Future trends involve integrating GS with high-throughput phenotyping, environmental data, and machine learning approaches to build a genotype-phenotype-environment predictive framework, thereby improving the understanding of G×E×M interactions and enhancing selection efficiency (Amaresh et al., 2025). Meanwhile, gene editing technologies such as CRISPR/Cas offer new opportunities for precisely regulating genes involved in sucrose metabolism, cell wall synthesis, and stress responses, with the potential to optimize carbon allocation and mitigate the physiological trade-offs between high yield and high sugar (Amaresh et al., 2025; Brant et al., 2025). Although the polyploid genome of sugarcane presents challenges, these technologies are rapidly advancing.

6.3 Integrated breeding approaches for coordinated high yield and high sugar

Because sugarcane yield and sugar content are complex traits, no single technology can achieve major breakthroughs; therefore, future improvement requires an integrated breeding system combining multiple approaches. Within the breeder's equation framework, it is necessary to simultaneously increase genetic variation, selection accuracy, and selection intensity while shortening breeding cycles. This relies on genome-wide data mining, multi-environment phenotyping, and modeling of G×E×M interactions (Amaresh et al., 2025). Thus, coordinated improvement should be conducted under a unified NTrait framework, rather than focusing on single traits independently.

In terms of germplasm resources, expanding the genetic base and strengthening pre-breeding are essential. Introducing wild species and diverse ecotypes can help identify genes associated with high biomass, high sugar content, and stress resistance (Eltaher et al., 2025). A continuous strategy of germplasm expansion-pre-breeding-targeted improvement can provide richer genetic resources for ideotype development. At the same time, breeding objectives should shift from single-trait selection to multi-trait ideotype design, incorporating NTrait components such as tillering, root system architecture, canopy structure, and carbon allocation efficiency to improve indirect selection efficiency.

At the implementation level, a hierarchical breeding pipeline should be established, integrating molecular prediction-phenotypic validation-multi-environment calibration. Early generations can be rapidly screened using molecular markers and GS; intermediate stages can evaluate key traits using high-throughput phenotyping and physiological indicators; and final stages can validate yield, sugar content, and stability through multi-environment trials (Amaresh et al., 2025). In addition, strategies such as recurrent genomic selection (RGS) and reciprocal recurrent genomic selection (RRGS) can be incorporated to accumulate favorable alleles while exploiting heterosis, thereby improving both parental development and hybrid performance and accelerating the coordinated breeding of high-yield and high-sugar sugarcane.

7 Effects of Agronomic Management on the Coordinated Improvement of Sugarcane Yield and Sugar Content

7.1 Regulation of stalk growth and sugar accumulation by water and fertilizer management

Water and nutrient management directly influence the balance between biomass formation and sucrose accumulation in sugarcane by regulating root uptake, canopy structure, and photosynthesis. Adequate water supply during early growth promotes germination, tillering, and rapid stalk elongation, thereby increasing millable cane number and single stalk weight and laying the foundation for high yield. However, excessive water supply in later stages may delay maturation, stimulate vegetative growth, and dilute sucrose concentration, reducing sugar accumulation efficiency. Studies on integrated water-fertilizer management indicate that water and nitrogen jointly promote population establishment and individual growth, but high water and high fertilizer inputs do not necessarily result in high sugar content, reflecting the trade-off between biomass and sugar concentration. Therefore, optimizing the timing and amount of water supply is critical for balancing yield and quality.

In terms of nutrient management, nitrogen, phosphorus, potassium, and micronutrients play distinct roles at different growth stages. Nitrogen promotes leaf area expansion and vegetative growth, but excessive application can delay maturity and reduce sugar content. Phosphorus supports root development and early population establishment, while potassium plays a key role in sucrose transport and synthesis. Recent studies have shown that combined application of potassium with micronutrients such as boron and zinc can improve both yield and sugar