Iranica Journal of Energy & Environment 2 (1): 32-46, 2011
ISSN 2079-2115
IJEE an Official Peer Reviewed Journal of Babol Noshirvani University of Technology

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A Review of Ventilation and Cooling Technologies in Agricultural Greenhouse Application

A. Ganguly and S. Ghosh

Department of Mechanical Engineering, Bengal Engineering and ScienceUniversity,
Shibpur, Howrah-711103, West Bengal, India

(Received: Oct 7, 2010; Accepted: Jan 15, 2011)

Abstract: This article presents a comprehensive review of the literature that deal with ventilation and cooling technologies applied to agricultural greenhouses. The representative application of each technology as well as its advantages and limitations are discussed. Advance systems employing heat storage in phase change materials, earth-to-air heat exchangers and aquifer-coupled cavity flow heat exchangers have also been discussed. For an agricultural greenhouse equipped with cooling and artificial ventilation system, availability of uninterrupted electric supply is important. To achieve grid independence, dedicated power generation and storage systems need to be integrated with the greenhouse. The relevant literature on such power generation system for greenhouse application has been reviewed and is discussed here. This review concludes by identifying some important areas where further research needs to be undertaken.

Key words: Greenhouse · Ventilation · Evaporative cooling · Shading

INTRODUCTION

The main objective of greenhouse cultivation is to provide a congenial inside microclimate to optimize the growth of plants. Thus, it promotes off seasonal cultivation of crops and also in areas, where the natural climate is not suitable for cultivation of a particular variety of flora. The plains of Indian subcontinent witness a hot climate for major part of a year, whereas the coastal areas experience a hot and humid climate. This hot and humid climate promotes the growth of pests and microorganisms which is detrimental to the growth of plants. Thus, cooling and ventilation are two major objectives of greenhouses located in the plains of tropical and subtropical countries like India.

This paper presents a review of the literature dealing with ventilation and cooling technologies for greenhouse application. The representative application of each ventilation and cooling technology in greenhouse system along with its advantages and limitations has been discussed. Particular attention has been given to advanced systems that include heat storage in phase change materials, earth-to-air heat exchangers and aquifer-coupled cavity flow heat exchange system to maintain a desired micro-climate inside a greenhouse.

For generation of an artificial microclimate inside a greenhouse, uninterrupted electricity is important and dedicated systems for power generation and storage need to be integrated with greenhouse to make it a standalone system. Relevant technical publications, that discuss dedicated power generation and storage systems for greenhouse application, have been reviewed and discussed in this article. Information provided herein would be useful to the researchers as well as to the users of greenhouse in identifying appropriate cooling and ventilation technology required for specific applications.

Ventilation: Ventilation methods help to replace the warm inside air in greenhouses with cold outside air and thus help in the removal of trapped heat from greenhouses. This air circulation may be accomplished naturally due to difference in density between the outside and inside air. If the ambient temperature and insolation level are high, then natural ventilation becomes ineffective and

Corresponding Author: S. Ghosh, Department of Mechanical Engineering, Bengal Engineering and Science University, Shibpur, Howrah-711103, West Bengal, India, Tel-+91-33-26684561-63, Fax-+91-33-26682916
E-mail: sudipghosh.becollege@gmail.com.

a) Ridge and side vents for natural ventilation. (Courtesy: HZP, West Bengal, India)

b) Fan induced ventilation system. (Courtesy: HZP, West Bengal, India)

Fig.1: A greenhouse having provision for natural and fan induced ventilation.

fan induced ventilation using blowers or induced draught fans are used. Figure 1 shows the photograph of a greenhouse having provisions for both natural (Fig.1a) as well as fan induced (Fig.1b) ventilation systems. In subsequent sections literature related to natural and fan induced ventilation systems are discussed.

Natural Ventilation: Natural ventilation results from the pressure difference created due to wind velocity and the effect of thermal buoyancy. This helps to maintain greenhouse inside air temperature close to that of ambient and is the most economical method to maintain a desired microclimate inside a greenhouse when the ambient conditions are moderate. Considerable research work has been done on naturally ventilated greenhouses. Many researchers have developed and presented analytical models to determine the temperature and air exchange rate in naturally ventilated greenhouses and in recent years advanced tools like CFD, Neural Network and Genetic Algorithm have been used to develop models for greenhouses operating under natural ventilation. A review of such works is presented below.

Kittas *et al.* [1] developed a model to determine air exchange rate in a Mediterranean greenhouse having ridge and side openings and validated the results of the model through experiment. Teitel and Tanny [2] developed a model based on mass and energy conservation and applied the model to study the transient response of air temperature and humidity profile inside a greenhouse. Dayan *et al.* [3] presented a model based on mass and energy balance to calculate the rate of ventilation in a greenhouse used for commercial cultivation of rose. Litago *et al.* [4] developed time series models to estimate and forecast the temperature and humidity dynamics in an unheated naturally ventilated greenhouse located in Lisbon. External and internal climate data recorded over four consecutive months during the growing season of tomato were used to build and validate the forecasting models. Jime'nez-Hornero *et al.* [5] described the air flow in greenhouses under natural ventilation using a two dimensional lattice Bathnagar, Groos and Krook (BGK) model, which is a modified version of the Lattice Boltzmann model. The capability of BGK model was qualitatively checked for mono and multi-span tunnel and asymmetric triangular roof greenhouses with different rolling ventilator configurations. Kumar and Tiwari [6] presented a thermal model to predict the air temperature and extent of moisture evaporation under natural convection in a greenhouse for jaggery-drying application. Results of the thermal model were validated through experiments carried out in a greenhouse located at Indian Institute of Technology (IIT) Delhi, India. Impron *et al.* [7] developed and experimentally validated a model to predict the microclimate of a naturally ventilated greenhouse under tropical low lands of Indonesia. Patil and Tantau [8] studied the variation of tropical greenhouse temperature using Auto Regressive (AR), Auto Regressive Moving Average (ARMA) and Neural Network Auto Regressive (NNAR) models. NNAR model predicted better results than the other two. Ganguly and Ghosh [9] presented a thermal model of a floricultural greenhouse with combined ridge and side vents suitable for operation in typical Indian climate under natural ventilation. The results of the thermal model were validated with experimental findings.

A number of researchers used tracer gas technique to measure natural ventilation rate in greenhouses. Papadakis *et al.* [10] used a tracer gas to measure the natural ventilation rate in a plastic greenhouse having continuous roof and side openings. The results showed that air exchange rate under natural ventilation strongly depend on wind velocity and total ventilator area, but not on wind direction. Kittas *et al.* [11] used a tracer gas to measure wind induced air exchange rate in a greenhouse tunnel equipped with continuous side openings. The results indicated that air exchange rate strongly depends on wind velocity and total ventilator area and can be expressed as a function of global wind coefficient. Bapitsa *et al.* [12] measured leakage and ventilation rate in a four span glasshouse having leeward ventilators using tracer gas techniques. Two methods were followed and the results obtained with both methods were in good agreement with each other. Munoz *et al.* [13] developed a model to predict air exchange rate under natural ventilation in multi-span tunnel greenhouse fitted with insect proof screen over the vents. They conducted experiments using a tracer gas to validate the results of the model. Parra *et al.* [14] characterised performance of parral greenhouses under natural ventilation using dynamic tracer gas method. A number of other researchers like Fernandez and Bailey [15], Boulard and Draoui [16] and Kittas *et al.* [17] also conducted similar studies in greenhouses using tracer gas techniques.

A number of research works have been done where sonic anemometers were used to measure air speed near the openings of naturally ventilated greenhouses to predict the inside temperature distribution and air exchange rate. Boulard *et al.* [18] measured the natural ventilation air flow rate in a greenhouse, equipped with continuous lateral windows, using both sonic anemometer and tracer gas. The study revealed that both the methods of measurement yielded results that were in good agreement with each other. In another study Boulard *et al.* [19] studied the air flow and associated sensible heat exchange in a naturally ventilated twin span greenhouse having continuous roof vent at gutter using a three dimensional sonic anemometer. The study showed that mean and turbulent components of sensible heat flux through the vent amounted to 58% and 42% of the total exchange between the greenhouse and environment. The study also revealed that stack effect is predominant only at low wind speed. Wang *et al.* [20] studied the air movement induced by natural ventilation in greenhouses using a networked two-dimensional sonic anemometer system. Wang and Deltour [21] experimentally investigated the lee side ventilation induced air movement in a multi-span glasshouse using multipoint two-dimensional sonic anemometers. Teitel *et al.* [22] carried out experiments to investigate the effect of ambient air speed and direction on mean and turbulent characteristics of airflow in a naturally ventilated greenhouse. Air velocity was measured simultaneously at two edges of openings using one-dimensional sonic anemometers and at mid span of the openings using a three dimensional sonic anemometer. Molina-Aiz *et al.* [23] studied airflow pattern under natural ventilation in an Almería-type greenhouse and calculated the wind coefficient from direct estimation of airflow at the openings using three-dimensional sonic anemometry.

A number of studies were reported by various researchers to show the effect of insect screen on the microclimate of naturally ventilated greenhouse. Teitel [24] conducted experiments to study the effect of insect proof screen provided in roof openings on the microclimate of a naturally ventilated greenhouse. The study revealed that fine mesh screen caused obstruction to airflow resulting in higher temperature and humidity level inside a greenhouse. Shilo *et al.* [25] performed experiments in a roof ventilated four span greenhouse provided with insect screen over the openings to determine the air flow pattern, heat flux and ventilation rate. Ajwang and Tantau [26] reported that the presence of an anti-thrips screen with discharge coefficient of 0.22 resulted in a greenhouse temperature 5°C higher than that of ambient when young plants with low transpiration rate was cultivated. Increase in temperature reduced to 3°C in the same greenhouse, when mature crop was grown under humid tropical climate. Soni *et al.* [27] experimentally investigated the effect of screen mesh size on vertical temperature distribution in naturally ventilated greenhouses located in tropics. A real time comparison was made between greenhouses having porosity screens of varying degree for two plant growth stages and under two plant density levels. Teitel [28] carried a review of literature regarding the use of insect proof screens in greenhouses. In another study, Tietel *et al.* [29] investigated experimentally the flow pattern and microclimate inside a mono-span naturally ventilated greenhouse having continuous screened side vents.

A number of researchers studied the phenomenon of natural ventilation in greenhouses using Computational Fluid Dynamics (CFD) technique. Boulard *et al.* [30] modeled the natural ventilation air flux inside a greenhouse using commercial CFD 2000 software and experimentally validated the results. Steady regime temperatures and flow patterns were investigated for single sided roof vent and for two symmetrical roof vents. In a subsequent study, Boulard *et al.* [31] modeled the distributed climate of a greenhouse using CFD technique. The study revealed that simulations involving CFD software were able to describe the main features of distributed climate inside a greenhouse with good accuracy. Bartzanas *et al.* [32] carried out a CFD based analysis in a tunnel greenhouse having insect screen in side openings to investigate the influence of screen on airflow pattern and temperature distribution inside the greenhouse. The study revealed that presence of insect screen significantly reduces airflow and increase thermal gradients in greenhouses. Fatnassi *et al.* [33] simulated the temperature, humidity and air flow pattern in a large scale Moroccan greenhouse fitted with insect proof net using CFD software. The results predicted by the CFD model were validated through experiments. The study revealed that significant increase in temperature and humidity take place inside a greenhouse due to presence of insect proof net. Campen and Bot [34] studied the natural ventilation performance of a Spanish 'parral' greenhouse having two types of roof openings using three-dimensional CFD technique. The results predicted by the CFD model were experimentally validated using tracer gas technique. Fatnassi *et al.* [35] investigated the effect of insect screen on airflow and climate in a multi-span greenhouse, using CFD technique and validated the results through experiment. Teitel *et al.* [36] explored the effect of insect screen inclination on natural ventilation air flow rate in a greenhouse. Both experimental investigations and CFD simulation were carried out and reported by them. Teitel [37] used CFD simulation to determine the pressure drops on woven screens. Khaoua *et al.* [38] analyzed using CFD technique, the effect of wind speed and roof vent opening configuration on airflow and temperature pattern in a compartmentalized glasshouse. Majdoubi *et al.* [39] carried out an experimental and CFD assisted study to investigate the air flow and inside microclimate pattern in a Canary type greenhouse.

In some other study on natural ventilated greenhouses, White and Aldrich [40] recommended that total area of ventilators should be 15-30% of floor area of the greenhouse. They found that above 30%, the effect of providing additional area of vents caused marginal improvement in performance.

Fan Induced Ventilation: Artificial ventilation using induced draught and exhaust fans, blowers, etc helps in maintaining a greenhouse temperature closer to ambient due to higher rate of air change than what could be achieved through natural ventilation. In most greenhouse applications, fan induced ventilation is employed in tandem with evaporative cooling system thus leading to fan-pad systems. Publications that discussed fan-pad evaporative cooling systems have been reviewed separately in section 3.1.1. Some works have also been reported in literature, where fan induced ventilation has been used solely for providing desired air change and without any accompanying evaporative cooling system. The pioneering work in this field may be attributed to

Goodhind [41], who reported a study, as back as in 1965, on the air movement in glasshouses equipped with fans. Fuchs *et al.* [42] studied the energy balance in a greenhouse having bare soil with four different ventilation arrangements. They observed that external wind speed and internal buoyancy forces affected passive ventilation, but had no significant effect on fan induced ventilation. High ventilation rates diminished soil heat flux, increased sensible heat flux and marginally reduced the latent heat flux. Willits [43] developed a thermal model to predict the microclimate inside a greenhouse having provisions of both fan induced ventilation and fan pad evaporative cooling system. The results of the model showed that when fans were alone put into use, little advantage could be obtained by increasing air flow rates beyond 0.05 $m^3\ m^{-2}\ s^{-1}$. But when evaporative cooling (fan-pad system) was employed both air and canopy temperatures reduced with increase in air flow rates till 0.13 $m^3\ m^{-2}\ s^{-1}$. Teitel *et al.* [44] conducted experiments to compare the temperature and humidity gradient generated inside a fan ventilated greenhouse with that of fan pad evaporative cooling system. Kittas *et al.* [45] developed and calibrated a simplified model for prediction of air temperature in a fan ventilated greenhouse situated in Greece. The aim of the study was to determine the influence of outside climatic variables, greenhouse characteristics and equipment on the inside air temperature. The study concluded that the difference between inside air temperature and outside air temperature was strongly related to rate of ventilation and incoming solar radiation.

Cooling Technologies

Evaporative Cooling: Evaporative cooling systems are based on conversion of sensible heat to latent heat of evaporated water, where water is supplied mechanically. The temperature of air reduced due to evaporation of water in air. Thus, the temperature decreases at the expense of increase in humidity, while the enthalpy of air remains constant in the process. At present evaporative cooling methods include fan pad, fogging system and roof evaporative cooling all of which have been reviewed and discussed in subsequent sections.

Fan-pad Evaporative Cooling: In this type of system induced draught fan(s) is installed in one side wall and a cooling pad on the opposite wall of the greenhouse. Water is circulated through the pad using a pump to keep it wet and air is forced to pass through the wet pad due to suction from induced draught fan(s). A greenhouse having fan pad evaporative cooling is shown in Fig.2.

The pioneering work related to fan pad evaporative cooling was done by Morris [46] long back when he developed a simple mathematical equation to determine the cooling potential of a fan pad ventilated greenhouse. Kittas *et al.* [47] investigated the temperature and humidity gradients during summer in a greenhouse used for cultivation of rose equipped with ventilated cooling pad system and a half shaded plastic roof. They reported that temperature inside the greenhouse was reduced by 10°C with respect to ambient. Jain and Tiwari [48] carried out theoretical and experimental studies in a greenhouse equipped with fan pad evaporative cooling. They reported that the inside air temperature was 4-5°C lower than that of ambient. They also attempted optimization of some greenhouse parameters such as length, height, air mass flow rate and cooling pad area. Kittas *et al.* [49] developed and experimentally validated a thermal model to predict the temperature gradient along the length of a large greenhouse (60 m length) equipped with fan pad ventilation system. The thermal model incorporated the effects of ventilation rate, roof shading and crop transpiration. The study showed that large temperature gradients up to 8°C were generated from pad end to fan end due to significant length of the greenhouse. Bartzanas and Kittas [50] conducted experiments in a large commercial greenhouse equipped with fan pad evaporative cooling system and a half shaded plastic roof. The study showed strong climatic heterogeneity inside the greenhouse with wide variation in vapour pressure deficit and transpiration rate from pad end to fan end. Perret *et al.* [51] presented a pilot design of a humidification- dehumidification system based on evaporative cooling pads and condensers in a Quonset greenhouse. Davies [52] reported a study where liquid desiccation along with solar regeneration was used to reduce the temperature inside a greenhouse having evaporative cooling system. The system performance was analyzed for climatic condition of Abu Dhabi and the performance was compared with that of a conventional evaporative cooling system. Fuchs *et al.* [53] developed and validated a procedure to evaluate the latent heat cooling by means of crop transpiration and free water evaporation in a fan pad ventilated greenhouse. The procedure was able to predict crop transpiration, foliage and air temperature as well as humidity level inside the greenhouse. The study revealed that rate of crop transpiration with wet pad is nearly independent of external humidity and ventilation rate. Al-Heelal *et al.* [54] investigated the performance of an evaporative cooling pad for a fan pad ventilated greenhouse powered through

a)View of the fan end (Courtesy: HZP, West Bengal, India)

b)View of the pad end (Courtesy: HZP, West Bengal, India)

Fig.2: A greenhouse with fan-pad evaporative cooling and shading.

solar photovoltaic source in summer season. Ganguly and Ghosh [55] presented a thermal model of a greenhouse having fan pad evaporative cooling system and compared the results of the thermal model with a reference study in literature. They concluded that a temperature reduction of 6°C can be achieved with fan pad evaporative cooling and shading during peak sunshine hours for a representative day in April in a place like Kolkata (India) that represents a mixed climate of coastal and plain areas. Shukla *et al.* [56] conducted experiments to see the effect of an inner thermal curtain in a cascade greenhouse equipped with fan pad evaporative cooling system. They also developed a thermal model to predict air temperature inside the cascade greenhouse. The results predicted by the thermal model matched closely with the experimental results.

From the foregoing discussion, it can be inferred that evaporative cooling using fan-pad is an effective method of lowering the air temperature inside a greenhouse. A temperature reduction of 4-5°C can be obtained if it is used alone and up to 10°C if combined with shading. But this method of cooling generates a temperature and humidity gradient inside the greenhouse due to which crops remain in a stressed condition. Continuous operation and presence of impurities and salt in water leads to progressive choking of the cooling pad, thereby reducing its effectiveness. Also, this method of cooling

a) Misting system (available online at www.aeromist.com/applications/greenhouses.asp)

b) Fogging system (available online at www. needeelee.com/green.htm)

Fig.3: A greenhouse with misting and fogging system

requires uninterrupted electric supply to drive the fans and water pump which becomes a major constraint for its application in rural areas, especially for developing countries like India where a considerable number of villages do not have access to uninterrupted electricity supply.

Fogging and Misting System: This method of evaporative cooling uses very small water droplets (2-60 ìm in diameter for fogging range) which are sprayed into greenhouse air under high pressure using nozzles. A fraction of water droplets evaporate while coming in contact with air and due to high latent heat of vapourization of water, air temperature gets reduced. Figures 3a and 3b show the photographs of a greenhouse having misting and fogging system respectively. In this section works related to fogging and misting system have been reviewed.

Montero *et al.* [57] carried out experiments to determine the effect of air water fogging system on the climate of two multi-arch greenhouses provided with shading screen of 45% transmissivity. They observed that during sunny days the maximum temperature reduction inside the greenhouse was 5°C compared to the control greenhouse. Arbel *et al.* [58] compared the performance of fogging system with that of fan pad cooling for greenhouse application. They concluded that fogging system was better as increase in temperature was less than 5°C and variation in relative humidity within the greenhouse was less than 20%. Katsoulas *et al.* [59] studied the effect of misting on rose canopy transpiration and water vapour conductance for a greenhouse located in coastal area of Greece. They found that only 40-50% of the misting water was effectively used for the purpose of cooling. They also calculated the crop water stress index and observed that the crops were less stressed under conditions of misting. Arbel *et al.* [60] conducted an experimental study where fogging system was used in combination with forced ventilation for cooling a ridge type greenhouse. The results revealed that inside the greenhouse an air temperature of 28°C and relative humidity of 80% could be maintained during the midday of summer. The arrangement provided uniformity in temperature and humidity inside the greenhouse along the length and vertical direction. ÖZTÜRK [61] conducted experiments in a multi span plastic greenhouse and determined the fog generating nozzle parameters to characterize the efficiency of fogging system. The results revealed that fogging system could maintain the greenhouse inside temperature 6.6°C lower than that of outside. Abdel-Ghany *et al.* [62] studied fog evaporation characteristics in a greenhouse and computed the fraction of fog evaporated after absorption of sensible heat from the inside air. In another study, Abdel-Ghany and Kozai [63] developed a dynamic simulation model for heat and water vapour transfer in a fog cooled, naturally ventilated greenhouse to predict the temperatures of air, plant, cover and floor surface as well as the inside relative humidity. Transpiration and evaporation rates were also predicted using the model which matched closely with the measured values. Toida *et al.* [64] studied the influence of increase in evaporation ratio on the cooling efficiency of a fog cooled greenhouse. The study revealed that an upward air stream achieved a higher fog evaporation rate resulting in an increased efficiency of cooling and reduced possibility of expansion of pathogen in a greenhouse. In another study, Toida *et al.* [65] presented a method for measurement of dry bulb temperature in a fog-cooled greenhouse. Kim *et al.* [66] studied the humidity distribution inside a greenhouse having fog cooling using CFD and validated the model results using experimental data. Perdigones *et al.* [67] developed and validated a dynamic model simulating the air temperature inside a greenhouse equipped with fogging system working with and without a shading screen. Li and Willits [68] compared the cooling performance of a low and high pressure fogging system for naturally ventilated greenhouses. The study revealed that on an average, the evaporation efficiency of the high pressure fogging system was at least 64% higher than the low pressure system. Also, the cooling efficiency for the high pressure fogging system was at least 28% more than the low pressure fogging system.

From the foregoing discussion, it can be stated that fogging and misting systems are quite effective in maintaining greenhouse air temperatures 5-6°C below that of ambient. Also, these systems provide more uniformity in temperature and humidity level inside greenhouses compared to fan pad system. But choking of nozzles due to continuous operation is a problem due to which the effectiveness of cooling of fogging or misting systems decline with passage of time. Also, there are considerable chances of condensation of fine water droplets on the flower petals making them more susceptible to attack by microorganisms and pests.

Roof Evaporative Cooling: Roof evaporative cooling is a technique in which water is circulated on the roof surface resulting in the formation of a water film. This water film helps to lower the sensible heat gain of the greenhouse air, thereby reducing its temperature. Research in this field commenced long back when Morris *et al.* [69] found that both sensible heat gain and greenhouse air temperature reduced by circulating water on greenhouse roof. Sodha *et al.* [70] concluded that roof evaporative cooling of water can substantially reduce the entry of heat flux in a greenhouse. Sutar and Tiwari [71] carried an experimental study in a polyethylene covered even span greenhouse, where water was circulated on the roof. A temperature reduction of 4-5°C was achieved compared to the control greenhouse. When a shade cloth was put on the roof, along with water circulation, the inside air temperature reduced by 10°C compared to the control greenhouse. Willits and Peet [72] conducted an experiment where water was applied intermittently to an externally mounted greenhouse shade cloth. The results revealed that rise in air temperature reduced by 41% under wet cloth and 18% under dry cloth compared to an unshaded greenhouse. Ghosal *et al.* [73] developed a mathematical model to study the effectiveness of cooling inside a greenhouse having shade cloth stretched over the roofs and south wall with water flowing it. The results predicted by the model were validated through experiments. The study revealed that greenhouse inside temperature reduced by 6°C and 2°C respectively in shaded with water flow and without water flow condition compared to un-shaded condition.

From this review on roof evaporative cooling, it is inferred that this method can be used to reduce greenhouse temperatures significantly, particularly when applied along with external shade nets. The method is advantageous as it does not increase the relative humidity of inside air as encountered with fan-pad or fogging systems. Thus, this method of cooling reduces the chance of growth of microorganisms inside a greenhouse which is a common problem for greenhouses located in the plains of tropical and subtropical countries.

Shading, Whitening and Covering Material: The entry of excessive solar radiation is prevented using shade nets or thermal screens placed on the roof and or side walls. Shading is also done using paints, but the problem is that they get washed away during rains. In this section various literature related to shading, whitening and covering materials for greenhouse application have been reviewed and presented.

Kittas *et al.* [74] studied the influence of covering material and shading on the spectral distribution of light in greenhouses. Willits [75] examined the performance of four externally mounted shade cloths with different shade ratings of manufacturer under both dry and wet condition for their ability to reduce temperature inside a greenhouse. Baille *et al.* [76] studied the influence of whitening a greenhouse roof on microclimate and canopy behaviour during summer in a greenhouse located in the coastal area of eastern Greece. The study revealed that whitening the greenhouse roof reduced the average greenhouse transmission coefficient for solar radiation due to which air temperature and vapour pressure deficit changed drastically, while the increase in rate of transpiration was marginal. Kittas *et al.* [77] studied the effect of two ultraviolet absorbing greenhouse cover on growth and yield of an eggplant soilless crop. The study showed that the eggplants grown inside a greenhouse having 0% transmission to Ultraviolet (UV) light were about 21% taller with 17% higher leaf product than plants cultivated in a greenhouse having 5% transmission to UV light. Cemek *et al.* [78] investigated the effects of ultraviolet stabilized polyethylene, infrared absorber polyethylene, double layered polyethylene and single layered polyethylene greenhouse cover on Aubergine growth, productivity and energy requirement in late autumn season. They observed that double layered polyethylene covered greenhouse resulted in higher productivity and lower heating requirement compared to other covering materials. Mutwiwa *et al.* [79] investigated the effect of NIR reflecting pigments on microclimate of naturally ventilated greenhouses. The results revealed that use of NIR reflecting pigment in naturally ventilated greenhouses can help to achieve cooling in areas having high ambient relative humidity and insolation level. Sonneveld *et al.* [80] investigated new greenhouse covering materials that could separate PAR and NIR components of solar radiatio. Only the PAR component was allowed to enter the greenhouse and NIR part (that contains half of the solar energy) was reflected back. The reflection of NIR resulted in reduction of thermal load inside the greenhouse without affecting the rate of photosynthesis. Mashonjowa *et al.* [81] investigated the effects of whitening and dust accumulation on optical properties of materials used for greenhouse covers.

From this review on greenhouse covering materials and shading it is observed that application of shade net in a greenhouse reduces the entry of Photosynthetically Active Radiation (PAR), which is vital for plants to carry out photosynthesis. Thus, the future work in this direction should be directed towards development of new covering materials and reflecting pigments that will allow only PAR component of solar radiation to enter the greenhouse during the day and reflect back the NIR. This will reduce the sensible heat gain of greenhouse air without affecting the rate of photosynthesis.

Greenhouse Integrated Systems: A number of studies have been reported in literature where advanced systems like earth-air heat exchangers, heat storage using phase change materials (PCM), aquifer-coupled cavity flow heat exchanger systems (ACCFHES) were integrated with a greenhouse.

Earth-air heat exchangers utilize the nearly constant sub surface temperature profile of the earth to maintain a fairly uniform inside air temperature in a greenhouse. While the ambient temperature varies widely over the climatic cycle, the sub surface temperature of the earth tunnels usually remains in the range 26-28°C. In summer warm air (ambient air or re-circulated air from greenhouse) is passed through buried pipes (buried at a depth of 2-4m) where its heat is dissipated to the underground soil. Sutar and Tiwari [82] analysed the cooling performance of a greenhouse having an earth-air tunnel integrated with it. In another study Tiwari *et al.* [83] conducted performance studies of an earth-air tunnel integrated with greenhouse in terms of instantaneous thermal efficiency. Analytical expressions were obtained for both cooling and heating conditions of the greenhouse. Ghosal *et al.* [84]

developed an analytical model to determine the year round effectiveness of a recirculation type earth air heat exchanger coupled with a greenhouse. Results predicted by the model were validated through experiments. The greenhouse air temperature was 3-4°C lower compared to the same greenhouse operated without earth air heat exchanger. Ghosal and Tiwari [85] developed a thermal model to investigate the temperature inside a greenhouse having an integrated earth air heat exchanger. The study revealed that the inside air temperature of such a greenhouse could be maintained at a level which is 5-6°C lower than what could be maintained without earth-air heat exchanger.

Najjar and Hasan [86] developed a mathematical model of a greenhouse using a phase change material for energy storage. It was observed that the inside temperature fluctuation was reduced considerably because of such energy storage and the daily temperature variation could be limited to 3-5°C only.

Sethi and Sharma [87, 88] designed and developed an aquifer-coupled cavity flow heat exchanger system (ACCFHES) for cooling and heating of an agricultural greenhouse established at Chandigarh, India. Their studies revealed that under extreme summer condition, the integration of ACCFHES with greenhouse helps in maintaining inside air temperature 6-7°C below that of ambient.

A number of technical papers discussed about automatic control systems for controlling the microclimate in greenhouses. Kia *et al.* [89] presented a scheme of automatic irrigation control based on fuzzy logic methodology. In another study Maliappis *et al.* [90] proposed introduction of computer-integrated management information system (MIS) in greenhouses.

In the last few years number of researchers worked in the area of powering a greenhouse through renewable energy. This is very important as this technology is highly relevant to rural development and in developing countries like India a considerable number of villages have no electricity. Even for a remote greenhouse receiving electricity from the power grid, there are power cuts during loadsheding and breakdowns. So developing of stand alone greenhouses is a genuine need of the hour.

The pioneering work for powering a greenhouse using solar photovoltaic-electrolyzer-fuel cell system was reported by Ghosh *et al.* [91] when they presented a concept and design of a solar powered floriculture greenhouse with electrolyzer-fuel cell back up. The study revealed that coupling of hydrogen generating device and fuel cell with solar photovoltaic system can make this technology suitable for use in areas away from electricity grid. Nayak and Tiwari [92] developed a mathematical model to study round the year effectiveness of a photovoltaic/thermal and earth air heat exchanger integrated with a greenhouse located at Indian Institute of Technology (IIT) Delhi. The yearly thermal energy generated by the system with annual net electrical energy savings were reported in the study. In another study, Nayak and Tiwari [93] presented and experimentally validated a thermal model of a greenhouse integrated with photovoltaic/thermal collector. Energy and exergy analysis of the integrated system were also carried out. Barnwal and Tiwari [94] conducted an experimental study using hybrid photovoltaic-thermal greenhouse dryer of 100 kg capacity to dry the Thompson seedless grapes. A DC fan was operated using power generated by two solar photovoltaic modules. The convective heat transfer coefficient of grapes both under greenhouse and open condition were computed and reported. Yano *et al.* [95] developed and operated a greenhouse side ventilation controller using solar photovoltaic energy. The study revealed that photovoltaic power systems can be applied for greenhouse environmental control system. In a subsequent study, Yano *et al.* [96] calculated the electrical energy generated by photovoltaic modules mounted on the roof of a north-south oriented greenhouse.

Concluding Remarks: This paper presents a review of the literature that deal with ventilation and cooling technologies for agricultural greenhouses. While giving an account of the international development of cooling and ventilation technologies over the years, this review also reflects the current state of the art of different greenhouse subsystems. The information gathered herein would be useful to the researchers in the field and should also provide valuable information as to the users of greenhouse.

The review revealed that quite a lot of work has been reported on naturally ventilated greenhouse which provides a cutting edge over forced ventilated systems. The critical factor for natural ventilated greenhouse is the rate of exchange of air through natural convection which depends on the total area of vents, wind speed and temperature difference between inside and outside air. For a naturally ventilated greenhouse it is concluded that the total area of vent openings should be 15-30% of floor area as further increase in vent openings give marginal increase in performance. But natural ventilation alone is insufficient to maintain a conducive microclimate inside a greenhouse in the plains of tropical and subtropical countries during summer months when the ambient temperature is very high along with weak wind. The future work in the field of natural ventilation should be directed towards development of new cladding materials and reflecting pigments that will allow only PAR component of solar radiation to enter the greenhouse during the day and reflect back the NIR.

As this review reveals, considerable research work has been done on different methods of evaporative cooling applied to a greenhouse in the last two decades. But it is inferred that none of the methods are perfect especially for regions characterised by high level of ambient humidity.

Earth to air heat exchanger integrated with greenhouse can reduce the inside air temperature by 3-4°C, but such integrated systems face a number of operational problems. Apart from high installation cost associated with digging of soil, there are problems related to maintenance as the buried pipes are subjected to corrosion. Use of phase change material and aquifer cavity flow heat exchanger for energy storage in greenhouses has shown promising results. Not many works have been reported in these areas and further research in those areas need to be undertaken.

Only a few studies deal with integrated power generation and storage systems based on solar or other renewable energy sources for greenhouse application. For a greenhouse equipped with cooling and artificial ventilation system, availability of uninterrupted electricity at low cost is an important factor, particularly for developing countries like India. Future work should be directed towards establishment of standalone grid independent greenhouses having dedicated and independent power generation system.

It is expected that these integrated systems will make this technology more attractive from technical and commercial point of view in years to come.

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