uncovering trait mechanisms. Studies have shown that multi-omics analyses can identify differentially expressed genes, metabolites, and key pathways associated with high yield and high sugar, mainly involving carbon metabolism, secondary metabolism, and hormone signaling networks (Li et al., 2024). Further integration with co-expression and metabolic network analyses enables the identification of key modules and hub genes related to sugar content, fiber, and yield, providing targets for NTrait marker development and molecular breeding.

In the regulation of sucrose accumulation, multi-omics approaches have moved beyond transcript-level analysis toward integrated protein-metabolite-phenotype systems. Evidence suggests that enzymes, transporters, and regulatory factors involved in sucrose metabolism act coordinately in time and space, with an expanding number of candidate proteins highlighting the importance of photosynthesis and primary carbon metabolism in high sugar formation (Fan et al., 2025). This indicates that future research should focus more on the integrated regulation of functional proteins and metabolic pathways. In addition, multi-omics studies reveal dynamic changes in carbon allocation during development, shifting from early growth and structural formation to later sugar storage and stabilization, providing insights into the regulation of maturation and source-sink relationships. In the future, integrating pan-omics with machine learning frameworks is expected to enable precise identification of key regulatory modules and trait prediction, advancing sugarcane breeding from association analysis to predictive design.

8.2 Integration of high-throughput phenotyping, smart breeding, and digital agriculture

In sugarcane breeding, low efficiency and limited accuracy of phenotyping have long been major bottlenecks for studying complex traits. Traditional field measurements are labor-intensive and subject to human error, making them unsuitable for large-scale population evaluation. Therefore, high-throughput phenotyping (HTP) technologies have emerged as a key breakthrough for improving breeding efficiency and precision. In recent years, UAV-based systems, multispectral/hyperspectral imaging, LiDAR, and field sensors have enabled rapid acquisition of key traits such as canopy structure, biomass, water status, and photosynthesis-related parameters. These traits are not only closely related to yield but can also serve as intermediate indicators in genomic selection models, transforming phenotypic data from static end-point measurements into dynamic traits across the entire growth cycle.

Future research should expand the scope of HTP to include NTrait indicators such as tillering dynamics, stalk number changes, early growth vigor, canopy temperature, and sugar accumulation processes, and evaluate their genetic relationships with final yield and sugar content (Amaresh et al., 2025). This will improve prediction accuracy for complex traits and enable early selection of superior genotypes. At the same time, integration of phenotypic, genomic, and environmental data is driving the development of smart breeding. Under the “Breeding 4.0” framework, machine learning-assisted genomic selection models can more accurately predict breeding values across environments, optimizing parental selection and breeding strategies. In addition, digital agriculture technologies integrating remote sensing, environmental monitoring, and management data can enable precise regulation of water and fertilizer use, pest control, and harvest timing. More advanced developments include the construction of digital twin breeding systems, which simulate breeding and management strategies in virtual environments and optimize decisions in real time (Wang et al., 2024a). Combined with data sharing and blockchain technologies, such systems will significantly enhance collaborative breeding and supply chain management efficiency.

8.3 Breeding directions for multi-objective coordinated improvement

With the diversification of the sugarcane industry toward sugar production, bioenergy, and biomaterials, future breeding objectives are shifting from single traits to multi-trait optimization. Ideal varieties should simultaneously possess high yield, high sugar content, strong stress resistance, wide adaptability, and suitability for mechanized harvesting (Lu et al., 2024; Wang et al., 2025). Thus, breeding targets are evolving into a comprehensive system encompassing yield, sugar content, stress resistance, mechanization, and industrial adaptability. In ideotype design, a series of NTrait intermediate traits play key roles, including optimal canopy structure, appropriate leaf angle, deep root systems, stay-green ability, and high single stalk weight. These traits contribute to efficient light use,