complex quantitative traits based on genome-wide markers; and CRISPR/Cas gene-editing technology enables precise modification of key functional genes. Currently, systematic gene and QTL databases, developed diagnostic markers, and continuously expanding functional gene studies are building molecular tool systems for pyramiding superior alleles associated with fruit size, organ size, parthenocarpy, continuous fruiting ability, and stress resistance. In the future, integrated "pan-omics" platforms combining genomics, transcriptomics, proteomics, metabolomics, phenomics, machine learning, and gene editing will become an important direction for accelerating high-yield and stable-yield cucumber breeding (Roychowdhury et al., 2023).

6 Effects of Cultivation Techniques on Yield Formation

6.1 Environmental regulation in protected cultivation

Protected cultivation is an important production system for achieving high and stable cucumber yield. Its core advantage lies in the artificial regulation of key environmental factors, including temperature, light, humidity, CO_2 concentration, and root-zone conditions, thereby creating relatively suitable ecological conditions for vegetative growth, reproductive development, and fruit enlargement. Cucumber is a thermophilic crop; low temperatures inhibit root vigor, nutrient uptake, and photosynthetic metabolism, whereas high temperatures can reduce pollen viability, decrease fruit set rate, hinder fruit development, and accelerate plant senescence. Therefore, in protected cultivation systems, maintaining appropriate day and night temperatures through ventilation, shading, covering, heating, cooling, and misting is an important basis for sustaining continuous fruiting and high yield formation. Comparative studies of commercial greenhouses have shown that optimized heating, cooling, and semi-hydroponic systems can significantly increase winter cucumber yield per plant and improve chlorophyll fluorescence parameters, indicating that low-stress and near-optimal environments are beneficial for maintaining high photosynthetic activity and productivity. Microclimate monitoring in polyethylene greenhouses has also demonstrated that appropriate natural ventilation and mist cooling can effectively reduce greenhouse temperature and maintain cucumber growth within a more suitable temperature range.

Light conditions are another key limiting factor affecting yield formation in protected cucumber cultivation. During winter and spring greenhouse production, insufficient natural light often leads to excessive stem elongation, reduced leaf functionality, inadequate female flower differentiation, and slow fruit enlargement. Therefore, optimizing canopy structure, implementing proper pruning practices, supplementary lighting, and spectral regulation are important measures for improving light energy utilization efficiency in protected cucumber populations. Different covering materials and light-conversion films can influence photosynthesis and yield performance by altering greenhouse spectral composition, temperature, and vapor pressure deficit (VPD). Near-infrared reflective plastic films can reduce greenhouse temperature and VPD, enhance photosynthetic rate and transpiration, and improve fruit characteristics and yield. Red-orange light-enhancing films (RPO) can increase photosynthetically active radiation, promote cucumber yield and nutritional quality, and simultaneously affect auxin content and related gene expression in the fruit pedicel (Li et al., 2024). These studies indicate that greenhouse covering materials and light-environment regulation not only affect source strength formation but also further influence fruit set and fruit development processes.

With the development of intelligent protected agriculture, environmental regulation technologies based on sensors, crop models, and machine learning have gradually been applied in cucumber production. Yield prediction and greenhouse microclimate modeling studies have shown that total radiation and air temperature are important environmental factors determining weekly greenhouse cucumber yield (Hong et al., 2024). Integrating light intensity, temperature, and CO_2 concentration with photosynthetic response models can dynamically optimize light saturation points, photosynthetic rates, and environmental control strategies, thereby improving production stability under different climatic and radiation conditions (Bello et al., 2023). Therefore, environmental regulation in protected cucumber cultivation is transitioning from experience-based management to model-driven and intelligent decision-making systems, with the goal not merely of optimizing individual environmental factors but of achieving coordinated optimization of temperature, light, gas exchange, water, and nutrient conditions.