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Abstract

The regulation of greenhouses microclimate is crucial for better plant development and higher yields. Chief microclimate parameters such as solar radiation, temperature, relative humidity, light and CO_2 can be manipulated by various control actions, such as heating, natural or forced ventilation, CO_2 dosing, humidification and dehumidification to provide suitable environmental conditions for all greenhouse crops. However, these modifications require further energy and fuel usage in the production process. Furthermore, greenhouse microclimate can be adversely affected by extreme climatic conditions and, therefore, optimal ambient control is required to perform complex operations involved in energy balancing, including low emissions and reduced cost of production. This paper presents the information on various parameters concerned with greenhouse climate regulation, their controlling methods and their influence on the crops cultivated inside the protected structure.

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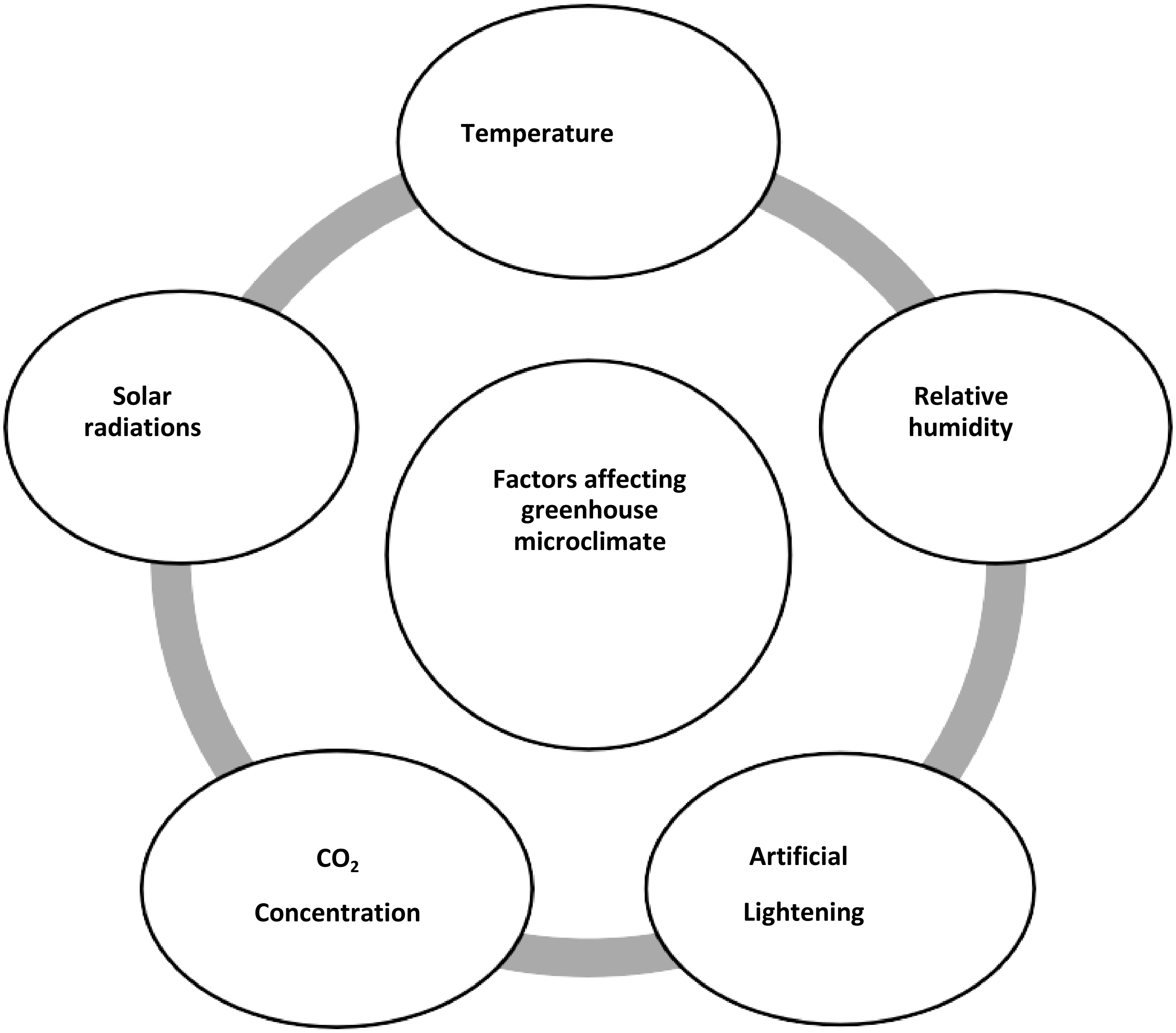
Introduction

Over the last two decades, there has been a surge in global interest in controlled environmental agriculture. People have realised that we need to improve intensive agriculture systems to meet our needs while conserving non-renewable resources during global population growth. Greenhouse agriculture allows the production of food crops outside of the growing season with higher yields than those obtained under the conventional system (Kalbande et al. 2013). Increased crop productivity while keeping a favourable environment for the plants is feasible with protected cultivation. As a result, the greenhouse production of vegetable crops has become more prevalent than in the past. Increasing the quality and quantity of farm harvests means cultivating the variety with good inheritance and supplying an optimal environmental condition. The ideal microclimate requirement differs with the plant variety and the growing stage. Sometimes, the environmental stress that retards the growth but improves the quality is also considered an optimal condition (Hashimoto 1989). Greenhouses are highly sophisticated structures designed to provide perfect conditions for plant growth and production throughout the year. Light, temperature, humidity, carbon dioxide concentration, and air composition should all be given and maintained at ideal levels for growth (Bailey 2002; Shamshiri and Ismail 2013; Santosh et al. 2017) as they all affect the internal environment of a greenhouse. Many studies have looked at the impacts of the greenhouse environment on crop growth, development, and productivity. Crop production is principally determined by plant responses to environmental variables (Ellis et al. 1990), such as temperature, which significantly impacts crop timing and output (Pearson et al. 1995), and light, the principal predictor of crop growth. The light transmission of the cover material affects greenhouse air temperature, humidity, and plant leaf temperature. Microclimate control in greenhouses is one of the priorities because, despite the good genetic properties of crops, improper temperature control, the humidity of the greenhouse, and poor carbon dioxide dosing can result in a significant drop in productivity, even leading to crop loss. The variation in greenhouse microclimate depends on different external and internal factors (Santosh et al. 2017). The external factors include ambient temperature, relative humidity, solar radiation intensity, velocity and direction of the wind, etc. While, internal factors include the greenhouse's geometric dimensions, the position of heating and ventilation system components, soil types, genetic characters, and crop types.

Control of greenhouse microclimate to an optimal level during the cultivation period can increase productivity by several folds. Greenhouses also permit the cultivation of four to five crops each year with a regulated microclimate and efficient use of several inputs such as water, fertiliser, seeds, and pesticides. Different types of protected structures can be installed for high crop production. However, low polyhouse tunnels can be a low-cost solution for creating a favourable microclimate around the crops for marginal farmers by raising the temperature and trapping carbon dioxide, boosting the plants' photosynthetic activity and thus crop output (Kumar et al. 2017). Furthermore, using computers and artificial intelligence, it is possible to automate irrigation, precise application of other inputs, and environmental controls for the acclimatisation of tissue culture plants in advance research programmes and the production of high-value crops in greenhouses.

Microclimate parameters in greenhouses

Plants require certain climatic factors to promote growth through photosynthesis. Therefore, the primary goal of microclimate control in greenhouses is to maximise plant growth and yield (Radojevic et al. 2014). Some of the critical microclimate parameters such as solar radiation, temperature, relative humidity, light and carbon dioxide are detailed in the following sections.



Solar radiations

Plant dry matter production decreases linearly as solar radiation values decrease. Generally, it is not possible to expect efficient dry matter production in higher latitudes during the winter without artificial lighting. The bare minimum of irradiation is required to ensure adequate growth and flowering. Artificial lightening is mainly needed in the case of long duration crops.

Effect of temperature and regulation

The most crucial factor that must be controlled in the greenhouse is temperature. Most plant processes, including photosynthesis, transpiration, respiration, germination, and flowering, are influenced by temperature, and it also regulates transpiration rate via stomatal control. The temperature requirements in a greenhouse are determined mainly by the type of crop to be grown. Temperature parameters such as maximum temperature, minimum temperature, day temperature, and night temperature, as well as the difference between day and night temperatures, must be taken seriously (Jain et al. 2017). Most plants grown in greenhouses are warm-season species adapted to average temperatures ranging from 20 to 30 ^{0}C, with approximate lower and upper-temperature limits of 10 and 35 ^{0}C, respectively. If the optimum minimum outside temperature is below 10 ^{0}C, the greenhouse will need to be heated, and when the optimum maximum outside temperature is less than 27 ^{0}C, ventilation will keep internal temperatures from rising too high during the day; however, if the average maximum temperature rises above 27-28 ^{0}C, artificial cooling will be required (Santosh et al. 2017). Most crops are harmed when the maximum greenhouse temperature exceeds 35 ^{0}C.

Relative humidity

Humidity affects plant development and is directly related to transpiration (Jain et al. 2017). Generally, plants thrive well in relative humidity levels ranging from 60 to 90 %. Extreme humidity (above 95 %) reduces plant transpiration, retard growth and promotes rapid development of fungus diseases, e.g., *Botrytis cinerea*. Reduced humidity levels (below 60%), on the other hand, may cause dehydration, water stress and a negative impact on plant growth (Kittas et al. 2012; Santosh et al. 2017). Ventilation is used to reduce humidity during the day. Humidity rarely has a direct and immediate negative impact on plant growth and is often overlooked as long as diseases do not appear (He & Ma 2010). Humidity control is critical for avoiding adverse effects and achieving a high-quality plant yield as it affects the growth and production of all primary greenhouse vegetables (Bakker 1991).

Light intensity

Plant growth is governed by three light processes: photosynthesis, photomorphogenesis, and photoperiodism. Every change in light has an immediate impact on these processes. Photosynthesis converts carbon dioxide into organic material and then releases oxygen in the presence of light. It is the most critical process, and light is the primary energy source that allows it to occur. Photomorphogenesis is how plants develop in response to different types of light. In contrast, photoperiodism is how the plant responds to different day lengths and whether it will flower or not (Santosh et al. 2017). Light levels are generally sufficient in many parts of India for effective plant production, and artificial lighting is only required for crops that require longer day lengths. Supplemental LED interlighting improved plant morphology and yield by improving fruit weight and dimensions (Paucek et al. 2020). Furthermore, Light quality modulates alternative plant growth mechanisms, and the responses were plant-dependent, implying that the effect of light quality on the plant requires further investigation (Wang et al. 2007).

Carbon dioxide (CO_2)

When a dense crop is growing, the CO_2 concentration inside a greenhouse can drop significantly below the outside level, even if the greenhouse is well ventilated. CO_2

concentration in the greenhouse reaches a peak in the early morning and then begins to fall as a function of ventilation rate to the lowest at noon (Akilli et al. 2000). Productivity declines as CO_2 concentrations limit photosynthesis in most vegetable species. 700–900 mol mol^{-1} appears to be the optimal CO_2 concentration for growth and yield (De Pascale & Maggio 2008; Santosh et al. 2017). CO_2 enrichment is critical for increasing produce quality, and a continuous or periodic increase in CO_2 inside the greenhouse may increase more than 20% in fruit production for both dry and fresh matter (Shanchez-Guerrero et al. 2005). The plant absorbs CO_2 through stomata, so effective CO_2 absorption in a greenhouse is highly dependent on other climate factors affecting the plant's stomata openings.

Tools for microclimate regulation in greenhouse

Control of microclimate can be achieved by using different types of protected structures depending upon the different climatic zones. Climatic parameters like temperature, relative humidity, CO_2 levels, electrical conductivity and soil moisture are controlled inside the greenhouse with the help of different types of equipment (pipe temperature, vents and curtains position) (Santosh et al. 2017) for proper microclimate regulation. Each microclimate parameter determined by crop type and state should be keptat its optimal level.

Ventilation cooling and shading

Ventilation must be considered a year-round process (Kalbande et al. 2013). The main concern for greenhouse climate management in hot climates is minimising the heat load, which can be accomplished by reducing incoming solar radiation and removing excess heat *via* air exchange. A combination of a roof vent, front doors, and fans can provide adequate ventilation in the greenhouse (Radojević et al. 2014). Shade nets and whitewash are the most common existing methods for reducing incoming solar radiation. Greenhouse ventilation effectively removes excess heat through air exchange when the outside air temperature is lower. Evaporative cooling is a popular method for reducing sensible heat load by increasing the latent heat fraction of dissipated energy (Santosh et al. 2017). Other cooling solutions like heat pumps, heat exchangers are available but are not widely used, particularly in India, due to high investment costs (Kittas et al. 2012).

Natural ventilation in the greenhouse

During times of high solar radiation, it is necessary to circulate air from outside to the inside of the greenhouse in a homogeneous manner to remove excess heat. Poor ventilation affects the composition of indoor air, primarily by lowering CO_2 concentrations (Lorenzo et al. 1990). Inadequate ventilation may lead to overheating and excessive transpiration, which causes problems like plant water stress and physiological disorders such as fruit cracking, flower and fruit abortion. Air pressure gradients and wind play a vital role in natural ventilation as air rises near the ceiling when it becomes hotter, and wind blowing over the roof creates a vacuum on the leeward side of the ridge (Shamshiri and

Ismail 2013; Nemali 2021). When the ridge vent is opened, it sucks warm air out of the greenhouse, regulating humidity and temperature build-up and ensuring adequate air exchange. Horizontal airflow fans should not be operated while using natural ventilation as the fans redistribute the hot air accumulated at the top of the greenhouse. Plastic mesh screens should be used to cover the sidewalls and roof vents to keep insects out of the greenhouse. Natural ventilation directly affects the climate inside the greenhouse (Kittas et al. 1996) and is an important consideration when designing. A well-designed ventilation system can improve climate control and reduce energy consumption. Furthermore, ventilation is also related to other factors such as temperature, humidity, and CO_2 concentration, all of which directly impact crop growth and development (Kittas et al. 2005). Natural ventilation efficiency is determined by temperature differences between the outside and inside of the greenhouse, wind speed and direction, greenhouse design, and the presence or absence of crops (Ould- Khaoua et al. 2006). Natural ventilation requires a total ventilator area of 15-30% of the floor area and the effect of additional ventilation area on temperature difference is negligible above 30% (Kittas et al. 2012; Santosh et al. 2017). Sufficient ventilation is critical for optimal plant growth, especially when the outside temperature and solar radiations are high.

Forced ventilation

The basic idea behind forced ventilation is to circulate air throughout the greenhouse and the movement of air caused by inlet and outlet fans assembly (Shamshiri and Ismail 2013). Forced ventilation with fans is the most effective way to ventilate a greenhouse, but it is energy-intensive. Fans are installed to keep the constant greenhouse temperature and humidity level. Fresh air enters from one side of the greenhouse and replaces hot air from the opposite side (Santosh et al. 2017). Exhaust fans should be placed on the leeward side of the greenhouse for effective forced ventilation. If this is not possible, the fan's capacity should be increased by at least 10%. For proper forced ventilation to occur, a clear space equal to 4 to 5 times the fan diameter must be maintained in front of the fans and fans should not be more than 25 feet apart (Nemali 2021). In a greenhouse with a crop, the airspeed should not exceed 0.5 ms^{-1}. When the fans are not in use, the openings must close automatically (Santosh et al. 2017).

Shade covers

Due to high temperatures, one of the primary tasks for greenhouses constructed in India is to reduce air temperature. In greenhouses, direct solar radiation is the primary source of heat gain. The use of shading or reflection techniques can be used to control the entry of unwanted radiation. Shading can be achieved through a variety of means, including the application of paints, external shade cloths, nets of various colours, partially reflective shade screens, and water film over the roof and liquid foams between the greenhouse walls (Kittas et al. 2012; Santosh et al. 2017). Shading may affect plant development and photosynthesis because of the reduction in light and the potential effect on ventilation rates. As a result, when deciding on the type of shading and associated control strategies, caution must be exercised. Shade nets contribute to increased production and positively affect the quality and uniformity of the produce (Briassoulis et al. 2007) and are more effective in hot, sunny climates (Al-Helal & Abdel-Ghany 2010). A wide range of plastic nets with varying optical properties are now available on the market. Producers can use various shade nets with special optical properties to change the composition of the transmitted solar radiation in the greenhouse, thereby improving crop performance (Oren-Shamir et al. 2001). According to Robledo & Martin (1981) the colour and transparency of the covering materials affect absorption, reflection, and transmission of short and long-wave radiations. Coloured shade nets in protected crops stimulate specific morphological and physiological reactions, improving produce quality (Shahak et al. 2002). The plant's response to light intensity and quality is vital in greenhouse production, where shade nets reduce the radiation load inside the greenhouse. A significant reduction in solar radiation is expected to slow the rate of leaf transpiration, raising the canopy temperature (Jakson et al. 1981).

Evaporative cooling

Evaporative cooling systems for greenhouses have been developed to prevent overheating in hot weather by controlling relative humidity and temperature (Montero 2006). In hot climates, greenhouse cultivation is characterized by high solar thermal load, which causes major problems inside the greenhouse environment and limits plant growth (Misra & Ghosh 2018). The use of evaporative cooling systems, which are based on the conversion of sensible heat into latent heat (Montero 2006) via evaporation of water supplied directly (mist or fog system, sprinklers) into the greenhouse atmosphere or through evaporative pads or wet pads, is one of the most efficient solutions for alleviating climatic conditions. The fogging system works by spraying water as tiny droplets at high pressure into the air above the plants to increase the water surface in contact with the air. The droplets' freefall velocity is slow, and the air streams inside the greenhouse easily carry them, resulting in high water evaporation efficiency while keeping the foliage dry. A wide range of fogging systems is available, which are used to increase relative humidity while cooling the greenhouse. In horticulture, the fan-and-pad cooling system is most commonly used (Kittas et al. 2012). Still, the advantage of fogging systems over wet pad systems is that they provide uniform conditions throughout the greenhouse, eliminating the need for forced ventilation and an airtight enclosure (Baeza et al. 2008; Shamshiri & Ismail 2013). The disadvantages are that it is an expensive installation with high operating costs, such as freshwater supply, electricity, and maintenance (Santosh et al. 2017). Furthermore, evaporative roof cooling entails spraying water onto a roof's external surface, resulting in a thin water layer on the surface. This reduces solar radiation transmissivity to the greenhouse and increases evaporation rate, lowering water temperature and closely surrounding air temperature and performs best in hot and dry climate zones.

Greenhouse heating

The heating system must be carefully planned and designed to provide uniform temperature distribution throughout the greenhouse. The type of heating system required is determined by the crops to be grown and the glazing material used (Kalbande *et al*. 2013). Greenhouse heating is mandatory in cold regions of the country, and heating costs significantly impact greenhouse production and profitability. To meet the heating and cooling needs of modern greenhouses, various heating systems are used (Ozgener & Hepbasli 2005). The unit heater system is the most common and least expensive. Warm air is blown from unit heaters with self-contained fireboxes in this system and is strategically placed throughout the greenhouse, with each heating system covering floor areas ranging from 180 to 500 m^2 (Kittas et al. 2012; Santosh et al. 2017). Unit heaters should be inspected every year to ensure their good working order. The most suitable time for maintenance is before the start of the heating season. The blower, fuel lines, valves, and exhaust vent are all components that should be inspected (Nemali 2021). Unlike unit heater systems, a portion of the heat from central boiler systems is delivered to the crop's root and crown zone, increasing crop growth and disease control. Perimeter wall heating with the help of wall pipe coils can provide some additional heat needed while also contributing to a more uniform thermal environment in the greenhouse. Heat loss through the roofs and gables is supplied by overhead pipes coils running the length of the greenhouse. These coils are located above the plants, not the most desirable heat source. The roots of the plants are heated more effectively by placing the heating pipes near the base of the plants (In bed-pipe coils) than the overhead coil system, which causes proper air movement and reduces humidity around the plant (Kittas et al. 2012; Santosh et al. 2017). Pipe/Rail heating is another heating system that maintains uniform temperatures and positively affects plant microclimate. These systems are appropriate for vegetable production systems.

Heating for anti-frost protection

Heating was used in these greenhouses to protect crops from freezing. It is also used to keep greenhouse air temperatures above critical thresholds for condensation control (Santosh et al. 2017). As a result, these greenhouses do not have large and complicated heating systems.

Solar radiation filtration

Global solar radiation entering a greenhouse is made up of three types of radiation: ultraviolet radiation (UV), photosynthetic active radiation (PAR), and near-infrared radiation (NIR). The Earth's atmosphere absorbs the majority of UV radiation. Excessive UV exposure of plants can cause the photosynthetic process to degrade. According to the above spectra, only the PAR component of the incoming radiation is absorbed by greenhouse plants and is essential for their growth and photosynthesis. This means that specific manipulations of the radiation entering the greenhouse interior space can benefit (Von Elsner et al. 2000; Lamnatou & Chemisana 2013). NIR is absorbed less by the plant and more by the greenhouse structure and equipment, increasing greenhouse ambient temperature. The greenhouse is cooled by changing the cover materials. NIR filtering can also be accomplished by using specific plastic cellophane, moveable screens, or NIR filtering shading paint.

CO_2 enrichment

Many studies have found that CO_2 enrichment systems positively affect plant growth by improving photosynthesis. The purest form of CO_2 enrichment is pure liquid CO_2 pumping from containers to the greenhouse via a pipeline network, similar to the fertigation system. Special gauges are installed on distribution pipes to measure CO_2 concentrations to detect potential gas hazards. The high cost of transporting gas containers is a disadvantage of this system. The combustion of fuel, such as liquid kerosene, propane-butane gas, or natural gas, emits CO_2 as part of the gas emissions from the burners. This type of operation generates heat, which is frequently the primary reason for the installation. The limitation of these systems is that CO_2 can only be dosed in the greenhouse when heat is also required. The type of fuel chosen is determined by availability, cost per unit, and the purity of the gas emissions. Dosing will be precisely controlled in greenhouses based on light levels, temperature, and ventilation to ensure maximum efficiency. However, some authors recommend supplying CO_2 even when ventilation is operating (Nederhoff 1994) to maintain the same CO_2 concentration in the greenhouse as outside and enriching to levels of about 700–800 mol mol^{-1} during the periods when the greenhouse is kept closed, usually in the early morning and late afternoon (Kittas et al. 2012).

The lighting system

The intensity of light significantly impacts other climate parameters in the greenhouse. Artificial lighting is used in the absence of natural light or when the area is overly shaded (Radojevic et al. 2014). Supplemental lighting is most beneficial for commercial greenhouse production in areas with less than 4.5 hours of average daily sunlight (Santosh et al. 2017). During the winter and on cloudy days, special lamps are used to provide enough light for optimum crop growth. LED bulbs, fluorescent lights, tube lamps, metal halide lamps, and heat lamps are examples of effective lighting systems.

Air humidification

Closed greenhouse humidification will be similar to open greenhouse humidification, i.e., a combination of heating and adding water vapour to the space (e.g., a fog system). Shelly et al. (1988) classified humidification methods into cold water humidifiers, hot water humidifiers, and nebulisers. The air in cold water humidifiers passes through the water in the reservoir. In this case, the temperature can remain constant or change only slightly. The principle of a cold-water humidifier is inexpensive and straightforward. Hot water humidifiers also follow the same principle as that of cold-water humidifiers, with the exception that hot water humidifiers use a heater to produce saturated vapour at the outlet. Instead of water vapour, the nebulisers will produce a supersaturated mist of water droplets. A plate oscillating at an ultrasonic frequency generates an aerosol of water droplets in this method (Vadiee & Martin 2012). Aside from fogger system installations for cooling and humidity control, steam boilers are frequently used in colder regions to provide heat or control humidity in greenhouses. Heaters generate saturated vapour, which is pumped into the greenhouse. Pulsators are commonly used for overhead irrigation, serving to humidify the greenhouse.

Dehumidification

The main challenge in closed greenhouse climate control is dehumidification because ventilation cannot be used in the fully closed greenhouse concept. However, ventilation can be used as a dehumidification system in a semi-closed greenhouse (Vadiee & Martin 2012). Dehumidification can be broadly classified into two methods: refrigeration and desiccant (Hauer et al. 1999). Refrigeration- based systems remove moisture in a condensation mechanism by cooling the air to saturation and then reheating it after enough moisture has been removed. As a result, in most cases, dehumidification and cooling can be performed concurrently. On the other hand, Desiccant systems directly extract moisture from the air in the vapour phase; this occurs without a cooling effect and results in the air with a higher temperature due to heat of adsorption, resulting in lower humidity content (Harriman et al. 1997).

Automatic greenhouse climate control systems

Greenhouse automation is all about efficient, accurate, and modern intensive agriculture that judiciously uses all available natural resources recycles information within the system and claims higher productivity, returns, and better quality while remaining environmentally friendly. (Shamshiri & Ismail 2013). Predicting the microclimate inside a greenhouse can assist growers in crop production management, and designers improve ventilation and heating systems. Experimentation and simulation can be used to investigate the internal microclimate. Compared to experiments, simulation methods can be completed more quickly, at a lower cost, and in a more flexible and repeatable manner. Natural ventilation and crop transpiration should be included more realistically than in most existing models and would significantly contribute to the energy and mass balances. Early studies of the greenhouse microclimate focused on determining the greenhouse's thermal behaviour (Walker 1965). Several basic static energy balance models were used to characterise the mean behaviour of a specific element in the greenhouse (Jolliet 1991). When the time response of the greenhouse becomes comparable to the rates of time change of the boundary conditions, the usefulness of static models decreases. As a result, several dynamic climate models have been created (Zhang et al. 1997). The dynamic behaviour of the microclimate is the result of many physical processes involving energy transfer and mass balance. These processes are affected by the external environmental conditions, greenhouse structure, crop type and state, and the effect of the control actuators. Because of the inherent complexity, the development of climate control systems has primarily relied on heuristic rules based on grower experience (Kamp and Timmerman, 1996). Various control techniques have been used to solve such problems in recent years, including feed-forward control (Rodrguez 2001), adaptive control (Sigrimis & Rerras 1996), optimal control (Tap et al. 1996), robust control (Moreno et al. 2002), predictive control (Pinon et al. 2002), and so on. Several efforts have been made to develop advanced computerised greenhouse climate control systems. Proportional, integral and derivative (PID) controllers, artificial intelligence (AI) such as fuzzy logic systems (FLS), artificial neural networks (ANNs), and genetic algorithms (GAs) are some of the crucial optimal control approaches proposed (Ioslovich et al. 2009) to use advanced techniques such as predictive, adaptive, robust, and non-linear control (Castaeda-Miranda et al. 2008).

Low-cost greenhouse structure for crop microclimate regulation

Greenhouses, poly houses, and net houses are among the most popular forcing techniques in western countries; however, these structures are more expensive and out of reach for small and marginal farmers. A different method is to use low or poly-tunnel technology to protect plants from cold temperatures and capture the market early in the season to get a good return on crop produce. Another advantage of this technology is that poly-tunnels can be quickly erected and dismantled for future use (Kumar et al. 2015). These tunnels allow for an increase in temperature and carbon dioxide trapping, which boosts plant photosynthetic activity and consequently yield. In addition, they create a favourable microclimate around the crops by protecting them from frost and pests and reducing moisture loss. Low tunnels help in growing high-quality crops such as tomatoes, cucurbits, and capsicum (Kumar et al. 2017). They are used in the early spring to help seedlings get a head start and warm the plant's environment. Although these covers allow air circulation, it is best to remove them in warm weather.

Conclusion

Greenhouse cultivation is a steadily evolving and competitive sector of agriculture in the world. Climate is a principal factor affecting the structural and functional aspects of all protected structures. The current paper reviewed various greenhouse microclimate parameters and strategies for controlling them to meet the crop requirements. The main variables directly linked to plant production are temperature and humidity. Unfortunately, research in various regions has not been sufficient to control and maintain the desired temperature, humidity, and other reasonable parameters through economic means. However, advanced technologies such as microprocessors, data loggers, and automated irrigation and fertigation systems enable total microclimatic and other input control. Therefore, researchers need to investigate various control methods and affordable designs of greenhouses that can be used in various climatic zones with proper microclimate regulation.

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