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Study on temperature reduction technologies inside protected enclosures in hot arid zone of India

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ABSTRACT

Excessive heat generation due to high solar radiation is a significant issue for agricultural greenhouses in India's hot, arid regions. This issue has become a significant concern for summer greenhouses and has been a continuous area of study. Effective cooling of greenhouses needs to be undertaken to minimize the issue. A study was conducted to evaluate the effectiveness of temperature reduction methods within shade net enclosures (75%) covering an area of 45 m^2. The temperature within a greenhouse typically increases by 10-15℃ above the surrounding ambient temperature due to the greenhouse effect. In contrast, the applications of a shade net result in a more moderate temperature increase of only 3-5℃. The temperature reduction methods examined include natural ventilation, forced ventilation, and the use of foggers. In the case of natural ventilation, the temperature was recorded at 41.5℃ °C, which is above the ambient temperature of 38℃, while forced ventilation recorded a temperature of 39.1℃, and the foggers achieved a lower temperature of 34.9℃. The findings of the study indicate that utilizing a fogger system allows for year-round cultivation within a shade net greenhouse, as the temperature was maintained at 3.1℃ below the ambient temperature of 38℃. This temperature can be further reduced by increasing the number of foggers employed.

Key words: Shade net greenhouse, hot arid region, greenhouse cooling, temperature reduction, protected agriculture, microclimate modification

INTRODUCTION

In hot climates, particularly in the arid zones of India, protected agriculture is primarily employed to regulate temperature, relative humidity, light intensity, and pest control. Numerous ventilation and cooling solutions are accessible to growers. Protected cultivation is crucial in contemporary agriculture, facilitating year-round crop production and significantly enhancing agricultural productivity, irrespective of external weather conditions (Maraveas *et al.,* 2023; Chen *et al.,* 2022). The cultivation of high-value off-season and off-region crops within protected enclosures has seen a remarkable increase in recent years, extending from temperate areas to the warmer regions of the tropics and subtropics. A variety of technologies have been developed to heat the internal environment of greenhouses to ensure optimal plant growth (Sethi *et al.,* 2013). In hot arid regions, greenhouse cultivation poses significant challenges due to the extreme temperatures that hinder plant growth (Pek and Hayles, 2014; Saran *et al.,* 2010). In such circumstances, it becomes essential to cool the greenhouse microclimate; however, this process is highly demanding in terms of energy and water usage. Therefore, in these areas, it is crucial to lower the air temperature within the greenhouse or to regulate it to be closer to the ambient temperature during the summer months to ensure successful crop production. Research indicates that employing a 75% shade net cover can reduce global solar radiation to nearly one-third of the levels received outside. Additionally, it has been observed that the temperature inside the greenhouse during the morning is often higher than that of the outside environment, and this increase is anticipated to be even more pronounced during the summer months.

Consequently, cooling is regarded as an essential requirement for the production of greenhouse crops in tropical and subtropical areas to address the challenges posed by elevated temperatures during the summer months. Developing an appropriate cooling system that creates a favorable microclimate for crop growth presents a significant challenge, as the design is intricately linked to the local environmental conditions. A variety of cooling techniques for the cultivation of crops in greenhouses have been identified; primarily, fan pad cooling systems and desert coolers, among other methods, have been widely employed in greenhouse cultivation; nevertheless, these systems require significant water consumption during the evaporation-driven cooling process

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(Kumar *et al.* 2009). Given the anticipated scarcity of water resources in the future, such fan-pad cooling systems may not be sustainable, particularly in hot arid regions. In arid areas, where extreme heat and water scarcity pose significant challenges, cooling strategies must focus on temperature regulation with minimal water usage. Approaches such as indirect evaporative cooling, fogging/misting systems equipped with water-recycling mechanisms, and thermal mass storage effectively regulate greenhouse temperatures while optimizing water consumption (Allali *et al.,* 2024). Additionally, closed-loop water recovery systems integrated with evaporative cooling further minimize water loss while ensuring effective climate control (Hegazy *et al.,* 2022).

Natural ventilation represents a passive greenhouse design that necessitates less energy input and equipment in comparison to active ventilation. It stands as the most economical method for cooling a greenhouse. Despite the widespread adoption of natural ventilation designs (Munoz *et al.,* 1999), it provides limited control over cooling and airflow within the greenhouse. Natural ventilation has become a vital approach for cooling greenhouses, especially in the context of passive cooling techniques that utilize natural processes to manage air temperature. Al-Helal *et al.* (2015) revealed that the cost-effectiveness and sustainability of natural ventilation, presenting advanced mathematical models to assess its influence on greenhouse microclimates. Lyu *et al.* (2022) cited guidelines from the American Society of Agricultural & Biological Engineers to improve the efficiency of natural ventilation through design parameters. Finally, Mao *et al.* (2024) investigated the effectiveness of natural ventilation in extreme weather conditions, indicating that it may require supplementation with mechanical cooling methods in more severe climates. Forced ventilation is achieved through the use of fans or ventilators, which facilitate heat removal and regulate relative humidity. Compared to natural ventilation, forced ventilation provides a more uniform air distribution within the greenhouse (Kolokosta *et al.,* 2010). It is frequently employed during hot summer days to dehumidify and cool the greenhouse. This method of ventilation plays a crucial role in managing the indoor environment, preventing overheating in greenhouse cultivation, and can either serve as a substitute for other prevalent cooling systems, such as fans and pad systems, or assist in reducing their energy consumption (Kittas *et al.,* 2005).

Fogging is a straightforward and widely utilized cooling technique primarily employed in commercial greenhouses. High-pressure fogging systems, which generate fine water droplets that cool the air without significantly increasing humidity, have proven particularly effective in water-scarce regions such as India, improving crop yield and quality with minimal water consumption (Sethi *et al.,* 2007). In Australia, these systems are also becoming popular to alleviate heat stress in crops (Hendricks *et al.,* 2022). High-pressure fogging systems can lower air temperature by about 7–12°C while ensuring humidity control, making them especially effective in arid regions (Sethi *et al.,* 2007). Typically, fogging systems are implemented as a supplementary method to the main cooling process, particularly during the summer months, and they demonstrate enhanced performance in hot and dry climate conditions (Ishii *et al.* 2014). This study aims to evaluate the performance of various cooling methods, including natural ventilation, forced ventilation, and foggers, for reducing temperature within protected enclosures in arid regions of India.

MATERIALS AND METHODS

Green structure for environmental control

A Quonset-type environmental control structure measuring 5.0 m in length and 4 m in width was constructed using angle iron and iron rods, and it was covered with a 75% agro-net, encompassing a surface area of approximately 45 m^2. The structure, which has a volume of 31 m^3, was oriented with its longer side facing east-west and included provisions for the installation of a misting unit on the west side and a door on the east side. The cooling system features an AC-operated mister, which consists of a rapidly rotating disc mounted on the axle of a 50W AC motor, designed to generate mist from water that is lifted and circulated by a small 18W AC submersible pump located in a steel water tank. To facilitate a cooling effect within the enclosure, a mechanism was established to direct a swift stream of air using a 40W DC fan assembly. This fan was installed in a specially designed chamber that allows for the regulation of both speed and direction of air to produce a fine mist. Additionally, a photovoltaic (PV) system was comprised, consisting of a 250Wp PV panel, a storage battery, and an inverter capable of powering both AC and DC loads, with the panel holder equipped with wheels for enhanced mobility. The systemutilized four such foggers.The complete system (Fig. 1) was operated to ascertain its functionality.

Fig. 1: Green structure with PV mister

Greenhouse thermal model

A simple first-order differential equation-based thermal model was proposed to predict the inside temperature of a greenhouse given as (Singh *et al.,* 2017; Singh *et al.,* 2000; Chandra *et al.,* 1989, and Landberg *et al.,* 1979). The value of ‘U’ was taken to be 6.0 W $m^{-2 0}C^{-1}$. The overall solar transmittance was measured to be 0.65 (Singh *et al.,* 2000), and reflectance was assumed to be 0.33. The bowen ratio (β) was taken as 20 for the dry surface.

$$\rho V C_p\left(\frac{dT}{dt}\right) = \left(\frac{\beta}{\beta+1}\right) T\alpha\, SA_g - UA_c(T_i - T_a) - 0.33\, NV\,(T_i - T_a) \text{-----1)}$$

The radiation available for the ground is partitioned into ground loss, heat gain through sensible heat, and latent heat. For a steady state condition, the energy balance for the floor can be written as:

$$\frac{dT}{dt} = 0 \text{--------------------- (2)}$$

and equ (1) can be written as,

$$UA_c(T_i - T_a) + 0.33\, NV\,(T_i - T_a) = \frac{\beta}{(\beta+1)}(\alpha T)S\,A_g$$

Or

$$T_i(UA_c + 0.33\, NV) = \frac{\beta}{(\beta+1)}(\alpha T)S\,A_g + (UA_c + 0.33\, N)T_a$$

$$\text{or} T_i = \left[\frac{\frac{\beta}{\beta+1}(\alpha\tau \times SA_g)}{UA_c + 0.33\, NV} + T_a\right] \text{------------(3)}$$

PV mister-based enclosure

The performance of PV PV-based controlled environment enclosure was evaluated under ventilation and cooling modes. With PV operated mister (50 W) and fan, the temperature could be reduced to 2.5–4.5°Cbelow ambient temperature. Energy balance components inside the enclosure were recorded, and a steady-state mathematical model was developed for mister-based cooling. A solar PV-based fogger was used for which the inside temperature (T_i) can be calculated using the following equation:

T_i=

$$\frac{Ta + \left[\frac{\eta_c mL \times number\ of\ foggers}{3600} - \left(\frac{\beta}{\beta+1}\right)(\alpha\tau)SA_g\right]}{UA_c + 0.33\, NV} \text{ - - - - - (4)}$$

Cooling Systems in Greenhouses

Ventilation systems are commonly used to maintain a suitable environment insidethe greenhouse, especially for air dehumidification and for decreasing the temperature.Two types of ventilation systems are used in greenhouses: natural ventilation and forcedventilation. Natural ventilation is carried out mainly via the roof or the side-wall openings,without any external input. Hence, it is the simplest and most cost-effective ventilationtechnique for controlling the humidity and temperature. However, in greenhouse environmentswith high humidity levels, in certain conditions, forced ventilation is required and can be carried out using air fans, which bring the enclosure temperature very close to ambient temperature. If the ambient temperature is very high (40°C), we should resort to the use of foggers.

Natural Ventilation

Natural ventilation inside the greenhouse is driven by the wind and the internalbuoyancy that is created by the air density gradient. The air density gradient is created by increasing the temperature and moisture values. Natural ventilation can be considered as apassive cooling system since it is based on a greenhouse design that does not resort to the useof equipment. Ganguly and Ghosh (2011) found that the climate of greenhouses is highly impacted by the rate of air exchange through natural convection, which mainly depends on the area of the openings. Therefore, the total area of the vents should be 15 to 30% of the ground area, withdifferent types of openings (side, ridge, roof), rather than one unique typeof vent. The inside temperature of enclosures is given as:

$$T_i = \left[\frac{\frac{\beta}{\beta+1}(\alpha\tau\times SA_g)}{UA_c+0.33\ NV} + T_a\right] \text{------------ (4)}$$

Putting the values of different terms

$$T_i = \left[\frac{\frac{2}{2+1}(0.18\times 800\times 20)}{10\times 45+0.33\times 10\times 31} + 38\right] = 41.5°\text{C--------- (5)}$$

where, T_i = Enclosure temperature (°C); α = Absorptivity, τ = Transmittance; S = Insolation (Wm^{-2}); A_g = Floor area (m^2); β = Bowen ratio (Sensible heat/Latent heat); U = Overall heat transfer coefficient; A_c = Surface area of enclosure (m^2), T_a = Ambient temperature, N = Number of air change (hours) and V = volume of enclosures (m^3).

Forced Ventilation

Forced ventilation systems help control temperature, humidity, and air quality, ensuring that crops receive the best environment for growth. This method can be particularly effective in larger greenhouses or regions with more extreme weather conditions. Forced ventilation ensures the control of the indoor environment to prevent overheating in greenhouse growing environments, and it can either replace other common cooling systems, for instance, fans and pad systems, or contribute to lowering their energy consumption (Kittas *et al.,* 2005 and Nikolaou *et al.,* 2019). Flores-Velazquez *et al.* (2014), maintaining a comfortable climate inside the greenhouse is induced by combining the roof opening and the ventilators, which is better than using forced ventilators only. The performance of the system was evaluated for 120 air changes per hour (ACH), then the inside temperature of enclosures is given as:

$$T_i = \left[\frac{\frac{\beta}{\beta+1}(\alpha\tau\times SA_g)}{UA_c+0.33\ NV} + T_a\right] \text{------------ (6)}$$

Putting the values of different terms

$$T_i = \left[\frac{\frac{2}{2+1}(0.18\times 800\times 20)}{10\times 45+0.33\times 120\times 31} + 38\right] = 39.14°\text{C------- (7)}$$

Fogging Systems

Fogging is one of the systems that canbe used in greenhouses to provide evaporative cooling, effectively lowering temperatures and increasing humidity by releasing a fine mist of water. This method helps manage greenhouse climate, preventing heat stress in plants and promoting optimal growing. High-pressure fogging systems have recently started to be used. Many researchers (Abdel-Ghany and Kozai, 2006; Perdigones *et al.,* 2008; and Ishii *et al.,* 2014) found that fogging systems provide an efficient cooling process that allows for adequate climate controland that prevents the plant dehydration and heat stress caused by high temperatures. To bring down the temperature below ambient temperature T_a, four numbers of foggers were used and the T_i was calculated as:

$$T_i = \frac{\left[\left\{\left(\frac{\beta}{\beta+1}\right)\times \alpha\tau\times SA_g\right)-\frac{mL}{3600}\times No\ of\ foggers\right\}\right]}{UA_c+0.33\ NV} + T_a \text{--- (8)}$$

$$T_i = \frac{\left[\left\{\left(\frac{2}{2+1}\right)\times 0.18\times 800\times 20\right)-\frac{2\times 2250000}{3600}\times 4\right\}\right]}{10\times 45+0.33\times 10\times 31} + 38\text{----(9)}$$

$$T_i = \frac{(1920-5000)}{10\times 45+0.33\times 10\times 31} + 38\text{------------ (10)}$$

T_i = 34.9°C

RESULTS AND DISCUSSION

The performance assessment of the PV-based controlled environment enclosure was conducted under conditions of natural ventilation, forced ventilation, and the use of foggers. For natural ventilation, the infiltration or natural ventilation rate was approximately 10 air changes per hour (ACH). This infiltration rate is typically represented in terms of changes in internal air volume per unit of time (for instance, air exchanges per hour). It was observed that the temperature within the enclosure reached 3-5°C higher than the ambient temperature (35°C) during peak hours, with solar radiation at 800 W/m^2. The forced ventilation mode reduced the temperature difference to between 1-1.5°C. Conversely, the use of four foggers resulted in a decrease in indoor temperature by 3-3.5°C compared to the ambient temperature. By employing a thermal model with input parameters such as ambient temperature and solar radiation, the internal temperature of the enclosure was calculated for all three temperature reduction methods (natural ventilation, forced ventilation, and foggers). The values of both the observed and calculated temperatures were found to be closely aligned. Kolokotsa *et al.* (2010) indicated that forced ventilation can provide a more uniform air distribution within the greenhouse compared to natural ventilation.

Hayashi *et al.* (1998) conducted measurements of temperature and humidity within a sliding door-type vent of a fog-cooled greenhouse. They found that the internal temperature decreased by 4-8°C compared to the ambient temperature within one minute after the fogging commenced. Arbel *et al.* (1999) developed a thermal model for a fog-cooled greenhouse system and carried out experiments in a four-span greenhouse, which was divided into two equal sections. Each section was fitted with both a fog system and a fan-pad evaporative cooling system. Their findings indicated that the fog cooling system outperformed the fan-pad evaporative cooling system. Misra and Ghosh (2017) developed a simplified thermal model for a fog-cooled greenhouse that operated under natural ventilation. They validated their model using an experimental arched shape plastic greenhouse located in eastern India. They concluded that with a low-pressure fogging system and appropriate ventilation, the internal temperature of the greenhouse could be maintained at 2-4°C lower than the ambient temperature. The results demonstrate that during extreme weather conditions, such as summer, the desired temperature can be reduced below the ambient level by increasing the number of foggers, thereby facilitating crop cultivation even in summer months within a greenhouse.

CONCLUSION

The present paper discusses climate control techniques and cooling systems, emphasizing their reliability in the hot arid climate of India. In a greenhouse covered with polyethylene sheets, summer temperatures can increase by 10-15°C above the ambient level. To mitigate this, a shade-net enclosure was implemented, which limited the temperature increase to 3.1°C, 1.1°C, and -3.1°C for natural ventilation, forced ventilation, and foggers, respectively. If necessary, the temperature can be further reduced by increasing the number of foggers. This research validates the effectiveness of shade nets in extreme climatic conditions.

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