

Review Article

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## A Review of Three Commonly Used Techniques of Controlling Greenhouse Microclimate

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### ABSTRACT

The production potential of a crop grown inside a protective structure is directly associated with the microclimatic conditions offered to the crop. Thus, the microclimate should be according to the crop grown for achieving the yield potential. Among the numerous available methods, natural ventilation, shading and evaporative cooling are three commonly used techniques for controlling the microclimate inside protective structures particularly under summer climatic conditions. Natural ventilation helps in dissipating the surplus heat and vapour through exchange between inside and outside air during summer. It excludes the excessive vapour and offers a suitable microclimate favourable to plant growth during winter. Shading has a positive impact on plant growth and development with reduced intensity of solar radiation and air temperature in plant community. Evaporative cooling helps in removing the sensible heat from interior of the protective structure. The greenhouse cooling efficiency can further be increased by combining evaporative cooling with reduced ventilation rate. Thus these techniques can be successfully adopted independently or in combination to obtain more efficient environmental conditions for optimal plant development and productivity.

#### Keywords

Evaporative cooling,  
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### Introduction

Microclimate is the assembly of the climatic parameters forming around living plants (Bailey 1985). It is strongly dependent on the outside conditions, particularly under unheated conditions. It directly affects the plant metabolic activities and therefore the production (Singh *et al.*, 2006). It is a

combination of physical processes involving energy and mass transport which are governed by environmental conditions, kind of structure, type of crop and state and effect of the control actuators (Bot 1983). In general, the greenhouse microclimate studies are undertaken to describe heat and mass exchange between plants, air and other surfaces. Thus, a better understanding of the

relationships between plants and microclimatic parameters is extremely important (Bailey 1985, Singh *et al.*, 2016) to offer most favourable conditions for improved plant growth and development under protective structures. Under hot climate, greenhouse cooling can be performed by different ways, either mechanically or naturally through wind and buoyancy (Willits 2003). Ventilation can be achieved by either by powered system (powered fans and intake vents) or passive ventilation (with no mechanical components i.e. no powered fans). Passive ventilation mainly takes place through convection (hot air becomes less dense and rises up) through ridge vents. Natural ventilation is the passive ventilation which can maintain optimum temperature and humidity range by replacing wet and warm air with dry and cool air. The microclimate inside a protective structure can be controlled by using three commonly techniques viz. natural ventilation, shading and evaporative cooling (fogging) independently or in combination.

### **Greenhouse microclimate and its effect on crop growth**

The climatic parameters viz. Solar radiation, light, temperature, relative humidity, carbon dioxide concentration, vapour pressure deficit (VPD) and crop transpiration significantly affects the plant growth and development. Numerous other factors which affect the plant growth and productivity are reported in Singh *et al.*, (2017a).

### **Solar radiation**

Solar radiation is the primary source of energy for greenhouse crop cultivation. It is one of the main climatic parameters needed to evaluate the suitability of climate of a region for protected cultivation. The least quantity of irradiation required for sufficient development and flowering corresponds to a daily global

radiation in the range of 2.0-2.3 kWh m<sup>-2</sup> day (Nisen *et al.*, 1984). For cucumber plant, a solar radiation of 100.0-169 Wm<sup>-2</sup> has been suggested for optimal growth of cucumber inside a naturally ventilated greenhouse (Singh *et al.*, 2017b).

### **Light**

Light is a key parameters which significantly affect the greenhouse crop production (Wilson *et al.*, 1992). Generally, three processes viz. photosynthesis, photoperiodism and photo morphogenesis are responsible for plant growth. Three kinds of light viz. Supplementary lighting can used to improve the yield when the light is not sufficient. Under hot climate, when light intensity becomes too high, shading can be performed (Stanghellini and Van Meurs 1992). Among these, photosynthesis is the most important process and plants use a maximum of 22.0% of the light absorbed in the region 400.0 to 700.0 nm (PAR) in the process of photosynthesis (Anon 2017b).

### **Temperature**

The temperature distribution inside a greenhouse influences the uniformity of the crop growth (Sauser *et al.*, 1998). The other climate parameters such as wind, temperature of growing media and composition of air influence to a lesser degree (Singh *et al.*, 2017a). Temperature and relative humidity significantly affect the cucumber growth, development, quality and consequently the yield (Gajc-Wolska *et al.*, 2008). Air temperature within plant community and root-zone temperature significantly affect the development and flowering of plants (Khah and Passam 1992) and thereby the crop yields (Pearson *et al.*, 1995). Thus, limiting temperature to a desired range is of great importance for optimal crop growth (De Koning 1996). The temperature for optimum

photosynthesis should lie between 21.0°C and 22.0 °C. The air temperature, leaf temperature and root-zone temperature should lie in the range of 22.0-27.0°C, 20.5-25.1°C, 16.9-22.9°C respectively for optimal growth and development of cucumber crop (Singh *et al.*, 2017b).

### **Relative humidity**

The relative humidity of the air within the plant community can be considered to be 100.0% (Papadakis *et al.*, 1994). However, the desired relative humidity for optimal growth of cucumber plant lies in the range of 60.0-85.0% (Singh *et al.*, 2017b). A value below 60.0% may result in plant water stress due to increased vapour pressure deficit or crop transpiration. On the other hand, a value greater than 85.0% for a long time especially during night may promote the incidence of fungus diseases. The relative humidity inside the protective structure can be maintained to desired range using ventilation during winter (reduction) and evaporative cooling during summer (increment).

### **Carbon dioxide**

Carbon dioxide (CO<sub>2</sub>) accumulated over the day is also an important variable which affects the plant growth in a greenhouse. It is an essential input parameter in photosynthesis process also significantly affects the greenhouse crop productivity (Rijkdjik and Houter 1993). Optimal CO<sub>2</sub> concentration for the greenhouse crop production lies in the range 700.0-900.0 ppm (Tremblay and Gosselin 1998, De Pascale and Maggio 2008). When CO<sub>2</sub> concentration is below the optimal range, CO<sub>2</sub> enrichment can be achieved through a standard practice for maximizing productivity (Slack *et al.*, 1988) and water use efficiency. A continuous increase in CO<sub>2</sub> concentration inside the greenhouse at a regular interval may increase the fruit yield

more than 20.0% for both fresh and dry matter (Sanchez-Guerrero *et al.*, 2005).

### **Vapour pressure deficit**

Vapour pressure deficit (VPD) is governed mainly by temperature, humidity and radiation level inside the solar greenhouses. It one of the parameters which affect the greenhouse crop transpiration (Jolliet and Bailey 1992) and therefore the irrigation management. It also affects the stomatal conductance of plant which plays an important role in the division of energy into sensible and latent heat (Choudhury and Idso 1985, Grantz and Zeiger 1986). The high VPD values may result in hampering of photosynthesis which in turn can limit the plant growth and dry matter accumulation and ultimately the yield. The mean fruit weight of cucumber gets reduced with an increase in VPD under high relative humidity (Bakker 1991). According to Singh *et al.*, (2017b), vapour pressure deficit should lie in the range of 0.53-1.10 kPa respectively for optimal growth and development of cucumber plant.

### **Transpiration**

Transpiration which plays an important role in irrigation management under greenhouse cropped conditions (Baille *et al.*, 1994) is linearly related to VPD even for higher values (>2.5 kPa) (Lorenzo *et al.*, 1998) or (>3.0 kPa) Medrano *et al.*, (2001, 2005). The increased transpiration particularly under hot climate may significantly increase the input irrigation water or nutrient solution. Thus, knowing transpiration may help to improve irrigation control in soilless cultivation of crops under greenhouse conditions (Medrano *et al.*, 2005). Furthermore, transpiration is directly related to plant production (Watts and Goltz 1985) and merely 1.0% of the water taken by plants is utilized in metabolic activities (Rosenberg *et al.*, 1983). Yang *et al.*, (1990a) reported an

average constant transpiration rate of  $20 \text{ g m}^{-2} \text{ hr}^{-1}$  from cucumber crop during night. Transpiration is a key component of energy budget of a plant and a critical measure of yield. The plant development is directly correlated to water available to plant either in plant tissues or water vapour present in the surrounding air. Thus, monitoring and controlling water applied to a greenhouse plant, plant root water uptake, internal transport of water and external transport through transpiration becomes essential for optimal plant growth. Under cropped conditions, a fraction of the incoming solar radiation is utilized in the process of transpiration and sensible heat is transferred to latent heat. Transpiration is reliant on intensity of incoming solar radiation above the plant canopy, while photosynthesis is dependent on photosynthetically active radiation (0.4-0.7 $\mu\text{m}$ ) engrossed by the plant canopy (Kittas and Bailie 1998) and thereby shaping the overall productivity of the crop.

Numerous authors have studied the greenhouse microclimate in past (Slack and Hand 1981, van de Vooren 1981, Linker *et al.*, 1999, Fatnassi *et al.*, 2015, Li *et al.*, 2017) and a few of them are discussed here. Slack and Hand (1981) investigated the response of cucumbers grown at night and day temperature in the range of 14.0-23.0°C and 16.0-25.0°C. Early fruit yield increased with increasing night temperature up to 23.0°C and no increase was noticed at day temperature above 22.0°C. The highest cumulative fruit yield was achieved at day or night temperature of 20.0°C (when day temperature was 20.0°C) and at a day temperature of 22.0°C (when night temperature was 19.0°C) after 20 weeks of picking. van de Vooren (1981) studied the effect of day and night temperature on earliness and production of a greenhouse winter cucumber crop from date of planting to start of production. According to the study, with an increase in night temperature from

12.0 to 20.0°C, the earliness was decreased and a further increase till 24.0°C did not affect the earliness. Increasing day temperature from 20.0 to 26.0°C decreased the earliness. A positive effect on yield and production of cucumber was observed by increasing day temperature. Linker *et al.*, (1999) conducted a study for controlling greenhouse air temperature and CO<sub>2</sub> concentration by means of simultaneous ventilation and enrichment. The temperature was maintained by adjusting the ventilation and CO<sub>2</sub> concentration was maintained through adjusting the enrichment. The CO<sub>2</sub> concentration controller assumed a constant ventilation rate and roughly identified at an interval of two minutes. The execution in an experimental greenhouse proved the capability of the controllers to meet the requirements. Fatnassi *et al.*, (2015) simulated distribution of solar radiation, thermal air, water vapour and the dynamic fields using the Computational Fluid Dynamic (CFD) model in two different prototypes of greenhouses (Asymmetric and Venlo) equipped with photovoltaic panels on their roof. Two arrangements of photovoltaic panels array were tested (straight-line and checkerboard) and the study confirmed more even distribution of solar radiation in the Venlo type than Asymmetric greenhouse. The mean solar radiation transmission in Asymmetric and Venlo greenhouse was 41.6% and 46.0% respectively. The checkerboard photovoltaic panel setup improved the balance of the spatial distribution of sunlight than the straight-line arrangement. Li *et al.*, (2017) evaluated the diurnal variations in temperature, relative humidity and solar radiation to analyze the microclimate inside different naturally ventilated single-sloped greenhouses. The study showed that greater height and shorter span facilitated energy conservation and saving in single-sloped greenhouses. This study provided a reference for further research to save energy, to achieve appropriate greenhouse microclimate for

improved quality, improved yield and shorter duration of cultivation in single-sloped greenhouses.

### **Methods of controlling greenhouse microclimate**

There are several methods to control the greenhouse microclimate depending upon the outside climatic conditions of the area (Table 1). These methods include the microclimate control through cooling during summer and heating during winter climates respectively. The present study has mainly focused on reviewing the three commonly used techniques viz. natural ventilation, shading and evaporative cooling (fogging or misting) for controlling greenhouse microclimate.

### **Microclimate control through natural ventilation, shading and evaporative cooling**

Protected cultivation is an efficient and feasible option, especially for the sustainable vegetable production in the regions of unfavorable climatic conditions. Temperature is considered as one of the main factors affecting the greenhouse crop productivity and quality. However, there are several factors such as ventilation rate, crop evapotranspiration, shading, evaporation from the wet pads (if any) and coefficient of heat loss from the cover affecting the greenhouse temperature distribution (Kittas *et al.*, 2003). Inside a protective structure, the choice of a cooling method during summer climate depends on many aspects, such as local climatic conditions, agronomic practices, design and covering materials. To achieve desirable benefits, the different cooling methods (natural ventilation, evaporative cooling and shading) can be used independently or in combination to create the most encouraging environment for plant growth. The main reason for microclimate

control in greenhouses is to achieve desirable plant growth and yield. A better control on greenhouse microclimate may help in extending the length of growing season in addition to improved fruit yield and quality (Bailey 2000).

### **Advantages of protected cultivation**

Offers an optimal growing environment for plant growth

Reduction in incidence of insect-pest or diseases

Faster growth

Allows year-round cultivation

Distinct advantage of productivity and quality compared to open field cultivation

Increased duration of crop season

Encouraging market price to the growers

Reduced application of agricultural chemicals

Reduces consumption of water and nutrients

### **Natural ventilation**

Natural ventilation is the cheapest, simplest and most energy efficient method of controlling microclimate inside a greenhouse in comparison to mechanical system (Flores-Velazquez *et al.*, 2011). In summer, natural ventilation helps in dissipating surplus heat and vapour through exchange between inside and outside air, while it can exclude excessive vapour and provide a suitable thermal climate in winter (Baptista *et al.*, 1999). A naturally ventilated greenhouse works effectively in temperature range of 15.0-35.0°C (Marcelis and de Koning 1995). Ventilation plays a significant role in greenhouse cooling by

replacing the inside warm air with outside cold air and consequently maintaining the inside temperature. Cooling through ventilation has always been an important problem for greenhouse operator in warm climates, potentially limiting production and constraining profits. Natural ventilation directly affects the crop growth and development in relation to the factors such as temperature, humidity and CO<sub>2</sub> concentration (Kittas *et al.*, 1996).

A naturally ventilated greenhouse allows realization of economic yield at a lower production cost (Enoch 1986). Wind and stack effect are the two main driving forces of natural ventilation (Baptista *et al.*, 1999). The efficiency of natural ventilation is dependent on the parameters such as speed and direction of wind, inside-outside temperature difference, presence or absence of a crop and the design of a greenhouse (Ould-Khaoua *et al.*, 2006). The poor ventilation has a negative effect on air composition inside the greenhouse chiefly due to reduction in CO<sub>2</sub> concentration (Lorenzo *et al.*, 1990).

The ventilation helps in maintaining an encouraging environment for plant growth and development (Hermanto *et al.*, 2006) and can be performed from sides and the roof for a naturally ventilated greenhouse. According to Teitel *et al.*, (2006), the combination of roof and side vents is more efficient methods in reducing inside humidity and temperature compared to roof-alone ventilation at a lower air flow resistance of side vents. According to Mutwiwa *et al.*, (2008), in areas with high ambient humidity and solar radiation levels, the combination of natural ventilation and NIR-reflection may help in cooling the greenhouses. Vapour pressure transport and transpiration are closely related to each other and increase with rate of ventilation (Bakker 1984). The ventilation rate is dependent on wind speed and size of opening of vent (Fatnassi *et al.*, 2002) and wind direction

(Teitel *et al.*, 2008). In past, numerous authors studied the effect of vent types and insect nets on greenhouse ventilation rate (Kittas *et al.*, 2005). Authors also made the attempts to model the ventilation of greenhouse (Fatnassi *et al.*, 2002, Romero *et al.*, 2006, Impron *et al.*, 2007).

A continuous effort has been made by the researchers to study the greenhouse ventilation under different crop and climatic conditions globally (Bakker 1984, Fatnassi *et al.*, 2002, Kittas *et al.*, 2005, Berenguel *et al.*, 2006, Hermanto *et al.*, 2006, Romero *et al.*, 2006, Teitel *et al.*, 2006, Kittas *et al.*, 2008, Mutwiwa *et al.*, 2008, Teitel *et al.*, 2008, Yang *et al.*, 2008, Villarreal-Guerrero *et al.*, 2014).

Bakker (1984) studied the effects of a sudden increase in ventilator aperture of greenhouse from 0.0 to 60.0% on performance of cucumber crop. According to the study, the crop transpiration and water vapour transport increased from 3.0 to 12.0 g m<sup>-2</sup> min<sup>-1</sup> and 1.0 to 28.0 g m<sup>-2</sup> min<sup>-1</sup> due to decrease in temperature and specific humidity with opened ventilations. Leaf burning occurred around the petiole due to loss of water because of increased transpiration in the upper layers of the crop. Ruther (1985) carried out a study to measure natural ventilation of closed greenhouses in relation to wind velocity, wind direction and difference in inside-outside air temperature. The study investigated a simple and efficient method for tightening leakages. Fatnassi *et al.*, (2002) examined the ventilation performance of a large Canarian-type greenhouse equipped with insect proof nets on the vent openings. The air exchange rate was measured by means of tracer gas method under cropped condition. A model of ventilation was worked out and the model simulation indicated an increased ventilation rate proportionally with wind speed and size of opening for a given wind direction. The

insect-proof net induced a strong additional pressure drop through the opening which significantly reduced the ventilation rate and increased the greenhouse air temperature. The

model was further used for studying the effects of anti-thrip and anti-aphid nets on the greenhouse ventilation and the resulting climate.

**Table.1** Methods of controlling microclimate under a protective structure

Methods	Mode	Types	Advantages
Ventilation	Natural Ventilation*	i. Roof vents ii. side vents or windows iii. Combination of side and roof vents	i. Lower construction and maintenance cost ii. Allows longer gutter from lengths along the greenhouse iii. No requirement for electricity iv. Optimum temperature and relative humidity is achieved v. Encourages pollination vi. Reduces incidence of insect-pest or disease vii. Supplies fresh oxygen (CO <sub>2</sub> )
	i. Forced ventilation*	Mechanical or Fan-Pad system (similar to evaporative cooling system)	i. Works best under hot and dry climate ii. This system cools inside air by passing outside air through a wet pad which in turn decreases temperature and increases humidity inside the greenhouse
Shading	Thermal shade net or shade screens	i. External blinds ii. Internal blinds iii. Netting (White wash, colored shade nets etc.)	i. It reduces intensity of incoming solar radiation to the plant canopy. ii. Results in improved fruit set, productivity and quality. iii. Reduces plant stress.
Evaporative cooling	Fogging or misting (Small diameter droplets)	-	i. Helps in removing the sensible heat from interior of the greenhouse under hot and dry climate. ii. Helps in reducing temperature and VPD with increased relative humidity.

Carbon dioxide injection system  
 Heating systems  
 Fertigation system  
 Covering and insulation: Keeping a gap between two plastic cover  
 Planting tress: West or south-west side of greenhouse  
 Low grade geothermal cooling  
 Cooling with chillers  
 Humidification\*\*: Process of increasing humidity (humidifiers)  
 Dehumidification: Process of decreasing humidity (dehumidifiers)

Kittas *et al.*, (2005) investigated the influence of vent type and of insect proof screens on ventilation rate of a round arch plastic greenhouse. Microclimatic parameters and the greenhouse ventilation rate (*G*) were measured. *G* was determined by two methods viz. the decay rate tracer gas method using N<sub>2</sub>O as tracer gas and the greenhouse energy balance method. The ventilation was

performed from roof only, side only and both roof and side vents. The study concluded tracer gas method as a better fit to the experimental data and the combination of roof and side vents as the most effective vent configuration. Berenguel *et al.*, (2006) developed a kind of feedback linearizing controller for a parral-type greenhouse for control of diurnal temperature through natural

ventilation. The controller represented a dynamical combination of feedback-feed forward control where unmodelled dynamics can be partially compensated by feedback. Hermanto *et al.*, (2006) optimized the greenhouse ventilation area in a naturally ventilated greenhouse under cropped condition and reported that the ventilation area of 60.0% provided at ridge and sides was capable of maintaining an encouraging greenhouse environment throughout the year for crop growth.

Romero *et al.*, (2006) studied the ventilation rate through optimization of greenhouse design constraints (area of inlet and outlet vents) and type of the insect screen using a Computational Fluid Dynamics (CFD) approach. The study indicated a significant effect of ventilation openings on the air exchange rate which increased by 25.0% with an increase in vent area (6.0 to 15.0% of the greenhouse ground area). Teitel *et al.*, (2006) studied the effect of the resistance to air flow through the roof and side vents on the microclimate and ventilation inside a multi span greenhouse under cropped condition. The study reported roof and side vents combination as more efficient in reducing humidity and temperature compared to roof-alone ventilation system at a low airflow resistance of the side vents. Kittas *et al.*, (2008) investigated the influence of vent type and anti-aphid insect screens on air flow, air temperature and vapor pressure deficit (VPD) distribution inside a mono-span greenhouse with vertical side walls under cropped condition.

### **Disadvantages of natural ventilation\***

Internal climate is highly dependent on external climate  
Difficult to determine and control the internal climate due to increased variability

Dehumidification\*\* can be achieved as

Combining heating with ventilation system

Condensation on cold surfaces

Forced ventilation in combination with heat exchangers

Using anti-drop covering materials

Absorption using hygroscopic material

The normalized air velocity was 58.0% lower in the greenhouse with insect screens on the side vent openings than without screens and the most uniform climatic conditions were achieved using roof openings only. The study provided a better understanding of the plant environment under different vent configurations and a high-resolution database for validating on-going efforts with computer simulations.

Mutwiwa *et al.*, (2008) investigated the effect of near infra-red (NIR) reflecting pigments on the greenhouse microclimate and plant growth in two naturally ventilated greenhouses provided with insect-proof nets on the sidewalls and roof ventilation openings. According to the study, the combination of natural ventilation and NIR-reflection may provide a solution for cooling greenhouses in areas with high ambient humidity and solar radiation levels. Teitel *et al.*, (2008) investigated the effect of wind direction on air flow patterns and air temperature distributions in a naturally ventilated greenhouse with vertical roof openings using computational fluid dynamics technique (CFD). The study indicated a significant effect of the wind direction on ventilation rate, airflow and crop temperature distributions. The observed ventilation rates were in good agreement with predicted ventilation rates. Yang *et al.*, (2008) numerically investigated the microclimate

inside four single span greenhouses using a commercial Computational Fluid Dynamics (CFD) package. The three-dimensional simulations were compared with experimental data and a good agreement was obtained. The ventilation rate and temperature distribution at different wind speeds were analyzed on the basis of numerical results. The study indicated that the ventilation rate of greenhouses was strongly affected by its relative location to wind direction (windward or leeward). Villarreal-Guerrero *et al.*, (2014) tested a greenhouse cooling strategy through computer simulation inside a natural ventilated greenhouse. The strategy used set points of air specific enthalpy ( $55.8 \text{ kJ kg}^{-1}$ ) and vapor pressure deficit ( $\text{VPD}=1.0 \text{ kPa}$ ) of the greenhouse air to control ventilator openings and fog rates to maintain an air temperature and relative humidity of  $24.0^{\circ}\text{C}$  and  $66.5\%$  respectively. The study indicated that the strategy was capable of maintaining the set points when cooling demands were present in the greenhouse regardless of the location and outside climate.

### Shading

Greenhouse shading can be used to control the entry of unwanted radiation (Hashem *et al.*, 2011). Shading favours the plant growth (Hashem *et al.*, 2011) and development irrespective of nutrients applied (Patil and Bhagat 2014) thereby enhancing the yield of greenhouse cucumbers (Lorenzo *et al.*, 2006). Shading has a positive impact on greenhouse crop production, quality and homogeneity (Briassoulis *et al.*, 2007). It helps in reducing the plant stress, intensity of sunlight entering the greenhouse, temperature with increased humidity and evapotranspiration (Hashem *et al.*, 2011). It is found more efficient in hot and sunny regions (Al-Helal and Abdel-Ghany 2010). Shaded cucumber plants grow taller than unshaded plants and produce a greater average internode length (El-Abd *et*

*al.*, 1994). Therefore, the quality of the solar radiation allowed by covering materials to enter the greenhouse is important for evaluating its influence on plant growth and development (Kittas *et al.*, 1999). The greenhouse shading also helps in reducing the crop temperature and the rate of transpiration (Dayan *et al.*, 2000). Under hot climate, shading can also be applied over a greenhouse to improve the fruit set, yield and quality (Gent 2008). Conversely, under mild climate, the yield of greenhouse vegetable crops normally reduces with shading (Cockshull *et al.*, 1992). Sumathi *et al.*, (2008) reported a positive effect of shading on growth and yield parameters in cucumber. Kittas *et al.*, (2009) also reported a 50.0% higher marketable production of tomato under shaded conditions than non-shaded conditions. Similarly, Hashem *et al.*, (2011) reported the best crop yield by using white net house. However, Gent (2008) reported a 30.0% reduction in crop yield with shading for six weeks than without shading. Similarly, Siwek *et al.*, (2010) reported the lowest yield of cucumber under shaded conditions. Shading can be achieved by limiting the light that directly reaches the plants (Siwek and Lipowiecka 2004).

Several studies in the past reported the effects of shading on crop yield and quality (Medany *et al.*, 1999, Kittas *et al.*, 2009, Patil and Bhagat 2014, Teitel *et al.*, 2012).

Medany *et al.*, (1999) studied the effect of night-set temperature, shading and season on growth rate of cucumber fruit. The study included two treatments of shading (shading with 33.0% black shade net and double polyethylene greenhouse without shading), two set point temperatures ( $10.0$  and  $18.0^{\circ}\text{C}$ ) and two seasons. The study reported highest fruit growth rate without shading at night-set temperature of  $18.0^{\circ}\text{C}$  during both seasons. Kittas *et al.*, (2009) conducted field

experiments to study the influence of four different shading screens on microclimate, growth and productivity of the crop grown. The canopy temperature and air vapour pressure deficit were significantly lower under the shading nets than the open field. The study indicated an increased leaf area index and total marketable yield with shading and reduced fruit cracking of about 50.0%. The marketable production was 50.0% higher under shaded than non-shaded conditions.

Kitta *et al.*, (2012) investigated the effect of greenhouse shading and irrigation water salinity on greenhouse microclimate, energy balance, crop transpiration and leaf photosynthesis in three similar plastic greenhouses with cucumber cultivated in hydroponic system. Two greenhouses were shaded using two different shading nets with shading intensity of 35.0 and 50.0% and the third greenhouse was taken as a control. Two levels of salinity were applied in each greenhouse (2.3 and 6.3 dS m<sup>-1</sup>). The study reported no significant effect of shading on greenhouse air temperature. However, the leaf photosynthesis and transpiration rate were reduced with shading with no significant effects of salinity. Teitel *et al.*, (2012) used shading net (30.0%) above the greenhouse on top of the polyethylene cover in one compartment (three spans). In second compartment (three spans), the net was stretched horizontally inside the compartment at gutter height in the second compartment. According to the study, the net position with a shading less than or equal to 30.0% did not significantly affect the greenhouse microclimate. Patil and Bhagat (2014) studied the yield response of cucumber grown under 35.0%, 50.0% and 75.0% shading and in open field condition. The study confirmed a better performance of crop grown inside the shade net than open field conditions irrespective of the nutrients applied.

#### **Evaporative cooling (fogging)**

The evaporative cooling helps in removing the sensible heat from interior of the protective structure with best working under hot and dry climate for the maximum evaporative cooling (Chung *et al.*, 2010). The greenhouse cooling efficiency can further be increased if evaporative cooling is combined with a reduced ventilation rate (Li *et al.*, 2006). Fogging system is based on spraying water in small droplets of diameter of 2.0-60.0  $\mu\text{m}$  with high pressure nozzles. In fogging, cooling is achieved by evaporation of droplets which in turn helps in increasing the relative humidity apart from cooling the greenhouse. Cooling air is desirable under several greenhouses to reduce the plant stress and improve the marketable quality of production (Nelson 1996). Evaporating cooling is one of the methods which help in lowering the temperature with an increase in humidity thereby reducing the vapour pressure deficit and transpiration (Arbel *et al.*, 1999, Willits 1999, Katsoulas *et al.*, 2001).

Several researchers adopted evaporating cooling (fogging) as a cooling method inside the protective structures (Arbel *et al.*, 1999, Ozturk 2003, Gazquez *et al.*, 2008, Li and Wang 2015)

Arbel *et al.*, (1999) tested the efficiency of the fog system with a droplet size of 2.0-60.0  $\mu\text{m}$  inside a greenhouse through a comparison between the results of fog system and fan-pad system. The study concluded fog system as superior than fan-pad system when temperature and relative humidity variations were less than 5.0°C and 20.0% respectively. Ozturk (2003) investigated the efficiency of fogging system (FS) inside a multi-span (11 spans) plastic greenhouse (PG). Three nozzle lines with 82 fog generating nozzles (FGN) operating at a pressure of 4.5 atm were installed in each span of the PG. The FS helped in keeping the air temperature inside

the PG 6.6 °C lower than the outside with an efficiency of 11.7-80.0%. The relative humidity inside the PG was increased by 25.0% by means of the FS system. Fogging system efficiency (FSE) increased linearly with evaporation flow rate and absolute humidity difference (AHD) between the inside and outside air.

Gazquez *et al.*, (2008) evaluated different cooling strategies *viz.* white washing, fogging, natural or forced ventilation and their effects on the microclimate, growth and yield of crop grown in three multi-tunnel greenhouses. Fogging was the most efficient method in controlling the maximum temperature and VPD values. The combination of whitening of the plastic cover and natural ventilation was the most efficient cooling system in terms of water and energy use. Li and Wang (2015) discussed some applicable and practical cooling technologies, reporting evaporation cooling as the most effective cooling method for controlling the temperature and humidity inside a greenhouse. According to the study, the shade net application with different perforated mesh size and their evaluation with respect to local climate and region are necessary to get cooling benefits in summer.

Natural ventilation, shading and evaporative cooling (fogging) are three engineering techniques commonly used worldwide for controlling the microclimate inside protective structures under cropped conditions. These techniques affect the greenhouse microclimate in a positive manner and can be successfully adopted independently or in combination to obtain more efficient environmental conditions for optimal plant development and productivity.

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