Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Greenhouse design and cooling technologies for sustainable food cultivation in hot climates: Review of current practice and future status

Marouen Ghoulem [a], *Khaled El Moueddeb* [a], *Ezzedine Nehdi* [a], *Rabah Boukhanouf* [b], *John Kaiser Calautit* [b,*]

[a] *Université de Tunis El Manar, Ecole Nationale d'Ingénieurs de Tunis, 05/UR/11-14 Unité de Recherche Energétique et Environnement, BP 37 Le Belvédère, 1002 Tunis, Tunisia*

[b] *Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, University Park, NG7 2RD Nottingham, UK*

ARTICLE INFO

Article history:
Received 7 October 2018
Received in revised form
24 March 2019
Accepted 23 April 2019
Published online 10 May 2019

Keywords:
Agriculture
Greenhouse design
Air cooling
Natural ventilation
Evaporative cooling
Hybrid system

Greenhouse technology is becoming an increasingly indispensable and a viable solution for modern methods of crop production. Technological advances have lessened the effect of severe weather conditions on the yield of greenhouse crops in hot climates. Cooling is crucial to guarantee the required range of temperatures and humidity inside the greenhouse. The purpose of this work is to review the design and systems used for greenhouse cooling applications in hot climates. Theoretical and practical aspects related to greenhouse cooling techniques are presented: working principles, working conditions and performance parameters. The review revealed that the combination and simultaneous usage of natural ventilation, evaporative cooling and shading has the potential to reduce greenhouse energy requirement and provide optimum indoor conditions required to maximise crop yields in greenhouses in hot climates. Hybrid cooling systems must be assisted by an effective control strategy to ensure that the required temperature and humidity levels and distributions are maintained in the greenhouse. The status of the research on the use of numerical modelling for the design of greenhouses in hot climates or conditions was investigated and the future challenges facing the development of greenhouses in hot climates identified. Recommendations for future research and development are proposed.

Abbreviations: CFD, Computational fluid dynamics; COP, Coefficient Of Performance; GA, Genetic algorithm; GHE, Ground Heat Exchanger; LES, Large eddy simulation; LAI, Leaf area index; LDPE, Low-density polyethylene; NIR, Near infrared radiation; PE, Polyethylene; PV, Photovoltaic.

* *Corresponding author.*
E-mail address: john.calautit1@nottingham.ac.uk (J. Kaiser Calautit).

https://doi.org/10.1016/j.biosystemseng.2019.04.016

1. Introduction

The nexus of world population growth (predicted to reach 10 billion by 2050) and climate change is putting increasingly severe strains on energy, clean water and food resources (World Population Forecast, 2018). The latter will require concerted effort to develop sustainable agriculture practices capable of feeding the world population. In the last few decades, viable technological and innovative solutions such as large-scale greenhouse farming have been introduced, improving both yield and quality of crops. A greenhouse is an agriculture structure that is able to extend the production season by providing controlled indoor microclimate conditions appropriate to the cultivation of various types of crops.

Cultivation of crops in large scale greenhouses in temperate climates of Europe has been successfully implemented whereas in regions of hot climates of tropics and subtropics the technology faces particular design challenges due to the high temperatures and humidity that can occur during summer months (Cuce & Riffat, 2016) requiring some form of air cooling to overcome overheating (Sethi & Sharma, 2007b).

Air cooling in greenhouses is energy intensive when using mechanical cooling technologies. Suitable technology is selected depending on the choice of the crops, upkeep, operational ease, local environmental conditions and economic viability (Sánchez-Hermosilla, Páez, Rincón, & Callejón, 2013). For example, Sethi and Sharma (2007b) reviewed current global greenhouse cooling technologies and discussed the applications of the different technologies while Kumar, Tiwari, and Jha (2009) reviewed the specific greenhouse cooling technologies and design for sub-tropical and tropical areas. Abdel-Ghany et al. (2012) reviewed covering materials incorporating radiation-preventing techniques used to meet greenhouse cooling challenges in arid regions. Cuce and Riffat (2016) focused on application and integration of evaporative cooling technologies.

In this paper, a comprehensive review of greenhouse design and cooling technologies in hot regions was presented, with a critical discussion and comparison between the various cooling systems. Figure 1 shows an overview of the functions and design elements of greenhouse microclimate management investigated in this work. Numerous and diverse publications were analysed and it was found that most articles were narrowly focusing on the technical characteristics and validation of theoretical models. Therefore, this review has been organised into four main sections namely, greenhouse design and functional characteristics, greenhouse cooling technologies and numerical modelling of the greenhouse environment. A summarising table was also included to assess the merits and limitation of each technique.

2. Greenhouse design in hot climates

Compared to open field agriculture, a modern greenhouse design can provide high degree of climate control and protect indoor crops from unfavourable changes in ambient conditions such as temperature, humidity, solar radiation, etc. Therefore, optimisation of greenhouse design requires taking into account these concurrent parameters to balance the return of the yield and the related capital and operational costs (Candy, Moore, & Freere, 2012). Vanthoor et al. (2012a) developed a model-based technique to design greenhouses for a wide range of climates. A low-tech greenhouse was found to decrease the risk of price path disparities in different years, while a more advanced greenhouse can better cover the risks related to the weather. The work highlighted that the proposed method is an appropriate technique to solve the resulting multifactorial aspects of the design. Vanthoor et al. (2012b) then used the method to optimise the design of the greenhouse and maximise economic benefits. The method's main components include a climatic model, tomato-yield model, an optimisation algorithm and economic model. The design method considers in detail the elements of greenhouse (e.g., structure, cover, properties of whitewash, screen, heating or cooling systems and CO_2 supply). The computer algorithm was used in design of greenhouses in Almeria (Spain, with hot Mediterranean climate). The study revealed that high transmissivity of light significantly improved the performance of the greenhouse while the geothermal heating, mechanical cooling and shade was observed to be not economical. It was also reported that for Spanish conditions, the heating system, whitewash and covering material should be optimised to improve the net financial result. This section will explore research on design features of greenhouses, considered important for optimising greenhouse design and operation in hot climates which can provide crops with suitable conditions for growth, thus improving yield and increasing greenhouse profitability. This includes greenhouse climate, size, shape, orientation, covering material, nets, screening and shading.

2.1. *Greenhouse climate*

Several studies focused on the analysis and optimisation of climatic conditions of greenhouse in hot climates using various approaches such as evolutionary algorithm, genetic algorithm, dynamic modelling and numerical modelling, which is discussed in detail in section 4. Guzman-Cruz et al. (2009) compared various evolutionary algorithms including evolutionary programming, evolutionary strategies and genetic algorithms to calibrate the parameters of a climatic model that simulates the air temperature and relative humidity distribution within a greenhouse used to grow tomatoes. The results showed that evolutionary programming was more effective and provide accurate estimations of both temperature and relative humidity values. Accurate prediction and assessment of greenhouse climate conditions help the growers to manage the production of the crops and designers to optimise the climate control systems. Kumar, Jha, Tiwari, and Singh (2010) developed a dynamic model to simulate air and canopy temperatures and vapour pressure in a greenhouse. The model quantified the effects of natural ventilation in the roof and walls and crop transpiration on the temperature and vapour pressure in two floricultural production greenhouses in India. The model was also validated with field experiments of a Sawtooth greenhouse for the

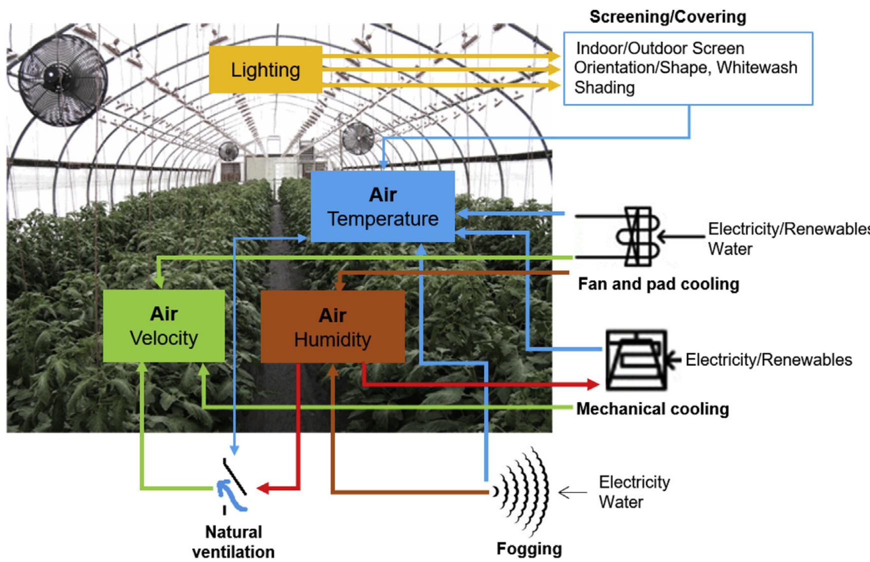

Fig. 1 – Functions and design elements for greenhouse microclimate management in hot climates.

cultivation of Gerbera Jassemini crop. The study revealed that model parameters such as roof vent angle, side ventilation width and leaf area index (LAI) significantly influenced the operating temperature. Vanthoor, Stanghellini, Van Henten, and De Visser (2011) established and validated a dynamic model that simulates the effects of the outdoor climatic conditions on climate conditioning equipment and construction parameters. Validation of the model was conducted for four greenhouse designs situated in Mediterranean, temperate marine and a semi-arid climate.

Hasni, Taibi, Draoui, and Boulard (2011) studied the use of simulation-based genetic algorithm (GA) and a particle swarm optimisation for determining the optimum size of the greenhouse under controlled temperature and pressure in Mediterranean climates. The proposed algorithm significantly improved the computation time and accuracy in identifying physical parameters of a horticultural greenhouse model. Piscia, Montero, Baeza, and Bailey (2012) developed a model to study condensation and relative humidity of greenhouses under variable soil heat flux (10–100 W m^{-2}) and sky temperature (263–276 K). The results showed that the roof had the lowest surface temperature in the greenhouse and the relative humidity was dependent on the soil heat flux more than the roof temperature. Xiao-wei, Jin-yao, and Xiao-ping (2013) established a model to investigate microclimate variables in a typical plastic greenhouse in China. A common radiation model was adopted and the effect of shape, configuration of openings and cover material on airflow patterns inside and outside the greenhouse were established. Validation of the model was carried out using experiments and the difference between the temperature values ranged between 0.8 and 1.7 °C. Mohammadi, Ranjbar, and Ajabshirchi (2018) also used experimental data to validate a dynamic model that predicts inside air and soil temperatures in a greenhouse located in Azerbaijan Province, Iran. The results showed that the dynamic model showed good agreement with the measurement values with the absolute error at 10.2%.

2.2. *Orientation and shape*

Greenhouse orientation and roof shape play a substantial role in optimising the solar radiation exposure to either maximise heat gain or reduce cooling loads (Von Elsner et al., 2000). Gupta and Chandra (2002) studied the effects of various shapes, orientations and energy conservation strategies such as glazing, fabric insulation and curtains on greenhouse energy consumption. A mathematical model based on heat and air moisture balance was developed to study a greenhouse situated in Delhi (India) during the summer. Energy savings of up to 30% can be achieved with the addition of insulation on the north wall of an east-west oriented Gothic arch greenhouse. Sethi (2009) developed a theoretical model for calculating the transmitted solar radiation at a specific latitude for both east-west and north-south greenhouse orientations. Five if the most common single span shapes greenhouses with same dimensions were compared including modified arch, vinery even span, uneven span and Quonset shape. The results showed that highest monthly solar radiation was received by the uneven span shape greenhouse, whereas the Quonset shape received the least. Mobtaker, Ajabshirchi, Ranjbar, and Matloobi (2019) investigated the effect of six types of greenhouse roof shapes including uneven, even and single span, arch type, vinery and Quonset on the solar radiation availability. The results showed that the east-west oriented single span greenhouse received 8% higher solar radiation all year as compared to the other roof shapes. Soriano, Hernández, Morales, Escobar, and Castilla (2004a) highlighted that the results of radiation studies on single span greenhouses are not suitable for multi span greenhouses. The results of their study showed that for a multi span greenhouse, relevant differences in radiation transmission was observed in different locations for example higher transmission was observed in the southern located span of the roof. In another study, Soriano et al. (2004b) investigated the effect of the roof slope and shape on the transmission of solar radiation in multi-span greenhouses using scaled experiments. The study showed that the increase in roof slope resulted in the significant increase in the transmission of direct solar radiation. The highest transmission was achieved in the greenhouse oriented east-west with a 27° roof slope.

Gupta, Tiwari, Kumar, and Gupta (2012) also evaluated the total solar fraction for various orientations by investigating the incoming transmitted solar radiation distribution on the floor and inner walls of a greenhouse in New Delhi, India. It was observed that the effect of orientation on the total solar fraction of a day was minimal. Though, a 45° clock-wise orientation (initially at east–west, 0°) resulted in maximum radiation loss during the summer and lowest during winter. It was also reported that for smaller greenhouses, as the angle of orientation increases, total solar fraction first increased then decreased after 45° during June. However, during the month of January, this process reversed.

Another study that focused on greenhouse shape was carried out by El-Maghlany, Teamah, and Tanaka (2015) to optimise solar energy transmission. The authors proposed an analytical model that investigates the impact of the aspect ratio of the ellipse curved surface on the captured solar energy. It was reported that solar energy captured was 4.544 GJ m^{-2} per season for a corresponding aspect ratio $Z = 4$. Stanciu, Stanciu, and Dobrovicescu (2016) estimated the received solar irradiance using an isotropic clear sky analysis model which was applied to a simplified greenhouse thermal model for simulating diurnal temperature. It was reported that the $E - W$ orientation greenhouse had lower interior air temperatures and solar heat gains when compared to $N - S$ orientation, resulting in 125 kW h d^{-1} of energy saving. The optimal selection of the orientation and shape of a greenhouse depends on the location, required solar irradiance in summer and winter, number of spans, plot size, the crop type and quantity and technology or method implemented for climate control.

2.3. *Covering materials*

The covering material and its properties play a vital role in optimising the energy consumption, the yield and the economics of the greenhouse. Covering materials plays a bi-functional role by blocking far infrared radiation and allowing solar radiation necessary for the plant growth. Feuilloley and Issanchou (1996) investigated the thermal properties of plastic film and glass greenhouse covering materials. Experimental tests revealed that condensation caused an increase in temperature of 0.2 °C–2.2 °C and 0.4 °C for plastic film and glass covers respectively. It was also shown that the overall heat transfer coefficient was expressed as a linear function of external ground temperature, Celestial vault and wind velocity. Shen and Yu (2002) suggested that in hot and humid conditions, a combination of ventilation fans with covering materials with near infrared reflection can effectively lower heat loads and avoid very high humid conditions in greenhouses. Runkle, Jaster, Heins, and Thill (2002) investigated a multi-layered near infrared reflecting film with minimal reduction of photosynthetically active radiation which can be a suitable alternative to metallised shading fabric.

Waaijenberg (2006) investigated cladding materials for greenhouses such as glass, plastic sheets and films and analysed design requirements, standards and factors affecting plant growth. The work found that in warm to hot countries, heat gain into greenhouses can be reduced by blocking unwanted near infrared radiation (NIR) using a PE plastic films. Arcidiacono, D'Emilio, Mazzarella, and Leonardi (2006) also compared three different covering materials (PE plastic film, insect proof net and photo-selective film) for maintaining indoor conditions in greenhouses in hot climates. The experimental results highlighted that the photo-selective film was not effective in controlling the rise in temperature during the summer period while for the insect proof nets, the conditions were very similar for the indoor and outdoor conditions. Raya, Parra, and Cid (2006) compared the influence on temperature, humidity and plant growth of traditional mesh net covers (6×6 filaments per cm) and plastic films, capable of improving pest control at the cost of ventilation. It was proposed that increasing the height of the structure by 1.5–3 m would compensate for the ventilation issue. Although the results showed better climatic performance for the higher structure, the difference between the temperature and relative humidity were small except for the extremes of the maximums and minimums that persisted longer in the lower height structure. Romacho et al. (2006) compared the effect of a clear and green coloured net covering on the indoor conditions and growth of tomatoes in hot conditions. The results showed minimal difference in terms of air temperature and humidity. In terms of yield, the green coloured net produced higher quality yield, 3.17 kg m^{-2} compared to 2.72 kg m^{-2} for the clear covering.

Garcia-Alonso et al. (2006) highlighted the disadvantages of using covering for greenhouses such as losses of photosynthetically active radiation and high cost. Hence, they proposed a low cost cool plastic film which blocks part of the near infrared radiation and tested in various hot and humid countries. López-Marín et al. (2008) also investigated the potential of cool plastic film covering with NIR-reflecting pigments for a greenhouse in Spain to alleviate the high temperatures during the summer. Abdel-Ghany et al. (2012) also investigated greenhouse covers that incorporated NIR reflectors. The authors showed the feasibility of NIR-reflecting plastic as a low-cost and simple cover for greenhouses in hot-arid climates capable of reducing indoor temperature by up to 5 °C. Though, this was insufficient in areas where the ambient temperature can exceed 45 °C during the summer and further development is required to improve the NIR-reflecting plastic film covers. Vanthoor, Stanghellini, van Henten, and Gázquez Garrido (2008) investigated the effect of various covering parameters on the production of tomato in a passive greenhouse which is only naturally ventilated and incorporated with seasonal whitewash. The work highlighted the importance of carrying out a multifactorial assessment to optimise the greenhouse conditions and production.

Although plastic film covering is effective for lowering the temperature in greenhouses, it is also subjected to degradation due to solar radiation exposure and also the chemicals used for the growing. Therefore, Stefani et al. (2008) proposed the used of fluoropolymer materials for plastic films for greenhouses to reduce the waste and environmental impact. The work developed a model based on the climate of southern

Italy and conducted tests to compare two types of films in terms of waste and service life: ethylene tetrafluoroethylene copolymer and polyolephinic films. The results showed that waste of plastic materials can be reduced by 5–10 times with the use of ethylene–tetrafluoroethylene copolymer films.

Magán et al. (2011) also investigated transmission and spatial uniformity of solar radiation but used multi-span greenhouses: a Venlo type glasshouse and a gothic arch-roofed greenhouse with plastic covering both east-west oriented, located in Almeria, Spain. Daily global radiation was recorded by the linear solarimeters along the transverse section of the spans at the eaves level. The study revealed that total and marketable yields of cultivated cucumber were higher in the plastic multi-span greenhouse than in the glasshouse. These differences were due to the quality of global radiation. The diffusive properties of the plastic cover induced higher content of diffuse radiation in the plastic greenhouse compared with the glasshouse.

The selection of a suitable covering material is important to attain the required growing environment. The accurate measurement of the thermal properties of the materials is necessary to achieve this and the measurements must be carried out under conditions resembling that of the greenhouse. Lee, Lee, Diop, and Na (2014) compared the heat transfer coefficient of covering materials with and without thermal screen using the hot box method. The result showed that two layers of covering material had 36% more insulation effect than a single layer covering.

Wei et al. (2016) carried out a study to improve the thermal performance of single span greenhouses with jute fibre board removable back wall. The experimental tests on greenhouses with the back wall either fully-removed (FRG) or half-removed (HRG) achieved a temperature reduction of 6.1 and 6.8 °C, respectively. The jute fibre is a biodegradable material. However, when wetted it loses its strength. Dehbi and Mourad (2016) conducted a comparative study on degradation and fracture behaviour under abrasion between mono-layer and tri-layers of low-density polyethylene (LDPE) films utilised as covering materials. Results of the mechanical properties analysis showed that the tri-layers film performed better under natural conditions (North of Algeria), with lifespan of these films being estimated to be 10 and 5 months respectively.

Thus, it can be seen that covering materials can enhance greenhouse cooling as they reduce transmitted solar radiation and at the same time controls the amount of radiation entering the greenhouse required for the crop growth. Several factors must be considered when selecting an appropriate covering material for the greenhouse such as location, desired greenhouse temperature and humidity profile and crop requirements, durability of material and cost.

2.4. *Insect-proof nets*

Creating a physical barrier using nets and screens helps hinder insect pests entering the production environment and reduce the need for garden chemicals (Castellano, Starace, De Pascalis, Lippolis, & Mugnozza, 2016). Insect-proof nets keep pests such as cabbage white butterfly, mosquitos and flea beetle off crops. In this section, works related to greenhouse insect-proof nets in hot regions have been reviewed. Campen (2005) used modelling in the design of a ventilated greenhouse in Indonesia and analysis of the influence of employing insect screens and plastic films on air flow rates. Insect screens reduced ventilation rates by more than 50% and the study also investigated the positive effects of roof top openings on wind driven air flow and temperatures. Harmanto, Tantau, and Salokhe (2006) also studied the effect of insect screens on the greenhouse microclimate conditions and air change rates but focused on various mesh sizes of nets (40, 52 and 78-mesh). Three greenhouses were covered with a plastic film on the top and various nets were used to cover the roof and sidewall ventilation openings. The results showed that the decrease of air change rate was 35% and 50% for the 52 and 78-mesh greenhouses, as compared to the 40-mesh greenhouse. As a result, the interior air temperature was also increased by 1–3 °C. It was concluded that the 52-mesh net was the most suitable for tropical regions.

Fatnassi, Boulard, Poncet, and Chave (2006) studied the influence of incorporating insect screens (anti-*Bemisia* and -*Thrips*) to a multi-span rose greenhouse on the airflow and microclimate conditions. The work developed a model which simulates the dynamics, thermal and water vapour transfer between the greenhouse air and crop cover. The insect nets were modelled as porous media with the following properties: anti-*Bemisia* (0.41 porosity and $8{\cdot}26 \times 10^{-10}$ permeability) and anti-*Thrip* (0.2 porosity and 2.67×10^{-10} permeability). The results were validated with experimental data of the air change rate collected in a greenhouse using tracer gas (N_2O) technique. The results showed that the ventilation and indoor conditions in the greenhouse can be improved by appropriate positioning of the roof vents and addition of side vents. Simultaneous opening of windward and leeward roof vents did not result in improved ventilation of the greenhouse. The work also observed that the anti-*Bemisia* and anti-*Thrip* nets both multiply the indoor air humidity and temperature difference between outdoor and indoor by a factor of 2 and 3 with respect to outdoor conditions, as compared to unscreened vents. Hirai et al. (2008) proposed the combination of evaporative cooling and radiative cooling by opening the shade screen net. The use of evaporative cooling during the day reduced ambient air temperature by 3 °C while the opening of shade screen reduced the temperature by 2 °C.

Fatnassi, Boulard, and Bouirden (2013) investigated the influence of different types of insect-proof nets on the microclimate of a greenhouse located in Agadir, Morocco. The experiment used a Canary type greenhouse with a polyethylene plastic cover and wooden frame. The results of the study showed that although both anti-*Aphid* and anti-*Thrip* nets were effective in providing protection against insects, it led to a sharp increase in interior air temperature and humidity, which would require using additional climate control techniques such as reducing incoming solar energy, vents and natural/artificial cooling methods.

Abdel-Ghany, Al-Helal, Picuno, and Shady (2016) also used nets to cover the sidewalls of a polygon-style and curved-arch roof net-greenhouses for arid regions. High porosities nets were adopted to increase the radiation and ventilation rate while nets with low porosity were utilised for the upper horizontal surfaces of the net-house to operate at around noon.

The results showed that the new system provides conditions similar to that in an evaporatively cooled greenhouse, while notably reducing the construction cost and water and electricity consumption. The net-house decreased the consumption of water by 13 kg m^{-2} d^{-1} in summer and reduced energy consumption by 0.26 kWh m^{-2} d^{-1}.

Recently, the number of screenhouses has increased, particularly in arid and semi-arid regions. Al-Mulla, Al-Balushi, Al-Rawahy, Al-Raisy, and Al-Makhmary (2008) assessed the impact of screenhouse microclimate on the production of cucumber using experimental tests. The results showed that the average internal temperature was only 0.2–0.8 °C lower than the outside. Variation on vapour pressure deficit and humidity was observed between the front and back section of the screenhouse which resulted in higher yield in the front side. Tanny, Teitel, Barak, Esquira, and Amir (2008a) investigated the impact of the height of screenhouse on various microclimatic variable. The results showed that net radiation was almost similar in the two screenhouses (4 and 2 m height). It was also observed that the air temperature deficit near the crops was higher (1.5 °C on average) in the 2 m screenhouse. Better mixing of air was also observed in the higher screenhouse. Tanny, Dicken, and Cohen (2008b) investigated the airflow and turbulence distribution in a large scale screenhouse using experimental tests during the summer. The results showed that the outdoor wind profile prevailed within the screenhouse and direction of the airflow was independent of the height.

Teitel et al. (2017) studied the impact of roof height on the microclimate and plant characteristics in an insect-proof screenhouse with water-resistant sidewalls. The experiments were carried out in two screenhouses with flat roof situated in southern Israel. The results revealed that increasing the screenhouse height from 4 to 6 m reduced the airflow through the screenhouse by 30%. On the other hand, increasing height did not generate any changes in yield, crop transpiration and plant development.

Teitel (2017) estimated the diurnal crop transpiration in an insect-proof screenhouse using the Penman–Monteith equation. The flat-roof house used for experiments was ventilated only through a screened roof. Net radiation, soil heat flux, transpiration and air velocity were measured inside the house and wind speed and direction were measured outside. The study revealed that at noon, global and net radiations inside the house were 0.68 and 0.44 of the outside global radiation, respectively. Soil heat flux was less than 3% of the external global radiation. It was also reported that the screened roof reduced the screenhouse air temperature by up to 1.3 °C. Flores-Velazquez, Ojeda, Villarreal-Guerrero, and Rojano (2017) used numerical modelling to investigate the thermal behaviour of a screenhouse in a hot arid climate. The results of the study showed that the difference between the ventilation rate of screen house with different mesh porosities was minimal and similar thermal distribution was also observed.

Thus, it can be seen that insect-proof nets can influence the greenhouse microclimate specifically the velocity, temperature and humidity. Several works have recommended to combine this method with shading to reduce incoming solar radiation and cooling techniques to maintain temperature and humidity conditions suitable for plant cultivation.

2.5. *Shading systems*

Shading is used to control the amount of solar radiation allowed into a greenhouse enclosure using paints, nets of different colours, external shade cloths, reflective shade screens, liquid foams between the walls and water film over the roof. Many studies have been conducted to explore the effects of shading on greenhouse performance in hot climates. Garcia, Medrano, Sanchez-Guerrero, and Lorenzo (2011) investigated the efficiency and climatic effects of external mobile shading and fogging using two identical greenhouses in Almeria, Spain. Both greenhouses were equipped with air vents covered with anti-insect netting. Variation of air temperature, vapour pressure deficit and incident radiation were monitored continuously and the fogging system provided the best performance in terms of radiation during the first stages of cultivation. However, this system requires a large amount of high-quality water which is limiting in areas with scarce water resources. The water consumption was 116 l m^{-2}, which is equivalent to 28% of the water absorption (l m^2 $cycle^{-1}$) of a tomato crop grown in Mediterranean conditions. The work suggested that future studies could focus on analysis the effect of parameters such as ventilation, transmissivity of the screen, density of the nozzle and crops. Furthermore, the combination of fogging methods and mobile shading based on the different stage of cultivation should be explored.

Ilic, Milenkovic, Stanojevic, Cvetkovic, and Fallik (2012) also assessed the influence of external shading but focused on the effect of light intensity using shade nets with various colours on the yield and quality of tomatoes. The results showed shading reduced cracking and eliminated sunscalds on tomato fruits. Red and pearl nets with 40% relative shading increased the total yield by 18.5%. Ahemd, Al-Faraj, and Abdel-Ghany (2016) studied the most common greenhouse shading techniques used in summer. The cooling effects of shading on greenhouse microclimate were investigated to determine the best shading method for hot and arid regions. The work showed that the combination of a shading method such as whitewash or shade netting with evaporative cooling and/or natural ventilation can lower indoor air temperature by up to 10 °C, increase relative humidity by up to 20% and reduces transmitted solar radiation by up to 50%, reducing consumption of water and energy and enhancing productivity and quality of crops.

Marucci and Cappuccini (2016) proposed a system consisting of rotating photovoltaic (PV) panels and highly reflective mirrors for shading in greenhouse to combine the production of crops and electrical energy (as shown in Fig. 2). The energy balance in completely clear sky conditions during a hot period in Lazio, Italy was studied to determine the energy flows of the installation.

The level of shading was determined by using the ratio of projection length of the photovoltaic panels and the distance from the rotation point. The results revealed that greenhouse relative humidity was decreased by 15% and solar radiation

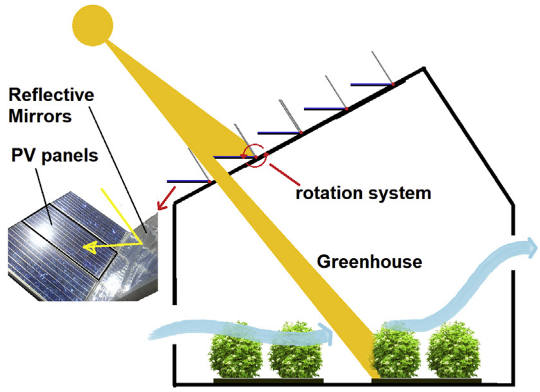

Fig. 2 – Schematic of a dynamic photovoltaic and shading system for greenhouse in hot climates.

measured inside the greenhouse varied from 100 to 950 W m^{-2}, for ambient solar radiation of 700 and 950 W m^{-2}. Nevertheless, the system uses mechanically driven panels which implies a high maintenance cost and reduced reliability.

Murakami, Fukuoka, and Noto (2017) proposed a different technique which includes two new NIR cutting nets that had high transmittance of visible light with strong absorption in the NIR region (700–2500 nm) to improve the melon fruits sweetness collected in midsummer. The nets were placed over a polyolefin film on the pipe houses. To allow for natural ventilation, the films were rolled on the north and south sides of the greenhouses up to 1.5 m height. The NIR-cut nets reduced the temperature of the greenhouse by up to 5 °C during a sunny day in the summer and increased sugar accumulation of fruits during maturation period. Santolini et al. (2018) utilised Computational Fluid Dynamics (CFD) to investigate the influence of shading screens on the airflow distribution in a greenhouse located in Bologna, Italy. Three screens were placed inside the greenhouse. Two internal screens were parallel to the external walls, while the third was placed horizontally, between the cultivation area and the roof, at eaves height. In addition, black shading screens were placed above the roof. The study revealed that using screens resulted in a more uniform airflow speed distribution within the greenhouse than having no screens, particularly near the regions with crops. From the reviewed studies, it can be stated that shading is effective in decreasing transmitted solar radiation and reducing greenhouse air temperature, especially when combined with other cooling techniques (e.g. ventilation and evaporative cooling). Thus, this technique can reduce energy consumption and improve crop yield and quality in hot climates.

3. Greenhouse cooling technologies

This section reviews the diverse greenhouse cooling methods and systems in hot climates that are available such as mechanical and natural ventilation, evaporative cooling by means of fan pad, mist/fog and roof cooling system, hybrid cooling and integration with solar PV.

3.1. *Mechanical cooling systems*

Mechanical systems are the most widely used cooling systems for greenhouses. Mechanical cooling which utilises fans, heat pumps and heat exchangers can maintain greenhouse temperature at low levels, especially in hot regions with high ambient temperatures and radiation levels (Kittas, Katsoulas, Bartzanas, & Bakker, 2013). Many research works were carried out to investigate and assess greenhouse mechanical cooling systems in hot regions. Chou, Chua, Ho, and Ooi (2004) investigated the performance of a heat pump for heating, cooling and dehumidification of the greenhouse using simulations based on steady-state models. The results showed that the heat pump with a 3.7 kW compressor, 30.0 kW condenser capacity and 37.0 kW evaporator capacity was adequate to sustain a daytime temperature of 27 °C, night time temperature of 18 °C and relative humidity of 40% in a 270 m^2 floor area greenhouse. Based on the changes in climatic condition, the COP and heat pump's specific energy consumption varied between 1.2 and 4.0 and 1,000–16,000 kJ kg^{-1}

Bakker, De Zwart, and Campen (2006) designed a cooling system with heat storage for a fully closed greenhouse. The system which included a fine wire heat exchanger was optimised to reduce the energy consumption. In order to calculate the heat flux and heat transfer from water to air, a numerical matrix-based model was developed. It was concluded that a heat pump was required to avoid energy loss due to dehumidification and sustain the temperature in the well cost. Yang and Rhee (2013) evaluated the performance of a greenhouse system that captures and use excess air thermal energy for heating and cooling. The system consisted of a heat pump, fan coil units and heat storage tanks. The results showed that the amount of excess air thermal energy measured were between 258 and 6259 MJ per month for a 100 m^2 floor area greenhouse. It was also reported that the maximum daily and monthly energy conservations were 76.3% and 25.7% respectively. However, the system was cumbersome and complex.

Okushima et al. (2014) investigated greenhouse cooling systems with a cool storage water tank and three types of heat pumps: air source-air supply, water source-air supply and water source-water supply. The cooling performances of the heat pump systems were calculated for different hot climate locations. The results showed that the cool storage and the heat exchangers could remove more heat than the water source-air supply heat pump. It was also concluded that if the control strategy were changed to anticipate night cooling by changing to ventilation earlier, some of the cool storage could be saved to supply the full night cooling. These partial cooling periods without ventilation might be useful for semi-closed greenhouses.

Katsoulas, Sapounas, De Zwart, Dieleman, and Stanghellini (2015) evaluated the influence of the capacity of cooling system on the ventilation requirements of a semi-closed greenhouses in various climatic conditions. The greenhouse climate and crop yields were simulated for several capacities of cooling system in the Mediterranean (Greece and Algeria) by applying a cooling module into an existing model of a greenhouse. The results showed that the increase in capacity of the cooling system resulted in an improved microclimate and decrease of water consumption which increased the crop yield.

Sultan, Miyazakia, Sahaa, Koyamaa, and Maisotsenko (2015) carried out an investigation of a thermally-driven adsorption air conditioning system, focusing on the uptake of water vapor adsorption by various types of adsorbents for greenhouse applications. The adsorbents used includes: silica gel, activated carbon powder and activated carbon fibre. The system consists of a direct and indirect evaporative cooler (using Maisotsenko cycle), a heat source and desiccant wheel.

The results showed that the activated carbon powder enabled maximum steady-state moisture cycled (based on 60% RH at the desiccant bed exit for air drying) at all regeneration temperatures, ideally sitting at 47 °C which was nearly 6.5 and 2.5 times of the silica gel and activated carbon fibre. Nevertheless, there was no significant variation in maximum moisture cycled by the activated carbon powder and activated carbon fibre at all regeneration temperatures more than 47 °C and 52 °C.

Based on the reviewed mechanical cooling systems for greenhouses, with high cooling capacity it is possible for a greenhouse to be fully closed, even at maximum solar radiation levels. However, these systems are major consumers of energy. Therefore, their return on investment is poor for hot regions (Kittas et al., 2013, pp. 63–95). Furthermore, some technologies are complex and require costly maintenance.

3.2. Natural ventilation

The technique of providing cooling in greenhouses using wind and buoyancy driven flows goes back to the start of controlled environments. This simple technique which requires little or no external energy and can be effective for greenhouse cooling applications in hot climates. It is driven by the difference in pressure between the greenhouse interior and outside environment (Fig. 3). This is achieved by careful positioning of side wall openings and roof openings. Research has been carried out to investigate the influence of natural ventilation on the microclimate of greenhouse in hot climates. The most common approach used for analysis that includes field experiments, laboratory scale testing and numerical modelling. Campen and Bot (2003) studied a naturally ventilated greenhouse using three-dimensional modelling. Two roof opening configurations were investigated: rollup type and flap type window. The simulation results were validated with experimental tracer gas measurements. The work revealed that the

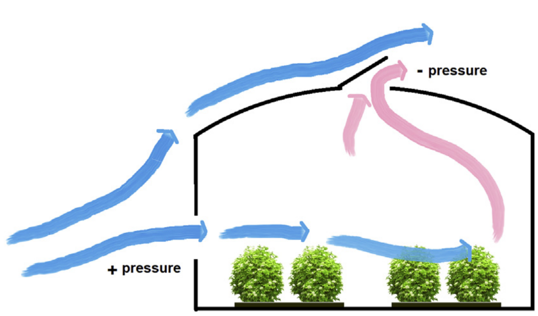

Fig. 3 – Naturally ventilated greenhouse driven by pressure difference.

rollup type window had higher ventilation rates due to the cover having larger openings. Mashonjowa, Ronsse, Milford, and Pieters (2013) modelled the performance of a naturally ventilated greenhouse in Zimbabwe using the Gembloux dynamic greenhouse climate mode. The model consists of a differential equations system based on the heat and mass balance of the greenhouse layers. The study showed that the wind effect and discharge coefficients were not only dependent on the ventilation system but also on the weather conditions.

Baeza et al. (2009) investigated the impact of side wall openings on the buoyancy driven flows in a multi span greenhouse using a validated numerical model. The results showed that the ventilation rate per unit ground area of a 20-span greenhouse with side wall and roof openings was 2 times higher than that of a greenhouse with only roof openings. While in a 3-span greenhouse, the ventilation rate was 7 times higher for a combined roof-side wall opening configuration than a roof vent. In terms of temperature distribution, a large percentage of the area (48.3–79%) of the greenhouse had an indoor–outdoor temperature difference of 4 °C and higher for the roof only ventilation. With this combined ventilation configuration, these areas were 23.4–36.1%. The work concluded the importance of the optimum design of the side wall vents for buoyancy driven ventilation in particular for greenhouses with lower number of spans. Furthermore, addition of insect nets over the vents can reduce the ventilation rates by up to 87% when air exchange is buoyancy driven.

Teitel, Montero, and Baeza (2012) investigated a new five-span greenhouse design which had a 30° slope roof with side wall vents and roof vents for each span. Deflectors were added to the ridge of the windward and leeward spans and on the side wall vents to prevent hot and dry wind impinging directly on the plants. The proposed design was compared to a typical parral-type greenhouse with a shallow slope roof, small vertical and sidewall vents and no deflectors. The results showed that the proposed design could provide ventilation rates up to 4 times higher than the parral-type greenhouse. An improvement in the air circulation and temperature distribution in the greenhouse was also observed. He, Chen, Sun, Liu, and Huang (2015) studied the influence of vent openings on a multi-span greenhouse microclimate during the summer and winter. A three-dimensional numerical model of an 11-span plastic greenhouse was developed. The model was validated experimentally. The results showed that vent configuration considerably influences the microclimate patterns and the distribution and behaviour of the indoor temperature and humidity. With the roof opening configuration, the airflow temperature and relative humidity dropped sharply in the first span and increased significantly in the last span. While for the roof plus side opening configuration, a good air temperature distribution was observed. However, there was a large variation in the humidity level between the two sides of the greenhouse. Additionally, it was observed that increasing the size of the vent opening induced a decrease in the dehumidification time.

Espinoza et al. (2017) assessed the influence of the configuration of ventilator on the flow distribution in a multi-span greenhouse in Spain, taking into account the impact of surrounding greenhouses. Two configurations were compared using experiments: a 2 and 3 half arch roof vents with side vents. Results showed that the 2 roof and side vents configuration had a lower overall ventilation flow rates but an improvement in the air movement was observed in the crop zone. Furthermore, the surrounding greenhouse on the leeward side decreased the ventilation capacity.

Recently, Reyes-Rosas, Molina-Aiz, Valera, López, and Khamkure (2017) predicted of temperatures of airflow, crops, cover and soil in a naturally ventilated greenhouse using a dynamic semi-empirical model. Synopta software (Hortisystems UK Ltd, West Sussex, UK) was used to control the vent opening. The study revealed that decreasing air movement produced an important heterogeneity in distribution of temperature, with difference of 7–8 °C between the zones near the plants, and close to the greenhouse covering in the middle of spans, where the hot air accumulated because of buoyancy driven flows.

Li, Huang, and Zhang (2017) studied variations of temperature, humidity and solar radiation inside a naturally ventilated greenhouses during the hot seasons in Shouguang, China. Two single-sloped greenhouses were used for the experimental study. A thermal model was also developed to establish the energy balance equations and control the microclimate parameters of the greenhouses. The results highlighted that air temperature varied between 21 °C and 26 °C. while the relative humidity varied from 96% to 84%. It was also reported that a shorter span and a greater roof height enhanced heat preservation and energy saving in a single-sloped greenhouse.

The application of natural ventilation for temperature and humidity control of a greenhouse, depends on the daily variation of various factors including the outdoor climate, crops, greenhouse orientation, the size and positioning of the openings. Hence, detailed studies are necessary to analyse and optimise the ventilation performance of greenhouses by considering all these factors. In areas with low wind speeds, side wall vents can be combined with roof to enhance natural ventilation. Addition of insect screens can reduce the supply airflow which further increases temperature within the greenhouse. Future analysis of naturally ventilated greenhouses should consider the impact of surrounding structures or greenhouses as it can affect the ventilation performance. In order to further enhance greenhouse cooling in hot regions, natural ventilation can be combined with other cooling techniques, such as evaporative cooling. Continued advances in the design of natural ventilation for greenhouse are providing improved control of temperature and humidity and lesser cost. Correct sizing, positioning and operation of the ventilation system can potentially provide similar or better control than with fan systems.

3.3. *Evaporative cooling*

One of the most efficient technologies for providing suitable greenhouse climatic conditions in hot and dry regions is to employ evaporative cooling, which converts sensible heat into latent heat through water evaporation supplied directly into the greenhouse via mist or fog system, sprinklers or evaporative cooling pads (Kittas et al., 2013, pp. 63–95). This technique can significantly reduce the air temperature below the ambient temperature and increase the humidity to the essential levels.

3.3.1. *Fan-pad system*

This system typically consists of fans on one of the greenhouse sidewalls and pads on the opposite sidewall as shown in Fig. 4. Evaporative cooling is achieved by spraying or sprinkling water over the pads and the outgoing airflow through the pads by the fans (Al-Helal, 2007). Over the past years, a number of studies have introduced fan-pad systems for cooling greenhouses in hot and arid regions, and a number of solutions have been proposed to improve their performance. Ganguly and Ghosh (2007) developed a thermal model of a floricultural greenhouse ventilated and cooled by a fan–pad system. Cooling was achieved by incorporating a combination of fan–pad system and shading devices, while forced ventilation was used to achieved dehumidification of the air. The study showed that the fan–pad ventilation system was most effective during the summer, whereas in the monsoon it was less effective due to high humidity levels of outdoor air, which limits the effectiveness of evaporative cooling. Ahmed, Abaas, Ahmed, and Ismail (2011) also studied fan-pad system but focused on evaluating the thermal performance of different types of evaporative pads; Celdek pads, straw pads and sliced wood pads in Khartoum, Sudan. A parametric study was conducted to evaluate temperature, humidity and crop parameters. The study revealed that the straw type pads provided the highest temperature decrease, while the sliced type wood pads provided the lowest. Furthermore, the lowest and highest relative humidity were achieved with sliced wood and straw pads respectively. It was also reported that the highest and lowest saturation efficiencies were obtained with the sliced wood and the straw pads respectively. However, the materials used in these pads often deteriorate rapidly.

Lopez, Valera, Molina-Aiz, and Pena (2012) investigated microclimate in three Mediterranean multi-span greenhouses with different cooling systems; pad-fan, fog and natural ventilation, without taking into account the crop's contribution to cooling and humidification. To homogenise the microclimate inside the greenhouse, interior fans were used. The air velocity vectors were analysed to understand the airflow pattern and its uniformity supplied by the cooling strategies. The results showed that the greatest reduction in

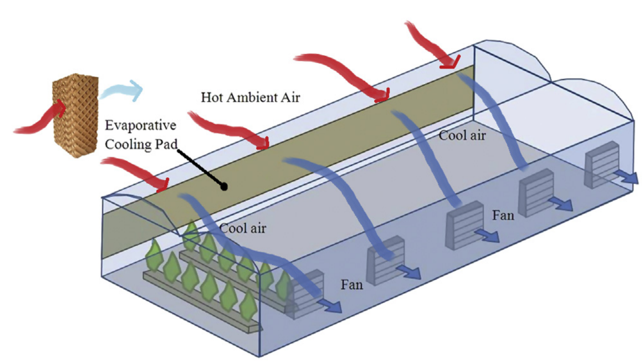

Fig. 4 – Schematic of a fan-pad cooling system for greenhouse.

temperature was achieved by the combined pad-fan cooling system with a shade screen. However, the use of this combination is limited for low crop evapotranspiration. Romantchik, Ríos, Sánchez, López, and Sánchez (2017) determined the energy required by a fan-pad system in span-type greenhouse with a double layer of polyethylene plastic cover. A model calibrated with experiments was developed to predicts the greenhouse temperatures, ventilation rates and energy consumption which allowed the reliable sizing of the PV systems. The work highlighted that the grid-connected photovoltaic system was able to generate all the energy consumed by the fans.

Rong, Pedersen, Jensen, Morsing, and Zhang (2017) used experiments to examine the dynamic performance of evaporative cooling pad under various control strategies including altering water supply duration and control time cycle strategies. A cross-fluted design of impregnated cellulose pad was used in the tests. The results showed that supplying water to the pad caused higher air resistance through the pad. In addition the highest cooling efficiency was observed at the lowest air speed (0.25 m s^{-1}). Nonetheless, a short time cycle may cause rapid ageing of the evaporative cooling pad.

From the reviewed studies, it can be established that the fan-pad systems can be effective for greenhouse cooling and humidification in hot and arid regions. In order to achieve optimal cooling, the water flow rate and distribution system, capacity of pump, recirculation and output rate of the system must be carefully calculated and designed to provide sufficient wetting of the pad and to avoid deposition of material. The average thickness of the pad should be 100–200 mm. The pad area depends on the airflow rate necessary for the cooling system and the permissible surface velocity over the pad. Average inlet velocities should be 0.75–1.5 m s^{-1}. Excessive velocity may cause problems with water drops entering the greenhouse. The pad area should be about 1 m^2 per 20–30 m^2 greenhouse area. The maximum fan-to-pad distance should be 30–40 m. The maximum distance between fans should be 7.5–10 m, and fans should not discharge towards the pads of an adjacent greenhouse less than 15 m away (Kittas et al., 2013, pp. 63–95). In areas where water availability is a common concern such as arid and semi-arid regions, the water consumption of evaporative cooling technologies such as the fan pad systems must be taken into consideration and minimised as possible. This was addressed by the study of Sabeh, Giacomelli, and Kubota (2006) which investigated the water consumption of an evaporative cooling pad system for greenhouses in semi-arid climate. Water usage was mainly affected by the air exchange rate. The pan fad system water consumption ranged between 0.145 and 0.389 g m^{-2} s^{-1} when the air exchange rates were between 0.017 and 0.079 m^3 m^{-2} s^{-1}. The study highlighted that the fan and pad system consumed 14.8 l m^{-2} d^{-1} to maintain air temperature between 18 and 24 °C. Franco, Valera and Peña (2014) investigated the water consumption of evaporative cooling cellulose pads for greenhouses. The study showed that the water consumption ranged between 1.8 and 2.6 l h^{-1} m^{-2} °C^{-1} at incoming airflow velocities between 1 and 1.5 m s^{-1}. The system utilised a 2.2 kW centrifugal fan to supply the airflow. The work highlighted the importance of regulating the air exchange rate in the greenhouse according to the requirements and minimise energy consumption. Powering the fans using solar PV is an option and has been suggested by several researchers. Although the capital cost can be high, it can be advantageous in areas with intermittent supply of electricity. Davies, Hossain, Lychnos, and Paton (2008) suggested that the fan speed can be modulated based on the sunlight so as full speed is only reached during peak times. The study showed that the energy consumption of the 2.2 kW fans can be reduced by up to 40% when modulated as compared to constant speed operation. One of the drawbacks of the system is the requirement for air tight greenhouse structure to ensure that the airflow to only pass through the cooling pads on one side and be extracted by the fans on the opposite side. This also means that temperature distributions will be uneven across the greenhouse, with maximum difference of up to 11.4 °C between the fans and the pads as observed by (Lopez et al., 2012) in their study.

3.3.2. *Fog/mist system*

This technology provides cooling by pressurising and spraying water through tiny nozzles to create micro-fine mist above the crops. The terminal velocity of the water droplets is low and the greenhouse air streams can easily transport water droplets (Fig. 5). This can result in high evaporation rate of water while keeping the crops dry (Abdel-Ghany & Kozai, 2006). Several studies were carried out to investigate fog and mist cooling systems for greenhouses. Katsoulas, Baille, and Kittas (2001) studied the influence of misting on transpiration and conductance of greenhouse rose canopy. Experiments were carried out during summer with a mist system operating when the relative humidity inside the greenhouse was below 75%. The results showed that the mist system contributed up to 20% to total evaporative cooling with only 40–50% of the mist water was being effectively used in cooling. On the other hand, calculated crop water stress index indicated that the crops were less stressed during misting conditions. In a further study, Katsoulas et al. (2006) investigated the influence of fog cooling on microclimate and quality of soilless pepper crop in a greenhouse. The greenhouse had two compartments cooled by natural ventilation via roof openings that maintained air temperature below 26 °C and fog cooling with open roof vents to the maximum aperture to keep relative humidity below 80%. The results showed that fog cooling can lower the interior air and leaf temperature by up to 3 °C as compared to

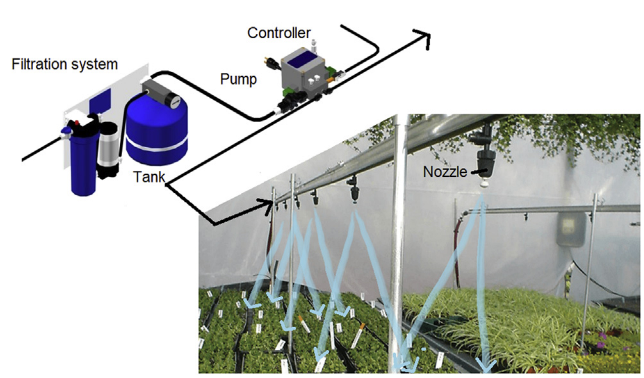

Fig. 5 – Schematic of a greenhouse fogging or misting system installation.

natural ventilation. Furthermore, the air vapour pressure deficit was lower than 2 kPa under fog conditions, even during the hottest period of the day. It was also reported that the fog system improved the mean crop weight and the percentage of marketable crops. However, it reduced considerably the total number of fruits per plant.

Abdel-Ghany, Goto, and Kozai (2006) developed a new method for simulating the fraction of fog that evaporates by absorbing sensible heat from the greenhouse. Experiments were conducted on a hot and sunny day in Tokyo inside a 26 m^2 naturally ventilated greenhouse. The heat and water vapour balances of the cooling process were used to estimate sensible heat. The values of sensible heat estimated from the heat balance were found to be identical to those predicted from the water vapour balance. In another study, Linker, Kacira, and Arbel (2011) developed a climate control system for a small greenhouse equipped with extracting fans and variable-pressure fogging system in Bet-Dagan, Israel. A total of 23 nozzles across two high-pressure fogging lines were installed. It was reported that the controller was able to maintain the indoor greenhouse conditions close to the set points with maximum mean deviations of 2.5 °C air temperature and 5% relative humidity observed over a 10 min period with constant set points.

Villarreal-Guerrero et al. (2012) simulated and compared two strategies for high-pressure fogging; constant fog rate (CFR), in which vents opened when the air temperature of greenhouse reached the set point and a variable vents and fog rates (VVFR) which had dynamic configurations of the vent. The results showed that when the greenhouse was operated under the VVFR strategy, lower average air temperature and closer vapour pressure deficit values to the set points were attained while reducing energy consumption by 30% and water by 36%. It was also highlighted that by varying the operating pressure of the system, the VVFR allowed smaller fluctuations in temperature and humidity. Sánchez-Hermosilla et al. (2013) experimentally investigated a fogging system for applying plant-protection products in a greenhouse located in Almería, Spain. The system with twin spray nozzles was compared to a manual spray to assess the spray deposition and losses to the soil.

The results showed that the air–water spray led to a deposition in the plant canopy that increased as the plants develop, since the number of droplets that reached the crops before evaporating were higher. It was also observed that the system caused a lower deposition over the crop than manual spray guns. From the reviewed studies, it can be inferred that fog and mist cooling systems can achieve high efficiency of water evaporation while also keeping the foliage dry. In addition, fog systems can induce a more uniform distribution of temperature and humidity in a greenhouse as compared to natural ventilation using roof vents (Katsoulas, Kittas, & Bartzanas, 2012). However, it has disadvantages when compared to the fan pad evaporative cooling system such as the lower air saturation efficiency (Franco et al., 2014), cost (Sethi & Sharma, 2007a), water and energy consumption (Lopez et al., 2012). The study of (Lopez et al., 2012) showed that the fog cooling system consumed 7.2–8.9 kWh while the fan pad consumed 5.1 kWh for one-hour operation.

3.3.3. *External surface/roof evaporative cooling*

As the roof surface of the greenhouse receives the maximum amount of solar radiation during the summer it is also responsible for a large portion of the cooling requirement. Hence, allowing water to evaporate on the surface can reduce heat flux through the roof. This can be achieved by keeping thin film of water over the exterior surfaces converting the surface sensible heat to latent heat of vaporisation for water evaporation. Some of the solar radiation received on the wet surface is reflected and the rest is absorbed for water evaporation. A mathematical model of a greenhouse evaporatively cooled by water film moving over external shade cloth was developed by Ghosal, Tiwari, and Srivastava (2003). Water was flowing on a shade cloth stretched over the roofs and south wall of an even-span greenhouse (Fig. 6). The model was experimentally validated for the climate of Delhi, India during the summer. The experiments were carried out under three configurations: shaded, unshaded and shaded greenhouse with water flow. The results showed that the interior air temperature was reduced by 6 °C and 2 °C in shaded with water flow and shaded configurations, as compared to unshaded configuration. It was also observed that the 0.25 kg s^{-1} was the optimum flow rate of the water film to achieve the required cooling in the studied greenhouse. In an earlier study, Willits and Peet (2000) carried out an experimental study of the cooling performance of greenhouse with shade cloth and water sprinkling system, which is utilised when outdoor solar levels were 400 W m^{-2} and higher. The results showed that the rise of the air temperature and electricity consumption was reduced by up to 41% and 21% when using roof evaporative cooling. Willits (2001) conducted further study of the roof evaporative cooling system but investigated the effect of the fabric type, shading percentage and colour in terms of reducing the rate of energy gain, rise in air temperature and energy consumption. The study showed that the fabric type and colour had minimal impact on the performance as compared to the shade rating. Helmy, Eltawil, Adoshieshaa, and El-Zan (2013) investigated the performance of an evaporatively cooled greenhouse with roof evaporative cooling using full scale experimental tests. The results showed that the addition of the roof water spray provided 1.1–5.4 °C lower temperature in the greenhouse which is useful during adverse hot conditions.

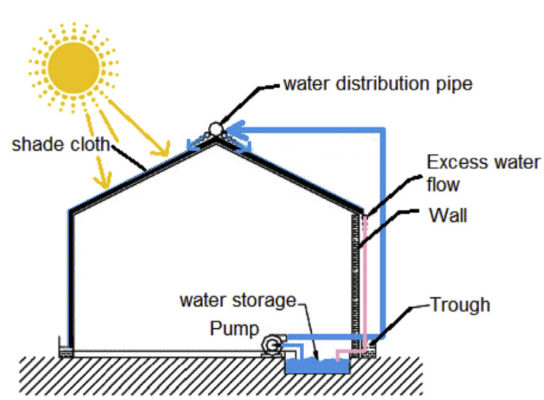

Fig. 6 – Schematic of a greenhouse with evaporative cooling by moving water film over external shade cloth.

Based on the review of literature, there are limited studies on the application of roof evaporative cooling for greenhouses and further investigations should be carried out to assess its viability. Future works should focus on the material utilised for the roof/cover, evaporating media, flow speeds, and more work is necessary to assess its performance under real world conditions.

3.4. *Combined/hybrid cooling systems*

One cooling technique may not be adequate to provide the required crop climate under hot and dry conditions. In order to achieve optimal greenhouse cooling in hot climates, cooling techniques can be combined. Hybrid systems can reduce energy consumption while improving greenhouse cooling performance. Over the last years, many researchers have introduced combinations of different cooling techniques. Ganguly, Misra, and Ghosh (2010) modelled an integrated system for greenhouses, consisting of solar PV, polymer electrolyte membrane fuel cell stacks and electrolyser bank. The study revealed that 51 solar photovoltaic modules each of 75 W_p, 3.3 kW electrolyser and two 480 W fuel cell stacks were able to provide the energy requirement of a floriculture greenhouse with 90 m^2 floor area equipped with fan-pad ventilation system. Guan, Bennett, and Bell (2015) investigated a hybrid air conditioning system to establish the benefits of multi-operating modes of a low-energy direct evaporative cooler in different hot climate regions in Australia. The system is a modified direct evaporating cooler, comprising of an open cycle – closed cycle cascade system, including multiple modes of operation: natural ventilation cooling, forced mechanical ventilation cooling, evaporative cooling and mixed heating. A new climate assessment tool was established to assess the hybrid system's performance. The tool can quantify and estimate the operating hours for each operating mode under several climate conditions and requirements. The results showed that the potential for direct evaporative cooling is noteworthy in Australian climates.

A different combination was proposed by Xu, Li, Wanga, Liu, and Zhou (2015) who evaluated the performance of an evaporative cooling fan-pad system combined with other methods such as internal thermal screens, shading nets and circulation fans for greenhouses in subtropical climate. The system was installed in a 2304 m^2 glass multi-span greenhouse. The study revealed that the fan–pad system can be an effective option for cooling greenhouses in humid climates. It was also observed that by combining evaporative cooling pad with shading, the greenhouse can be kept 2–3 °C lower than the ambient temperature at 80% relative humidity. The internal thermal screens prevented solar radiation from entering the lower part of the greenhouse during the summer. Recently, Banik and Ganguly (2017) developed a thermal model of a distributed fan-pad evaporative cooler coupled with solar desiccation (as shown in Fig. 7) used in a floricultural greenhouse in Indian sub-continent. The study considered the influence of crop transpiration and other parameters such as area index and characteristic length of crop leaf.

The study concluded that coupling desiccants with evaporative cooling provides improved cooling effect. The maximum temperature in the greenhouse was predicted as 26.6 °C in June, while the temperature of the conventional fan-pad system reached up to 28 °C, as predicted by the model in (Kittas, Bartzanas & Jaffrin, 2003). The predicted payback period for the system was relatively short (6 years). However, the system is less effective when the ambient relative humidity increases. From the reviewed studies, it is highlighted that the combination and simultaneous usage of natural ventilation, evaporative cooling and shading has the potential to reduce greenhouse energy requirement and provide optimum indoor conditions for year-round cultivation. A hybrid cooling system must be assisted by an effective control strategy to ensure that the required temperature and humidity levels and distributions are maintained in the greenhouse.

3.5. *Solar powered cooling*

Over the past years, numerous researchers have proposed solar powered systems for greenhouse cooling in hot regions in order to reduce energy costs. Lychnos and Davies (2012) built and tested prototypes of a solar-powered liquid desiccant cooling system for greenhouses in hot climates. Figure 8 illustrates the three process fluids in the system: liquid desiccant, cooling water and air. The outdoor air initially flows through the desiccator which is made of porous material and is dehumidified before being cooled by the evaporative cooling pad. The system uses a solar regenerator to provide the required latent heat to remove the water from the liquid desiccant and restore the dehumidifying ability. The desiccator also includes cooling tubes to remove the latent heat of condensation of the desiccant. Air is driven through the greenhouse using an exhaust fan. The results were compared with previous studies that used other liquid desiccants. The performance of the cooled greenhouse was predicted for hot regions including Chittagong, Bangladesh; Messina, Italy; Mumbai, India; Muscat, Oman; Havana, Cuba and Sfax, Tunisia using a computational model.

The results showed that magnesium chloride liquid desiccant system reduced the greenhouse temperature by 5.5 °C–7.5 °C in the selected locations, as compared to standard evaporative cooling. Furthermore, at periods of year when the liquid desiccant system provides lower temperatures than desired, it could run in evaporative cooling mode only. The work suggested that further testing should be carried out by means of pilot scale trials.

Hassanien, Li, and Lin (2016) reviewed the solar energy technologies for agricultural greenhouses. According to the economic study, solar thermal cooling was found to be less cost-effective in moderate European climates than in hot climates. It was also reported that PV and solar thermal systems would be convenient options for cooling greenhouses especially in desert areas. The reduction of PV module prices will make the PV greenhouses and PV powered water pumping systems more feasible in the near future and will reduce their payback time. In the same year, Abu-Hamdeh and Almitani (2016) designed a solar regenerated desiccant evaporative cooling system for greenhouses in Saudi Arabia. The air temperature inside the greenhouse was numerically simulated and experimentally validated. The study revealed that the desiccant evaporative cooling system lowered the average

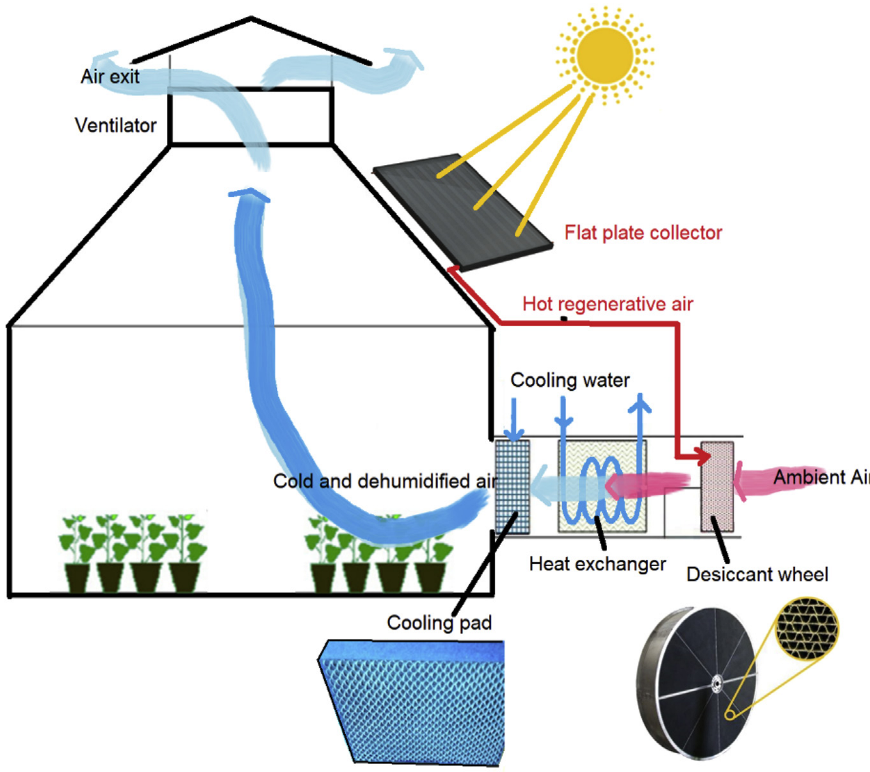

Fig. 7 – Schematic diagram of the solar desiccant assisted distributed fan-pad ventilated greenhouse system.

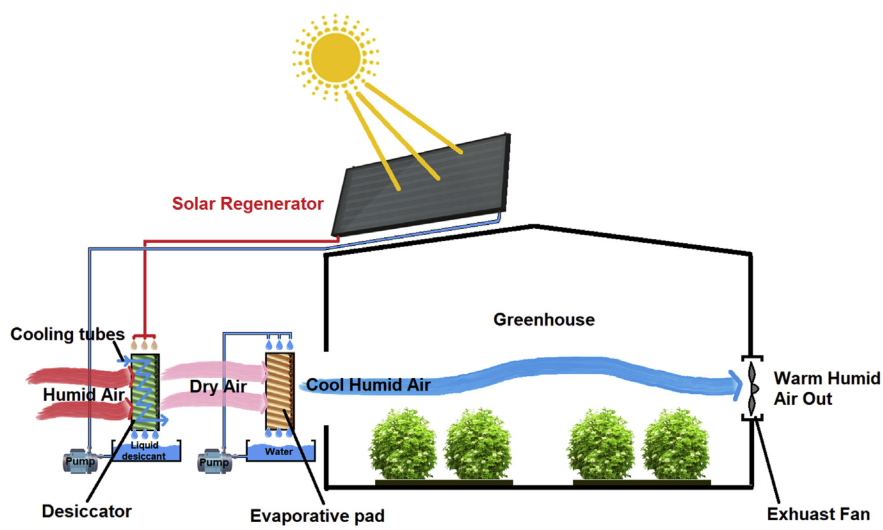

Fig. 8 – Schematic of the solar powered liquid desiccant cooling system for greenhouses in hot climates.

daily temperatures by up to 6 °C as compared to a standard evaporative cooling system. It was also reported that convective heat transfer coefficient was improved by 5.5–9%, 6.2–12.3% and 7.2–14.4% for 0.01–0.04 volume fractions of ZnO-W, Fe_3O_4-W and Al_2O_3-W nanofluids. Similarly, Ghosh and Ganguly (2017) investigated a solar powered desiccant evaporative cooling system for a greenhouse in hot and humid climates but focused on a partially closed configuration which recirculates some of the return air. The study developed a thermal model which was validated with data from the literature. The work showed that the COP of the cooling system varied between 0.64 and 0.74 during the most humid months of the year while maintaining the required indoor temperature conditions for the target crop (lettuce).

Campiotti, Morosinotto, Puglisi, Schettini, and Vox (2016) also proposed a solar system for greenhouse cooling but designed a plant with absorption cooling for thermal control. The plant consisted of a single-effect LiBr-H_2O absorption chiller fed by evacuated-tube solar collectors. A simulation model was developed in Matlab-Simulink to investigate the plant configurations and controls and perform dynamic simulation of the cooling demand and the solar field production. The study showed that the porposed system could provide significant energy saving for greenhouse cooling. Nevertheless, the solar collectors have low $COP_{thermal}$ (0.70). Yildirim and Bilir (2017) investigated a hybrid cooling system for greenhouses which consisted of a ground source heat pump powered by a grid connected solar PV. In order to have uniform solar insolation in the greenhouse, only 50% of the southern face part of the roof was covered with photovoltaic panels or 77.8 m^2 of solar panel area. Design builder and Energy Plus software was used to predict the heating, cooling and lighting loads accounting for the ideal growing temperature of the crops. The results showed that PV electricity generation can meet 33–67% of greenhouse demand in summer months, depending of the type of crop with various indoor temperature requirements: tomato (20 °C), cucumber (26 °C) and lettuce (14 °C). From the literature on greenhouse solar powered cooling, it is established that the application of solar energy enhances overall energy efficiency and reduces energy costs. This technology can be combined with ground source heat pump systems in order to optimise greenhouse cooling in hot climates. In humid climates, it can be combined with desiccant assisted cooling systems to provide the heat required for regenerating the desiccant.

3.6. *Ground systems/geothermal heat pump*

The stored thermal energy of the earth can be used for conditioning greenhouse in hot climates, using the soil as a heat sink for cooling the greenhouse in the summer. As shown in Fig. 9, in a closed loop underground air tunnel system, the heat is transferred from air to the earth via the pipes drawing warm air from the greenhouse. As a result, the air temperature at the outlet is much lower than that of the ambient. Over the past years, a number of studies have been conducted to highlight this potential. Ozgener et al. (2010) evaluated the exergetic performance of an underground air tunnel system for cooling greenhouses in order to identify process efficiencies and losses. The system consists of a fan circuit for cooling and a ground heat exchanger (GHE).

A galvanized pipe of 56 cm diameter and 47 m length was buried in the soil at about 3 m. The tests were conducted on the ground heat exchanger under steady state conditions. The study revealed that exergetic efficiency of the air tunnel ranged from 57.8 to 63.2%. The temperature decrease is however limited to 4.2 °C.

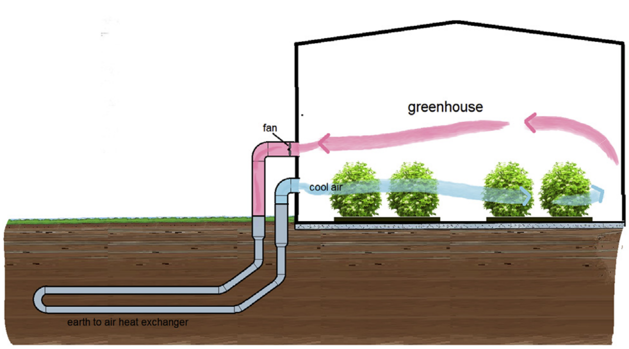

Fig. 9 – Schematic of a greenhouse closed loop underground air tunnel system.

Ozgener, Ozgener, and Goswami (2011) predicted the total thermal resistance of a closed-loop earth to air heat exchanger for cooling greenhouses. The results showed that total thermal resistance of the systems changes with direct soil wetness. Average total heat exchanger thermal resistance was found to be 0.02 K m W^{-1} under steady state condition. However, the study did not consider the thermal contact resistance due to the assumptions made in the modelling of the system. Later on, Mongkon, Thepa, Namprakai, and Pratinthong (2013) investigated a horizontal earth tube system for cooling greenhouses in Chiang Mai (northern Thailand). The system was constructed from an iron tube positioned into a series of six rows of serpentine, at a depth of 1 m under a short lawn surface north of the greenhouse. The results showed that the system was capable of providing up to 75% of cooling requirement during the summer. It was also highlighted that the system can be improved by increasing the soil moisture in order to enhance the thermal conductivity.

Attar et al. (2014) also used experiments to evaluate the effectiveness of ground thermal energy for cooling a chapel greenhouse. Polypropylene capillary heat exchangers suspended in the air and buried into the ground were used to store or utilise the excess solar energy. A theoretical study was conducted in order to find the optimum spacing between the buried exchangers. The results showed that using the heat exchangers passed by cold water decreased the greenhouse air temperature by 12 °C and made the greenhouse suitable for cultivation of pepper. However, the configuration used in this study can cause air stratification. Ceylan, Ergün, Acar, and Aydin (2016) performed a thermodynamic and psychometric analysis of a ground source evaporative cooling system suitable for greenhouses in hot areas. The system consisted of a cooling water circulation, cooling pad and ground source cooling line. The system was investigated by modifying the amount of air blowing to the site and absorbed from the site and the amount of pulverised water. The results showed that the indoor relative humidity ranged between 50.2% and 59.3%. System efficiencies were low when compared to mechanical systems, and considerable amount of water was needed for the cooling.

Aljubury and Ridha (2017) investigated an indirect-direct evaporative cooling unit using groundwater for cooling greenhouses as shown in Fig. 10. The two-stage evaporative cooling system consist of an indirect evaporative cooling heat exchanger and three pads as a direct evaporative cooler. The system was constructed, and installed in Baghdad, Iraq. A simple energy balance was implemented to evaluate the cooling loads of the greenhouse, considering infiltration, ventilation energy exchange and solar energy. The results showed that the use of high flow rate of well water (4 l min^{-1}) for the heat exchanger with two passages give the maximum evaporative efficiency. It was also highlighted that combing the proposed IDEC system with shading can further lower microclimate greenhouse temperature to 24 °C. From the reviewed studies on greenhouse ground cooling systems in hot climates, it can be established that this technique has the potential to decrease greenhouse temperature, while contributing to reducing energy costs. In order to ensure optimal functioning of the above-mentioned technologies, the proper

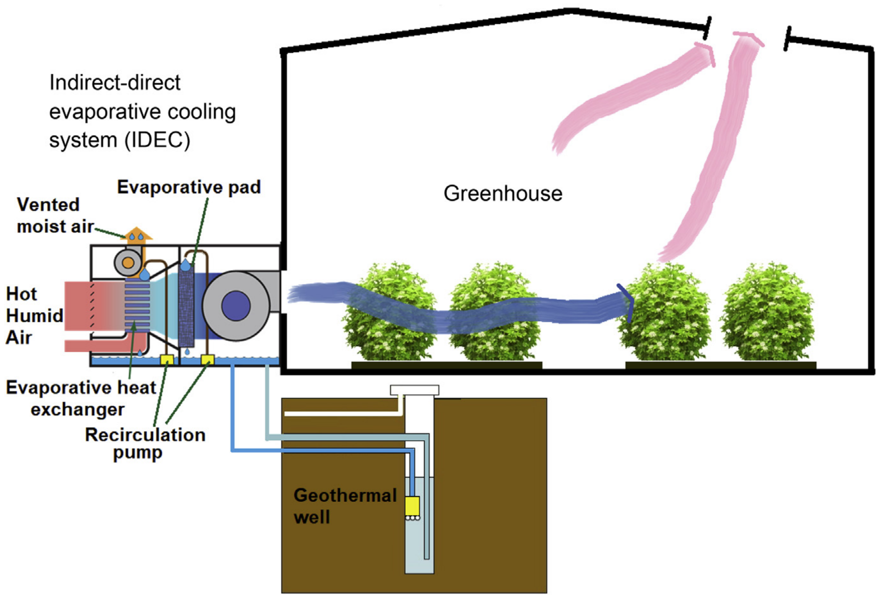

Fig. 10 – Schematic of an indirect-direct evaporative cooling system and geothermal well for greenhouses in hot climates.

monitor and control system should be properly designed and added to the greenhouse.

Tables 1–3 summarises greenhouse design features and cooling technologies in Africa and Middle East, in Asia and Australia countries in European and American countries with hot climates or during hot conditions.

Figure 11 illustrates the distribution of greenhouse cooling technologies for hot conditions worldwide. Based on the reviewed studies, most of the research works were conducted in Asia. In addition, many of these countries are "developing countries" in need of technologies that promote agriculture, which is the main sector their economy relies on.

4. Numerical modelling for greenhouse ventilation and cooling technologies

Over the last few decades, numerical modelling tools computational fluid dynamics (CFD) has gained ground and the number of CFD studies of airflow and climate in greenhouses is continuously growing. With the increase of computational power and development of new techniques, CFD models are proving to be more reliable and accurate and at the same time cost lower than traditional experimental tests. CFD modelling has been applied in the improvement of greenhouse design, optimisation of the crop system, climate control and design of greenhouse cooling/heating technologies (Boulard, 2011). This section will not add more on the state of the art concerning the CFD modelling of the greenhouse design due to the abundance of work on this topic but will aim to focus on the application of CFD on the analysis of greenhouse ventilation/cooling technologies. This section will highlight the modelling approaches and the various numerical models for exploring the different cooling technologies. Furthermore, it will also provide an overview of the approaches used in the field for verifying and validating the CFD model which are important to demonstrate the accuracy of the CFD modelling and be used with confidence when making design decisions. CFD is useful for investigating complex fluid flows. For example, it is particularly useful for the simulation of complex multi-phase flows in evaporative cooling spray systems in greenhouses (Chen, Cai, Xu, Hu, & Ai, 2014; Kim et al., 2008). CFD can provide detailed analysis of the data on the relevant parameters i.e. velocities, temperature, humidity, CO_2 etc. in all locations of the computational domain. This is important for the analysis of the distribution of the indoor climate parameters which should be optimised for the production of plants. On the other hand, CFD modelling easily allow parametric studies to assess different design configurations of greenhouses (Santolini et al., 2018). A typical CFD workflow for CFD modelling of greenhouse natural/mechanical ventilation systems is shown in Fig. 12.

CFD modelling has been have been actively used in the field to predict the air flow and thermal patterns of natural and mechanically ventilated greenhouses (Lee & Short, 2000; Bartzanas et al., 2014; Flores-Velazquez, Montero, Baeza, & Lopez, 2014; Piscia, Muñoz, Panadès, & Montero, 2015). Campen and Bot (2003) used three-dimensional CFD modelling (FLUENTv5, Fluent Inc., Lebanon, NH, USA) to assess a naturally ventilated greenhouse, focusing on wind driven forces. The simulation model included the effect of surrounding structures which increased the size of the overall domain. Grid sensitivity analysis was carried out by comparing the results of the simulation of the model with three different mesh sizes. The model was validated using tracer gas measurements with the predictions within 15% of experimental data. The study highlighted that the variations of only 10° in wind angle can increase the ventilation rate up to 50% in some cases. With regards to the CFD modelling, it was pointed out the importance of carrying out 3D simulations for the assessment of ventilation rates as it is significantly influence by the wind angle. The study of He et al. (2015)

Table 1 – Summary of greenhouse design features and cooling technologies in Africa and Middle East.

Technology	Methodology	Location	Climate	Advantages	Limitations	Performance parameters/ Design factors	Performance	Cooling	Humidity control	References
Modified plastic net-houses	Measurement of solar radiation transmittance	Riyadh, Saudi Arabia	Hot and arid, with high solar irradiance	• Can be scaled-up to any size	• Humidity level depends on the evapotranspiration of mature crops • Insufficient cooling in summer	• Net-house transmittance • Spectral transmittance • Temperature • Relative humidity • Integrated solar radiation • Evapotranspiration	• Reduction of the costs for construction, water consumption and electric energy	• Yes, but depends on the porosity, shading factor and colour of the nets	• Yes	Abdel-Ghany et al. (2016)
Variable-pressure fogging system with variable-speed extracting fans	Quantitative feedback theory	Bet-Dagan, Israel	Mediterranean	• Acceptable performance of the system	• High disturbances inherent to greenhouses	• Pressure • Enthalpy • Water flow rate • Temperature	• The performance of the controllers was not affected by setpoints	• Yes, can be controlled to the required levels	• Yes	Linker et al. (2011)
Ground source heat pump and grid connected solar photovoltaic panels	Design Builder software, Energy Plus software	Izmir, Turkey	Mediterranean	• Short payback period	• Electricity lacking during summer operation	• Temperature • Solar radiation • Cooling demand	• Electricity generation can meet 33.2–67.2% of greenhouse demand during summer operation	• Yes	Not available	Yildirim and Bilir (2017)
Air conditioning system using ground water	Theoretical study to find the best spacing between the buried exchangers. Experimental study to estimate the overall heat transfer coefficient of the capillary heat exchanger	Borj Cedria, Tunisia	Mediterranean	• Energy saving by ground energy storage	• Cold water circulation cannot eliminate the phenomenon of air stratification in the ground	• Temperature • Coefficient of performance • Heat transfer coefficient	• Can reduce the greenhouse air temperature by 12 °C	• Yes, can maintain temperature to the required levels during summer period	Not available	Attar et al. (2014)
Evaporative cooler enhanced by solar-regenerated liquid desiccant cooling system	Mathematical modelling, numerical simulation and experimental validation	Saudi Arabia	Hot and dry with high solar irradiance and high humidity	• Low cost	• Complex design	• Air temperature • Humidity • Energy effectiveness • Heat transfer coefficient • Air flow	• Decrease of air temperature by 6 °C compared to a conventional evaporative cooler • Energy effectiveness enhancement up to 50.10%	• Yes, can be controlled to the required levels for all period	• Yes, can lower the humidity to the required levels using a desiccant pad	Abu-Hamdeh and Almitani (2016)
Ground source evaporative cooling system	Psychometric and thermodynamic analysis	Karabuk, Turkey	Humid subtropical	• Water saving • Environment friendly system	• Complex system	• Temperature • Relative humidity • Evaporative cooling efficiency • Latent heat gain • Absorbed heat	• Refreshment efficiency of 38%	• Yes, can be maintained to the required levels	• Yes, 54% on average	Ceylan et al. (2016)

Indirect-direct evaporative cooling (IDEC) unit using groundwater	Estimation of the cooling loads of the greenhouse using a simple energy balance	Baghdad, Iraq	Hot and dry	• Water saving	• Dependant to groundwater availability	• Temperature • Relative humidity • Evaporative cooling efficiency • Solar intensity	• Higher cooling efficiency as compared to the direct evaporative cooler	• Yes, temperature decrease from 12.1 to 21.6 °C	• Yes, can increase relative humidity from 8 to 62%	Aljubury and Ridha. (2017)
Naturally ventilated greenhouse	Gembloux Dynamic Greenhouse Climate Model	Harare, Zimbabwe	Subtropical, warm	• Inexpensive technology	• Relatively high mean standard errors	• Air temperature • Relative humidity • Solar radiation • Wind speed	• Not available	• Yes, can lower air temperature by 10 °C	• Yes, can lower relative humidity	Mashonjowa et al. (2013)
Fan pad evaporative cooling system	Complete Randomise Design (CRD) coupled with Duncan's multiple range tests	Khartoum, Sudan	Hot and dry	• Low energy consumption	• Short life cycle of the pads	• Air temperature • Relative humidity • Saturation efficiency • Cooling efficiency	• Cooling efficiency up to 90%	• Yes, can decrease air temperature by 11.77%	• Yes, can increase relative humidity to 57.16%	(Mohammed Ahmed et al., 2011)

also used a 3D CFD modelling to evaluate the effects of various vent sizes and configurations on the indoor climate of a 11-span plastic greenhouse. The pre-processing software Gambit 2.3.16 (Fluent Inc., Lebanon, NH, USA) was utilised to create a large computational domain (90 m × 132 m × 30 m) around the greenhouse model. The study revealed that the roof and side openings were most suitable for cooling in summer, while the roof opening was most suitable for dehumidification in winter. The measurements and predicted temperature profile showed good agreement with an error of less than 1 °C.

As shown in Fig. 12, one of the important steps in the development of the greenhouse CFD model is sizing of the computational domain which typically includes the indoor and outdoor domain. This depends on the objectives of study and requirements of the CFD simulation i.e. is the outdoor domain and parameters (wind speed, wind direction, temperature, solar radiation, etc.) required for the analysis or the modelling of the indoor domain of the greenhouse is sufficient for the analysis. Typically, naturally ventilated greenhouse or hybrid systems would require the simulation of the external/outdoor domain (Norton et al., 2007) to take account of the coupling between both internal and external environments and in some cases, it should also include the surrounding structures/buildings which can affect the local airflow and ventilation performance. Modelling of the indoor environment only for natural ventilation studies can lead to unrealistic results. As shown in Fig. 13, in the study of Lee, Lee, and Kim (2018), the computational domain created around the greenhouse structure is sized as follows: 15H (15 times the height of the greenhouse) for the distance between the inlet and wind ward façade and outlet and leeward façade and 10H for the ground to the top (Bournet & Boulard, 2010). There are no exact criteria with regards to designing computational domains of greenhouses but recommendations in (Franke et al., 2004) can be followed. Clearly, a large domain would require more mesh elements and computational resources, however sufficient spacing between the model and surfaces of the domain must be set. A too small a domain may cause artificial forcing onto the flow and create unrealistic velocity fields. It is also important to consider the impact of surrounding structures and setting up of a realistic wind profile or atmospheric boundary layer.

The choice of the grid design is essential since it may strongly interfere with results. As shown in Fig. 13, the grids closer to the greenhouse were more refined to more accurately analyse the airflow and thermal patterns around and in the greenhouse. Clearly a more refined grid or lower size grid would require more computational resource and hence a balance or compromise must be found. Typically, a grid sensitivity analysis or grid adaptation is carried out to evaluate and verify the results based on different mesh sizing. Detailed grid analysis of a greenhouse models was carried out by Bartzanas, Kittas, Sapounas, and Nikita-Martzopoulou (2007) and Kim et al. (2008). Other factors that can be used to evaluate the grid quality are skewness, yplus (A non-dimensional wall distance for a wall-bounded flow) and aspect ratio.

The selection of turbulence model is another important step in the CFD workflow (Fig. 12) and will have a significant

Table 2 – Summary of greenhouse design features and cooling technologies in Asia and Australia.

Technology	Methodology	Location	Climate	Advantage	Limitations	Performance parameters/Design factors	Performance	Cooling	Humidity control	References
Hybrid low energy direct evaporating cooler	Climate Assessment Tool	Adelaide, Brisbane, Canberra, Darwin, Hobart, Melbourne, Perth, Sydney, Australia	Hot humid summer, warm winter (Darwin), warm humid summer, mild winter (Brisbane), hot dry summer with cool winter (Perth), temperate climate (Sydney, Melbourne and Adelaide) and mild to warm summer with cold winter (Hobart and Canberra)	• Many operating modes (cooling, heating and humidity control) • Can work in various climates • Advanced controls • Optimised performance • High efficiency • High level of control of indoor space	• More costly than standard evaporative cooler • More complex operation • May not be useful for all climate conditions • Relatively longer payback period	• Air speed • Air change • Temperature • Relative humidity • Energy	• Reductions of the energy consumption of the order of 40–60% or higher if optimised	Yes, can be controlled to the required levels for all period	Yes, can be controlled to the required levels for all period but can significantly increase energy consumption	Guan et al. (2015)
Natural ventilation	Development of a thermal model/regression analysis method	Shouguang, China	Warm temperate monsoon climate	• Low cost	• Cannot increase relative humidity	• Temperature • Relative humidity • Solar radiation • Height from the ground	• Energy saving	• Yes, can be controlled to the required levels	• Yes, can decrease relative humidity to the required levels	Li et al. (2017)
Surplus air heat pump system	Control algorithm for the surplus air thermal energy utilisation and temperature control	Hwasung, South Korea	Moderate	• High values of surplus air thermal energy	• Long payback period	• Temperature • Water flow rate • Electricity consumption • Surplus air thermal energy • Solar radiation • Coefficient of performance (COP)	• Energy conservation up to 76.4%	• Yes, can be maintained to the required levels for all period	• No	Yang and Rhee (2013)
Evaporative cooling by moving water film over external shade cloth	Mathematical model, experimental validation	Delhi, India	Humid subtropical	• Energy saving • Simple technology	• Limited air temperature decrease	• Air temperature • Relative humidity • Water flow rate • Length of roof • Absorptivity of shading material	• 0.5 as maximum low instantaneous loss efficiency	• Yes, can lower air temperature by 6 °C	• No	Ghosal et al. (2003)

Heat pump air conditioner	Steady-state model	Bangkok, Thailand	Tropical	• Low specific energy consumption (1000 –16000 kJ kg^{-1})	• COP limited to 4.0	• Air temperature • Relative humidity • COP • Evaporator and condenser capacities	• COP of the order of 1.2 –4.0	• Yes, can lower air temperature to 18 °C	• Yes, can maintain relative humidity at 40%	Chou et al. (2004)
Air conditioner with a cool storage water tank and three heat pump systems: air source-air supply (A–A), water source-air supply (W-A), and water source-water supply (W-W)	Steady-state simulation model	Abashiri, Yamagata, Tokyo and Kagoshima, Japan	Cold (Abashiri), humid subtropical (Yamagata, Tokyo and Kagoshima)	• Low energy consumption if using the W-W heat pump (400 kW)	• Cannot supply all the cooling demands during hot days	• Air temperature • Cooling capacity • Heat pump size	• Can cover 62 –100% of the greenhouse cooling demands	• Yes, can lower air temperature to 15 °C in night time cooling	• No	Okushima et al. (2014)
Solar photovoltaic-electrolyser-fuel cell hybrid power system	Four-parameter model including a photocurrent source, a parallel diode and a series resistor	Kolkata, India	Tropical with high solar radiation	• Energy saving	• Solar radiation dependence	• Cell voltage • Power density • Conversion efficiency	• Can support the energy requirement of a $90m^2$ floriculture greenhouse with fan-pad ventilated system	• Yes	• Yes	Ganguly et al. (2010)
Fan pad evaporative cooling system combined with shading mechanisms	Thermal modelling considering steady state condition	Kolkata, India	Hot and dry	• Effective during summer period	• Limited temperature decrease (6 K)	• Temperature • Ventilation rate • Radiation intensity • Relative humidity	• 0.88 of saturation efficiency of cooling pad	• Yes, can maintain air temperature below 303 K	• Yes	Ganguly and Ghosh (2007)

Table 3 – Summary of greenhouse design features and cooling technologies in Europe and America.

Technology	Methodology	Location	Climate	Advantages	Limitations	Performance parameters/Design factors	Performance	Cooling	Humidity control	References
Different colored shade-nets	Variation of relative shading intensities	Moravac near Aleksinac, Serbia	Mild with high solar radiation	• wind damage to the crop is reduced by more than 50% by restricting air movement	• Temperature decrease limited to 3 °C	• Solar radiation • Photosynthetically active radiation • Lycopene and β-carotene content	• Improvement of productivity by alleviating temperature extremes	• Yes	• Yes	Ilic et al. (2012)
Rotative photovoltaic panels and reflective aluminium mirrors, with mechanical and natural ventilation	Energy balance equation	Lazio, Italy	Warm Mediterranean	• Shading can be adjusted depending on weather conditions and crops requirements • The reflected solar is recovered	• Cannot lower maximum solar radiation	• Temperature • Relative humidity • Solar radiation • Shading percentage • Energy flow • Photovoltaic energy production	• Decrease of minimum solar radiation by 600 W m^{-2}	• Yes, adjusted to maintain inside temperature at 26 °C	• Yes, can lower the relative humidity by 15%	Marucci and Cappuccini (2016)
Solar cooling plant with absorption cooling machine	Dynamic simulation model developed using Matlab-Simulink	Bari, Southern Italy	Mediterranean with high solar radiation	• The cooling power is not provided for the entire volume of the greenhouse, but only for the air volume surrounding the crop	• Requires important amount of water	• Temperature • Relative humidity • Cooling capacity	• Important energy saving • Reduction of primary energy consumption	• Yes, can be maintained to the required levels for all period	• Yes	Campiotti et al. (2016)
Fan-pad system supplied by photovoltaic panels	Mathematical model that predicts the greenhouse temperatures and ventilation rates	Chapingo, State of Mexico, Mexico	Oceanic with pleasant summer and mild winter	• Cheap photovoltaic system • Energy saving	• Cannot control temperature if the solar radiation is greater than 450 W/m^2	• Temperature • Relative humidity • Solar radiation • Ventilation rate	• Can generate up to 10,533 kWh per year for a 1500 m^2 greenhouse	• Yes, can maintain temperature below 25 °C	• Yes	Romantchik et al. (2017)
Naturally ventilated greenhouse with a polypropylene mulch covering the soil	Semi-empirical dynamic model validated using experimental data	Almeria, Spain	Mediterranean	• Simple technology	• Discrepancies of the model during spring at noon	• Air temperature • Ventilation rate • Wind speed • Solar radiation	• Energy saving	• Yes	• Not available	Reyes-Rosas et al. (2017)
Naturally ventilated greenhouse equipped with a mist system	Thermal model	Volos, Eastern Greece	Mild Mediterranean with low humidity	• High evaporative cooling potential • Can provide comfortable conditions for crops	• Cannot lower temperature to low values	• Temperature • Relative humidity • Transpiration rate • Air vapour pressure deficit	• Evaporative cooling potential of 245 W per m^2	• Yes	• Yes, adjusted to maintain relative humidity above 75%	Kastoulas et al. (2001)

Fog cooled greenhouse	Experimental study	Arta, Western Greece	Mild Mediterranean	• Enhancement of the mean crop weight and the percentage of marketable crops	• Limited temperature decrease	• Temperature • Relative humidity • Transpiration rate • Air vapour pressure deficit	• Vapor pressure deficit was about 45% lower under fog than under no fog conditions	• Yes, adjusted to maintain temperature below 26 °C	• Yes, adjusted to maintain relative humidity above 80%	Kastoulas et al. (2006)
Air conditioning system with heat storage system and a fine wire heat exchanger	Numerical matrix based model – CFD model	Wageningen, The Netherlands	Temperate oceanic	• Energy saving • Cost effective	• Only 40% of the hot stored cooling water can be extracted	• Air temperature • Relative humidity • Heat transfer coefficient • Cooling capacity	• Cooling capacity of 20 kW	• Yes, can lower air temperature to 25 °C	• Yes, can maintain relative humidity below 90%	Bakker et al. (2006)
Fan pad evaporative cooling system	Wind tunnel measurements, constant water flow rate	Aarhus, Denmark	Humid continental	• Simple technology • Low energy consumption	• Cooling efficiency decreases when air speed and pump-on time increase	• Air speed • Pump-on time • Cooling efficiency • Air temperature	• Cooling efficiency up to 69.2%	• Yes, can lower air temperature by 10 °C	• Yes	Rong et al. (2017)
Roof cooling system using direct evaporation from a porous layer	Experimental study	Manchester, United Kingdom	Temperate oceanic	• Low energy consumption • Simple technology	• No humidity control	• Surface temperature • Relative evaporation rate • Radiation flux • Cumulative mass loss	• Relative evaporation rate up to 1.2	• Yes, can lower air temperature by 5 °C	• No	Shokri Kuehni, Bou-Zeid, Webb and Shokri (2016)
Naturally ventilated greenhouse equipped with screens	Numerical study	Bologna, Italy	Hot	• Uniform air velocity distribution inside the greenhouse • Simple technology	• No humidity control	• Air velocity • Vents openings • Greenhouse height	• Not available	• Yes, can lower air temperature	• Not available	Santolini et al. (2018)

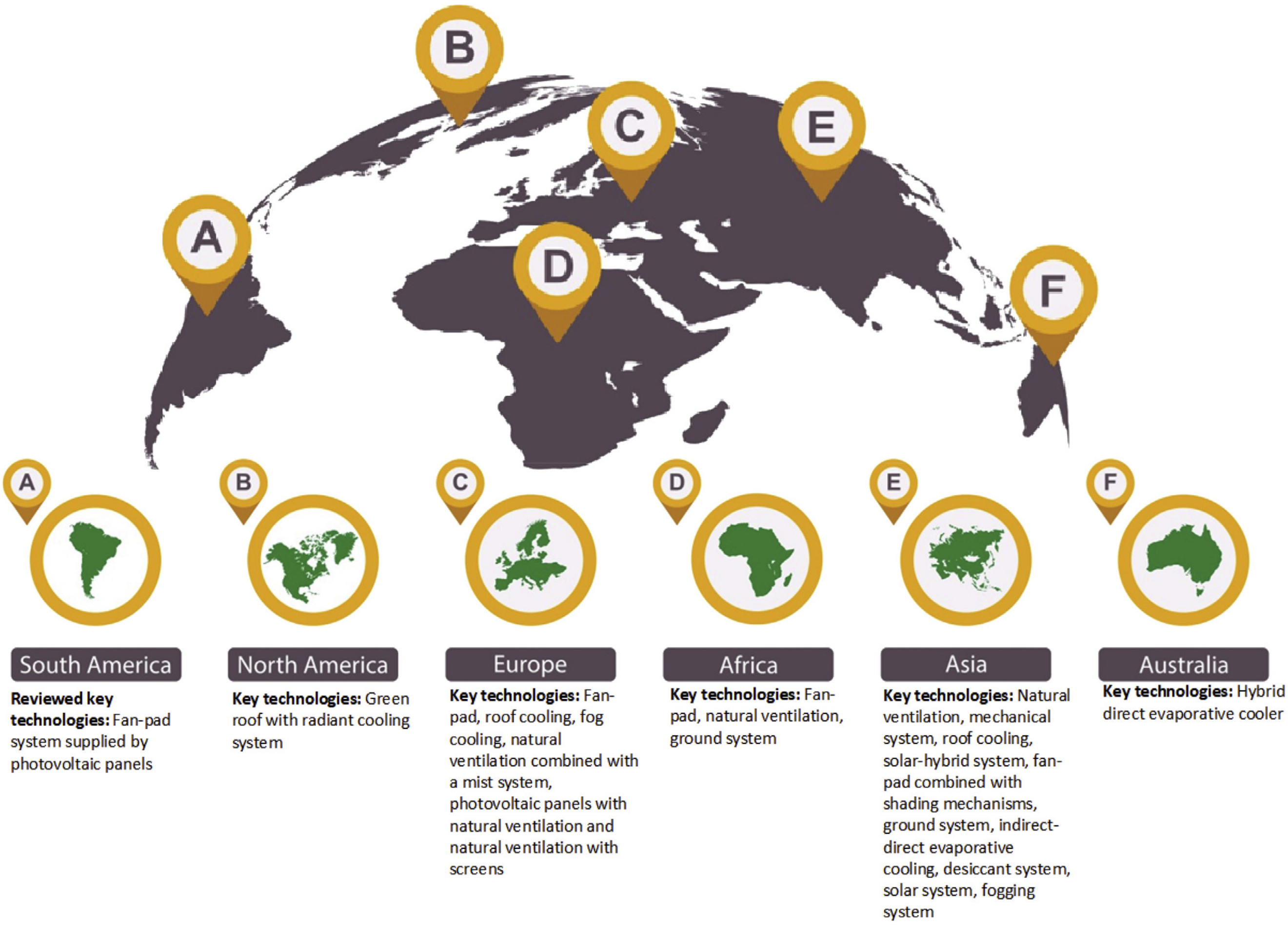

Fig. 11 – Map of the distribution of the reviewed greenhouse cooling technologies worldwide.

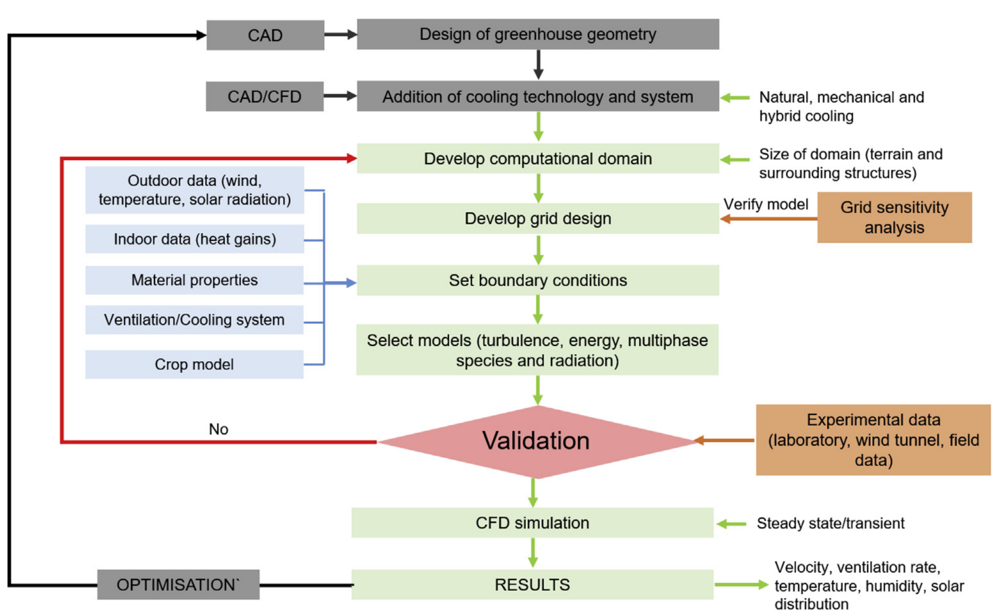

Fig. 12 – Typical workflow for the numerical modelling, validation and optimisation of greenhouse ventilation and cooling systems.

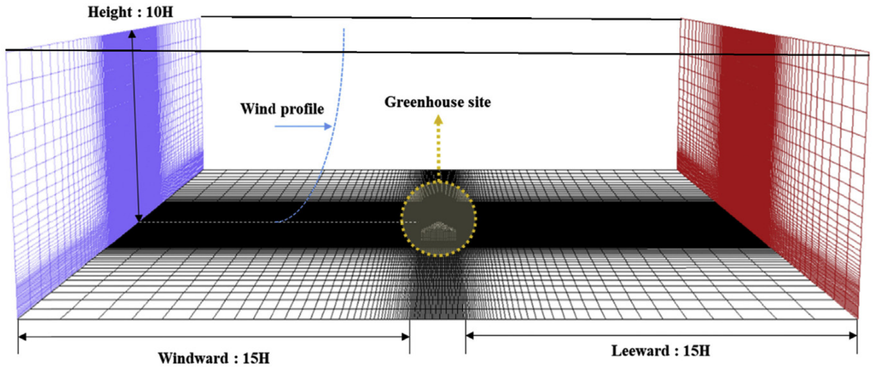

Fig. 13 – Design of the CFD simulation model domain and grid (Lee et al., 2018).

impact on the airflow patterns and turbulence characteristics in the greenhouse model. The selection depends on various factors such as the objectives of the simulation, accuracy requirement and availability of resources for the computational work. A large number of CFD studies on greenhouse climate use the standard k-ε model. Although the k-ε model is numerically robust and appropriate for many greenhouse simulation configurations, it has some limitations such as the inaccurate prediction of the separation and reverse flows in and outside the greenhouse model. The studies of Bartzanas et al. (2007), Lee et al. (2018) and Bournet and Boulard (2010) compared the prediction accuracy of the most common turbulence model used for greenhouses, an example for a single span greenhouse is shown in Fig. 14. Due to the increasing computational power, many recent studies are also implementing large eddy simulation (LES) models for greenhouse simulations for example (Chu, Lan, Tasi, Wu, & Yang, 2017).

The crops within the greenhouse affects the ventilation and thermal performance of the greenhouse and must be incorporated into the CFD model and is typically simulated as a porous medium and can be considered as a source or sink of heat and water vapour. Chu et al. (2017) used LES CFD modelling to investigate the air flow obstruction of the crops on the cross flow ventilation in a greenhouse. The CFD model was validated with wind tunnel experiment and showed good agreement in particular the flows leeward of the crops. The study assessed the effect of the number of rows of cops on the ventilation rates and patterns (see Fig. 15).

Wang, Luo and Li (2013) used the commercial CFD software FLUENT to assess microclimate variables of a plastic greenhouse. For the simulation of the coupled radiative energy exchanges at roof and cover, the authors utilised the discrete ordinates radiation model. Then, a fractal permeability model was integrated with the Darcy–Forchheimer equation to model the greenhouse crops as porous medium with fractal characteristics. The study revealed that soil surface temperature was 302 K while cover and indoor temperatures were similar (287 K) due to high transmittance and wind cooling. It was also highlighted that specific humidity of air inside the canopy was higher than outside due to evapotranspiration. The error between simulation values and measurements ranged between 0.8 and 1.7 °C.

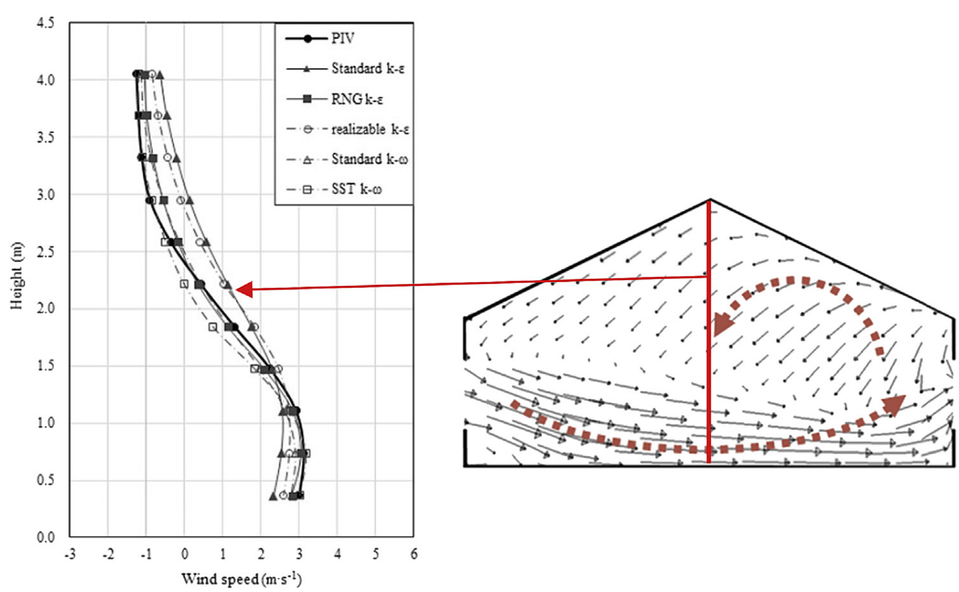

Fig. 14 – Turbulence model tests for the air speed distribution in the naturally ventilated greenhouse (Lee et al., 2018).

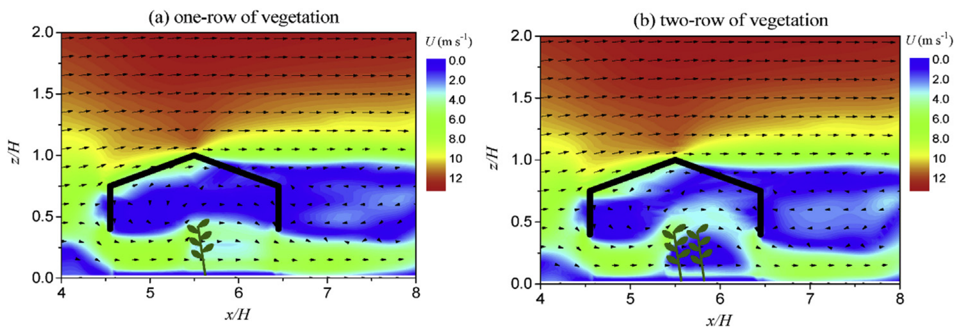

Fig. 15 – Comparison of the effect of rows of vegetation on the cross-flow ventilation in a single span greenhouse (Chu et al., 2017).

Porous medium modelling approach can also be applied when simulating screens or nets incorporated into greenhouse models. Santolini et al. (2018) performed CFD simulations of a ventilated greenhouse with and without screens using ANSYS FLUENT. The standard k-ε turbulence model, with user defined functions for the profiles of inlet velocity and turbulence were adopted. The screens were modelled as porous surfaces with the permeability and porosity obtained from experiments. Furthermore, the optimisation of the position and characteristics of the screens can significantly contribute to producing a uniform air velocity distribution near the crops. A good correlation was observed between the predicted and measured velocities, max difference of 0.02 m s^{-1}. Fatnassi, Boulard, and Bouirden (2003) also used porous medium approach to simulate the crops and insect proof nets in a large-scale greenhouse. The CFD model was modified to simulate the heat exchanges between the crop and airflow. The results of the study showed that the addition of the insect proof nets significantly increased the temperature levels in the greenhouse. Campen (2005) investigated the effects of the insect screens and wind speed and direction on plastic greenhouse ventilation for different configurations using CFD modelling. The insect screening material was modelled as a porous medium in the numerical modelling. The study showed that the design without a roof opening had the highest ventilation rate and lowest max temperature during windy conditions. In the case of days with low or no wind, the indoor conditions in the design without top ventilation was worse as compared to the other designs.

Another type of greenhouse cooling system which is modelled and evaluated by many researchers using CFD is evaporative cooling (Sapounas, Bartzanas, Nikita-Martzopoulou, & Kittas, 2008a and b; Franco, Valera, Pena, & Pérez, 2011; Bartzanas, Fidaros, Baxevanou, & Kittas, 2013; Chen et al., 2014). Evaporative cooling devices such as evaporative pads can also be modelled in CFD using the porous medium approach. The resistance produced by the evaporative pad as airflow passes though it into the greenhouse increases as the porosity of the pad decreases, which is mainly dependent on the water flow and volume of water retained by the pads. Higher airflow resistance can hamper the greenhouse ventilation and increase the fan energy consumption. Franco et al. (2011) investigated four corrugated evaporative cooling pads which are commonly used in Mediterranean greenhouses to determine the influence of water flow on porosity and pressure drop resulting from air flow. The pads were constructed using stacked sheets of corrugated cellulose alternating angles of incidence on the horizontal so that they do not coincide. A numerical model was created using ANSYS-CFX (ANSYS, Inc. Pennsylvania, USA) and validated with experimental data and a good agreement was observed with max 9% error for dry pads. The results showed that the pressure drop due to the pad increased as the water flow rate increased, but to a lesser extent than at a higher air flow rate. Bartzanas et al. (2013) investigated the thermal performance of a greenhouse with evaporative cooling pad device using CFD. The three-dimensional CFD model was validated with experimental data and showed good agreement with the error not higher than 4%. The model was used to investigate the effect of increasing the airflow rate of the fan pad device on the indoor temperature and relative humidity. Chen et al. (2014) used FLUENT to simulate the velocity and temperature distribution in a greenhouse with fan and pad evaporative cooling system. The model utilised the k-e turbulence model and discrete ordinates model to simulate the solar radiation into the greenhouse. The model validated with experiments was utilised to investigate the effect of positioning of the fan pad device on its cooling performance. Sapounas, Nikita-Martzopoulou, Bartzanas, and Kittas (2008c) compared the accuracy of numerical CFD modelling with an analytical model of a greenhouse with fan and pad evaporative cooling. The results of both methods were compared with experimental data and the average error was 3.5% for the CFD model and 7.6% for the analytical model.

Another type of evaporative cooling system for greenhouses which has been widely studied in the literature using CFD is fog evaporative cooling system. The fog droplet movements are complex and dynamic and can result in uneven distribution of temperature and humidity in the greenhouses and hence 3D simulation is necessary for its analysis. Various authors (Kim et al., 2007, 2008; Tamimi & Kacira, 2013)) utilised the species model and discrete phase model to carry out the simulation of fog evaporative cooling systems. The model can track the path of water droplets and analysed the heat transfer for the fog cooling device. Kim et al. (2007) developed a CFD model to simulate the indoor conditions in a multi-span greenhouse with a fog evaporative cooling system. The validation showed that the predicted temperature values were within 0.1–1.4 °C of the experimental data while the relative humidity values were within 0.3%–6%. The CFD model was utilised to optimise the positioning of the nozzles and improve the uniformity of air temperature and humidity. The study showed that locating the nozzles within the air entry of the side wall openings was the most effective configuration.

Kim et al. (2008) developed a CFD model to predict the humidity distribution in a single span greenhouse with fog cooling system. The model utilised the realisable $k-\varepsilon$ model, discrete ordinates model to simulate the solar radiation, species transport and discrete phase model for simulating the fog cooling system. Validation of predicted results with experiments showed errors ranging between 0.1% and 18.4% for the humidity values. The CFD model was useful in locating non uniformity in the distribution of humidity in the greenhouse. Tamimi and Kacira (2013) also focused on improving the uniformity of humidity in the single span greenhouse with high pressure fog cooling system. Similarly, species and discrete phase models were utilised to simulate droplet evaporation and evapotranspiration. The validation showed that the predicted temperature values were within 6–16% of the experimental data while the relative humidity values were within 14–27%. The study highlighted the capabilities of the model to optimise the indoor conditions by varying the position and angle of the nozzles.

5. Summary and recommendation for future works

This work presented an extensive review of the common designs of greenhouses and associated technological development of cooling systems for application in regions with hot climate. The review has explored research on design features of greenhouses, considered important for optimising greenhouse design and operation in hot climates which can provide crops with suitable conditions for growth, thus improving yield and increasing greenhouse profitability. Several studies focused on the analysis and optimisation of climatic conditions of greenhouse in hot climates using various methods such as evolutionary algorithm, genetic algorithm, dynamic modelling and numerical modelling. Model-based design methods using genetic algorithms and evolutionary programming can be effective approaches for dealing with multifactorial design aspects of greenhouses.

The selection of the orientation and shape of greenhouse must be aligned with the required solar irradiance in summer and winter, number of spans, plot size, the crop type and quantity and technology or method implemented for climate control. Building covering materials plays a bi-functional role by blocking far infrared radiation and allowing solar radiation necessary for the plant growth. The review revealed that using covering layers can reduce solar intensity by up to 40%. Plastic film covering is one of the effective methods for lowering the temperature in greenhouses, however it is also subjected to degradation due to solar radiation exposure and also the chemicals used for the growing. It was suggested that waste of plastic materials can be reduced by 5–10 times with the use of ethylene–tetrafluoroethylene copolymer films. Creating a physical barrier using nets and screens helps hinder insect pests entering the production environment and reduce the need for garden chemicals. The review showed that insect proof nets such as anti-Aphid and anti-Thrips were effective in providing protection against insects, however it led to a sharp increase in interior air temperature and humidity, which would require using additional climate control techniques such as reducing incoming solar energy, vents and natural/artificial cooling methods. Shading can be effective in decreasing transmitted solar radiation and reducing greenhouse air temperature, especially when combined with other cooling techniques such as white wash, netting, natural ventilation and evaporative cooling. The combination of rotating PV panels and highly reflective mirrors can be an effective shading method while at the same time producing energy on site also.

The selection of climate control technologies should suit the cultivated crop and be aligned with local climatic conditions. Forced/mechanical ventilation systems can increase and maintain the ventilation rates through the greenhouse whenever required however it may not be sufficient to lower the indoor temperature to meet the required levels during peak conditions in the summer. Hence, it should be combined with other cooling technologies. While natural ventilation techniques require very little to no external energy and can be effective for greenhouse cooling applications. This is achieved by careful positioning of side wall openings and roof openings. In areas with low wind speeds, side wall vents can be combined with roof to enhance natural ventilation. For maximum efficiency, ventilators should be located at the ridge, on the sidewalls and the gable of the greenhouse. Total ventilator area should be equivalent to 15–30% floor area. Above 30 percent, the effect on the temperature difference is negligible. The review also highlighted the importance of considering the impact of surrounding structures or greenhouses as it can affect the natural ventilation performance. Similar to mechanical ventilation, it may not be sufficient to lower the indoor temperature to meet the crop temperature requirements during peak conditions in the summer, especially when there are low wind speeds. In order to further enhance greenhouse cooling in hot regions, natural ventilation can be combined with other cooling techniques, such as evaporative cooling.

Evaporative cooling technologies such as fan pad and fog cooling are effective means to control climatic condition in hot and arid locations. As compared to fog cooling, fan pad system has a higher air saturation efficiency, lower cost, water and energy consumption. One of the studies showed that fan pad consumed 5.1 kW h for one-hour operation while fog cooling system consumed 7.2–8.9 kW h. In areas where water availability is a common concern such as arid and semi-arid regions, the water consumption of evaporative cooling technologies must be taken into consideration and minimised as possible. It was highlighted that the fan and pad system consumed 14.8 $\mathrm{l\,m^{-2}\,d^{-1}}$ to maintain air temperature between 18 and 24 °C. One of the drawbacks of the fan pad is the uneven temperature distributions across the greenhouse, with maximum difference of up to 11.4 °C between the fans and the pads. An advantage of fog and mist cooling systems is that it can achieve high efficiency of water evaporation while also keeping the foliage dry. A mist system can contribute up to 20% of the total evaporative cooling with only 40–50% of the mist water being effectively used in the actual cooling of the greenhouse, with a significant fraction of mist water transferred directly to the outside through the vents. In addition, crops are less stressed under misting conditions. The work suggested that future studies could focus on analysis the effect of parameters such as ventilation, transmissivity of the screen, density of the nozzle and crops. Furthermore, the combination of fogging methods and mobile shading based on the growth stage should be explored. Another type of evaporative cooling method explored in the literature is roof cooling which can reduce the indoor temperature by up to 6 °C. Future works can focus on the material utilised for the roof/cover, evaporating media, flow speeds, and more work is necessary to assess its performance under real conditions.

From the reviewed studies, it is highlighted that the combination and simultaneous usage of natural ventilation, evaporative cooling and shading has the potential to reduce greenhouse energy requirement and provide optimum indoor conditions for year-round cultivation. Studies have shown that the combination of ventilation and/or evaporative cooling with shading can lower the greenhouse air temperature by up to 10 °C and increase the relative humidity by up to 20%. A hybrid cooling system must be assisted by an effective control strategy to ensure that the required temperature and humidity levels and distributions are maintained in the greenhouse. Electricity generated from a hybrid system consisting of a grid connected solar photovoltaic panels and heat pump can provide 33.2–67.2% of the greenhouse demand in the summer periods. Ground cooling system can reduce the air temperature in greenhouses by up to 12 °C. In addition, the use of groundwater can enhance indirect-direct evaporative cooling system's efficiency higher as compared to direct evaporative cooling.

In hot and humid areas where airflow requires to be dehumidified to the required growing conditions, solar regenerators can be combined with desiccant assisted cooling systems to provide the heat required for regenerating the dehumidifying ability of the desiccant.

Greenhouse aspects and technologies must be incorporated early on to completely realise their potential for the optimisation of the greenhouse design and avoid the problems of late incorporation in the development cycle or ensuing in-situ installation. The impacts of external climatic conditions and interior greenhouse components on its microclimate should be more investigated. Considerable focus should be oriented towards studying the impacts of rate of shading and its configuration on the distribution of air temperature, humidity, solar radiation, photosynthetically active radiation in crop zones and the uniformity of crop growth/productivity. Another potential area to explore is the integration of fogging methods and movable shading according to growth stage. More investigation is required regarding the ventilation rates, transmissivity of screen and nozzle densities. Improving greenhouse cladding can be achieved by changing the raw materials of glass type or by the addition of microstructural treatment or coatings to the surface, which influences the light reflection and transmittance, in order to mitigate NIR. On the other hand, for greenhouses in tropical and sub-tropical countries, the addition of NIR blocking additives to plastic films must be explored further.

From the review on numerical modelling of greenhouse in hot climates, it was identified that CFD is valuable tool for predicting air flow, temperature and humidity distributions inside the greenhouse. This is important for the analysis of the distribution of the indoor climate parameters which should be optimised for the production of plants. It was pointed out the importance of carrying out 3D simulations for the assessment of natural ventilation in greenhouses as it is significantly influence by the wind angle. Typically, naturally ventilated greenhouse or hybrid systems would require the simulation of the external/outdoor domain. Modelling of the indoor environment only for natural ventilation studies can lead to unrealistic results. It is also important to consider the impact of surrounding structures and setting up of a realistic wind profile or atmospheric boundary layer. Grid sensitivity analysis or grid adaptation can be carried out to evaluate and verify the results based on different mesh sizing. The standard k-ε turbulence model is numerically robust and appropriate for many greenhouse simulation configurations, it has some limits such as the inaccurate prediction of the separation and reverse flows in and outside the greenhouse model. Porous media modelling approach can be applied for the simulation of crops, nets and mesh screens and evaporative cooling pads. Species and discrete phase modelling can be employed to carry out the simulation of fog evaporative cooling systems. Like any type of modelling, validation of the numerical model should be carried out. To validate the predicted CFD results, many woks compared the simulation results with the data of laboratory and field experiments.

Acknowledgement

The authors would like to thank The Energetics and Environment Research Unit (05/UR/11-14) - National Engineering School of Tunis (University of Tunis El Manar) for providing financial support to this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biosystemseng.2019.04.016.

REFERENCES

Abdel-Ghany, A. M., Al-Helal, I. M., Alzahrani, S. M., Alsadon, A. A., Ali, I. M., & Elleithy, R. M. (2012). Covering materials incorporating radiation-preventing Techniques to meet greenhouse cooling challenges in arid regions: A review. *The Scientific World Journal, 11*.

Abdel-Ghany, A. M., Al-Helal, I. M., Picuno, P., & Shady, M. R. (2016). Modified plastic net-houses as alternative agricultural structures for saving energy and water in hot and sunny regions. *Renewable Energy, 93*, 332–339.

Abdel-Ghany, A. M., Goto, E., & Kozai, T. (2006). Evaporation characteristics in a naturally ventilated, fog-cooled greenhouse. *Renewable Energy, 31*, 2207–2226.
Abdel-Ghany, A. M., & Kozai, T. (2006). Dynamic modeling of the environment in a naturally ventilated, fog-cooled greenhouse. *Renewable Energy, 31*, 1521–1539.
Abu-Hamdeh, N. H., & Almitani, K. H. (2016). Solar liquid desiccant regeneration and nanofluids in evaporative cooling for greenhouse food production in Saudi Arabia. *Solar Energy, 134*, 202–210.
Ahemd, H. A., Al-Faraj, A. A., & Abdel-Ghany, A. M. (2016). Shading greenhouses to improve the microclimate, energy and water saving in hot regions: A review. *Scientia Horticulturae, 201*, 36–45.
Ahmed, E. M., Abaas, O., Ahmed, M., & Ismail, M. R. (2011). Performance evaluation of three different types of local evaporative cooling pads in greenhouses in Sudan. *Saudi Journal of Biological Sciences, 18*, 45–51.
Al-Helal, I. M. (2007). Effects of ventilation rate on the environment of a fan-pad evaporatively cooled, shaded greenhouse in extreme arid climates. *Applied Engineering in Agriculture, 23*, 221–230.
Al-Mulla, Y. A., Al-Balushi, M., Al-Rawahy, M., Al-Raisy, F., & Al-Makhmary, S. (2008). Screenhouse microclimate effects on cucumber production planted in soilless culture. *Acta Horticulturae, 801*, 637–644.
Aljubury, I. M. A., & Ridha, H. D. (2017). Enhancement of evaporative cooling system in a greenhouse using geothermal energy. *Renewable Energy, 11*, 321–331.
Arcidiacono, C., D'Emilio, A., Mazzarella, R., & Leonardi, C. (2006). Covering materials to improve greenhouse microclimate during summer in hot climates. *Acta Horticulturae, 719*, 247–254.
Attar, I., Naili, N., Khalifa, N., Hazami, M., Lazaar, M., & Farhat, A. (2014). Experimental study of an air conditioning system to control a greenhouse microclimate. *Energy Conversion and Management, 79*, 543–553.
Baeza, E., Pérez-Parra, J., Montero, J., Bailey, B., López, J., & Gázquez, J. (2009). 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. *Biosystems Engineering, 104*, 86–96.
Bakker, J. C., De Zwart, H. F., & Campen, J. B. (2006). Greenhouse cooling and heat recovery using fine wire heat exchangers in a closed pot plant greenhouse: Design of an energy producing greenhouse. *Acta Horticulturae, 719*, 263–270.
Banik, P., & Ganguly, A. (2017). Performance and economic analysis of a floricultural greenhouse with distributed fan-pad evaporative cooling coupled with solar desiccation. *Solar Energy, 147*, 439–447.
Bartzanas, T., Boulard, T., & Kittas, C. (2014). Effect of vent arrangement on windward ventilation of a tunnel greenhouse. *Biosystems Engineering, 88*, 479–490.
Bartzanas, T., Fidaros, D., Baxevanou, C., & Kittas, C. (2013). Climate distribution in a fan and pad evaporative cooled greenhouse: A CFD approach. *Acta Horticulturae, 1008*, 185–190.
Bartzanas, T., Kittas, C., Sapounas, A. A., & Nikita-Martzopoulou, C. (2007). Analysis of airflow through experimental rural buildings: Sensitivity to turbulence models. *Biosystems Engineering, 97*, 229–239.
Boulard, T. (2011). Advantages and constraints of CFD greenhouse modelling. *Acta Horticulturae, 893*, 145–153.
Bournet, P. E., & Boulard, T. (2010). Effect of ventilator configuration on the distributed climate of greenhouses: A review of experimental and CFD studies. *Computers and Electronics in Agriculture, 74*, 195–217.
Campen, J. B. (2005). Greenhouse design applying CFD for Indonesian conditions. *Acta Horticulturae, 691*, 419–424.
Campen, J. B., & Bot, G. P. A. (2003). Determination of greenhouse-specific aspects of ventilation using three-dimensional computational fluid dynamics. *Biosystems Engineering, 84*, 69–77.
Campiotti, C. A., Morosinotto, G., Puglisi, G., Schettini, E., & Vox, G. (2016). Performance evaluation of a solar cooling plant applied for greenhouse thermal control. *Agriculture and Agricultural Science Procedia, 8*, 664–669.
Candy, S., Moore, G., & Freere, P. (2012). Design and modeling of a greenhouse for a remote region in Nepal. *Procedia Engineering, 49*, 152–160.
Castellano, S., Starace, G., De Pascalis, L., Lippolis, M., & Mugnozza, G. S. (2016). Test results and empirical correlations to account for air permeability of agricultural nets. *Biosystems Engineering, 150*, 131–141.
Ceylan, I., Ergün, A., Acar, B., & Aydin, M. (2016). Psychometric and thermodynamic analysis of new ground source evaporative cooling system. *Energy and Buildings, 119*, 20–27.
Chen, J., Cai, Y., Xu, F., Hu, H., & Ai, Q. (2014). Analysis and optimization of the fan-pad evaporative cooling system for greenhouse based on CFD. *Advances in Mechanical Engineering, 6*, 1–8.
Chou, S. K., Chua, K. J., Ho, J. C., & Ooi, C. L. (2004). On the study of an energy-efficient greenhouse for heating, cooling and dehumidification applications. *Applied Energy, 77*, 355–373.
Chu, C., Lan, T., Tasi, R., Wu, T., & Yang, C. (2017). Wind-driven natural ventilation of greenhouses with vegetation. *Biosystems Engineering, 164*, 221–234.
Cuce, P. M., & Riffat, S. (2016). A state of the art review of evaporative cooling systems for building applications. *Renewable and Sustainable Energy Reviews, 54*, 1240–1249.
Davies, P. A., Hossain, A. K., Lychnos, G., & Paton, C. (2008). Energy saving and solar electricity in fan-ventilated greenhouses. *Acta Horticulturae, 797*, 339–346.
Dehbi, A., & Mourad, A. I. (2016). Durability of mono-layer versus tri-layers LDPE films used as greenhouse cover: Comparative study. *Arabian Journal of Chemistry, 9*, 282–289.
El-Maghlany, W. M., Teamah, M. A., & Tanaka, H. (2015). Optimum design and orientation of the greenhouses for maximum capture of solar energy in North Tropical Region. *Energy Conversion and Management, 105*, 1096–1104.
Espinoza, K., López, A., Valera, D., Molina-Aiz, F., Torres, J., & Peña, A. (2017). Effects of ventilator configuration on the flow pattern of a naturally-ventilated three-span Mediterranean greenhouse. *Biosystems Engineering, 164*, 13–30.
Fatnassi, H., Boulard, T., & Bouirden, L. (2003). Simulation of climatic conditions in full-scale greenhouse fitted with insect-proof screens. *Agricultural and Forest Meteorology, 118*, 97–111.
Fatnassi, H., Boulard, T., & Bouirden, L. (2013). Development, validation and use of a dynamic model for simulate the climate conditions in a large scale greenhouse equipped with insect-proof nets. *Computers and Electronics in Agriculture, 98*, 54–61.
Fatnassi, H., Boulard, T., Poncet, C., & Chave, M. (2006). Optimisation of greenhouse insect screening with computational fluid dynamics. *Biosystems Engineering, 93*, 301–312.
Feuilloley, P., & Issanchou, G. (1996). Greenhouse covering materials measurement and modelling of Thermal properties using the hot box method, and condensation effects. *Journal of Agricultural Engineering Research, 65*, 129–142.
Flores-Velazquez, J., Montero, J. I., Baeza, E. J., & Lopez, J. C. (2014). Mechanical and natural ventilation systems in a greenhouse designed using computational fluid dynamics. *International Journal of Agricultural and Biological Engineering, 7*, 1.

Flores-Velazquez, J., Ojeda, W., Villarreal-Guerrero, F., & Rojano, A. (2017). Effect of crops on natural ventilation in a screenhouse evaluated by CFD simulations. *Acta Horticulturae, 1170*, 95–102.
Franco, A., Valera, D. L., Pena, A., & Pérez, A. M. (2011). Aerodynamic analysis and CFD simulation of several cellulose evaporative cooling pads used in Mediterranean greenhouses. *Computers and Electronics in Agriculture, 76*, 218–230.
Franco, A., Valera, D. L., & Peña, A. (2014). Energy efficiency in greenhouse evaporative cooling techniques: cooling boxes versus cellulose pads. *Energies, 7*, 1427–1447.
Franke, J., Hirsch, C., Jensen, A. G., Krüs, H. W., Schatzmann, M., Westbury, P. S., et al. (2004). Recommendations on the use of CFD in wind engineering. In J. P. A. J. van Beeck (Ed.), *COST action C14, impact of wind and storm on city life built environment. Proceedings of the International Conference on Urban wind Engineering and building aerodynamics*. Sint-Genesius-Rode, Belgium: von Karman Institute.
Ganguly, A., & Ghosh, S. (2007). Modeling and analysis of a fan–pad ventilated floricultural greenhouse. *Energy and Buildings, 39*, 1092–1097.
Ganguly, A., Misra, D., & Ghosh, S. (2010). Modeling and analysis of solar photovoltaic-electrolyzer-fuel cell hybrid power system integrated with a floriculture greenhouse. *Energy and Buildings, 42*, 2036–2043.
Garcia-Alonso, Y., Espi, E., Salmeron, A., Fontecha, A., Gonzalez, A., & Lopez, J. (2006). New cool plastic films for greenhouse covering in tropical and subtropical areas. *Acta Horticulturae, 719*, 131–138.
Garcia, M. L., Medrano, E., Sanchez-Guerrero, M. C., & Lorenzo, P. (2011). Climatic effects of two cooling systems in greenhouses in the Mediterranean area: External mobile shading and fog system. *Biosystems Engineering, 108*, 133–143.
Ghosal, M. K., Tiwari, G. N., & Srivastava, N. S. L. (2003). Modeling and experimental validation of a greenhouse with evaporative cooling by moving water film over external shade cloth. *Energy and Buildings, 35*, 843–850.
Ghosh, A., & Ganguly, A. (2017). Performance analysis of a partially closed solar regenerated desiccant assisted cooling system for greenhouse lettuce cultivation. *Solar Energy, 158*, 644–653.
Guan, L., Bennett, M., & Bell, J. (2015). Evaluating the potential use of direct evaporative cooling in Australia. *Energy and Buildings, 108*, 185–194.
Gupta, M. J., & Chandra, P. (2002). Effect of greenhouse design parameters on conservation of energy for greenhouse environmental control. *Energy, 27*, 777–794.
Gupta, R., Tiwari, G. N., Kumar, A., & Gupta, Y. (2012). Calculation of total solar fraction for different orientation of greenhouse using 3D-shadow analysis in Auto-CAD. *Energy and Buildings, 47*, 27–34.
Guzman-Cruz, R., Castañeda-Miranda, R., Garcia-Escalante, J. J., Lopez-Cruz, I. L., Lara-Herrera, A., & De la Rosa, J. I. (2009). Calibration of a greenhouse climate model using evolutionary algorithms. *Biosystems Engineering, 104*, 135–142.
Harmanto, Tantau, H. J., & Salokhe, V. M. (2006). Microclimate and air exchange rates in greenhouses covered with different nets in the humid Tropics. *Biosystems Engineering, 94*, 239–253.
Hasni, A., Taibi, R., Draoui, B., & Boulard, T. (2011). Optimization of greenhouse climate model parameters using particle swarm optimization and genetic algorithms. *Energy Procedia, 6*, 371–380.
Hassanien, E. R. H., Li, M., & Lin, W. D. (2016). Advanced applications of solar energy in agricultural greenhouses. *Renewable and Sustainable Energy Reviews, 54*, 989–1001.
He, K. S., Chen, D. A., Sun, L. J., Liu, Z. L., & Huang, Z. Y. (2015). The effect of vent openings on the microclimate inside multi-span greenhouses during summer and winter seasons. *Engineering Applications of Computational Fluid Mechanics, 9*, 399–410.
Helmy, M. A., Eltawil, M., Ado-shieshaa, R. R., & El-Zan, N. M. (2013). Enhancing the evaporative cooling performance of fan-pad system using alternative pad materials and water film over the greenhouse roof. *Agricultural Engineering International: CIGR Journal, 15*, 173–187.
Hirai, M., Yoshikoshi, H., Kitano, M., Wakimizu, K., Sakaida, T., Yoshioka, T., et al. (2008). Production of value-added crop of green tea in summer under the shade screen net: Canopy microenvironments. *Acta Horticulturae, 797*, 411–417.
Ilic, Z. S., Milenkovic, L., Stanojevic, L., Cvetkovic, D., & Fallik, E. (2012). Effects of the modification of light intensity by color shade nets on yield and quality of tomato fruits. *Scientia Horticulturae, 139*, 90–95.
Katsoulas, N., Baille, A., & Kittas, C. (2001). Effect of misting on transpiration and conductances of a greenhouse rose canopy. *Agricultural and Forest Meteorology, 106*, 233–247.
Katsoulas, N., Kitta, E., Kittas, C., Tsirogiannis, I. L., Stamati, E., & Sayvas, D. (2006). Greenhouse cooling by a fog system: Effects on microclimate and on production and quality of a soilless pepper crop. *Acta Horticulturae, 719*, 455–462.
Katsoulas, N., Kittas, C., & Bartzanas, T. (2012). Microclimate distribution in a greenhouse cooled by a fog system. *Acta Horticulturae, 927*, 773–778.
Katsoulas, N., Sapounas, A., De Zwart, F., Dieleman, J. A., & Stanghellini, C. (2015). Reducing ventilation requirements in semi-closed greenhouses increases water use efficiency. *Agricultural Water Management, 156*, 90–99.
Kim, K., Giacomelii, G. A., & Yoon, J. (2007). CFD modeling to improve the design of a fog system for cooling greenhouses. *Japan Agricultural Research Quarterly, 41*, 283–290.
Kim, K., Yoon, J., Kwon, H., Han, J., Son, J., Nam, S., et al. (2008). 3-D CFD analysis of relative humidity distribution in greenhouse with a fog cooling system and refrigerative dehumidifiers. *Biosystems Engineering, 100*, 245–255.
Kittas, C., Bartzanas, T., & Jaffrin, A. (2003). Temperature gradients in a partially shaded large greenhouse equipped with evaporative cooling pads. *Biosystems Engineering, 85*, 87–94.
Kittas, C., Katsoulas, N., Bartzanas, T., & Bakker, S. (2013). Greenhouse climate control and energy use. In *FAO plant production and protection paper. 217. Good Agricultural Practices for greenhouse vegetable crops: Principles for Mediterranean climate areas* (pp. 63–95) (Rome).
Kumar, K. S., Jha, M. K., Tiwari, K. N., & Singh, A. (2010). Modeling and evaluation of greenhouse for floriculture in subtropics. *Energy and Buildings, 42*, 1075–1083.
Kumar, K. S., Tiwari, K. N., & Jha, M. K. (2009). Design and technology for greenhouse cooling in tropical and subtropical regions: A review. *Energy and Buildings, 41*, 1269–1275.
Lee, H. W., Lee, J. W., Diop, S., & Na, O. H. (2014). Measurement of overall heat transfer coefficient of covering material with thermal screens for plastic greenhouse. *Acta Horticulturae, 1037*, 219–224.
Lee, S., Lee, I., & Kim, R. (2018). Evaluation of wind-driven natural ventilation of single-span greenhouses built on reclaimed coastal land. *Biosystems Engineering, 171*, 120–142.
Lee, I., & Short, T. (2000). Two-dimensional numerical simulation of natural ventilation in a multi-span greenhouse. *Transactions of the ASAE, 43*, 745–753.
Li, A., Huang, L., & Zhang, T. (2017). Field test and analysis of microclimate in naturally ventilated single-sloped greenhouses. *Energy and Buildings, 13*, 479–489.
Linker, R., Kacira, M., & Arbel, A. (2011). Robust climate control of a greenhouse equipped with variable-speed fans and a variable-pressure fogging system. *Biosystems Engineering, 110*, 153–167.

López-Marín, J., González, A., García-Alonso, Y., Espí, E., Salmerón, A., Fontecha, A., et al. (2008). Use of cool plastic films for greenhouse covering in Southern Spain. *Acta Horticulturae, 801*, 181–186.
Lopez, A., Valera, D. L., Molina-Aiz, F. D., & Pena, A. (2012). Sonic anemometry to evaluate airflow characteristics and temperature distribution in empty Mediterranean greenhouses equipped with pad-fan and fog systems. *Biosystems Engineering, 113*, 334–350.
Lychnos, G., & Davies, P. A. (2012). Modelling and experimental verification of a solar-powered liquid desiccant cooling system for greenhouse food production in hot climates. *Energy, 40*, 116–130.
Magán, J. J., López, J. C., Granados, R., Pérez-Parra, J., Soriano, T., Romero-Gámez, M., et al. (2011). Global radiation differences under a glasshouse and a plastic greenhouse in Almeria (Spain): Preliminary report. *Acta Horticulturae, 907*, 125–130.
Marucci, A., & Cappuccini, A. (2016). Dynamic photovoltaic greenhouse: Energy balance in completely clear sky condition during the hot period. *Energy, 102*, 302–312.
Mashonjowa, E., Ronsse, F., Milford, J. R., & Pieters, J. G. (2013). Modelling the thermal performance of a naturally ventilated greenhouse in Zimbabwe using a dynamic greenhouse climate model. *Solar Energy, 91*, 381–393.
Mobtaker, H., Ajabshirchi, Y., Ranjbar, S., & Matloobi, M. (2019). Simulation of thermal performance of solar greenhouse in north-west of Iran: An experimental validation. *Renewable Energy, 135*, 88–97.
Mohammadi, B., Ranjbar, S. F., & Ajabshirchi, Y. (2018). Application of dynamic model to predict some inside environment variables in a semi-solar greenhouse. *Information Processing in Agriculture, 5*, 279–288.
Mongkon, S., Thepa, S., Namprakai, P., & Pratinthong, N. (2013). Cooling performance and condensation evaluation of horizontal earth tube system for the tropical greenhouse. *Energy and Buildings, 66*, 104–111.
Murakami, K., Fukuoka, N., & Noto, S. (2017). Improvement of greenhouse microenvironment and sweetness of melon (Cucumis melo L.) fruits by greenhouse shading with a new kind of near-infrared ray-cutting net in mid-summer. *Scientia Horticulturae, 218*, 1–7.
Norton, T., Sun, D. W., Grant, J., Fallon, R., & Dodd, V. (2007). Applications of computational fluid dynamics CFD in the modelling and design of ventilation systems in the agricultural industry: A review. *Bioresource Technology, 98*, 2386–2414.
Okushima, L., Mears, D. R., Sase, S., Takakura, T., Moriyama, H., Furuno, S., et al. (2014). Capacities for heat pump cooling systems for greenhouses in Japan. *Journal of the Society of Agricultural Structures, 45*.
Ozgener, L., & Ozgener, O. (2010). An experimental study of the exergetic performance of an underground air tunnel system for greenhouse cooling. *Renewable Energy*, 35, 2804–2811.
Ozgener, O., Ozgener, L., & Goswami, D. W. (2011). Experimental prediction of total thermal resistance of a closed loop EAHE for greenhouse cooling system. *International Communications in Heat and Mass Transfer, 38*, 711–716.
Piscia, D., Montero, J. I., Baeza, E., & Bailey, B. J. (2012). A CFD greenhouse night-time condensation model. *Biosystems Engineering, 111*, 141–154.
Piscia, D., Muñoz, P., Panadès, C., & Montero, J. I. (2015). A method of coupling CFD and energy balance simulations to study humidity control in unheated greenhouses. *Computers and Electronics in Agriculture, 115*, 129–141.
Raya, V., Parra, M., & Cid, M. C. (2006). Influence of changes in cover and height on the climate of Canary-screenhouses for tomato growth: Preliminary results. *Acta Horticulturae, 719*, 535–542.
Reyes-Rosas, A., Molina-Aiz, F. D., Valera, D. L., López, A., & Khamkure, S. (2017). Development of a single energy balance model for prediction of temperatures inside a naturally ventilated greenhouse with polypropylene soil mulch. *Computers and Electronics in Agriculture, 142*, 9–28.
Romacho, I., Hita, O., Soriano, T., Morales, M. I., Escobar, I., Suarez-Rey, E. M., et al. (2006). The growth and yield of cherry tomatoes in net covered greenhouses. *Acta Horticulturae, 719*, 529–534.
Romantchik, E., Ríos, E., Sánchez, E., López, I., & Sánchez, J. R. (2017). Determination of energy to be supplied by photovoltaic systems for fan-pad systems in cooling process of greenhouses. *Applied Thermal Engineering, 114*, 1161–1168.
Rong, L., Pedersen, P., Jensen, T. L., Morsing, S., & Zhang, G. (2017). Dynamic performance of an evaporative cooling pad investigated in a wind tunnel for application in hot and arid climate. *Biosystems Engineering, 156*, 173–182.
Runkle, E. S., Jaster, P., Heins, R. D., & Thill, C. (2002). Environmental conditions under an experimental near infra red reflecting greenhouse film. *Acta Horticulturae, 578*, 181–185.
Sabeh, N. C., Giacomelli, G. A., & Kubota, C. (2006). Water use for pad and fan evaporative cooling of a greenhouse in a semi-arid climate. *Acta Horticulturae, 719*, 409–416.
Sánchez-Hermosilla, J., Páez, F., Rincón, V. J., & Callejón, A. J. (2013). Evaluation of a fog cooling system for applying plant-protection products in a greenhouse tomato crop. *Crop Protection, 48*, 76–81.
Santolini, E., Pulvirenti, B., Benni, S., Barbaresi, L., Torreggiani, D., & Tassinari, P. (2018). Numerical study of wind-driven natural ventilation in a greenhouse with screens. *Computers and Electronics in Agriculture, 149*, 41–53.
Sapounas, A. A., Bartzanas, T., Nikita-Martzopoulou, C., & Kittas, C. (2008a). Aspects of CFD modelling of a fan and pad evaporative cooling system in greenhouses. *International Journal of Ventilation, 6*, 379–388.
Sapounas, A. A., Nikita-Martzopoulou, C. H., Bartzanas, T., & Kittas, C. (2008c). Fan and pad evaporative cooling system for greenhouses: Evaluation of a numerical and analytical model. *Acta Horticulturae, 797*, 131–137.
Sapounas, A. A., Nikita-Martzopoulou, C. H., & Martzopoulos, G. (2008b). Numerical and experimental study of fan and pad evaporative cooling system in a greenhouse with tomato crop. *Acta Horticulturae, 801*, 987–994.
Sethi, V. P. (2009). On the selection of shape and orientation of a greenhouse: Thermal modeling and experimental validation. *Solar Energy, 83*, 21–38.
Sethi, V. P., & Sharma, S. K. (2007a). Experimental and economic study of a greenhouse thermal control system using aquifer water. *Energy Conversion and Management, 48*, 306–319.
Sethi, V. P., & Sharma, S. K. (2007b). Survey of cooling technologies for worldwide agricultural greenhouse applications. *Solar Energy, 81*, 1447–1459.
Shen, Y., & Yu, S. L. (2002). Cooling methods for greenhouse in tropical region. *Acta Horticulturae, 578*, 323–327.
Shokri Kuehni, S., Bou-Zeid, E., Webb, C., & Shokri, N. (2016). Roof cooling by direct evaporation from a porous layer. *Energy and Buildings, 127*, 521–528.
Soriano, T., Hernández, J., Morales, M. I., Escobar, I., & Castilla, N. (2004a). Radiation transmission differences in east-west oriented plastic greenhouses. *Acta Horticulturae, 633*, 91–97.
Soriano, T., Montero, J. I., Sánchez-Guerrero, M. C., Medrano, E., Antón, A., Hernández, J., et al. (2004b). A study of direct solar radiation transmission in asymmetrical multi-span greenhouses using scale models and simulation models. *Biosystems Engineering, 88*, 243–253.
Stanciu, C., Stanciu, D., & Dobrovicescu, A. (2016). Effect of greenhouse orientation with respect to E-W axis on its

required heating and cooling loads. *Energy Procedia, 85*, 498–504.

Stefani, L., Zanon, M., Modesti, M., Ugel, E., Vox, G., & Schettini, E. (2008). Reduction of the environmental impact of plastic films for green house covering by using fluoropolymeric materials. *Acta Horticulturae, 801*, 131–138.

Sultan, M., Miyazakia, T., Sahaa, B. B., Koyamaa, S., & Maisotsenko, V. S. (2015). Steady-state analysis on thermally driven adsorption air-conditioning system for agricultural greenhouses. *Procedia Engineering, 118*, 185–192.

Tamimi, E., & Kacira, M. (2013). Analysis of climate uniformity in a naturally ventilated greenhouse equipped with high pressure fogging system using computational fluid dynamics. *Acta Horticulturae, 1008*, 177–183.

Tanny, J., Dicken, U., & Cohen, S. (2008b). Vertical variations in airflow and Turbulence in a large banana screenhouse. *Acta Horticulturae, 797*, 81–86.

Tanny, J., Teitel, M., Barak, M., Esquira, Y., & Amir, R. (2008a). The effect of screenhouse height on the crop microclimate. *Acta Horticulturae, 801*, 107–114.

Teitel, M. (2017). Diurnal energy-partitioning and transpiration modelling in an insect-proof screenhouse with a tomato crop. *Biosystems Engineering, 160*, 170–178.

Teitel, M., Montero, J. I., & Baeza, E. J. (2012). Greenhouse design: Concepts and trends. *Acta Horticulturae, 952*, 605–620.

Vanthoor, B. H. E., Gazquez, J. C., Magan, J. J., Ruijs, M. N. A., Baeza, E., Stanghellini, C., et al. (2012a). A methodology for model-based greenhouse design: Part 4, economic evaluation of different greenhouse designs: A Spanish case. *Biosystems Engineering, 111*, 336–349.

Vanthoor, B. H. E., Stanghellini, C., Van Henten, E. J., & De Visser, P. H. B. (2011). A methodology for model-based greenhouse design: Part 1, a greenhouse climate model for a broad range of designs and climates. *Biosystems Engineering, 110*, 363–377.

Vanthoor, B., Stanghellini, C., van Henten, E., & Gázquez Garrido, J. C. (2008). The combined effects of cover design parameters on tomato production of a passive greenhouse. *Acta Horticulturae, 801*, 383–392.

Vanthoor, B. H. E., Stigter, J. D., Van Henten, E. J., Stanghellini, C., De Visser, P. H. B., & Hemming, S. (2012b). A methodology for model-based greenhouse design: Part 5, greenhouse design optimisation for southern-Spanish and Dutch conditions. *Biosystems Engineering, 111*, 350–368.

Villarreal-Guerrero, F., Kacira, M., Fitz-Rodrıguez, E., Linker, R., Kubota, C., Giacomelli, G. A., et al. (2012). Simulated performance of a greenhouse cooling control strategy with natural ventilation and fog cooling. *Biosystems Engineering, 3*, 217–228.

Von Elsner, B., Briassoulis, D., Waaijenberg, D., Von Zabeltitz, M. C., Gratraud, J., Russo, G., et al. (2000). Review of structural and functional characteristics of greenhouses in European Union countries: Part I, design requirements. *Journal of Agricultural Engineering Research, 75*, 111–126.

Waaijenberg, D. (2006). Design, construction and maintenance of greenhouse structures. *Acta Horticulturae, 710*, 31–42.

Wang, X., Luo, J., & Li, X. (2013). CFD based study of heterogeneous microclimate in a typical Chinese greenhouse in Central China. *Journal of Integrative Agriculture, 12*, 914–923.

Wei, B., Guo, S., Wang, J., Li, J., Wang, J., Zhang, J., et al. (2016). Thermal performance of single span greenhouses with removable back walls. *Biosystems Engineering, 141*, 48–57.

Willits, D. H. (2001). SE—structures and environment: The effect of cloth characteristics on the cooling performance of external shade cloths for greenhouses. *Journal of Agricultural Engineering Research, 79*, 331–340.

Willits, D. H., & Peet, M. M. (2000). Intermittent application of water to an externally mounted greenhouse shade cloth to modify cooling performance. *Transactions of the ASAE, 43*(5), 1247–1252.

World Population Forecast. (2018). *Worldometers*. http://www.worldometers.info/world-population/#table-forecast. (Accessed 25 May 2018).

Xiao-wei, W., Jin-yao, L., & Xiao-ping, L. (2013). CFD based study of heterogeneous microclimate in a typical Chinese greenhouse in Central China. *Journal of Integrative Agriculture, 12*, 914–923.

Xu, J., Li, Y., Wanga, R. Z., Liu, W., & Zhou, P. (2015). Experimental performance of evaporative cooling pad systems in greenhouses in humid subtropical climates. *Applied Energy, 138*, 291–301.

Yang, S. H., & Rhee, J. H. (2013). Utilization and performance evaluation of a surplus air heat pump system for greenhouse cooling and heating. *Applied Energy, 105*, 244–251.

Yildirim, N., & Bilir, L. (2017). Evaluation of a hybrid system for a nearly zero energy greenhouse. *Energy Conversion and Management, 148*, 1278–1290.