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Climate regulation in protected structures: a review

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Abstract

For improved plant growth and increased harvests, greenhouse microclimate management is essential. To create ideal environmental conditions for all greenhouse crops, a variety of control measures, including heating, forced or natural ventilation, CO₂ dosing, humidification, and dehumidification, can be used to manipulate key microclimate parameters like solar radiation, temperature, relative humidity, light, and CO₂. However, the manufacturing process needs to use more fuel and energy as a result of these alterations. Furthermore, inclement weather may have a negative impact on the greenhouse microclimate. As a result, good ambient management is necessary to carry out the intricate processes involved in energy balance, such as low emissions and lower production costs. This document provides information on a number of greenhouse temperature management elements, how to adjust them, and how they affect the crops grown inside the protected structure.

Keywords:

CO₂, temperature, relative humidity, greenhouse, microclimate, and sun radiation.

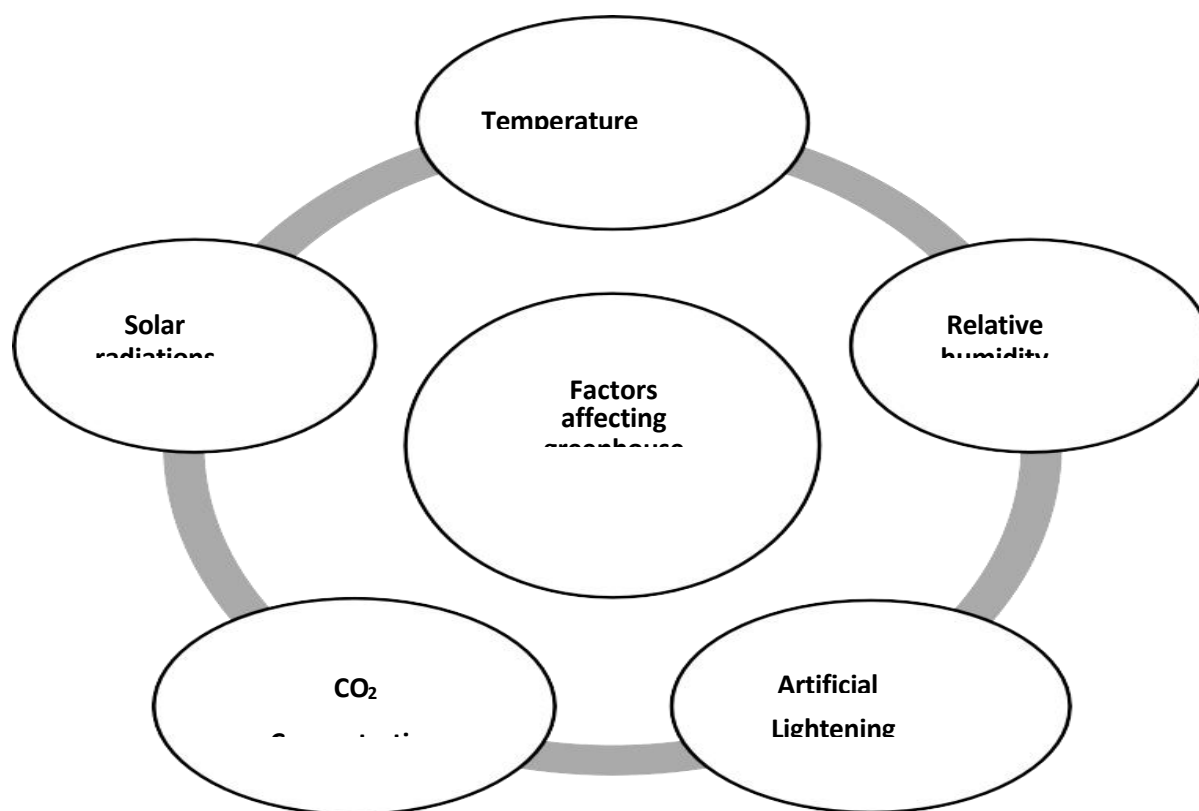
Introduction

Global interest in managed environmental agriculture has increased within the last 20 years. People have understood that as the world's population grows, we must enhance intensive agricultural systems to fulfil our demands while preserving non-renewable resources. According to Kalbande et al. (2013), greenhouse agriculture makes it possible to produce food crops with greater yields outside of the growing season. Protected agriculture makes it possible to increase crop output while maintaining a suitable environment for the plants. As a consequence, growing vegetables in greenhouses is now more common than it was in the past. Cultivating a variety with excellent heredity and providing ideal climatic conditions are necessary to increase the quality and quantity of agricultural crops. Depending on the kind of plant and stage of growth, different climatic requirements apply. Environmental stress that slows development but enhances quality is sometimes seen as an ideal state (Hashimoto 1989). Greenhouses are very complex buildings designed to provide ideal growing and production conditions for plants all year round. The indoor environment of a greenhouse is influenced by light, temperature, humidity, carbon dioxide concentration, and air composition, all of which should be provided and maintained at optimal levels for development (Bailey 2002; Shamshiri and Ismail 2013; Santosh et al. 2017). The effects of the greenhouse environment on crop growth, development, and production have been the subject of several research. Plant reactions to environmental factors, such as temperature, which has a major influence on crop timing and output (Pearson et al. 1995), and light, which is the main predictor of crop growth, are the main factors that govern crop production (Ellis et al. 1990). Plant leaf temperature, humidity, and greenhouse air temperature are all impacted by the cover material's light transmission. Although crops have high genetic

qualities, inappropriate temperature control, greenhouse humidity, and inadequate carbon dioxide dosage may cause a major decline in production and even crop loss. For this reason, microclimate management in greenhouses is one of the top concerns. Variations in greenhouse microclimates are caused by a variety of internal, external causes (Santosh et al. 2017). The ambient temperature, relative humidity, solar radiation intensity, wind speed and direction, etc. are examples of external influences. Internal elements, on the other hand, include crop varieties, soil types, genetic traits, heating and ventilation system components, and the geometric dimensions of the greenhouse. Productivity may be increased many times over by maintaining an ideal greenhouse environment throughout the growing season. With a controlled microclimate and effective use of various inputs including water, fertiliser, seeds, and pesticides, greenhouses also enable the production of four to five crops annually. High agricultural productivity may be achieved by installing various kinds of shielded structures. However, by increasing the temperature and retaining carbon dioxide, low polyhouse tunnels may be an inexpensive way for marginal farmers to create a beneficial microclimate around their crops, increasing photosynthetic activity and, therefore, crop yield (Kumar et al. 2017). Additionally, for the production of high-value crops in greenhouses and the acclimatisation of tissue culture plants in advanced research programs, computers and artificial intelligence can automate irrigation, precise application of other inputs, and environmental controls.

Microclimate parameters in greenhouses

Certain climatic conditions are necessary for plants to develop via photosynthesis. Thus, maximising plant development and production is the main objective of microclimate management in greenhouses (Radojevic et al. 2014). The next sections go into depth into some of the crucial microclimate characteristics, including solar radiation, temperature, relative humidity, light, and carbon dioxide.



Solar radiations

As solar radiation levels drop, plant dry matter output falls linearly. In general, without artificial illumination, it is

impossible to anticipate effective dry matter production in higher latitudes throughout the winter. To guarantee sufficient development and blooming, very little radiation is needed. For long-duration crops, artificial lighting is mostly required.

Effect of temperature and regulation

Temperature is the most important aspect that has to be managed in the greenhouse. Temperature affects the majority of plant functions, such as photosynthesis, transpiration, respiration, germination, and blooming. It also controls the rate of transpiration via stomatal regulation. The kind of crop to be cultivated mostly dictates the temperature requirements in a greenhouse. It is important to pay attention to temperature factors such maximum and minimum temperatures, day and nighttime temperatures, and the difference between day and nighttime temperatures (Jain et al. 2017). With estimated lower and higher temperature limitations of 10 and 35 °C, respectively, the majority of plants cultivated in greenhouses are warm-season species that are acclimated to typical temperatures between 20 and 30 °C. The greenhouse will need to be heated if the ideal minimum outside temperature is below 10 °C, and ventilation will prevent internal temperatures from rising too high during the day if the ideal maximum outside temperature is less than 27 °C; artificial cooling will be necessary if the average maximum temperature rises above 27-28 °C (Santosh et al. 2017). When the highest temperature in a greenhouse rises over 35 °C, most crops suffer damage.

.Relative humidity

Humidity has an impact on plant growth and is closely linked to transpiration (Jain et al. 2017). In general, plants do best in relative humidity ranges between 60 and 90%. Extreme humidity (over 95%) slows down plant growth, decreases transpiration, and speeds up the development of fungal diseases like *Botrytis cinerea*. Conversely, dehydration, water stress, and a detrimental effect on plant development might result from lower humidity levels (below 60%) (Kittas et al. 2012; Santosh et al. 2017). During the day, ventilation is employed to lower humidity. As long as illnesses do not manifest, humidity is often disregarded and seldom has a direct and immediate detrimental effect on plant development (He & Ma 2010). Since humidity influences the development and production of all principal greenhouse vegetables, controlling it is essential to preventing negative impacts and obtaining a high-quality plant output (Bakker 1991).

Light intensity

Three light-related processes—photosynthesis, photomorphogenesis, and photoperiodism—control plant development. These processes are immediately affected by any change in light. In the presence of light, photosynthesis releases oxygen after converting carbon dioxide into organic matter. Light is the main energy source that enables this very important operation to take place. Plants respond to various forms of light via a process known as photomorphogenesis. On the other hand, photoperiodism describes how a plant reacts to varying day lengths and whether or not it will blossom (Santosh et al. 2017). In many places of India, light levels are usually enough for productive plant cultivation; artificial lighting is only used for crops that need longer days. By increasing fruit weight and dimensions, supplemental LED interlighting enhanced plant morphology and yield (Paucek et al. 2020). Additionally, the responses were plant-dependent and light quality modifies various plant development pathways, suggesting that additional research is needed to fully understand how light

quality affects plants (Wang et al. 2007).

Carbon dioxide (CO₂)

Even with good ventilation, the CO₂ concentration within a greenhouse may fall considerably below the outside level during the growth of a dense crop. According to Akilli et al. (2000), the greenhouse's CO₂ content peaks in the early morning and then starts to decline as a function of ventilation rate, reaching its lowest point around midday. When CO₂ concentrations restrict photosynthesis in the majority of vegetable species, productivity decreases. The ideal CO₂ concentration for development and yield seems to be between 700 and 900 mol mol⁻¹ (De Pascale & Maggio 2008; Santosh et al. 2017). CO₂ enrichment is essential for improving the quality of output, and a steady or sporadic rise in CO₂ inside the greenhouse may boost fruit yield by more than 20% for both fresh and dry matter (Shanchez-Guerrero et al. 2005). Since the plant uses its stomata to absorb CO₂, various climatic elements that influence the plant's stomata openings have a significant impact on how well CO₂ is absorbed in a greenhouse.

Tools for microclimate regulation in greenhouse

Depending on the various climatic zones, several kinds of protected buildings may be used to control the microclimate. According to Santosh et al. (2017), the greenhouse's temperature, relative humidity, CO₂ levels, electrical conductivity, and soil moisture are all regulated by a variety of equipment, including pipe temperature, vents, and curtain position. Every microclimate parameter that depends on the kind and stage of the crop should be maintained at its ideal level.

Ventilation cooling and shading

According to Kalbande et al. (2013), ventilation must be seen as a year-round activity. Reducing incoming solar radiation and eliminating surplus heat via air exchange are two ways to minimise the heat load, which is the primary issue for greenhouse climate control in hot areas. The greenhouse may be well ventilated by using fans, front doors, and a roof vent (Radojević et al. 2014). The most popular techniques now in use for lowering incoming sun radiation are shade netting and whitewashing. When the outside air temperature is lower, greenhouse ventilation efficiently eliminates extra heat via air exchange. By raising the latent heat portion of dissipated energy, evaporative cooling is a widely used technique for lowering sensible heat load (Santosh et al. 2017). Due to their high investment costs, other cooling options like heat pumps and heat exchangers are not often employed, especially in India (Kittas et al. 2012).

Natural ventilation in the greenhouse

In order to eliminate extra heat during periods of intense solar radiation, air must be uniformly circulated from the greenhouse's outside to its inside. The main way that poor ventilation alters the composition of indoor air is via reducing CO₂ concentrations (Lorenzo et al. 1990). Overheating and excessive transpiration brought on by inadequate ventilation may result in physiological illnesses such fruit breaking, flower and fruit abortion, and plant water stress. Natural ventilation is greatly aided by air pressure gradients and wind. As the temperature increases, air rises close to the ceiling, and wind blowing over the roof generates a vacuum on the leeward side of the ridge (Shamshiri and Ismail 2013; Nemali 2021). Warm air is drawn out of the greenhouse when the ridge vent is opened, controlling temperature and humidity buildup and guaranteeing sufficient air exchange. Because horizontal airflow fans disperse hot air that has gathered at the top of the greenhouse, they should not be used while employing natural ventilation. To keep insects out of the greenhouse, the sides and roof vents should be covered with plastic mesh screens. When planning, natural ventilation is crucial since it has a direct

impact on the greenhouse's climate (Kittas et al., 1996). A well-thought-out ventilation system may save energy use and enhance temperature management. Additionally, temperature, humidity, and CO₂ concentration—all of which have a direct bearing on crop growth and development—are linked to ventilation (Kittas et al. 2005). Temperature variations between the greenhouse's interior and outside, wind direction and speed, greenhouse design, and the presence or absence of crops all affect natural ventilation effectiveness (Ould-Khaoua et al. 2006). According to Kittas et al. (2012) and Santosh et al. (2017), natural ventilation necessitates a total ventilator area of 15–30% of the floor area, and the impact of extra ventilation area on temperature differential is minimal beyond 30%. For plants to flourish as best they can, adequate ventilation is essential, particularly during periods of high outside temperature and sun radiation.

Forced ventilation

The fundamental concept of forced ventilation is to move air about the greenhouse via the arrangement of input and output fans (Shamshiri and Ismail 2013). The best method for ventilating a greenhouse is forced ventilation using fans, however it requires a lot of energy. In order to maintain a consistent greenhouse temperature and humidity level, fans are placed. Hot air from one side of the greenhouse is replaced by fresh air from the other (Santosh et al. 2017). For efficient forced ventilation, exhaust fans should be positioned on the greenhouse's leeward side. The fan's capacity should be raised by at least 10% if this isn't feasible. Fans must be spaced no more than 25 feet apart and have a clean area in front of them that is four to five times the fan diameter in order for forced ventilation to function properly (Nemali 2021). The airspeed in a greenhouse with a crop should not be higher than 0.5 ms⁻¹. The holes must automatically shut when the fans are not in use (Santosh et al. 2017).

Shade covers

Reducing air temperature is one of the main difficulties for greenhouses built in India because of the high temperatures. The main source of heat gain in greenhouses is direct sun radiation. Unwanted radiation may be controlled by using shade or reflection methods. Paints, external shade cloths, nets of different colours, partly reflective shade screens, water film over the top, and liquid foams between the greenhouse walls are some of the ways to provide shading (Kittas et al. 2012; Santosh et al. 2017). Due to the decrease in light and possible impact on ventilation rates, shading may have an impact on plant growth and photosynthesis. Therefore, care must be used while choosing the kind of shade and related control techniques. Shade nets are more productive in hot, sunny areas (Al-Helal & Abdel-Ghany 2010) and have a beneficial impact on produce quality and uniformity (Briassoulis et al. 2007). There are currently several different types of plastic nets on the market with different optical qualities. To improve crop performance, producers may alter the composition of transmitted solar radiation in the greenhouse by using different shade nets with unique optical characteristics (Oren-Shamir et al. 2001). The colour and transparency of the covering materials have an impact on the absorption, reflection, and transmission of both short- and long-wave radiation, according to Robledo & Martin (1981). In protected crops, coloured shade nets promote certain physiological and morphological responses that enhance the quality of the output (Shahak et al. 2002). In greenhouse production, where shade nets lower the radiation burden within the greenhouse, the plant's reaction to light intensity and quality is crucial. It is anticipated that a considerable decrease in

solar radiation would increase the canopy temperature by slowing the rate of leaf transpiration (Jakson et al. 1981).

Evaporative cooling

By regulating temperature and relative humidity, evaporative cooling systems for greenhouses have been created to minimise overheating during hot weather (Montero 2006). High solar thermal load is a characteristic of greenhouse farming in hot regions, which inhibits plant development and creates serious issues inside the greenhouse environment (Misra & Ghosh 2018). One of the most effective ways to improve climate conditions is to use evaporative cooling systems, which are based on the conversion of sensible heat into latent heat (Montero 2006) through the evaporation of water supplied directly (mist or fog system, sprinklers) into the greenhouse atmosphere or through evaporative pads or wet pads. In order to increase the amount of water surface in contact with the air, the fogging system sprays water as small droplets under high pressure into the air above the plants. The slow freefall velocity of the droplets and their easy transportation by the greenhouse's air streams lead to a high water evaporation efficiency while maintaining the dryness of the foliage. There are several different types of fogging systems that are used to chill the greenhouse and raise relative humidity. The fan-and-pad cooling method is the most used in horticulture (Kittas et al. 2012). However, fogging systems have an advantage over wet pad systems in that they provide consistent conditions throughout the greenhouse, which eliminates the requirement for an airtight enclosure and forced ventilation (Baeza et al. 2008; Shamshiri & Ismail 2013). The costly installation and high running expenses, including freshwater supply, energy, and maintenance, are the drawbacks (Santosh et al. 2017). Additionally, evaporative roof cooling involves misting water onto the outside of a roof to create a thin layer of water on the surface. This works best in hot and dry climatic zones by decreasing solar radiation transmissivity to the greenhouse and increasing evaporation rate, which lowers the temperature of the water and the surrounding air.

Greenhouse heating

For the heating system to distribute the temperature evenly throughout the greenhouse, meticulous planning and design are required. The crops to be cultivated and the kind of glazing material used dictate the sort of heating system needed (Kalbande et al. 2013). In the nation's colder areas, greenhouse heating is required, and heating expenses have a big influence on greenhouse output and profitability. Modern greenhouses utilise a variety of heating technologies to satisfy their heating and cooling requirements (Ozgener & Hepbasli 2005). The most popular and affordable technology is the unit heater. Each heating system covers floor surfaces ranging from 180 to 500 m², and warm air is blasted from unit heaters with self-contained fireboxes throughout the greenhouse (Kittas et al. 2012; Santosh et al. 2017). To make sure they are in proper operating condition, unit heaters should be tested annually. Prior to the beginning of the heating season is the best time to do maintenance. It is necessary to examine the blower, fuel lines, valves, and exhaust vent (Nemali 2021). In contrast to unit heater systems, some of the heat from central boiler systems is transferred to the root and crown zone of the crop, promoting crop development and preventing disease. With the aid of wall pipe coils, perimeter wall heating may contribute to a more consistent thermal environment in the greenhouse while also

supplying some extra heat that is required. Overhead pipe coils that span the length of the greenhouse provide heat loss via the roofs and gables. These oils are not the best source of heat; rather, they are situated above the plants. By positioning the heating pipes close to the base of the plants (in bed-pipe coils) as opposed to the overhead coil system, which promotes appropriate air flow and lowers humidity around the plant, the roots of the plants are heated more efficiently (Kittas et al. 2012; Santosh et al. 2017). Another heating method that keeps temperatures consistent and improves the microenvironment of plants is pipe/rail heating. Vegetable production systems are suitable for these systems.

Heating for anti-frost protection

These greenhouses used heating to keep crops from freezing. Additionally, it is used to maintain greenhouse air temperatures above crucial levels for the management of condensation (Santosh et al. 2017). Consequently, these greenhouses lack sizable and intricate heating systems.

Solar radiation filtration

Ultraviolet radiation (UV), photosynthetic active radiation (PAR), and near-infrared radiation (NIR) are the three forms of global sun radiation that enter a greenhouse. Most UV light is absorbed by the Earth's atmosphere. Plants that are exposed to too much UV light may experience a deterioration in their photosynthetic function. The aforementioned spectra show that greenhouse plants only absorb the PAR component of the incoming light, which is necessary for their development and photosynthesis. Accordingly, some adjustments to the radiation entering the inside of the greenhouse may be advantageous (Von Elsner et al. 2000; Lamnatou & Chemisana 2013). The structure and equipment of the greenhouse absorb more NIR than the plant does, raising the ambient temperature in the greenhouse. The cover materials are changed to cool the greenhouse. Additionally, certain plastic cellophane, movable screens, or NIR filtering shading paint may be used to provide NIR filtering.

CO₂ enrichment

By enhancing photosynthesis, CO₂ enrichment systems have been shown in several studies to have a favourable impact on plant development. Pure liquid CO₂ pumped from containers to the greenhouse via a pipeline network, akin to the fertigation system, is the purest method of CO₂ enrichment. Distribution pipes are equipped with special gauges that monitor CO₂ concentrations in order to identify any gas risks. One drawback of this technology is the high expense of transporting gas canisters. CO₂ is one of the gas emissions from the burners when fuel, such as natural gas, propane-butane gas or liquid kerosene, is burnt. Heat produced by this kind of action is often the main justification for the installation. These systems' drawback is that CO₂ can only be added to the greenhouse when heat is also needed. The availability, cost per unit, and purity of the petrol emissions all influence the fuel type that is used. To achieve optimal efficiency, dosing will be carefully regulated in greenhouses according to temperature, ventilation, and light conditions. To maintain the same CO₂ concentration in the greenhouse as outside and to enrich to levels of roughly 700–800 mol mol⁻¹ during the times when the greenhouse is kept closed, typically in the early morning and late afternoon (Kittas et al. 2012), some authors advise supplying CO₂ even when ventilation is operating (Nederhoff 1994).

The lighting system

Other greenhouse climatic characteristics are greatly impacted by light intensity. When natural light is lacking or the space is too shadowed, artificial lighting is used (Radojevic et al. 2014). In regions with fewer than 4.5 hours of average daily sunshine, supplemental illumination is most advantageous for commercial greenhouse production (Santosh et al. 2017). Special lamps are utilised to give adequate light for the best possible crop development in the winter and on gloomy days. Effective lighting solutions include LED bulbs, fluorescent lights, tube lamps, metal halide lamps, and heat lamps.

Air humidification

Similar to open greenhouse humidification, closed greenhouse humidification involves heating the area and introducing water vapour (for example, via a fog system). Shelly et al. (1988) divided humidification techniques into three categories: nebulisers, hot water humidifiers, and cold water humidifiers. In cold water humidifiers, the air travels through the reservoir's water. The temperature may either stay the same or simply slightly fluctuate in this situation. A cold-water humidifier's working premise is simple and affordable. With the exception of using a heater to create saturated vapour at the output, hot water humidifiers operate on the same principle as cold water humidifiers. The nebulisers will create a supersaturated mist of water droplets rather than water vapour. This approach creates an aerosol of water droplets by vibrating a plate at an ultrasonic frequency (Vadiee & Martin 2012). In colder climates, steam boilers are often used to provide heat or regulate humidity in greenhouses in addition to fogger systems for cooling and humidity management. Saturated vapour produced by heaters is pushed into the greenhouse. In order to humidify the greenhouse, pulsators are often used for overhead watering.

Dehumidification

Dehumidification is the primary difficulty in controlling the environment of a closed greenhouse as the totally closed greenhouse idea does not allow for ventilation. In a semi-closed greenhouse, however, airflow may serve as a dehumidification system (Vadiee & Martin 2012). Refrigeration and desiccant are the two general categories into which dehumidification may be divided (Hauer et al. 1999). By chilling the air to saturation and then warming it after sufficient moisture has been eliminated, refrigeration-based systems eliminate moisture via a condensation process. Consequently, dehumidification and cooling may usually be done simultaneously. Desiccant systems, on the other hand, directly remove moisture from the air in the vapour phase; this happens without a cooling effect and raises the temperature of the air because of the heat of adsorption, which lowers the humidity content (Harriman et al. 1997).

Automatic greenhouse climate control systems

Greenhouse automation is all about contemporary, accurate, and efficient intensive agriculture that utilises all available natural resources wisely, recycles information within the system, and promises improved quality, production, and returns while being ecologically benign. (Ismail & Shamshiri 2013). Growers can regulate crop productivity and designers may enhance ventilation and heating systems by forecasting the microclimate within a greenhouse. The interior microclimate may be studied via simulation and experimentation. Simulation techniques are faster, less expensive, more flexible, and reproducible than experiments. Crop transpiration and natural ventilation should be included more accurately than in the majority of current models, since this would greatly improve the energy and mass balances. Determining the greenhouse's thermal behaviour was the main goal of early research on the microclimate (Walker 1965). The mean behaviour of a particular element in the greenhouse was described using a number of simple static energy balance models (Jolliet 1991). Static models become less effective as the greenhouse's time response approaches the rates of time change of the boundary conditions. Consequently, a number of dynamic climate models have been developed (Zhang et al. 1997). Numerous physical processes including mass balance and energy transfer contribute to the microclimate's dynamic nature. Crop kind and status, greenhouse construction, external environmental conditions, and the impact of control actuators all have an impact on these processes. The development of temperature control systems has mostly depended on heuristic principles based on farmer experience because to the intrinsic complexity (Kamp and Timmerman, 1996). In recent years, a variety of control strategies have been used to address these issues, such as feed-forward control (Rodrguez 2001), adaptive control (Sigrimis & Rerras 1996), optimum control (Tap et al. 1996), robust control (Moreno et al. 2002), predictive control (Pinon et al. 2002), and so on. A

number of attempts have been made to create sophisticated computerised temperature control systems for greenhouses. Some of the key optimal control approaches suggested (Ioslovich et al. 2009) to employ sophisticated methods like predictive, adaptive, robust, and non-linear control (Castaeda-Miranda et al. 2008) include proportional, integral, and derivative (PID) controllers, artificial intelligence (AI) such as fuzzy logic systems (FLS), artificial neural networks (ANNs), and genetic algorithms (GAs).

Low-cost greenhouse structure for crop microclimate regulation

Among the most used forcing methods in western nations are greenhouses, poly houses, and net houses; however, small and marginal farmers cannot afford these buildings due to their higher cost. Utilising low or poly-tunnel technology is an alternative strategy for protecting plants from freezing temperatures and gaining market share early in the growing season in order to maximise crop yield. Poly-tunnels may be swiftly constructed and disassembled for later usage, which is another benefit of this technique (Kumar et al. 2015). Increased warmth and carbon dioxide trapping made possible by these tunnels improve plant photosynthetic activity and, ultimately, output. Additionally, by shielding the crops from pests and frost and minimising moisture loss, they provide a beneficial microclimate. High-quality crops like tomatoes, cucurbits, and capsicum may be grown with the use of low tunnels (Kumar et al. 2017). They are employed in the early spring to warm the plant's surroundings and give seedlings a head start. In warm weather, it is better to remove these coverings even if they provide air circulation..

Conclusion

A competitive and ever changing area of agriculture worldwide is greenhouse cultivation. All protected constructions' structural and functional elements are significantly impacted by the climate. The present study examined a number of greenhouse microclimate factors and methods for regulating them to satisfy crop needs. Temperature and humidity are the primary factors directly related to plant productivity. Unfortunately, there hasn't been enough study done in different areas to economically regulate and maintain the proper temperature, humidity, and other suitable requirements. However, complete microclimatic and other input control is made possible by cutting-edge technology like microprocessors, data loggers, and automated irrigation and fertigation systems. As a result, researchers must look into different management strategies and reasonably priced greenhouse designs that may be used in different temperature zones with appropriate microclimate regulation.

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