experiments have shown that under natural light conditions, moderately reducing planting density does not reduce weekly or total yield per unit area but instead increases yield per plant, dry matter allocation to fruits, and nutritional quality while reducing nitrite content. However, in recirculating hydroponic systems with sufficient water and nutrient supply, higher planting density combined with double-stem pruning significantly increases total and marketable yield, indicating that the optimal density is not fixed but depends on greenhouse environment, cultivar type, and resource availability (Babatunde et al., 2023).

Pruning and vine training are important techniques for regulating canopy structure and assimilate allocation in protected cucumber cultivation. Appropriate pruning reduces the consumption of nonproductive branches and leaves, improves ventilation and light penetration, and promotes assimilate allocation to fruits. Greenhouse studies comparing different planting densities and pruning methods have shown that higher density and double-stem pruning increase total and marketable yield but reduce fruit diameter, reflecting the trade-off between fruit number and fruit size. Comparative studies of single-stem pruning and natural growth in different cucumber cultivars have also demonstrated that both cultivar type and pruning method significantly influence plant height, leaf area, biomass allocation, and production performance. Single-stem pruning promotes biomass allocation to reproductive organs and alters root-to-shoot ratio and tissue water content (Cheng et al., 2025). Therefore, pruning strategies should be optimized according to cultivar vigor, target yield, fruit size requirements, and cultivation environment rather than simply maximizing branch number or fruit number.

Row spacing configuration and spatial arrangement also affect cucumber canopy light environment, water and fertilizer supply efficiency, and convenience of field management. In solar greenhouses, wide-narrow row configurations combined with drip irrigation lines arranged in narrow rows while wide rows serve as operation channels can improve ventilation and light conditions in the middle and lower canopy while simultaneously accommodating efficient water and fertilizer supply and field management requirements (Wang et al., 2025). In addition, emerging cultivation systems such as substrate cultivation, soilless cultivation, vertical cultivation, and recirculating hydroponics can improve root-zone conditions and enhance land-use and resource-use efficiency, representing important directions for green and efficient cucumber production in protected cultivation systems. Overall, the core objective of cultivation pattern optimization is not to identify a single optimal parameter but to establish integrated cultivation schemes based on cultivar characteristics, greenhouse type, light and temperature conditions, water and fertilizer supply, and market demand in order to achieve coordinated improvement of high yield, superior quality, stable production, and efficient resource utilization.

7 Existing Problems and Future Development Trends

7.1 Current problems in research

Although significant progress has been made in recent years regarding cucumber yield-related traits and their formation mechanisms, the dissection of complex quantitative traits still faces considerable challenges. Cucumber yield is jointly influenced by multiple genes, regulatory networks, environmental factors, and genotype-by-environment interactions, exhibiting characteristics of polygenic control, small genetic effects, and strong environmental sensitivity. Numerous QTLs and functional genes have been reported, including 81 simply inherited genes or major-effect QTLs and 322 QTLs associated with 42 traits; however, these data remain fragmented, and QTL nomenclature systems, cross-population comparisons, and integration standards have not yet been unified. Only a limited number of loci have been successfully cloned, functionally validated, and widely applied in breeding practice. In addition, many identified QTLs explain only a small proportion of phenotypic variation, and insufficient attention has been paid to QTL-by-environment interactions, limiting the application of stable high-yield traits across different ecological regions and cultivation systems.

Insufficient exploitation and utilization of cucumber germplasm resources also represent important constraints on yield improvement. Although large numbers of landraces, wild relatives, and breeding materials are conserved worldwide, practical breeding still faces problems such as inadequate mining of superior alleles, narrow genetic backgrounds of parental lines, and repeated use of core germplasm. Long-term directional selection has promoted improvements in fruit quality, maturity, and adaptation to protected cultivation, but it may also reduce genetic