Evaporative cooling technologies for greenhouses: a comprehensive review

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Abstract: Excessive heat generation by the high solar radiation is the major issue for agricultural greenhouses in hot climatic regions. This issue has become the great concern for summer greenhouses and has continuously been under study. Effective cooling of greenhouses needs to be undertaken to minimize the issue. There are several techniques of greenhouse cooling and among them, evaporative cooling has completely revolutionized the system of cooling in greenhouses since the nineteenth century and still it is being used around the world. The current paper presents a review study covering the past and the latest kinds of evaporative cooling techniques, which have been utilizing for agricultural greenhouses in summer. The paper attempted to show the performance characteristics of the individual cooling systems, like fan-pad systems, fog cooled systems, roof cooling systems, dissector pad-fan systems, two-stage cooling system and seawater greenhouse systems. A brief survey of literature revealed that evaporative cooling could be applied to any environmental condition to reduce greenhouse excess thermal load depending upon the types of the system. Finally, some innovative cooling ideas have been provided for further studies.

Keywords: evaporative cooling, greenhouse, fan-pad system, fog-cooled, roof cooling, two-stage evaporative cooling, India

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1 Introduction

The greenhouses are developed for the purpose of quality production which cannot be produced in an open field due to adverse climatic conditions. In hot climatic regions, greenhouse cultivation is characterized by high solar thermal load that creates major problems inside the environment of the greenhouse and restricts plant growth. According to Castilla et al. (2005), the growth and quality of the crop inside a greenhouse are commonly affected when temperatures are below 12ºC or above 30ºC. In this context, it is very much necessary to remove excess heat load from the greenhouse during hot periods. There are numerous techniques by which favorable microclimate could be maintained in a greenhouse for effective plant growth. In mild temperature regions, natural ventilation is the most common technique to moderate greenhouse microclimate. But natural ventilation frequently fails to extract the excess thermal load in high radiation periods. In order to remedy this fan ventilation can be incorporated as a substitution to extract excess heat. In some of the cases, shading nets (inside or outside the greenhouse) are very much effective to restrict solar radiation in which a part of solar radiation enters into the greenhouse. Again, though shading net decreases the heat load and air temperature, low intensity of light may decrease plant growth rate. Roof whitening also reduces greenhouse thermal load as some of the solar radiation reflected back to the atmosphere. Among the above-mentioned techniques, evaporative cooling systems are the most effective way for the reduction of greenhouse excess thermal load owing to high levels of solar irradiation during hot periods. Evaporative cooling in greenhouses is usually accomplished by natural or fan ventilation to enhance its cooling performance.

In an evaporative cooling process, heat and mass

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exchange occur between air and water. The sensible heat of air is transferred into the water and when this heat becomes equivalent to latent heat, water starts to evaporate. As water is evaporated taking heat from the air, the temperature of air decreases. Since the evaporative cooling is based on the heat and mass exchange between air and water, the dry air has greater cooling effect as compared to wet air. Thus, it is more efficient in hot and dry climatic areas but it can also be used in humid areas by incorporating suitable desiccation media. It is more convenient to use than other cooling methods; it requires low energy, easy maintenance, installation, and operation. Evaporative cooling methods which are being used nowadays for greenhouse cultivation are fogging, fan-pad method, and misting**.** This paper is intended to review and discuss how different types of evaporative cooling methods have been utilized for greenhouse cultivation all over the world along with their cooling performances. The paper also reviewed two-stage evaporative cooling technologies, which have been applicable for excessive hot climatic regions like desert climate.

2 Types of evaporative cooling

There are three main kinds of greenhouse evaporative cooling systems: direct evaporative cooling, indirect or roof evaporative cooling and two-stage or mixed mode cooling systems. The cooling performance of each method depends on the extent to which the dry-bulb temperature of the supplied air exceeds the wet-bulb temperature of the air.

In direct evaporative cooling, water is directly applied by suitable mechanical equipment into the air, mostly with water spray or soaked surface. During evaporation, water takes heat from the warm air, thus reducing the amount of the dry bulb temperature. These methods are very common in greenhouses. The schematic diagram is shown in Figure 1.

In indirect evaporative cooling energy exchange occurs between two air streams, separated by a heat exchanging device with a dry-side where only air is being cooled and a wet-side where both air and water are being cooled. In this cooling system, on the dry-side of the heat exchanger, hot primary air is supplied to cool. On the wet-side, secondary air passes over the heat exchanger surfaces, the water evaporates and the surfaces are cooled, the moist secondary air was exhausted to the outside. The schematic diagram is shown in Figure 2.

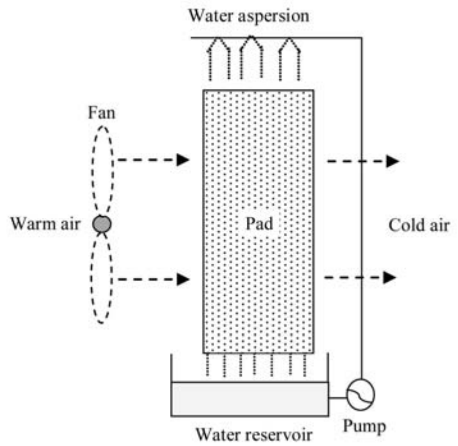

Figure 1 Simplified schematic diagram of direct evaporative cooling system

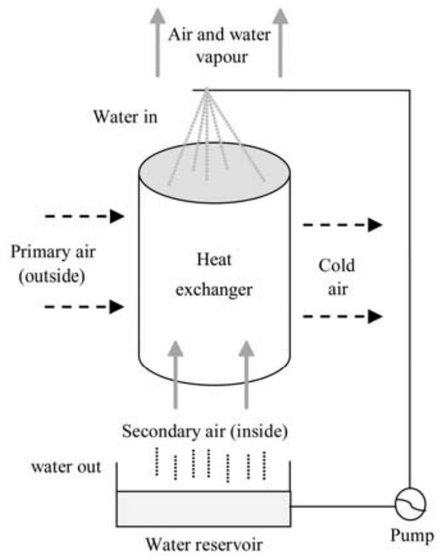

Figure 2 General arrangement of an indirect evaporative cooling system

In two-stage evaporative cooling, a non-mixing type heat exchanger is used in combination with a direct evaporative system. During the first stage of cooling, the incoming air stream passes through a heat exchanger where only sensible cooling takes place and it doesn't pick up any extra moisture. In the second stage of cooling, the same air stream passes through a wetted pad where the additional cooling occurs and the air picks up some moisture which increases the humidity.

In the onward sections, a detailed review of the different kinds of evaporative cooling techniques for greenhouse application has been presented. The survey of the literature shows that indirect evaporative cooling alone had not been applied in a greenhouse. Most of the literatures are available in the mixed mode of cooling i.e. in the combination of direct and indirect cooling system.

2.1 Direct evaporative cooling

A detailed analysis, as well as literature review related to various kinds of direct evaporative cooling systems on greenhouses application, is presented in this section.

2.1.1 Fan-pad system

The fan-pad evaporative cooling has been applied since 1954 and is still the most common system in greenhouses during summer (Purohit, 2012). Fan and pad system is comprised of three main equipment circulation pumps, exhaust fan and evaporative pad. An exhaust fan is fitted on one side of the greenhouse wall while a wetted pad is fitted on the opposite side of the wall. A pump is placed near the pad to circulate water over and through the pad. Warm outside air is drawn through the wetted pad when the fan is in operation and as a result, the warm air loses its heat due to the evaporation of water. So, greenhouse air remains cold. The following section is intended to review the literature related to the fan-pad system in greenhouses. Baily (1968) carried out a general study on a fan-pad evaporative cooling greenhouse. He mentioned that shredded aspen wood could be utilized as pad material which provides maximum dry bulb depression when air moved with a velocity of 150 feet per minute. The efficiency of such kind of cooling pad was approximately 85%. He suggested some significant concept of fan and pad sizing, installation of the fan-pad system and how to avoid pad clogging. He also mentioned some hazards which may occur in greenhouses cooled by fan-pad evaporative cooling. Jimenez and Casas-Vazquez (1978) did a work related to greenhouse evaporative cooling. They carried out several experiments to modify the microclimate of a glasshouse in hot summer. The glasshouse was built on the aluminum frame and fitted with two fan-induced ventilators and a water curtain made by three perforated plastic tubes. The first perforated plastic tube was placed at the entrance of the house to cool greenhouse air whenever ventilators draw air through it; the second perforated plastic tube was placed on the roof for roof cooling by intermittent or continuous irrigation; the third plastic tube was placed at the centre for irrigation and to reduce the ground temperature. They concluded that recorded temperatures at the micrometeorological inside of the glasshouse could be maintained same to recorded temperatures at the micrometeorological screen outside the house in summer. Landsberg et al. (1979) theoretically investigated that how much cooling could be possible in a glasshouse with single-stage evaporative cooling. Analysis revealed that by using evaporative cooling methods greenhouse air temperature was 8ºC-12ºC below the outside air temperature though outside radiations were very high. The cooling effect was observed by Chandra et al. (1989) on a fan-pad greenhouse. They used Landsberg’s model for computing the greenhouse air temperature and reported that temperature was stayed in between 4ºC-5ºC below the outside air. Jamal (1994) investigated a performance study on a commercial greenhouse in a hot area with a pad-fan system. He determined that the amount of cooling required was depended on the rate of air volume flowed through the pad (i.e. air changes per hour; ACH). It was found that 20 ACH was sufficient to provide a suitable microclimate during hot and dry conditions. They also determined the amount of water required for the evaporative cooling system. The water evaporation and air flow rate were computed by Abdel-Wahab (1994) for different farm structures having an evaporative cooling system. They developed a thermal model by taking energy (heat and mass) balance equations of the farm structures. The model had been validated using a multi-span fan-pad ventilated greenhouse located in a hot and dry climatic condition (Saudi Arabia). It was observed that when the cooling efficiency increased, both the rate of water evaporation and flow rate of air decreased. They suggested that with external shading and improvement of cooling efficiency provided a better result for saving energy and water requirement. Jain and Tiwari (2002) developed a thermal model for an even-span greenhouse fitted with cellulose pad and fan and compared the results of the model with experimental data. From their model, they calculated the thermal load level inside the greenhouse for composite

Indian climatic regions. They found that inside air temperature of the greenhouse was 4ºC-5ºC lower than that of the outside. The cooling system parameters (like length, height, air mass flow rate and cooling pad area) were optimized against the peak temperature and thermal load leveling in different zones of the greenhouse. The temperature variation inside a long (60 m) and multi-span partially shaded greenhouse with fan-pad arrangement studied by Bartzanas and Kittas (2005). They observed that the pad end temperature was 10°C less than the ambient air temperature when the ambient climatic condition was hot and dry. It was also observed that fan end temperature was 8°C higher than pad end temperature as air moved through a long path. They reported that pad end to fan end i.e. along the length of the greenhouse there was non-uniform climatic variations. Radhwan and Fath (2005) presented an integrated greenhouse system in combination with solar distillation and evaporative cooler in Saudi Arabia. The greenhouse roof was fitted with a set of solar basins to reduce greenhouse cooling load as well as to produce fresh water. During summer, the greenhouse was cooled by the evaporative cooler with a forced blower. It was found that on a hot summer day, the greenhouse inside temperature could be reduced 8ºC -10ºC at the inlet and 3ºC-6ºC at the outlet of the greenhouse than that of ambient. Fuchs et al. (2006) revealed a technique to determine latent heat cooling using the crop transpiration and evaporation of water in a fan- pad evaporative cooling greenhouse. Their technique was capable of predicting crop transpiration, the temperature of foliage and the inner climate. They reported that cooling took place if the ambient relative humidity and air temperature were below 50% and 35ºC respectively. They concluded that greenhouse temperature and the rate of crop transpiration with the wet pad was not dependent on external factors. Al-Heelal et al. (2006) carried out a performance study on an evaporative cooling greenhouse comprised of fan-pad system and photovoltaic power system under extreme summer conditions. They emphasized on the pad clogging which occurred as a result of salt deposition, reduced the pad effectiveness significantly. They observed that when pad clogging occurred, greenhouse air temperature was increased up to 55ºC and relative humidity inside the greenhouse was decreased up to 8%. Pad clogging also decreased the proper yield of plants. It was also found that power consumption was highly influenced by the ambient temperature. Sukla et al. (2006) carried an experiment in a cascade greenhouse having fan-pad evaporative cooling with thermal curtain placed inside to restrict incoming solar radiation to reduce greenhouse air temperature. In their greenhouse, they also considered an earth to air heat exchanger to provide a better cooling effect. It was found that during a hot summer day, the inside temperature of the greenhouse could be reduced 5ºC -8ºC than the outside air temperature by employing combined cooling systems. Ganguly and Ghosh (2007) developed a simplified model for a fan-pad ventilated greenhouse system. The model was built considering the total greenhouse structure as a single element and energy exchange occurred on that element. They compared the results of the thermal model with a reference study of literature. They found that a temperature reduction of 6ºC was attained with 75% shading screen placed inside the greenhouse during a hot summer in Kolkata. Max et al. (2009) conducted experiments during a dry season in four east–west oriented tomato cultivated greenhouses. The two greenhouses with net covered vents were fan ventilated, while the other two were fully plastic covered having a fan-pad evaporative cooling system. Authors had made a comparative study between these two sets of the greenhouses in terms of temperature reduction, crop vapour pressure deficit, crop water consumption and crop yield. It was found that mean temperature variations between two kinds of greenhouses during a day and night period was 2.6ºC and 1.2ºC respectively. Ahmed et al. (2011) mentioned off seasonal cultivation of crop inside the greenhouses by maintaining a suitable evaporative cooling system. They carried out experiments using three different kinds of pads; straw pads, celdek pads, and sliced wood pads. They observed that no significant variation between the inner and outside air temperature of the greenhouse was found in the morning while significant differences were found at noon and afternoon periods. The differences in relative humidity were highly significant in between 8 am and 1 pm. The saturation efficiency was dependent on cooling pad materials; highest saturation efficiency was given by sliced wood pads while straw pads gave the lowest. Lo´pez et al. (2012) investigated the characteristic of air flow by using sonic anemometry for two distinct greenhouses with evaporative cooling systems. They selected a greenhouse equipped with a fan-pad cooling system and a low-pressure water/air fog cooled greenhouse for the study. It was found that the pad-fan system with shading screen was able to maintain more suitable conditions than the fog system. They found that in an empty greenhouse fan-pad system reduced the inner air temperature by 11.6ºC lower than the naturally ventilated one while fog system reduced the temperature up to 10.4ºC. Alghannam (2012) conducted several studies to determine the efficiency of several control systems incorporated in a pad-fan cooled greenhouse. He carried out five different tests, Proportional Controller Test (P), Proportional-Integral Controller Test (PI), Proportional Derivative Controller Test (PD), Proportional Integral Derivative Controller Test (PID) and Fuzzy Logic Controller (FLC). All the tests were accomplished to cool the greenhouse from 40°C to 25°C in the extreme summer conditions. He had compared the five control systems theoretically and experimentally. To check the temperature gradient along the length of a conventional fan-pad greenhouse, Misra and Ghosh (2013) proposed longitudinally placed pads with ridge ventilated system. In their greenhouse system, the induced draught fans were fitted at the top of the roof, while the cooling pads were fitted on the sidewalls, as shown in Figure 3. They established a thermal model to predict the inner temperatures considering the energy balance of the greenhouse components. The model results had been validated with a contemporary literature. They reported that temperature in the plantation zone was decreased by 5ºC-7ºC below the ambient temperature providing 1.2 ACM ventilation rate and 50% canopy shading during summer in Kolkata.

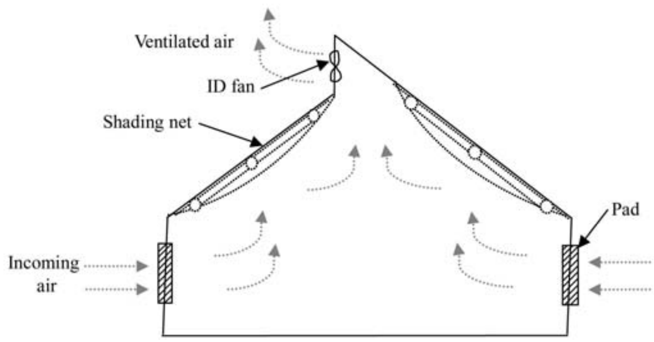

Figure 3 Longitudinal evaporatively cooled greenhouse; sectional side elevation (Misra and Ghosh, 2013)

Chen et al. (2014) presented a CFD simulation for a greenhouse and validated it with an experimental greenhouse equipped with the external and internal shading screens and fan-pad evaporative cooling system. They found a healthy match between the simulated and measured values. The variations of measured and simulated results were 0.9ºC to 3ºC and less than 0.15 m s^{-1} in terms of temperature and velocity respectively. They also suggested what should be the location of pad or fan for the optimum cooling effect of the crop. Lengthwise climatic parameters of a fan-pad cooled greenhouse were studied by Ali Dayioglu (2015). He measured the internal and external climatic parameters. It was observed that the temperature variations along the length were not uniform while humidity variations remained approximately constant due to the crop transpiration. The results showed that approximately 7ºC temperature variation occurred between pad end and fan end. The hourly average cooling effect and cooling efficiency was found to be 6.96ºC and 76.8% respectively. Xu et al. (2015) investigated the thermal environment of a fan-pad greenhouse with thermal screens or external shade and air circulatory fans in a humid subtropical climate. Finally, they concluded that under high RH condition, inside air could be kept in between 27ºC-29ºC while using both the cooling pad and shading the inner air temperature could be maintained 2ºC-3ºC below the outside air temperature with 80% relative humidity. Thipe et al. (2017) reviewed the effect of naturally ventilated system and fan-pad system in crop growth for the greenhouse in arid climatic regions. They summarized that the internal microclimate of the greenhouse could be controlled by side or roof vents in natural ventilation or by using fan-pad arrangement. They stated that natural ventilation showed poor performance for reducing the thermal load in arid or semi-arid regions. On the other hand, fan-pad system is not so effective in sub-humid regions. They also stated that fan-pad ventilation showed better result than natural ventilation in Southern African regions, while in the tropical and Mediterranean climates, natural ventilation performed better. The energy required by fan-pad systems for the cooling process incorporating photovoltaic system in greenhouses had been calculated by Romantchik et al. (2017). They developed a mathematical model that predicted the greenhouse temperatures and ventilation rates which was calibrated with experimental data. It was observed that mathematical model was reliable enough to supply the energy requirement for the cooling process in a hot summer day. They finally concluded that in order to design any photovoltaic system it was mandatory to determine appropriate ventilation rate created by fan power. Misra and Ghosh (2017a) carried out a performance study of a greenhouse system surrounded by shallow water ponds and floating wetted surfaces under dual ventilation mode. They predicted the greenhouse temperatures using thermal models with or without evaporative cooling under natural ventilation as well as fan-induced ventilation. They reported that greenhouse temperature could be reduced by 3ºC-6ºC lower than that of the ambient temperature under dual ventilation mode when saturation efficiency and shading were 70% and 75% respectively.

2.1.2 Fogging system

Fogging system is based on spraying water into the air stream as fine droplets (in the range of 2-60 μm in diameter) in which direct contact with water in the air takes place. The size of the fine droplet is beneficial since it disperses into the air quickly and evaporates early before they fall on plant foliage. The key feature of the fogging system is high water evaporation rate though it creates high humidity. In this section literature related to the fogging system is reviewed and presented.

Montero and Anton (1990) examined that fine fog generation with the use of air and water could moderate the greenhouse microclimate. They used twin fluid nozzles provided for supplying compressed air as well as water at 300-600 kPa pressure and similar flow rates which were mixed in order to produce dense fog. Two multi-arched greenhouses were considered with 45% radiation transmitting shading where total 26 fog nozzles were fitted. It was observed that 3ºC temperature difference could be achieved by fog cooling compared un-fogged greenhouse. Luchow and Von Zabeltitz (1992) carried out an experiment on greenhouse cooling system for arid climatic regions. They examined the overall performance of the greenhouse considering the temperature and RH of the entering air, exchange of heat between inside air and water spray and the pressure of the nozzles. They found that counter current flow between air and water stream was provided about 100% heat exchanging efficiency. It was also found that optimum results were achieved when the pressure of the nozzle was 21.05 bar and a water/air coefficient was 0.09 kg of water per kg air. Boulard (1993) developed a fog evaporative cooling model for a naturally ventilated greenhouse to explain a complex iteration between aeration and water spray effect on greenhouse cooling. The model computed greenhouse temperature, humidity of the air, and the plant foliage temperature and plant transpiration. The results of computed values showed a good agreement with measured data. Montero et al. (1994) developed a comparative performance study between fog-cooled greenhouse and un-cooled greenhouse. They considered air water fogging system with 45% transmissivity of shading screen during sunny days. Maximum temperature reduction was observed 5ºC as compared to the un-cooled greenhouse. Hayashi et al. (1998) measured the temperature and humidity inside a three-span glasshouse with fully open ridge vent and a sliding door type vent of a fog-cooled greenhouse. The fog water was sprayed intermittently by the fog-nozzle placed at 2 m above the floor level. They observed that the inside temperature was lowered by 4ºC-8ºC and greenhouse temperature approached to wet bulb temperature within 1 min after fogging started. Arbel et al. (1999) developed a thermal model of a fog cooled greenhouse system. They conducted an experiment in a four-span greenhouse which was equally divided into two parts. Each part of the greenhouse was equipped with fog system as well as with fan-pad evaporative cooling system. They did a comparative study by operating each cooling system in the two parts alternately and reported that fog cooling system performed better than the fan-pad evaporative cooling system. The misting effect on the inside air and plant in a rose crop greenhouse was examined by Katsoulas et al. (2001). They estimated that only 40%-50% of the mist water could be effectively utilized for evaporative cooling. They calculated crop water stress index and reported that crop was less stressed under misting conditions. In another work, Arbel et al. (2003) presented a cooling arrangement for a greenhouse combined with high pressure fogging and fan-induced ventilation system. It was stated that with such type of cooling arrangement the temperature and relative humidity was 28ºC and 80% respectively during mid-summer. Öztürk (2003) carried out an experiment in a multi-span fog-cooled plastic greenhouse to determine the fogging system efficiency. They reported that the fogging system had reduced the inner greenhouse temperature around 6.6ºC than the ambient air temperature. The average fogging system efficiency was 50.5%. Handarto et al. (2006) investigated the dry bulb temperature, relative humidity, plant temperature and cooling efficiency for a single span greenhouse with the fogging system during a mid-summer day in Japan. During the experimental observation, side-walls and continuous roof ventilators of the greenhouse were fully open. They found that during the experiment, the fogging system could lower the inside dry bulb temperature (T_{idb}) 6°C below the outside temperature. It was observed that during the fogging time period, T_{idb} was mostly the same as T_{leaf} (leaf temperature) and during the interval periods, T_{idb} increased while T_{leaf} remained unchanged. Cooling efficiency was found to be in-between 57%-80%. Ahmed et al. (2006) established a dynamic model for a fog cooled greenhouse under natural ventilation. The developed model predicted the greenhouse air temperature, plant temperature, cover temperature, floor surface temperature, relative humidity, transpiration, and evaporation rate. The model results have been compared with an experimental greenhouse installed in Tokyo. Abdel-Ghany et al. (2006) suggested a new definition of cooling efficiency for a fog-cooled greenhouse system. They investigated the cooling efficiencies for different fogging cycles. The expression was derived from mass and energy balance of warm (un-cooled) air inside the greenhouse. They had also shown that the increasing evaporation rate decreased the air temperature thus increased the cooling efficiency. Ishii et al. (2006) investigated the ventilation effect on plant microenvironment and the use of water (cooling and plant transpiration) in a semiarid fog-cooled greenhouse system. Experiments were conducted considering two combinations of roof and side vents. They found that in natural ventilation fog cooling method was capable of maintaining the greenhouse inside temperature within 23ºC-26ºC for the both vent cases. They reported that while the relative humidity increased, the ventilation rate and water requirement in the greenhouse was decreased. A comparative study between a low pressure (4.05 bar) fogging system and high pressure (40.5 bar) fogging system was studied by Willits et al. (2008). They observed that high-pressure fogging system provided the better cooling than low-pressure systems. A comparative study relating to cooling and evaporation effectiveness also had been shown in this work. In another work, Katsoulas et al. (2006) carried out a study to identify the effect of fogging in greenhouse microclimate for soilless pepper crop production. They studied the humidity control influence on greenhouse environment, the rate of crop transpiration and yield and fruit quality of the crop. They found that compared to no-fogging, greenhouse air temperature and plant leaf temperature were about 3°C lower in fog cooled condition. Again, Katsoulas et al. (2009) studied the effect of high pressure fogging in greenhouse microclimate where eggplants were cultivated. Measurements were carried out dividing the whole greenhouse into two compartments; one compartment involved natural ventilation and another one was with fog cooling system. It was examined that temperature of the fog-cooled compartment was dropped by 2.5ºC-3.5ºC in comparison with the other naturally cooled compartment. The fog cooling lowered the average fruit temperature around 3°C and kept greenhouse temperature below 32°C. Garcia et al. (2011) investigated the efficiency of two cooling methods, employing external movable shading and spraying fog water in a plastic covered greenhouse in Mediterranean region. They conducted several experiments considering different settings of shading to restrict the solar radiation falling into the greenhouse. They investigated that as compared to fixed shading, cooling efficiencies were likely similar for all the cases. Linker et al. (2011) developed a robust control approach to maintaining the expected inner environment in a small greenhouse fitted with a variable flow rate high pressure fog nozzles and variable-speed extracting fans. The controllers were designed by the quantitative feedback theory (QFT), which sustained suitable performance. Sánchez-Hermosilla et al. (2013) carried out a comparative study between a fog-cooled system and cooling with a conventional spray-gun in a greenhouse. The total greenhouse was divided into two modules, one for the spray-gun system and another for the fogging system. They reported using spray gun the crop deposition values were far less than that of using the fog system. Ishigami et al. (2014) experimented on two separate fog- cooled greenhouses, each having 26.4 m^2 floor areas. They observed that twin fluid nozzle system had higher evaporation rate and lower degree of wetting of plant foliage as compared to single fluid nozzle system. It was observed that twin fluid nozzle system produced the same cooling effect as single fluid nozzle system. Yasutake et al. (2014) designed and developed a fogging and circulation system into a greenhouse to control daytime humidity and airflow. The cooling system composed of nine mist sprayers and two fans of diameter 0.3 m each. They found that fogging and circulation systems could improve the greenhouse microclimate during the daytime. White (2015) presented a cooling system comprised of vent, fan, and fog (VFF) for a large (72 m wide × 139.5 m long) Velno greenhouse that could effectively cool the greenhouse environment in hot and dry seasons. The greenhouse was shaded by 61% shading screen and fitted with high pressure fog nozzles. There were eighteen exhaust fans, nine in each of the north and south gable ends walls while others were placed on the concrete nib walls, close to ground level. The fans provided a nominal air flow of 0.0188 $m^3\ s^{-1}\ m^{-2}$. It was reported that in such kind of cooling arrangements, the inside temperature of the greenhouse could be lowered in the range of 5.8ºC to 10.8°C with a mean of 9°C cooling at the time of maximum greenhouse temperature and 10ºC to 14.9°C with a mean of 12°C cooling at the time of the ambient maximum. Misra and Ghosh (2017b) developed a simplified thermal model for a fog-cooled greenhouse operating under natural ventilation and validated the model with an experimental arched shape plastic greenhouse situated in eastern Indian. They observed that greenhouse inside temperature solely depends on fogging configurations and found that optimum fogging cycle when spray time to interval time was 1.5-2.0 min. The schematic diagram is shown in Figure 4. Finally, they concluded that with the low pressure fogging system with suitable ventilation greenhouse inside temperature could be maintained 2ºC-4°C lower than the ambient temperature.

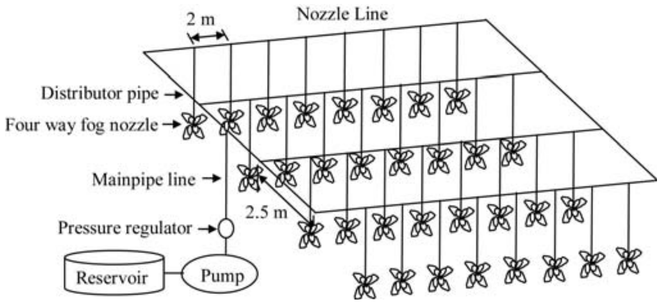

Figure 4 Schematic diagram of fogging system components (Misra et al., 2017)

2.2 Indirect or roof evaporative cooling

Roof evaporative cooling is one of the simple methods of evaporative cooling systems. In this cooling system, cooling is achieved by spraying water on the roof of the greenhouse. The water evaporates taking heat from roof and cools the roof surface

Sutar and Tiwari (1995) conducted a study to understand the effect of roof cooling on greenhouse environment. They selected a plastic greenhouse covered with a wet cloth (water film) in Delhi. They found that the inner air temperature was decreased by 4ºC-5ºC than the controlled greenhouse. It was also found that with wet roof cloth of the greenhouse, the inner air temperature was decreased about 10ºC. Morris et al. (1958) observed that by sprinkling water on the roof of a glasshouse, the solar radiation transmissivity was decreased by 6%. It also lowered the inside air temperature by lowering the temperature of the glass surface. Cohen et al. (1983) carried out a study in glasshouses providing water on roof surface and misting on plant foliage and soil surfaces. They intended to find the temperature of inner air and the surface of the glasshouse. The experiments were conducted when ambient solar radiation was high. It was investigated that roof cooling was not so much effective in lowering the greenhouse and plant foliage temperatures than misting on the plant foliage and soil surface. With the combined evaporative cooling of roof as well as plant foliage and soil surface, greenhouse temperature could be reduced by nearly 5ºC and plant foliage temperature was reduced by around 7ºC than the ambient temperature. Giacomelli et al. (1985) conducted two types of cooling system, a wetted over headed energy saving blanket and fog nozzle on a movable boom system. The blanket was wetted by mist nozzle and placed at greenhouse attic. The temperature reduction was observed 4ºC by wetted blanket system and 10ºC reduction was observed by fog nozzle on a movable boom system. Sutar and Tiwari (1995) analyzed the different conditions of evaporative cooling for controlled environment agriculture (CEA) system. The proposed CEA system was designed for a low-cost polyethylene covered even span greenhouse having 20 m^2 of floor area with a provision of roof cooling by water. They reported that with water sprinkling over the roof and wall of the CEA system, enclosure temperature could be achieved even lower than the plant temperature. Willits and Peet (2000) examined the cooling performance of a greenhouse covering by flat-woven poly-propylene shade. The observations were accomplished maintaining the shade cloth both in wetted and dried conditions accordingly. The experiment was conducted by supplying of water on the roof shade cloth and observed that the inside temperature was decreased by 41% using wet cloth than that of dry cloth where this reduction was 18%. Willit (2001) studied out the utilization of shade cloths on greenhouse roof to reduce the temperature of a greenhouse both in dry and wet conditions. They considered four kinds of shade cloths for their examination. It was observed that heavier shade cloths under wetted condition provided better cooling. Ghosal et al. (2003) presented a roof evaporative cooling model considering thin film of water on roof surface in an even span greenhouse. They validated their model with an experimental greenhouse located in Delhi. The experiments were conducted under three distinct conditions of the greenhouse; shading with water sprinkling on roof, roof shading and roof un-shading conditions. It was observed that the greenhouse temperature was decreased by 6ºC and 2^{o}C in shading with water sprinkling and shading without flow of water conditions respectively in comparison to un-shading conditions. The schematic diagram is shown in Figure 5.

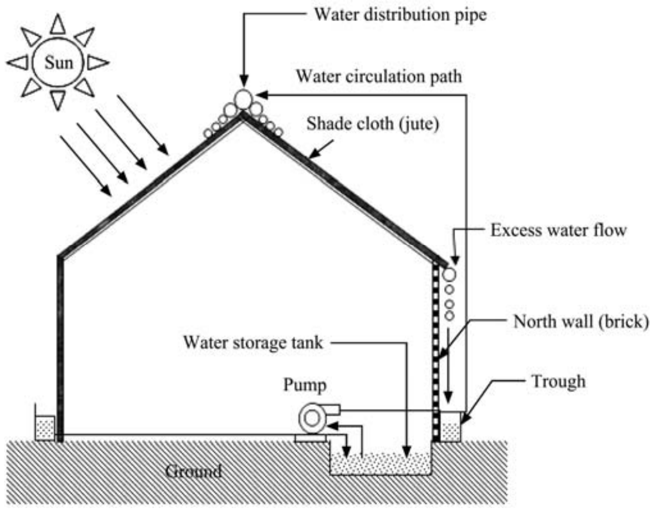

Figure 5 Schematic diagram of a greenhouse with wetted roof shade cloth (Ghosal et al., 2003)

Ghosal and Das (2012) presented a mathematical model of an even span greenhouse in which roof cooling was done by a film of moving water. Thin film of water flow on roof was maintained by jute cloth stretched on the roofs of greenhouse. The developed model was capable of investigating the effectiveness of cooling system. Helmy et al. (2013) carried out an experimental study on two small (6 m^2) identical greenhouses with combined evaporative cooling system on roof as well as interior. It was revealed that the combined cooling system provided better performance than the fan-pad system and nearly 1.1ºC-5.44ºC temperature difference existed between these two systems in the morning and afternoon respectively. They had experimented on various kinds of pad materials to search best pad material in terms of cooling efficiency.

2.3 Two-stage evaporative and mixed mode cooling

In this section, literature related to combined or mixed mode cooling as well as the two-stage evaporative cooling system are presented.

Bailey (1998) presented a greenhouse system which could be used to produce suitable microclimate for plant production as well as to provide irrigation water for coastal greenhouses. Their model simulation showed that greenhouse temperature could be reduced to 4.1ºC than ambient and yearly water production was 900 kg m^{-2} of the greenhouse when condenser cooling water was 3ºC lower than surface seawater. Sablani et al. (2003) carried out a study based on thermodynamic simulation of a seawater greenhouse. The seawater greenhouse system is shown in Figure 6. They reported that seawater greenhouse was an important way for crop growth as well as for the generation of fresh water in hot and arid regions. In their greenhouse system, a small stream of seawater had fallen into a porous evaporator and the air was drawn by the fan to cool the air. The greenhouse roof material had received selected radiations which were utilized for plant photosynthesis as well as to keep the greenhouse cool. The air was again supplied to a second evaporator it further gained moisture and became saturated. The saturated air moved through the condenser, which was cooled by deep cold seawater. The saturated air condensed at the condenser and freshwater was generated.

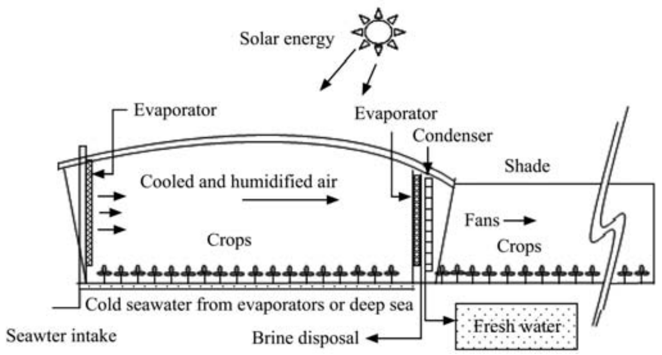

Figure 6 Seawater greenhouse system (Sablani et al., 2003)

Perret et al. (2005) presented a Quonset greenhouse, where humidification and dehumidification systems were suitably designed. The greenhouse was equipped with two humidifiers that were used to reduce temperature and raise relative humidity of the air and two dehumidifiers (i.e. condensers) which condensed the water vapour to reduce the temperature of the air below its dew-point. Davies and Paton (2005) presented a CFD model and calibrated with a prototype seawater greenhouse constructed in UAE. The schematic diagram is shown in Figure 7. The model calibration could be able to predict the inside temperatures and airflow. According to Davies (2005) liquid desiccators along with solar regeneration can be regarded for lowering the temperature of an evaporatively cooled greenhouse. He proposed a scheme similar to a traditional fan-pad system along with a desiccant pad fitted prior to the first evaporator pad. He undertook an experiment in the Gulf climate in Abu Dhabi and reported that liquid-desiccant cooling system could lower the greenhouse temperature by 5ºC than that of the traditional fan-pad system. Mahmoudi et al. (2010) established a model using a passive condenser for the improvement of fresh water generation. The greenhouse provided a cold climate to the plants. The simulated results showed that the passive condenser had a higher capability to produce fresh water than the actual pump operated system. Wong et al. (2011) develop a conceptual design of the mechanical equipment required to cool, store heat, and heat a greenhouse operation, employing aquifer thermal energy storage (ATES) system. They developed a detail thermal energy model using TRNSYS software for a greenhouse that is capable of simulating the energy performance for both the traditional (open) and the “closed” greenhouse energy operation in the Canadian climate.

Abbouda and Almuhanna (2012) designed a two-stage evaporative cooling system comprising of a direct evaporative cooling (DEC) consisting of the cooling pad and indirect cooling consisting of the cooling coils unit (CCU) for greenhouse application. In the DEC heat is absorbed during the evaporation of supplied water, whereas in the CCU heat load of the hot air was transferred while passing through the cooling coil. It was found the CCU could provide the only hourly average temperature drop of 8.1ºC, with the effectiveness of 47.4%. On the other hand, the DEC had an hourly average effectiveness of 75.12%. Again, in the combined cooling mode (both CCU and DEC), the hourly mean greenhouse air temperature was reduced by 19.1ºC during daytime and 9.0ºC at night. Lychnos and Davies (2012) carried out a theoretical model to investigate the performance study of a greenhouse coupled with solar power regenerator, $MgCl_2$ desiccators, and an evaporative pad. The model had been developed for both the regenerator and the desiccators and its results showed healthy match with the experimental values conducted in hot summer. They reported that compared to the traditional evaporative cooling system, the desiccators with pad system reduced the average daily maximum temperatures by 5.5ºC-7.5ºC in the hot season. Al-Busaidi and Al-Mulla (2014) carried out the experimental investigation on two different greenhouses, seawater greenhouse (SWGH) and conventional greenhouse (CGH) in an arid region in Oman. Both the greenhouses equipped with fans and pad evaporative cooling system but SWGH utilized seawater instead of fresh water for the cooling requirement. Besides, the cooling SWGH included desalination unit to produce fresh water for irrigation needs of cucumber planted inside the greenhouse. It was observed that SWGH reduced the greenhouse temperature 4.8°C while conventional greenhouse reduced the temperature 7.4°C than the ambient. It was also observed that most of the time CGH could not maintain the inside humidity above than 60% whereas SWGH could. Abu-Hamdeh et al. (2016) designed and developed a solar desiccant evaporative cooling system that could be able to cool the greenhouse in high humid climatic regions. They investigated that the proposed cooling could reduce the inside temperature close to 6ºC compared to traditional water evaporation cooling. Aljubury et al. (2017) presented a two-stage evaporative cooling system (indirect-direct cooling system; IDEC) for protecting plants inside a greenhouse located in the desert climate where the temperature of ambient air frequently reaches to 50ºC. The cooling system comprised of one indirect evaporative cooling (IEC) heat exchanger and three pads divided into three stages. They designed the indirect-direct evaporative cooling (IDEC) system to investigate the greenhouse microclimate. Geothermal water was used as a cooling fluid of indirect heat exchanger as well as for wetting pads. They found that the IDEC system had been raised evaporative cooling efficiency to 108% compared to the direct evaporative cooling (DEC) efficiency which was 77.5%. Finally, they concluded that the IDEC with ground water as a coolant had been deceased greenhouse temperature nearly 12.1ºC to 21.6ºC and increased relative humidity from 8% to 62% compared to the ambient conditions. Banik and Ganguly (2017) developed a thermal model of a desiccant assisted distributed fan-pad ventilated greenhouse system to predict the inside air temperature. They validated the model with a reference model study available in the literature. It was found that in a hot and humid season the greenhouse could be capable of reducing 4.3ºC than ambient whereas conventional fan-pad system did 2.5ºC below the ambient. They also included a cumulative cash flow model to observe the payback period and the Net Present Value of the greenhouse system.

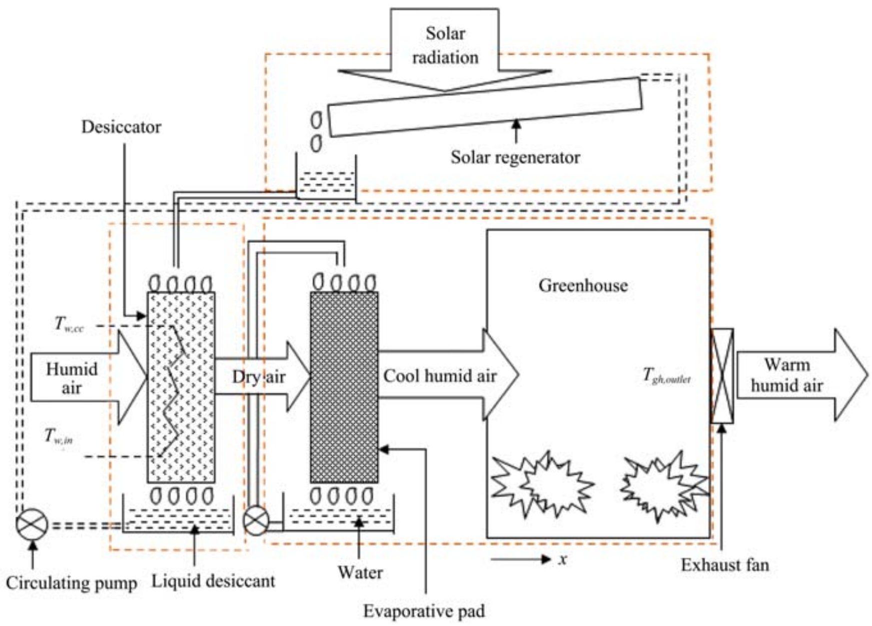

Figure 7 Schematic diagram of evapotatively cooled greenhouse system with the solar assisted liquid desiccant pad (Davies, 2005)

3 Summary and conclusion

The current paper is intended to review the researches of various researchers in the form of theoretical and experimental studies in connection with evaporative cooling systems of greenhouses. The study has been concentrated on fan-pad cooling, fog cooling, roof cooling as well as some promising cooling systems like desiccated pad evaporative cooling, two-stage evaporative cooling, and seawater greenhouses. The work emphasized on the key issues of evaporative cooling and performance features of the systems. The study shows that in greenhouses, evaporative cooling is not applied alone but with some form of ventilation and shading as well. There are some advantages and disadvantages of each evaporative cooling system. Selection of appropriate cooling system depends mainly on local environmental condition as well as greenhouse design and construction. The review shows that the evaporative cooling systems have been continuously redesigned and enhanced depending upon the climatic conditions to achieve better cooling performance. This advancement is based on the development of relevant theory and practice. The researches have been rapidly progressed, which leads to the increasing numbers of published articles in many countries. The evaporative cooling system also has been developed for extremely hot and dry regions (desert climate) and such climatic regions two-stage evaporative cooling is very much effective to provide suitable microclimate inside of a greenhouse than that of direct evaporative cooling. Again, the review has been done on seawater greenhouse where saline water of sea has been used for cooling as well as irrigation. It is observed that the evaporative cooling system has been exhibited as a quite efficient technique for greenhouse cooling. The survey of literature revealed that, direct evaporative cooling is able to cool the greenhouse environment 2ºC-12ºC lower than that of the ambient, evaporative cooling with desiccation pad reduce the greenhouse temperature in between 4.3ºC-7.5ºC than that of the ambient and two-stage evaporative cooling using geothermal water can effectively cool the greenhouse environment around 8ºC-21.4ºC than the ambient.

4 Recommendations for future research

Based on the brief survey of literature, it is observed that lots of researches yet to be done relating to indirect and mixed mode (combination of direct and indirect) of evaporative cooling applicable in a greenhouse environment. More scope of further research is still remaining which can be done in the hot and humid tropic and subtropics. After studying the evaporative cooling system, the following fields are recommended for further research for greenhouse applications.

- System design and control of photovoltaic evaporative chimney
- Design of evaporative cooling system with solar chimney assisted ventilation
- Integrated control of the evaporative cooling and the shading screen
- Design and development of passive evaporative cooling
- System design of regenerative evaporative cooling
- Application of renewable energy (solar and geothermal) for direct or indirect evaporative cooling

Practical implementation of the above-mentioned concepts in greenhouse application may face lots of challenges which could be the subject of further research.

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