breeding and ideal plant architecture selection in cucumber (Negi et al., 2025). Previous studies have shown that traits such as vine length, branching ability, and leaf area contribute substantially in principal component analysis and cluster analysis and are important agronomic indicators for distinguishing different cucumber germplasm resources.

The vegetative growth process essentially reflects the plant's capacity to establish source-sink relationships and directly influences assimilate accumulation, transport, and subsequent fruit formation. In general, plants with strong vegetative vigor usually possess larger functional leaf areas and higher photosynthetic efficiency, thereby providing sufficient assimilates for female flower differentiation, fruit set, and fruit enlargement. Correlation and path coefficient analyses have demonstrated that traits such as vine length, leaf area, branch number, and leaf number are significantly positively correlated with yield per plant and yield per unit area and may indirectly promote yield formation by increasing fruit number and single fruit weight (Patidar et al., 2024; Lnu et al., 2025; Negi et al., 2025). However, excessive vegetative growth may also lead to excessive vine elongation, canopy overcrowding, and imbalance between vegetative and reproductive growth, thereby reducing fruit set rate and yield stability during later developmental stages.

Leaves and roots are the two core organs affecting vegetative growth efficiency in cucumber. Leaves serve as the primary site of photosynthesis, and their size, chlorophyll content, and photosynthetic rate directly determine canopy light-use efficiency and dry matter accumulation capacity. Roots influence sustained plant growth and stress adaptability by regulating water and mineral nutrient uptake. Under protected cultivation conditions, root vigor is closely associated with continuous fruiting ability, and well-developed root systems enhance tolerance to stresses such as drought, salinity, and high temperature. Therefore, coordinating aboveground canopy development with belowground root growth and maintaining balanced source-sink relationships are important physiological foundations for achieving high and stable cucumber yields.

2.2 Reproductive growth traits

Cucumber is a typical monoecious crop with separate male and female flowers, and its reproductive growth process is most directly associated with yield formation. Reproductive growth-related traits mainly include flowering time, node position of the first female flower, female-to-male flower ratio, number of female flowers, fruit set rate, fruit number, fruit length, fruit diameter, and single fruit weight. Among these traits, flowering time and first harvest time vary significantly among cucumber materials and exhibit moderate to high heritability in some studies, indicating considerable potential for improving early yield through selection for earliness (Negi et al., 2025). Studies have shown that total yield is negatively correlated with the periods from seedling emergence to flowering and from seedling emergence to fruiting, suggesting that earlier transition into the reproductive stage is beneficial for increasing cucumber yield (Serhiienko et al., 2025).

The capacity for female flower formation and fruit set are key determinants of cucumber fruiting potential. Generally, plants with a higher proportion of female flowers and lower node positions of the first female flower tend to exhibit stronger early fruiting ability. In modern cucumber breeding, gynoecious lines and parthenocarpic materials have been widely utilized in the development of high-yield hybrids. Gynoecious lines can significantly increase the number of female flowers, whereas parthenocarpic materials are capable of setting fruit without pollination, thereby improving yield stability under protected cultivation conditions (Dey et al., 2023; Kaur et al., 2024; Lnu et al., 2025). The genetic mechanisms underlying these traits are relatively complex, involving additive effects, dominant effects, and epistatic interactions among multiple genes. Therefore, integrated improvement strategies combining heterosis utilization and marker-assisted selection are generally required in breeding practice.

Fruit development traits constitute the core components of cucumber yield. Numerous studies have demonstrated that fruit number, fruit length, fruit diameter, and average single fruit weight are key determinants of yield per plant and yield per unit area (Patidar et al., 2024; Negi et al., 2025). These traits generally exhibit high phenotypic variation coefficients, heritability, and genetic advance, indicating substantial selection potential (Table 1) (Lnu et al., 2025). Meanwhile, plant hormones such as ethylene, auxin, and gibberellins play important regulatory roles in sex expression, fruit set, and fruit enlargement in cucumber. The elucidation of related functional genes and