

In cold periods, a variety of heating systems are required to maintain the optimal temperature: hot water pipes and air furnaces are traditional ways to heat greenhouses, while geothermal and air source heat pumps are energy-saving alternatives. Using water heated by heat pumps (air or geothermal) to heat the substrate can keep the root zone temperature stable at around 18.4 °C throughout the year, increasing yield by 21% to 36% compared to the control group. Geothermal systems can especially reduce electricity consumption and enhance production sustainability (Jo and Shin, 2022; Moritani et al., 2023). In winter cultivation, using positive temperature coefficient films to heat the root zone can accelerate flower bud germination, increase fruit yield and improve quality (Jo and Shin, 2022).

In warm climates or when solar radiation is strong, efficient cooling is also critical: natural ventilation and forced exhaust fans are commonly used to exhaust hot air to maintain a suitable temperature; evaporative cooling systems can further reduce greenhouse temperatures, especially in areas with higher ambient temperatures (Yin et al., 2023; Lei, 2024). Smart greenhouse systems integrate sensors and automatic control functions to dynamically adjust cooling (and heating) measures based on real-time temperature data to achieve dual optimization of plant growth and resource utilization (Mubarakah et al., 2023 ; Tarigan, 2023; Lei, 2024).

3.2 Light and photoperiod management

When natural sunlight is inadequate, artificial lighting becomes essential for quality strawberry production. LED systems now outperform traditional lights due to their adjustable spectra, energy savings, and durability, making them ideal for modern growing facilities. Evidence shows using LED lights at 132~235 $\mu\text{mol}/\text{m}^2/\text{s}$ intensity for 16 hours daily can boost yields over 30% while improving water efficiency and fruit traits (Hidaka et al., 2015; Park et al., 2023; Kaur et al., 2024).

Compared with traditional high-intensity discharge lamps (HID), LED systems have obvious advantages in light quality control and energy saving and consumption reduction (Hidaka et al., 2015; Guiamba et al., 2022; Tang et al., 2023). In addition, when supplementary lighting measures are combined with carbon dioxide concentration management, the yield of strawberries can be increased by more than 50%, and the soluble solids content of the fruit is also increased simultaneously, showing the significance of the synergistic effect (Qiu et al., 2023).

Light environment optimization technology also includes shading regulation and spectrum management. The use of new shading materials such as OPV components can accurately adjust the photosynthetically active radiation (PAR), which can ensure normal fruit development and promote the accumulation of soluble solids within the light intensity range of 387-437 $\mu\text{mol}/\text{m}^2/\text{s}$ (Tang et al., 2020). Specific light quality ratios have a significant regulatory effect on the growth and development of strawberries: a 7:3 ratio of red to blue light can promote plant morphology and yield formation; while blue light and far-red light affect flowering time and stolonogenesis by regulating the expression of photosensitive pigment-related genes (Díaz-Galián et al., 2020; Guiamba et al., 2022; Prisca et al., 2022; Yang et al., 2024). Spectral regulation can also activate secondary metabolic pathways and significantly increase the content of functional components and antioxidant activity in fruits (Díaz-Galián et al., 2020; Warner et al., 2021).

3.3 Humidity and CO₂ regulation

Maintaining a relative humidity range of 60%-80% is most beneficial to the growth and development of strawberries. This range can not only ensure normal transpiration, but also effectively reduce the risk of disease. Greenhouse cultivation practice shows that 65%-75% relative humidity is the best control range: too high humidity will inhibit transpiration and assimilate transport, and too low humidity will lead to water stress, both of which are not conducive to plant growth and fruit quality improvement (Miyoshi et al., 2023; Kaur et al., 2024).

Carbon dioxide application technology has shown significant advantages in improving the photosynthetic efficiency of strawberries, and has become an important means of high and stable yields in greenhouse cultivation. Relevant studies have shown that by artificially increasing the carbon dioxide concentration in the greenhouse, the strawberry yield can be increased by more than 23%, and when this technology is used in conjunction with