using SLAF-seq technology have further improved QTL mapping resolution, and some major-effect loci can explain a relatively large proportion of phenotypic variation, thereby providing important foundations for candidate gene mining and marker-assisted selection. However, because of strong interactions among populations, environments, and cultivation conditions, some QTLs still exhibit environmental dependency and insufficient stability.

In addition to SNPs and InDels, structural variation and pan-genome studies have further revealed the deeper genetic basis underlying complex cucumber yield traits. Pan-genome analyses have identified large numbers of structural variations in cucumber, some of which are closely associated with important agronomic traits such as flowering time, fruit surface characteristics, and root development. Large chromosomal rearrangements and structural variations can directly influence the expression of key genes and may also regulate multiple yield components through linkage effects and pleiotropy. To date, numerous functional genes and QTLs related to fruit size, fruit number, and flowering time have been identified in cucumber, and molecular marker systems applicable to breeding are gradually being established. At the same time, advances in transcriptomics, metabolomics, and functional genomics, as well as the application of genetic transformation and CRISPR/Cas gene-editing technologies, have provided new technical approaches for elucidating the mechanisms underlying high-yield formation and for the targeted improvement of key yield traits in cucumber.

4 Physiological Mechanisms of Cucumber Yield Formation

4.1 Photosynthesis and assimilate accumulation

Cucumber yield formation is highly dependent on leaf photosynthetic carbon assimilation capacity and the efficiency of assimilate allocation to fruits. Through photosynthesis, leaves fix CO_2 and synthesize carbohydrates, thereby providing the material and energy sources required for vine growth, root development, female flower formation, and fruit enlargement. Therefore, photosynthesis constitutes the core physiological basis for dry matter accumulation and yield formation in cucumber. Studies have shown that increasing the activity of enzymes related to photosynthetic carbon metabolism can significantly enhance net photosynthetic rate and biomass accumulation in cucumber, indicating that improving photosynthetic biochemical capacity is an important approach for promoting greenhouse cucumber growth and increasing yield. In addition, cucumber fruit is a typical strong “sink” organ, and its continuous enlargement process is highly dependent on assimilate supply. Therefore, high-yield formation depends not only on the photosynthetic capacity of source organs but also on the competitive strength of sink organs and the coordination between source and sink.

The transport and distribution of assimilates in cucumber exhibit typical “source-sink-flow” regulatory characteristics. Functional leaves serve as the major “source” organs, fruits act as the primary “sink” organs, and phloem transport constitutes the pathway for assimilate translocation. Previous studies have demonstrated that cucumber fruit growth dynamics are closely related to assimilate supply capacity and sink activity, while temporary assimilate storage and redistribution can partially buffer imbalances between source and sink relationships. When vegetative and reproductive growth remain coordinated, assimilates are preferentially transported to fruits, thereby promoting fruit set and fruit enlargement. In contrast, excessive vegetative growth, premature leaf senescence, or reduced root vigor decreases assimilate transport efficiency, ultimately restricting fruit development and reducing yield. Therefore, maintaining balanced source-sink relationships is an important physiological basis for achieving high cucumber yield.

Environmental conditions can significantly influence photosynthesis and assimilate accumulation in cucumber. Increasing CO_2 concentration enhances carbon assimilation capacity, increases soluble sugar content, carbon-to-nitrogen ratio, and fruit dry matter accumulation, and promotes greater assimilate allocation to fruits, thereby improving fruit weight and yield. Root-zone temperature and nitrogen supply further affect photosynthetic acclimation and carbon-nitrogen balance. Increasing root-zone temperature and coordinating NO_3^- supply can alleviate photosynthetic inhibition under elevated CO_2 conditions and improve leaf nitrogen content and photosynthetic efficiency. In addition, canopy structure and light environment are important factors influencing canopy light-use efficiency. Under low-light conditions in winter, appropriate leaf area and supplemental lighting