In addition, canopy structure and ecological regulation further influence photosynthetic efficiency and dry matter production. Populations with more erect leaves, uniform canopy distribution, and good ventilation and light penetration typically exhibit higher canopy photosynthetic efficiency and biomass production (Mehdi et al., 2024). Water and nitrogen are key environmental factors affecting this process: adequate supply supports leaf area development and photosynthetic activity, whereas severe drought or nitrogen deficiency significantly suppresses photosynthetic efficiency, stalk formation, and yield (Mehdi et al., 2024). Under certain maturation stages, moderate stress may promote carbon allocation toward stem sugar storage, but excessive stress can simultaneously reduce biomass and sugar accumulation. Therefore, sustained high photosynthetic capacity, stable dry matter accumulation, and proper ecological regulation are essential prerequisites for achieving high yield and high sugar content in sugarcane.

3.2 Role of source-sink relationships and assimilate partitioning in sugar accumulation

Sugar accumulation in sugarcane is regulated by a typical source-sink relationship. Leaves act as the primary source, fixing CO_2 and synthesizing carbohydrates, while the stem serves as the main sink, particularly mature internodes that accumulate high concentrations of sucrose (Önder et al., 2025). Therefore, the capacity of source assimilation, phloem transport efficiency, unloading mechanisms, and sink storage capacity collectively determine sugar accumulation. High sugar accumulation in sugarcane is not merely the result of increased sugar production in leaves, but rather the coordinated balance between source supply and sink demand.

This source-sink relationship varies significantly across developmental stages. During early growth, leaves and young stems function mainly as growth sinks, and assimilates are primarily used for cell division, organ formation, and structural dry matter production. As internodes elongate and mature, stem sink strength increases, and mature internodes become the main carbon sinks where sucrose is extensively accumulated. Strong sink capacity allows continuous uptake and storage of sucrose from leaves, enhancing sugar content. Conversely, if transport or unloading is limited, sugars may accumulate in leaves and feedback-inhibit photosynthesis, reducing overall productivity. Thus, high photosynthetic capacity does not automatically translate into high sugar yield; the key lies in whether the sink has sufficient pull strength.

At the molecular level, source-sink coordination is finely regulated by sucrose transport, unloading, and metabolic pathways. Key enzymes such as SPS, SuSy, and various invertases determine whether sucrose entering the stem is directly stored, degraded for respiration and growth, or converted into structural carbohydrates. High-sugar genotypes typically exhibit higher SPS activity and lower acid invertase activity during maturation, favoring sucrose storage. In contrast, high-biomass genotypes often show higher SuSy and invertase activities, supporting rapid growth and cell wall synthesis but potentially reducing sugar concentration per unit fresh weight (Martins et al., 2024). Therefore, assimilate partitioning efficiency is the key link between biomass formation and sugar accumulation. If early growth prioritizes population establishment and stem elongation, followed by a gradual shift toward sugar storage in later stages, it is possible to enhance sugar accumulation without significantly compromising biomass, thereby achieving coordinated high yield and high sugar content.

3.3 Effects of hormonal regulation and stress responses on high yield and high sugar formation

Plant hormones are key integrators regulating sugarcane growth, maturation, stress adaptation, and carbon allocation. Hormones such as indole-3-acetic acid (IAA), gibberellins (GA), and cytokinins (CK) are primarily involved in stem elongation, cell division, tillering, and maintenance of leaf function, thereby influencing population structure, biomass accumulation, and sustained photosynthetic capacity (Ain et al., 2024; Lu et al., 2025). Appropriate levels of GA promote internode elongation, while IAA and CK support organ development and functional leaf maintenance, collectively forming the physiological basis for high yield. However, optimal performance depends not on the increase of a single hormone, but on the balance among different hormones and their coordination with metabolic networks (Lu et al., 2025).

Hormones closely related to maturation and carbon metabolism, such as abscisic acid (ABA), ethylene, and jasmonic acid (JA), play critical roles in sugar accumulation and stress responses. ABA is involved in maturation induction, sugar metabolism regulation, and stress signaling integration, and can promote assimilate transport to