilation for dehumidification is their high electricity consumption. The economic and environmental advantage of this approach depends on the price and source of electricity.

Adsorption or desiccant-based systems are other alternatives for energy-efficient dehumidification of greenhouses. The main advantage of adsorption systems is that the latent heat is directly converted into

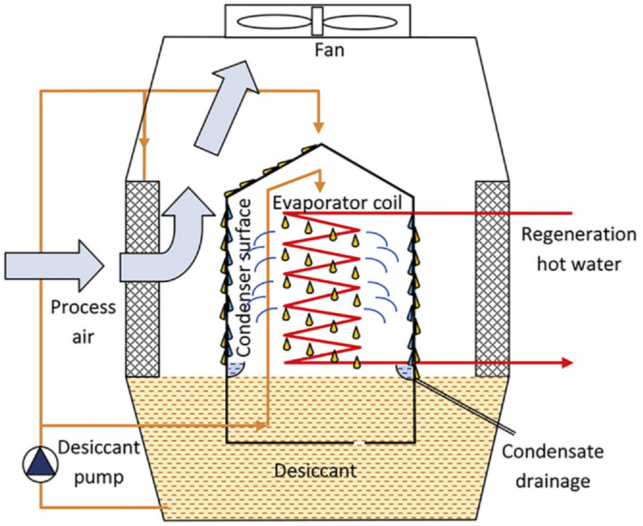

Fig. 12. Schematic conceptual diagram of the liquid desiccant dehumidification system proposed by Longo and Gasparella [96].

sensible heat. In other words, the latent heat released during the adsorption process goes back to the greenhouse and assists in heating the greenhouse air. Since adsorption processes are thermally-driven, they can be used as an alternative to traditional electricity-driven vapor compression refrigeration systems, resulting in electricity consumption reduction. Once this type of thermally-driven system is powered by free energy sources, such as waste heat or solar energy, it can reduce the operating costs remarkably; however, the complexity of the system, the environmental risks, and the heat required for regeneration of the material make soprtion less practical for use in greenhouses. As discussed, desiccant systems can be categorized into liquid desiccant, and solid desiccant systems and their advantages and disadvantages are listed in Table 4. It can be concluded that solid desiccant dehumidification systems have the potential to be employed in greenhouse environments.

For better illustration, a comparison analysis was conducted to evaluate the energy consumption as well as operating cost of each dehumidification approach. For this purpose, an outdoor design condition of T = −10°C and RH = 75% was selected, which represents a continental climate [111]. The indoor temperature and RH set points were considered as 20°C and 70%, respectively, and an average

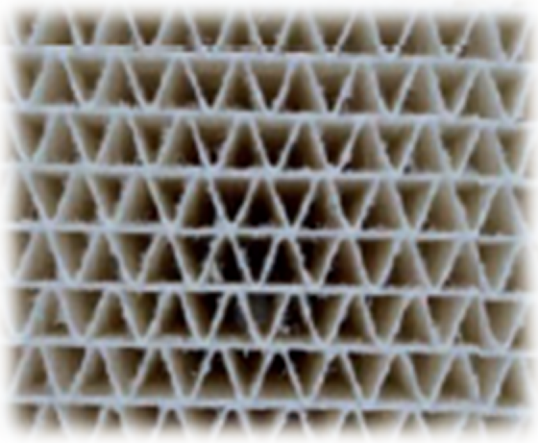

Fig. 14. A desiccant block used in the work of Mahmood et al. [102].

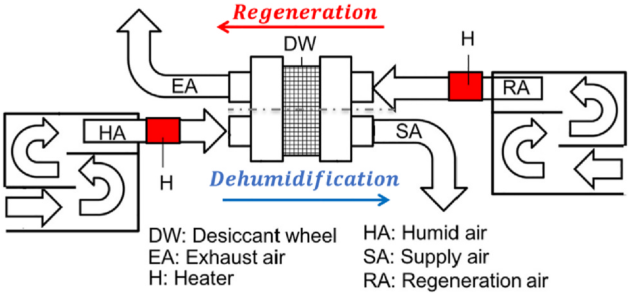

Fig. 15. A desiccant wheel dehumidifier with humidity swing adsorption in a greenhouse [106].

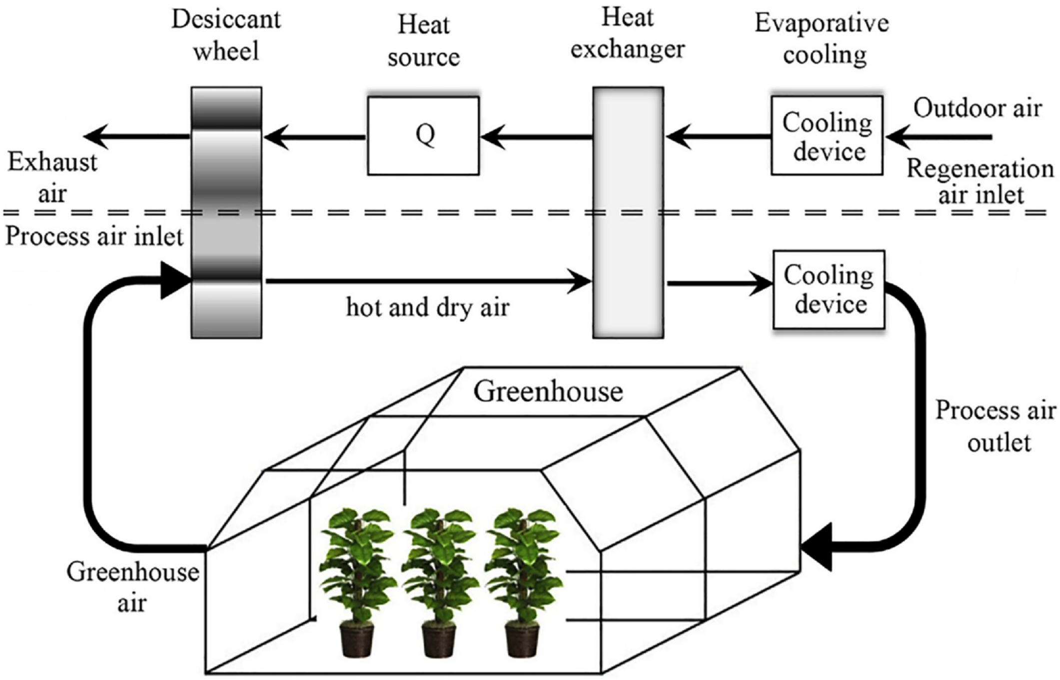

Fig. 13. A block diagram of a solid desiccant system for agricultural greenhouses [23].

Table 4
Advantages and disadvantages of each desiccant methods.

Desiccant type	Advantages	Disadvantages
Solid	● Highly durable ● Environmentally friendly ● Inexpensive	● Higher regeneration temperature ● Higher pressure drop in the air flow
Liquid	● Lower pressure drop across the system ● Low regeneration temperature ● Higher moisture removal capacity	● Corrosive and can damage the system ● Capable of chemically reacting with moist air ● Any carry-over of liquid desiccant along with supply air stream can cause significant harm to the health of the occupants. ● Crystallization occurrence

evapotranspiration rate of 200 g/(hm^2) was assumed. In this analysis, a heat pump with COP of 4, heat exchanger with sensible effectiveness of 65%, and a desiccant-based system with COP of 0.5 were considered, which are easily available in the market. For example, the Mitsubishi Electric Corporation manufactures heat pump systems with COP in the range of 3–5 with various cooling/heating capacities [112]. Daikin Industries designs and produces heat recovery exchangers for a wide range of residential and commercial applications with sensible effectiveness in the range of 60–80% and different air flow rates [113]. The Desiccant Technologies Group, a European company, produces desiccant dehumidifiers with various air flow rates (160–18,000 m^3/h), dehumidification capacities (0.6–102.6 kg/h), and power supplies (1–165 kW) [114].

Fig. 16 shows the performance of various dehumidification methods in terms of their energy consumption and operating cost. As can be seen from Fig. 16(a), the net energy consumption of the heat pump is negative, which means that the heat pump generates more heat energy than required input energy since its COP is greater than unity. By using heat pumps, the greenhouse heating system can be even shut down for some time. In terms of energy, the heat pump system is the most efficient method for greenhouse dehumidification in cold climates, followed by heat recovery exchangers and desiccant systems and then conventional ventilation systems. Fig. 16(b) illustrates the operating cost of each method, assuming natural gas and electricity prices of $2/GJ and $0.12/kWh respectively. The desiccant-based dehumidification system has the lowest operating cost, followed by the air-to-air heat exchanger, ventilation, and the heat pump system. Although heat pump systems are the most energy-efficient option, their operating cost is the highest, making them unpopular for greenhouse dehumidification, especially in cold climates. It should be noted that the operating cost of heat pumps is highly dependent on the price and source of energy. It is concluded that desiccant-based systems and air-to-air heat exchangers are promising dehumidification systems in greenhouses, considering energy consumption and operating cost.

5.1. *Future research prospects*

The present review shows that most studies on alternative dehumidification methods concentrate on condensation on a cold surface by using a heat pump, followed by air-to-air heat exchangers and adsorption systems. All the existing literature on adsorption-based dehumidification focuses on liquid desiccants. Solid-desiccant systems are promising but understudied alternatives for energy-efficient dehumidification of greenhouses. A hybrid of heat pump and desiccant systems can also increase the energy efficiency and cost-effectiveness of humidity control in greenhouses. Finally, in closed greenhouses, a heat recovery system integrated into the condensation or adsorption-based dehumidification system can reduce the net energy consumption. Based on the present review, very few dehumidification methods are commercially suitable for greenhouse producers in cold regions, such as the Canadian Prairie Provinces. The systems have drawbacks, such as high energy consumption, maintenance requirements, high capital and operation costs, and undue complexities of installation. Development of efficient, economical, and practical dehumidification technologies is in order.

6. Conclusions

Humidity control is crucial in greenhouse horticulture, mainly to provide optimal growth conditions and prevent fungal diseases. While humidification and dehumidification are both conventional in greenhouse horticulture, dehumidification is more complicated and more energy-intensive. The main approaches to greenhouse dehumidification are ventilation, maintaining a high temperature, condensation on a cold surface, and adsorption by hygroscopic materials, which were reviewed and discussed in this paper.

Ventilation has been proposed as the most common approach, including natural and forced ventilation. Although natural ventilation is the simplest method, it leads to considerable heat losses, especially in colder climates. Moreover, natural ventilation is difficult to control and hardly delivers uniform climate conditions inside the greenhouse. Ventilation can also be induced by mechanical fans or blowers and an air distribution system inside the greenhouse. Forced ventilation offers more control over the ventilation rate, and the intake air can be mixed and distributed more homogeneously inside the greenhouse.

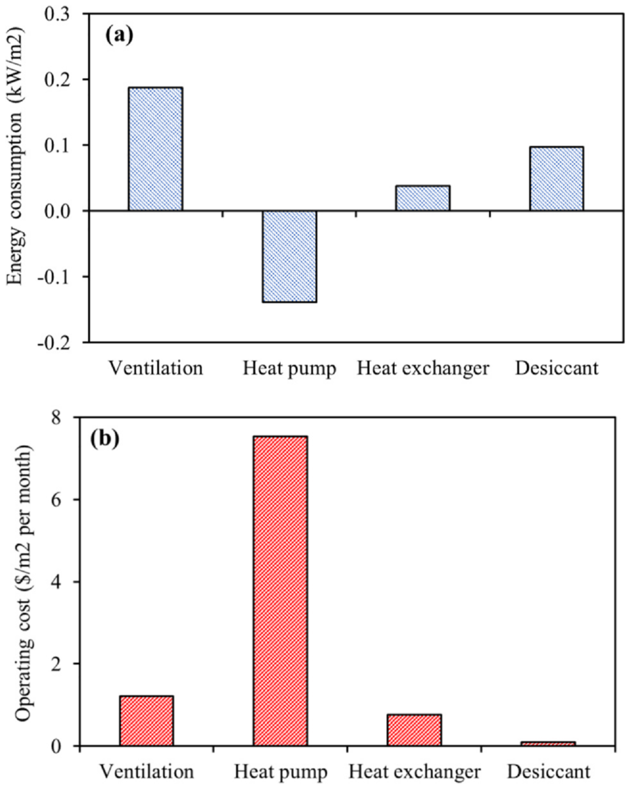

Fig. 16. (a) Energy consumption; and (b) the operating cost of different dehumidification approaches.

Maintaining a high temperature inside the greenhouse is another method that is effective only for reducing the RH in the evening.

Controlled condensation on a cold surface is widely used in the horticulture industry, usually done by heat pumps and air-to-air heat exchangers. Using heat pumps, less than 50% of the total energy consumption is spent on dehumidification, i.e., the removal of latent heat. The rest must be spent on sensible cooling of the air to reach the saturation point. In order to reduce energy losses, the energy extracted from the condensation process can be used to re-heat the supply air. The relative cost advantage of heat pumps over natural ventilation for dehumidification purposes is directly dictated by the energy costs, i.e., electricity vs. natural gas. Air-to-air heat exchangers are another type of controlled condensation mechanism which is preferred in cold climates. Additional energy efficiency enhancements can be achieved using heat recovery systems that recover energy from the warm exhaust air, decreasing the net heating demand in the greenhouse.

Adsorption by hygroscopic materials is another method for greenhouse dehumidification. The main advantage of this method is the direct transformation of the latent heat into sensible heat, which can be used for heating the greenhouse. Moreover, desiccant systems can work with low-grade heat such as solar thermal energy or waste heat, thereby significantly reducing electricity demand. Sorption-based dehumidification systems can effectively reduce the greenhouse humidity, maintain a homogeneous vertical temperature profile over the crop canopy, and reduce the overall energy consumption. Nonetheless, the complexity of the current sorption systems makes them less practical for application in commercial greenhouses. Further research and development aimed at scalable, cost-effective, low-temperature systems can help the proliferation of sorption technology for environmental control in greenhouses, bringing about significant cost savings and greenhouse gas emission reductions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] F. Kempkes, H.F. de Zwart, P. Munoz, J.I. Montero, F.J. Baptista, F. Giuffrida, C. Gilli, A. Stepowska, C. Stanghellini, Heating and dehumidification in production greenhouses at northern latitudes: energy use, Acta Hortic. (1164) (2017) 445–452, https://doi.org/10.17660/ActaHortic.2017.1164.58.

[2] D.W. Hand, Effects of atmospheric humidity on greenhouse crops, Acta Hortic. (229) (1988) 143–158, https://doi.org/10.17660/ActaHortic.1988.229.12.

[3] R.R. Shamshiri, J.W. Jones, K.R. Thorp, D. Ahmad, H.C. Man, S. Taheri, Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: a review, Int. Agrophys. 32 (2) (2018) 287–302.

[4] E. Cuce, D. Harjunowibowo, P.M. Cuce, Renewable and sustainable energy saving strategies for greenhouse systems: a comprehensive review, Renew. Sustain. Energy Rev. 64 (2016) 34–59, https://doi.org/10.1016/j.rser.2016.05.077.

[5] G. Li, L. Tang, X. Zhang, J. Dong, M. Xiao, Factors affecting greenhouse microclimate and its regulating techniques: a review, IOP Conf. Ser.: Earth Environ. Sci. 167 (2018) 012019, https://doi.org/10.1088/1755-1315/167/1/012019.

[6] M. Chand Singh, J.P. Singh, S. Kumar Pandey, N. Gladwin Cutting, P. Sharma, V. Shrivastav, P. Sharma, A review of three commonly used techniques of controlling greenhouse microclimate, Int. J. Curr. Microbiol. App. Sci. 7 (1) (2018) 3491–3505, https://doi.org/10.20546/ijcmas.2018.701.411.

[7] Guillermo De la Torre-Gea, Computational fluid dynamics in greenhouses: a review, African J. Biotechnol. 10 (2011). https://doi.org/10.5897/AJB10.2488.

[8] A. Vadiee, V. Martin, Energy management in horticultural applications through the closed greenhouse concept, state of the art, Renew. Sustain. Energy Rev. 16 (7) (2012) 5087–5100, https://doi.org/10.1016/j.rser.2012.04.022.

[9] A.M. Syed, C. Hachem, Review of construction; geometry; heating, ventilation, and air-conditioning; and indoor climate requirements of agricultural greenhouses, J. Biosyst. Eng. 23 18–27. https://doi.org/10.1007/s42853-019-00005-1.

[10] S. Ghani, F. Bakochristou, E.M.A.A. ElBialy, S.M.A. Gamaledin, M.M. Rashwan, A.M. Abdelhalim, S.M. Ismail, Design challenges of agricultural greenhouses in hot and arid environments – a review, Eng. Agric. Environ. Food 12 (2019) 48–70, https://doi.org/10.1016/j.eaef.2018.09.004.

[11] M.A. Boles, Y.A. Çengel, Thermodynamics: An Engineering Approach, 8th ed., McGraw-Hill Education, n.d.

[12] J.B. Campen, Ventilation of small multispan greenhouse in relation to the window openings calculated with CFD, Acta Hortic. (2006) 351–356, https://doi.org/10.17660/ActaHortic.2006.718.40.

[13] J.B. Campen, Vapour removal from the greenhouse using forced ventilation when applying a thermal screen, Acta Hortic. (2008) 863–868, https://doi.org/10.17660/ActaHortic.2008.801.101.

[14] M. Farooq, A. Wahid, N. Kobayashi, D. Fujita, S.M.A. Basra, Plant drought stress: effects, mechanisms and management, Agron. Sustain. Dev. 29 (2009) 185–212, https://doi.org/10.1051/agro:2008021.

[15] I.V. Pollet, J.G. Pieters, Condensation and radiation transmittance of greenhouse cladding materials, part 3: results for glass plates and plastic films, J. Agric. Eng. Res. 77 (2000) 419–428, https://doi.org/10.1006/jaer.2000.0628.

[16] J.C. Bakker, Analysis of Humidity Effects on Growth and Production of Glasshouse Fruit Vegetables, Wageningen University, Wageningen, 1991.

[17] M. Babadoost, Leaf mold (Fulvia fulva), a serious threat to high tunnel tomato production in illinois, Acta Hortic. (2011) 93–96, https://doi.org/10.17660/ActaHortic.2011.914.14.

[18] A. Vadiee, V. Martin, Energy management strategies for commercial greenhouses, Appl. Energy 114 (2014) 880–888, https://doi.org/10.1016/j.apenergy.2013.08.089.

[19] M. Sultan, T. Miyazaki, S. Koyama, B. Saha, Utilization of desiccant air-conditioning system for improvement in greenhouse productivity: a neglected area of research in Pakistan, Int. J. Env. 4 (2014) 1–10.

[20] T.H. Short, A. El-Attal, H.M. Keener, R.P. Fynn, A decision model for hydroponic greenhouse tomato production, Acta Hortic. (1998) 493–504, https://doi.org/10.17660/ActaHortic.1998.456.59.

[21] D.B. Anderson, Relative humidity or vapor pressure deficit, Ecology 17 (1936) 277–282, https://doi.org/10.2307/1931468.

[22] V. López-Morales, O. López-Ortega, J. Ramos-Fernández, L.B. Muñoz, JAPIEST: An integral intelligent system for the diagnosis and control of tomatoes diseases and pests in hydroponic greenhouses, Expert Syst. Appl. 35 (2008) 1506–1512, https://doi.org/10.1016/j.eswa.2007.08.098.

[23] M. Sultan, T. Miyazaki, B.B. Saha, S. Koyama, Steady-state investigation of water vapor adsorption for thermally driven adsorption based greenhouse air-conditioning system, Renew. Energy 86 (2016) 785–795, https://doi.org/10.1016/j.renene.2015.09.015.

[24] F.J. Baptista, B.J. Bailey, J.M. Randall, J.F. Meneses, Greenhouse ventilation rate: theory and measurement with tracer gas techniques, J. Agric. Eng. Res. 72 (1999) 363–374, https://doi.org/10.1006/jaer.1998.0381.

[25] M. Kacira, S. Sase, L. Okushima, Effects of side vents and span numbers on wind-induced natural ventilation of a gothic multi-span greenhouse, Japan Agric. Res. Q. JARQ 38 (2004) 227–233, https://doi.org/10.6090/jarq.38.227.

[26] A. Mistriotis, G.P.A. Bot, P. Picuno, G. Scarascia-Mugnozza, Analysis of the efficiency of greenhouse ventilation using computational fluid dynamics, Agric. For. Meteorol. 85 (3-4) (1997) 217–228, https://doi.org/10.1016/S0168-1923(96)02400-8.

[27] C. Kittas, M. Karamanis, N. Katsoulas, Air temperature regime in a forced ventilated greenhouse with rose crop, Energy Build. 37 (2005) 807–812, https://doi.org/10.1016/j.enbuild.2004.10.009.

[28] G. Papadakis, M. Mermier, J.F. Meneses, T. Boulard, Measurement and analysis of air exchange rates in a greenhouse with continuous roof and side openings, J. Agric. Eng. Res. 63 (3) (1996) 219–227, https://doi.org/10.1006/jaer.1996.0023.

[29] T. Boulard, A. Baille, Modelling of air exchange rate in a greenhouse equipped with continuous roof vents, J. Agric. Eng. Res. 61 (1) (1995) 37–47, https://doi.org/10.1006/jaer.1995.1028.

[30] T. Bartzanas, T. Boulard, C. Kittas, Effect of vent arrangement on windward ventilation of a tunnel greenhouse, Biosyst. Eng. 88 (4) (2004) 479–490, https://doi.org/10.1016/j.biosystemseng.2003.10.006.

[31] E. Rico-Garcia, I.L. Lopez-Cruz, G. Herrera-Ruiz, G.M. Soto-Zarazua, R. Castaneda-Miranda, Effect of temperature on greenhouse natural ventilation under hot conditions: computational fluid dynamics simulations, J. Appl. Sci. 8 (24) (2008) 4543–4551, https://doi.org/10.3923/jas.2008.4543.4551.

[32] S. Benni, P. Tassinari, F. Bonora, A. Barbaresi, D. Torreggiani, Efficacy of greenhouse natural ventilation: environmental monitoring and CFD simulations of a study case, Energy Build. 125 (2016) 276–286, https://doi.org/10.1016/j.enbuild.2016.05.014.

[33] T. Boulard, B. Draoui, Natural ventilation of a greenhouse with continuous roof

vents: measurements and data analysis, J. Agric. Eng. Res. 61 (1995) 27–35, https://doi.org/10.1006/jaer.1995.1027.

[34] T. Boulard, P. Feuilloley, C. Kittas, Natural ventilation performance of six greenhouse and tunnel types, J. Agric. Eng. Res. 67 (4) (1997) 249–266, https://doi.org/10.1006/jaer.1997.0167.

[35] T. Boulard, H. Fatnassi, J.C. Roy, J. Lagier, J. Fargues, N. Smits, M. Rougier, B. Jeannequin, Effect of greenhouse ventilation on humidity of inside air and in leaf boundary-layer, Agric. For. Meteorol. 125 (2004) 225–239, https://doi.org/10.1016/j.agrformet.2004.04.005.

[36] P.E. Bournet, S.A. Ould Khaoua, T. Boulard, C. Migeon, G. Chasseriaux, Effect of roof and side opening combinations on the ventilation of a greenhouse using computer simulation, Trans. ASABE 50 (2007) 201–212, https://doi.org/10.13031/2013.22401.

[37] P.E. Bournet, S.A. Ould Khaoua, T. Boulard, Numerical prediction of the effect of vent arrangements on the ventilation and energy transfer in a multi-span glasshouse using a bi-band radiation model, Biosyst. Eng. 98 (2) (2007) 224–234, https://doi.org/10.1016/j.biosystemseng.2007.06.007.

[38] J.B. Campen, G.P.A. Bot, Determination of greenhouse-specific aspects of ventilation using three-dimensional computational fluid dynamics, Biosyst. Eng. 84 (1) (2003) 69–77, https://doi.org/10.1016/S1537-5110(02)00221-0.

[39] J.E. Fernández, B.J. Bailey, Measurement and prediction of greenhouse ventilation rates, Agric. For. Meteorol. 58 (3-4) (1992) 229–245, https://doi.org/10.1016/0168-1923(92)90063-A.

[40] J.E. Fernandez, B.J. Bailey, Predicting greenhouse ventilation rates, Acta Hortic. (1993) 107–114, https://doi.org/10.17660/ActaHortic.1993.328.7.

[41] T. Boulard, R. Haxaire, M.A. Lamrani, J.C. Roy, A. Jaffrin, Characterization and modelling of the air fluxes induced by natural ventilation in a greenhouse, J. Agric. Eng. Res. 74 (2) (1999) 135–144, https://doi.org/10.1006/jaer.1999.0442.

[42] A. Ganguly, S. Ghosh, Model development and experimental validation of a floriculture greenhouse under natural ventilation, Energy Build. 41 (5) (2009) 521–527, https://doi.org/10.1016/j.enbuild.2008.11.021.

[43] D. de Halleux, L. Gauthier, Energy consumption due to dehumidification of greenhouses under northern latitudes, J. Agric. Eng. Res. 69 (1998) 35–42, https://doi.org/10.1006/jaer.1997.0221.

[44] Harmanto, H.J. Salokhe, V.M. Tantau, Optimization of ventilation opening area of a naturally ventilated net greenhouse in a humid tropical environment, Acta Hortic. (2006) 165–172, https://doi.org/10.17660/ActaHortic.2006.719.16.

[45] K.-S. He, D.-Y. Chen, L.-J. Sun, Z.-l. Liu, Z.-y. Huang, The effect of vent openings on the microclimate inside multi-span greenhouses during summer and winter seasons, Eng. Appl. Comput. Fluid Mech. 9 (1) (2015) 399–410, https://doi.org/10.1080/19942060.2015.1061553.

[46] J.I. Montero, G.R. Hunt, R. Kamaruddin, A. Antón, B.J. Bailey, SE—structures and environment, J. Agric. Eng. Res. 80 (2001) 99–107, https://doi.org/10.1006/jaer.2000.0694.

[47] S.A. Ould Khaoua, P.E. Bournet, C. Migeon, T. Boulard, G. Chassériaux, Analysis of greenhouse ventilation efficiency based on computational fluid dynamics, Biosyst. Eng. 95 (1) (2006) 83–98, https://doi.org/10.1016/j.biosystemseng.2006.05.004.

[48] J.C. Roy, T. Boulard, CFD prediction of the natural ventilation in a tunnel-type greenhouse: influence of wind direction and sensibility to turbulence models, Acta Hortic. (2005) 457–464, https://doi.org/10.17660/ActaHortic.2005.691.55.

[49] A. Shklyar, A. Arbel, Numerical model of the three-dimensional isothermal flow patterns and mass fluxes in a pitched-roof greenhouse, J. Wind Eng. Ind. Aerodyn. 92 (12) (2004) 1039–1059, https://doi.org/10.1016/j.jweia.2004.05.008.

[50] E.J. Baeza, J.J. Pérez-Parra, J.I. Montero, B.J. Bailey, J.C. López, J.C. Gázquez, Analysis of the role of sidewall vents on buoyancy-driven natural ventilation in parral-type greenhouses with and without insect screens using computational fluid dynamics, Biosyst. Eng. 104 (1) (2009) 86–96, https://doi.org/10.1016/j.biosystemseng.2009.04.008.

[51] T.H. Short, I. Lee, Temperature and airflow predictions for multi-span naturally ventilated greenhouse, Acta Hortic. (2002) 141–152, https://doi.org/10.17660/ActaHortic.2002.578.16.

[52] M. Teitel, J. Tanny, Natural ventilation of greenhouses: experiments and model, Agric. For. Meteorol. 96 (1999) 59–70, https://doi.org/10.1016/S0168-1923(99)00041-6.

[53] M. Teitel, G. Ziskind, O. Liran, V. Dubovsky, R. Letan, Effect of wind direction on greenhouse ventilation rate, airflow patterns and temperature distributions, Biosyst. Eng. 101 (3) (2008) 351–369, https://doi.org/10.1016/j.biosystemseng.2008.09.004.

[54] M. Teitel, O. Liran, J. Tanny, M. Barak, Wind driven ventilation of a mono-span greenhouse with a rose crop and continuous screened side vents and its effect on flow patterns and microclimate, Biosyst. Eng. 101 (1) (2008) 111–122, https://doi.org/10.1016/j.biosystemseng.2008.05.012.

[55] A. Mistriotis, C. Arcidiacono, P. Picuno, G.P.A. Bot, G. Scarascia-Mugnozza, Computational analysis of ventilation in greenhouses at zero- and low-windspeeds, Agric. For. Meteorol. 88 (1-4) (1997) 121–135, https://doi.org/10.1016/S0168-1923(97)00045-2.

[56] T. Boulard, J.F. Meneses, M. Mermier, G. Papadakis, The mechanisms involved in the natural ventilation of greenhouses, Agric. For. Meteorol. 79 (1996) 61–77, https://doi.org/10.1016/0168-1923(95)02266-X.

[57] C. Kittas, B. Draoui, T. Boulard, Quantification of the ventilation of a greenhouse with a roof opening, Agric. For. Meteorol. 77 (1995) 95–111.

[58] D.T.S. K.N. Tiwari, V.K. Singh, A.R.G. Reddy, Micro climate control in greenhouse, Int. J. Curr. Microbiol. Appl. Sci. 6 (2017) 1730–1742. https://doi.org/10.20546/ijcmas.2017.603.199.

[59] D. Kolokotsa, G. Saridakis, K. Dalamagkidis, S. Dolianitis, I. Kaliakatsos, Development of an intelligent indoor environment and energy management system for greenhouses, Energy Convers. Manag. 51 (2010) 155–168, https://doi.org/10.1016/j.enconman.2009.09.007.

[60] M. Fuchs, E. Dayan, E. Presnov, Evaporative cooling of a ventilated greenhouse rose crop, Agric. For. Meteorol. 138 (2006) 203–215, https://doi.org/10.1016/j.agrformet.2006.05.002.

[61] C.-F. Liang, Z.-F. Chen, W.-X. Li, L.-T. Xu, G.-R. Huang, Effects of different dehumidified treatments on tomato growth and nutrients accumulation inside greenhouses, Chinese J. Eco-Agric. 14 (2006) 79–81.

[62] H. Wang, H. Mao, Experimental research on regulating and controlling of the temperature and humidity in a TAZ4. 9 PC board multi-span greenhouse, Agric. Equip. Technol. 31 (2005) 1–19.

[63] J. Flores-Velazquez, J.I. Montero, E.J. Baeza, J.C. Lopez, Mechanical and natural ventilation systems in a greenhouse designed using computational fluid dynamics, Int. J. Agric. Biol. Eng. 7 (2014) 1–16, https://doi.org/10.3965/j.ijabe.20140701.001.

[64] J.B. Campen, F.L.K. Kempkes, G.P.A. Bot, Mechanically controlled moisture removal from greenhouses, Biosyst. Eng. 102 (4) (2009) 424–432, https://doi.org/10.1016/j.biosystemseng.2009.01.001.

[65] J.B. Campen, G.P.A. Bot, Design of a low-energy dehumidifying system for greenhouses, J. Agric. Eng. Res. 78 (2001) 65–73, https://doi.org/10.1006/jaer.2000.0633.

[66] J.B. Campen, G.P.A. Bot, Dehumidification in greenhouses by condensation on finned pipes, Biosyst. Eng. 82 (2002) 177–185, https://doi.org/10.1006/bioe.2002.0058.

[67] A. Saye, W.K.P. van Loon, G.P.A. Bot, H.F. de Zwart, The solar greenhouse: a survey of energy saving methods, Acta Hortic. (2000) 131–138, https://doi.org/10.17660/ActaHortic.2000.534.14.

[68] I. Yildiz, D.P. Stombaugh, Heat pump cooling and greenhouse microclimates in open and confined greenhouse systems, Acta Hortic. (2006) 255–262, https://doi.org/10.17660/ActaHortic.2006.719.28.

[69] C. Gilli, F. Kempkes, P. Munoz, J.I. Montero, F. Giuffrida, F.J. Baptista, A. Stepowska, C. Stanghellini, Potential of different energy saving strategies in heated greenhouse, Acta Hortic. (2017) 467–474, https://doi.org/10.17660/ActaHortic.2017.1164.61.

[70] J. Han, H. Guo, R. Brad, D. Waterer, Mechanical refrigeration dehumidifier performance evaluation in a tomato greenhouse in cold regions, Trans. ASABE 59 (2016) 933–941, https://doi.org/10.13031/trans.59.11662.

[71] E. Chantoiseau, C. Migeon, G. Chasseriaux, P.-E. Bournet, Heat-pump dehumidifier as an efficient device to prevent condensation in horticultural greenhouses, Biosyst. Eng. 142 (2016) 27–41, https://doi.org/10.1016/j.biosystemseng.2015.11.011.

[72] C. Migeon, A. Pierart, D. Lemesle, A. Travers, G. Chassériaux, A dehumidifying heat pump for greenhouses, Acta Hortic. (2012) 485–492, https://doi.org/10.17660/ActaHortic.2012.952.61.

[73] I.H. Lycoskoufis, G. Mavrogianopoulos, A hybrid dehumidification system for greenhouses, Acta Hortic. (2008) 55–60, https://doi.org/10.17660/ActaHortic.2008.797.5.

[74] A. Arbel, M. Barak, A. Shklyar, G. Lidor, Y. Elad, M. Sofer, H. Yehezkely, D. Shmueli, A. Slepoy, L. Ganot, Performance of combined heating and dehumidification system for greenhouses, Acta Hortic. (2012) 449–456, https://doi.org/10.17660/ActaHortic.2012.952.56.

[75] H.F. de Zwart, Energy conserving dehumidification of greenhouses, Acta Hortic. (2014) 203–210, https://doi.org/10.17660/ActaHortic.2014.1037.21.

[76] J.M. Cámara-Zapata, J.A. Sánchez-Molina, F. Rodríguez, J.C. López, Evaluation of a dehumidifier in a mild weather greenhouse, Appl. Therm. Eng. 146 (2019) 92–103, https://doi.org/10.1016/j.applthermaleng.2018.09.107.

[77] G. Chasseriaux, Heat pumps for reducing humidity in plastics greenhouses, Plasticulture 73 (1987) 29–40.

[78] T. Boulard, A. Baille, J. Lagier, M. Mermier, E. Vanderschmitt, Water vapour transfer in a plastic house equipped with a dehumidification heat pump, J. Agric. Eng. Res. 44 (1989) 191–204, https://doi.org/10.1016/S0021-8634(89)80081-2.

[79] G. Chassériaux, O. Gaschet, A multifunction dehumidifying heat pump for greenhouses, Acta Hortic. (2011) 469–476, https://doi.org/10.17660/ActaHortic.2011.893.46.

[80] J. Han, Z. Gao, H. Guo, R. Brad, D. Waterer, Comparison of greenhouse dehumidification strategies, Appl. Eng. Agric. 31 (2015) 133–142, https://doi.org/10.13031/aea.31.10723.

[81] J.B. Campen, G.P.A. Bot, H.F. de Zwart, Dehumidification of greenhouses at northern latitudes, Biosyst. Eng. 86 (4) (2003) 487–493.

[82] D.R. Rousse, D.Y. Martin, R. Thériault, F. Léveillée, R. Boily, Heat recovery in greenhouses: a practical solution, Appl. Therm. Eng. 20 (8) (2000) 687–706, https://doi.org/10.1016/S1359-4311(99)00048-4.

[83] L.D. Albright, M.L. Behle, An air-liquid-air heat exchanger for greenhouse humidity control, Trans. ASAE 27 (1984) 1524–1530, https://doi.org/10.13031/2013.32998.

[84] J. Han, H. Guo, R. Brad, Z. Gao, D. Waterer, Dehumidification requirement for a greenhouse located in a cold region, Appl. Eng. Agric. (2015) 291–300, https://doi.org/10.13031/aea.31.10844.

[85] K. Maslak, S. Nimmermark, Thermal energy use for dehumidification of a tomato greenhouse by natural ventilation and a system with an air-to-air heat exchanger, Agric. Food Sci. 26 (2017) 56, https://doi.org/10.23986/afsci.58936.

[86] S.Z.B. Zhou, Y. Zhang, Q. Yang, H. Fang, W. Lu, Dehumidification in a Chinese solar greenhouse using dry outdoor air heated by an active heat storage-release system, Appl. Eng. Agric. 32 (2016) 447–456, https://doi.org/10.13031/aea.32.11496.

[87] https://www.epsalesinc.com/heat-recovery-ventilator-hrv-vs-energy-recovery-

ventilator-erv-whats-right-unit-home/.
[88] T. Bergman, F. Incropera, A. Lavine, D. DeWitt, Fundamentals of heat and mass transfer, 2011.
[89] S.R. Agami, B. Riccardo, W. Werner, H.M. Jeffrey, V. Sanjay, G. Yogi, Hans, Solar thermal energy conversion, Handb. Energy Effic. Renew. Energy. Sl Taylor & Fr. Group, LLC, 2007.
[90] X. Zheng, T.S. Ge, R.Z. Wang, Recent progress on desiccant materials for solid desiccant cooling systems, Energy 74 (2014) 280–294, https://doi.org/10.1016/j.energy.2014.07.027.
[91] C. Aprea, A. Greco, A. Maiorino, The application of a desiccant wheel to increase the energetic performances of a transcritical cycle, Energy Convers. Manag. 89 (2015) 222–230, https://doi.org/10.1016/j.enconman.2014.09.066.
[92] http://ashraemadison.org/downloads/Meeting_Presentations/jan_2014_tech_presentation.pdf.
[93] J. Murphy, B. Bradley, Advances in desiccant-based dehumidification, Trane Eng. Newsl. 34 (2005) 1–8.
[94] A. Ali, K. Ishaque, A. Lashin, N. Al Arifi, Modeling of a liquid desiccant dehumidification system for close type greenhouse cultivation, Energy 118 (2017) 578–589, https://doi.org/10.1016/j.energy.2016.10.069.
[95] X. Hao, J. Zheng, L. Celeste, X. Guo, S. Kholsa, Liquid desiccant dehumidification system for improving microclimate and plant growth in greenhouse cucumber production, Acta Hortic. (2017) 861–866, https://doi.org/10.17660/ActaHortic.2017.1170.110.
[96] G.A. Longo, A. Gasparella, Three years experimental comparative analysis of a desiccant based air conditioning system for a flower greenhouse: assessment of different desiccants, Appl. Therm. Eng. 78 (2015) 584–590, https://doi.org/10.1016/j.applthermaleng.2014.12.005.
[97] G.A. Longo, A. Gasparella, Comparative experimental analysis and modelling of a flower greenhouse equipped with a desiccant system, Appl. Therm. Eng. 47 (2012) 54–62, https://doi.org/10.1016/j.applthermaleng.2012.03.008.
[98] N.H. Abu-Hamdeh, K.H. Almitani, Solar liquid desiccant regeneration and nanofluids in evaporative cooling for greenhouse food production in Saudi Arabia, Sol. Energy 134 (2016) 202–210, https://doi.org/10.1016/j.solener.2016.04.048.
[99] A. Ghosh, A. Ganguly, Performance analysis of a partially closed solar regenerated desiccant assisted cooling system for greenhouse lettuce cultivation, Sol. Energy 158 (2017) 644–653, https://doi.org/10.1016/j.solener.2017.10.030.
[100] G. Lychnos, P.A. Davies, Modelling and experimental verification of a solar-powered liquid desiccant cooling system for greenhouse food production in hot climates, Energy 40 (2012) 116–130, https://doi.org/10.1016/j.energy.2012.02.021.
[101] M. Sultan, T. Miyazaki, B.B. Saha, S. Koyama, V.S. Maisotsenko, Steady-state analysis on thermally driven adsorption air-conditioning system for agricultural greenhouses, Procedia Eng. 118 (2015) 185–192, https://doi.org/10.1016/j.proeng.2015.08.417.
[102] M.H. Mahmood, M. Sultan, T. Miyazaki, Solid desiccant dehumidification-based air-conditioning system for agricultural storage application: theory and experiments, Proc. Inst. Mech. Eng. Part A J. Power Energy 234 (2020) 534–547, https://doi.org/10.1177/0957650919869503.
[103] A. Rjibi, S. Kooli, A. Guizani, The effects of regeneration temperature of the desiccant wheel on the performance of desiccant cooling cycles for greenhouse thermally insulated, Heat Mass Transf. 54 (2018) 3427–3443, https://doi.org/10.1007/s00231-018-2369-4.
[104] D. Chugh, R. Nasr Isfahani, K. Gluesenkamp, O. Abdelaziz, S. Moghaddam, A Hybrid Absorption Cycle for Water Heating, Dehumidification, and Evaporative Cooling, in: Vol. 3 Adv. Fabr. Manuf. Emerg. Technol. Front. Energy, Heal. Water-Appl. Nano-, Micro- Mini-Scale Devices; MEMS NEMS; Technol. Updat. Talks; Therm. Manag. Using Micro Channels, Jets, Sprays, ASME, 2015: p. V003T05A003. https://doi.org/10.1115/IPACK2015-48816.
[105] K.R. Gluesenkamp, D. Chugh, O. Abdelaziz, S. Moghaddam, Efficiency analysis of semi-open sorption heat pump systems, Renew. Energy 110 (2017) 95–104, https://doi.org/10.1016/j.renene.2016.07.075.
[106] T. Tsujiguchi, Y. Osaka, A. Kodama, Feasibility study of simultaneous heating and dehumidification using an adsorbent desiccant wheel with humidity swing, Appl. Therm. Eng. 117 (2017) 437–442, https://doi.org/10.1016/j.applthermaleng.2017.02.067.
[107] S. Bouadila, S. Kooli, S. Skouri, M. Lazaar, A. Farhat, Improvement of the greenhouse climate using a solar air heater with latent storage energy, Energy. 64 (2014) 663–672, https://doi.org/10.1016/j.energy.2013.10.066.
[108] V.P. Sethi, K. Sumathy, Chiwon Lee, D.S. Pal, Thermal modeling aspects of solar greenhouse microclimate control: A review on heating technologies, Sol. Energy 96 (2013) 56–82, https://doi.org/10.1016/j.solener.2013.06.034.
[109] O. Ozgener, A. Hepbasli, Experimental investigation of the performance of a solar-assisted ground-source heat pump system for greenhouse heating, Int. J. Energy Res. 29 (2005) 217–231, https://doi.org/10.1002/er.1049.
[110] O. Ozgener, A. Hepbasli, An economical analysis on a solar greenhouse integrated solar assisted geothermal heat pump system, J. Energy Resour. Technol. 128 (2006) 28–34, https://doi.org/10.1115/1.2126984.
[111] M.C. Peel, B.L. Finlayson, T.A. McMahon, Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci. 11 (2007) 1633–1644. https://doi.org/10.5194/hess-11-1633-2007.
[112] https://www.mitsubishi-electric.co.nz/materials/aircon/brochures/@HeatPumpRange.pdf.
[113] https://www.daikin.eu/content/dam/document-library/catalogues/Ventilationcatalogue-ECPEN13-203_Catalogues_English.pdf.
[114] https://destech.eu/products/.