quality (Manzoor et al., 2023). In addition, fertilizer source, placement, and timing are important factors, and synchronizing nutrient supply with crop demand can significantly enhance nutrient use efficiency. Overall, stage-specific and precise water and nutrient management-promoting biomass accumulation in early stages and moderately restricting water and nitrogen in later stages-can redirect carbon flow toward sucrose storage and achieve coordinated improvement of yield and sugar content.

7.2 Effects of planting density and population structure on yield and quality

Planting density and spatial configuration influence sugarcane yield and quality by regulating canopy structure and resource use efficiency. Moderate increases in planting density can enhance millable cane number, leaf area index, and light interception, thereby improving canopy photosynthesis and dry matter accumulation (Joseph et al., 2024). However, excessive density intensifies competition among plants, reduces light penetration and ventilation, inhibits individual stalk development, and lowers sucrose accumulation efficiency. Therefore, optimal density should achieve a dynamic balance between increasing population size and maintaining individual plant quality, rather than simply maximizing or minimizing density.

From a long-term production perspective, moderate density is generally more favorable for maintaining population stability across both plant cane and ratoon crops. Although low density may promote individual plant growth, it is less conducive to sustained high yield. Spatial arrangements, such as row spacing and double-row planting, also affect the coordination between yield and quality, with different configurations favoring either biomass production or sugar accumulation (Joseph et al., 2024). In addition, varietal characteristics and belowground conditions can modify density effects, as plants may compensate through adjustments in stalk number and individual stalk weight. An ideal population should have a moderate leaf area index, good light penetration and ventilation, and uniform stalk distribution to balance photosynthetic efficiency and sugar accumulation, thereby achieving both high yield and high sugar content.

7.3 Importance of growth stage regulation and timely harvest for high yield and high sugar formation

The formation of sugarcane yield and sugar content is highly dependent on developmental stages. The tillering and elongation phases determine population size and biomass foundation, while the maturation phase governs sucrose accumulation and quality improvement. By regulating planting time, water and nutrient supply, and irrigation withdrawal, it is possible to coordinate the timing of peak biomass formation and peak sugar accumulation. Moderate restriction of water and nitrogen during maturation can suppress excessive vegetative growth and promote carbon allocation to sucrose storage. In contrast, continuous high water and nutrient supply may increase biomass but often reduces sugar concentration. Therefore, proper regulation of the maturation process is essential for achieving synchronized improvements in yield and quality.

Planting and harvesting windows are also closely related to varietal maturity types and regional climatic conditions. Appropriate planting time is critical for achieving high yield, whereas delayed planting often results in yield reduction. Different maturity types require different optimal harvest times, and moderately delayed harvesting generally improves quality traits such as Brix, purity, and CCS. Moreover, harvest season and scheduling significantly affect sugar yield, and optimized harvest planning can greatly enhance overall production efficiency and economic returns (Gebrehiwot et al., 2025). Therefore, timely harvesting should be determined based on variety characteristics, environmental conditions, and processing capacity, ensuring coordination between production and processing to maximize the potential for high yield and high sugar content.

8 Future Research Directions and Development Trends

8.1 Multi-omics integration for deciphering mechanisms of high yield and high sugar traits

With advances in genomics, transcriptomics, and metabolomics, the coordinated improvement of yield and sugar content in sugarcane increasingly relies on multi-omics integration to systematically elucidate the continuum from genetic variation-physiological processes-agronomic performance. Since yield and sugar content are complex quantitative traits involving multiple layers such as carbon fixation, sucrose metabolism, source-sink partitioning, and hormonal regulation, single-omics approaches are insufficient to fully explain their formation. Therefore, integrating genomic, transcriptomic, proteomic, metabolomic, and phenomic data has become a key strategy for