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Diversity and Cultivation of Sugarcane: From Traditional Practices to Modern Breeding Techniques

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Abstract Genome selection, marker-assisted breeding and the integration of biotechnology methods are accelerating the development of excellent sugarcane varieties. This study explores the diversity and cultivation of sugarcane with a focus on the evolution from traditional practices to modern breeding techniques, aiming to study the genetic diversity of sugarcane species, assess traditional and modern cultivation methods, and highlight advances in breeding techniques that significantly increase yield, disease resistance, and environmental adaptability. The findings show that while traditional methods provided the foundation for sugarcane cultivation, modern genomic tools and molecular breeding methods have revolutionized crop improvement, increasing productivity and sustainability, and the combination of genetic diversity with advanced breeding techniques is expected to further optimize sugarcane cultivation, contributing to global agriculture and biofuel production.
Keywords Sugarcane diversity; Traditional practices; Modern breeding techniques; Genomic selection; Sustainable agriculture

1 Introduction

Sugarcane (*Saccharum* spp.) is a vital crop globally, serving as the primary source of sugar and a significant contributor to biofuel production. It accounts for approximately 80% of the world's sugar supply and 40% of biofuel production (Zan et al., 2020; Budeguer et al., 2021). The crop is cultivated extensively in tropical and subtropical regions, with Brazil and India being the leading producers (Luo et al., 2023). Sugarcane's importance extends beyond sugar production; it is also a key raw material for ethanol and electricity generation, making it a cornerstone of the bioenergy sector (Mahadevaiah et al., 2021; Guo, 2024). The plant's complex polyploid genome, resulting from interspecific hybridization, poses challenges for breeding but also offers opportunities for significant genetic improvements (Yadav et al., 2020; Luo et al., 2023).

Sugarcane's role in agriculture and industry is multifaceted. Agriculturally, it is a high-yielding crop that supports the livelihoods of millions of farmers worldwide. Industrially, it is indispensable for producing sugar, ethanol, and various byproducts such as fibers and bioenergy (Shabbir et al., 2021). The demand for sugarcane-derived products is consistently increasing, driven by the need for renewable energy sources and the global shift towards sustainable practices (de Morais et al., 2015). Modern biotechnologies and genetic engineering have further enhanced sugarcane's resilience to environmental stresses, making it a more reliable crop in the face of climate change (Shabbir et al., 2021; Li et al., 2023). Additionally, sugarcane breeding programs have focused on developing varieties with high sucrose content, drought tolerance, and efficient nitrogen use, thereby reducing environmental impacts and improving overall productivity (de Morais et al., 2015; Yadav et al., 2020).

This study explores the genetic makeup of sugarcane, breeding methods, and the potential for future innovations to increase its productivity and sustainability, and provides a comprehensive overview of the role of sugarcane in modern agriculture and industry, highlighting advances in breeding techniques and efforts to meet the growing global demand for sugarcane-derived products. The aim of this study is to explore sugarcane diversity and cultivation, trace its evolution from traditional practices to modern breeding techniques, provide a comprehensive overview of sugarcane genetic diversity and its impact on breeding programs, evaluate the progress of modern breeding techniques such as molecular marker-assisted breeding, genome selection, genetic transformation and examine their impact on sugarcane improvement within the context of global agricultural and industrial needs, assess the challenges and future prospects of sugarcane farming.

2 Sugarcane Diversity: Origins and Global Distribution

2.1 Historical origins and domestication of sugarcane

Sugarcane (*Saccharum* spp.) has a rich history of domestication that dates back to prehistoric times. The initial domestication involved the selection of desirable clones and interspecific hybrids, which brought many agronomically useful traits into the cultivated species. The primary species involved in the domestication process were *Saccharum officinarum* and *S. spontaneum*, with *S. officinarum* being the main contributor to the high sucrose content in modern cultivars (Budeguer et al., 2021). The domestication process was complex and involved multiple stages of selection and hybridization, leading to the development of the noble cane varieties that are widely cultivated today (Mirajkar et al., 2019).

2.2 Genetic diversity in sugarcane species

The genetic diversity within sugarcane species is crucial for the crop's adaptability and yield improvements. Modern sugarcane cultivars are highly polyploid and aneuploid hybrids with extremely large genomes, originating from artificial crosses between *S. officinarum* and *S. spontaneum* (Budeguer et al., 2021). Despite the genetic complexity, the genetic diversity in modern cultivars is relatively narrow due to intensive breeding practices (Aitken et al., 2018; Liu et al., 2018). Studies have shown that the genetic diversity in sugarcane cultivars from the USA and China is low, with Chinese cultivars exhibiting particularly low diversity (Liu et al., 2018). However, wild species like *S. spontaneum* still harbor a significant amount of genetic diversity, which can be utilized for breeding programs to introduce traits such as stress tolerance and disease resistance (Lu et al., 2004; Aitken et al., 2018).

2.3 Global distribution and cultivation regions

Sugarcane is cultivated in tropical and subtropical regions around the world, with major production areas in Brazil, India, China, and the USA (Yang et al., 2018). The crop is a major source of sugar and biofuel, contributing to approximately 80% of the world's sugar and 40% of biofuel production (Budeguer et al., 2021). The global distribution of sugarcane is influenced by climatic conditions, with the majority of cultivation occurring in regions with warm temperatures and adequate rainfall (Yang et al., 2018). The genetic diversity of sugarcane cultivars varies by region, with some areas like Indonesia and China showing higher diversity in wild species compared to cultivated varieties (Aitken et al., 2018).

2.4 Importance of genetic diversity for adaptation and yield improvements

Genetic diversity is essential for the adaptation of sugarcane to various environmental conditions and for improving yield. The narrow genetic base of modern cultivars poses a risk to the crop's resilience against pests, diseases, and changing climatic conditions (Liu et al., 2018). Utilizing the genetic diversity present in wild species like *S. spontaneum* can help introduce beneficial traits into modern cultivars, enhancing their stress tolerance and overall performance (Lu et al., 2004; Aitken et al., 2018). Molecular markers and genomic selection techniques are being employed to identify and incorporate these valuable traits into breeding programs, aiming to broaden the genetic base and improve the adaptability and yield of sugarcane (Singh et al., 2020; Yadav et al., 2020; Mahadevaiah et al., 2021).

3 Traditional Cultivation Practices

3.1 Overview of early sugarcane cultivation methods

Early sugarcane cultivation methods were primarily based on natural selection and conventional breeding techniques. These methods were labor-intensive and relied heavily on the manual selection of superior plants for propagation. The process was slow and required extensive field trials to identify desirable traits such as high sugar content and disease resistance. Traditional breeding programs often took over a decade to develop new varieties due to the complex polyploid nature of sugarcane and its low fertility under natural conditions (Budeguer et al., 2021; Ram et al., 2021).

3.2 Indigenous knowledge and practices in sugarcane farming

Indigenous knowledge played a crucial role in the early cultivation of sugarcane. Farmers utilized their understanding of local environmental conditions and crop management practices to optimize sugarcane growth. This included selecting planting sites with optimal soil and water conditions, using organic fertilizers, and implementing crop rotation to maintain soil fertility. Indigenous practices also involved the use of traditional pest control methods and the selection of disease-resistant varieties through experiential knowledge passed down through generations (Ram et al., 2021; Zhao et al., 2022).

3.3 The role of cultural traditions in sugarcane agriculture

Cultural traditions significantly influenced sugarcane agriculture, particularly in regions where sugarcane has been cultivated for centuries. In India, for example, sugarcane cultivation dates back to 5 000 BC, and cultural practices have evolved to support the crop's growth and sustainability. Festivals and rituals often coincided with planting and harvesting seasons, reinforcing the importance of sugarcane in the community's social and economic life. These traditions helped preserve valuable agricultural knowledge and ensured the continued cultivation of sugarcane through community involvement and shared practices (Ram et al., 2021; Zhao et al., 2022).

4 Challenges in Traditional Sugarcane Cultivation

4.1 Issues related to pests, diseases, and environmental factors

Traditional sugarcane cultivation faces significant challenges due to pests, diseases, and environmental factors. Sugarcane is highly susceptible to various biotic stresses, including fungi, bacteria, viruses, and insect pests, which can severely impact crop yield and quality. Additionally, abiotic stresses such as drought, salt, cold, heat, waterlogging, and heavy metals further constrain sugarcane production (Krishna et al., 2023). The complex polyploid genome of sugarcane makes it difficult to breed varieties that are resistant to these stresses using conventional methods (Budeguer et al., 2021). The vulnerability to pests and diseases has also been a major factor in the stagnation of yield improvements in traditional sugarcane cultivation (Rott, 2018).

4.2 Limitations of yield potential with traditional varieties

Traditional sugarcane varieties often exhibit limited yield potential due to their genetic makeup and the lengthy breeding cycles required for varietal development. The classic breeding programs for sugarcane can take up to 12~14 years to identify and develop new varieties, which significantly slows down the rate of genetic gain (Mahadevaiah et al., 2021). Moreover, the low narrow-sense heritability for major commercial traits and the strong non-additive genetic effects involved in quantitative trait expression further limit the yield potential of traditional varieties (Yadav et al., 2020). The high propensity for lodging and suckering, influenced by environmental factors and crop management practices, also complicates precise phenotyping and yield prediction (Mahadevaiah et al., 2021).

4.3 Water usage, soil management, and sustainability concerns

Water usage and soil management are critical concerns in traditional sugarcane cultivation. Sugarcane is a water-intensive crop, and traditional irrigation practices often lead to inefficient water use and increased vulnerability to water scarcity (Silva et al., 2023). Soil health is another major issue, as continuous sugarcane cultivation can lead to soil degradation, reduced biodiversity, and negative environmental impacts. The sustainability of traditional sugarcane farming practices is further challenged by the need for effective soil management strategies to maintain soil fertility and structure (Rott, 2018). The high water demand and the need for sustainable soil management practices highlight the importance of adopting more efficient and environmentally friendly cultivation techniques.

4.4 Economic and labor-intensive challenges

Traditional sugarcane cultivation is labor-intensive and economically challenging. The process of planting, maintaining, and harvesting sugarcane requires significant manual labor, which can be costly and time-consuming. The genetic complexity and low fertility of sugarcane under natural growing conditions make traditional breeding improvement laborious and expensive. Additionally, the need for intensive and sophisticated tissue culture and plant generation procedures for genetic transformation further adds to the economic burden (Budeguer et al., 2021). These economic and labor-intensive challenges underscore the need for modern breeding techniques and technological advancements to improve the efficiency and cost-effectiveness of sugarcane cultivation. By addressing these challenges through modern breeding techniques and sustainable cultivation practices, the potential for improving sugarcane yield and resilience can be significantly enhanced.

5 Advances in Sugarcane Breeding

5.1 The Transition from traditional breeding to modern techniques

The transition from traditional breeding to modern techniques in sugarcane has been driven by the need to overcome the challenges posed by the crop's genetic complexity and low fertility under natural conditions. Traditional breeding methods, which involve visual clonal selection and manual screening for traits such as cane stalk weight and sugar content, are laborious and time-consuming, often taking 10 to 12 years to complete a breeding cycle (Luo et al., 2023). The advent of genetic engineering and molecular marker-assisted selection (MAS) has revolutionized sugarcane breeding by enabling more precise and efficient selection processes. Techniques such as electroporation, Agrobacterium tumefaciens-mediated transformation, and biobalistics have been developed to introduce desirable traits like herbicide resistance, disease resistance, and improved tolerance to environmental stresses. Despite these advancements, the genetic transformation of sugarcane remains a technical challenge due to the need for optimized tissue culture and plant generation procedures for each genotype (Budeguer et al., 2021).

5.2 Hybridization and the development of high-yield varieties

Hybridization has played a crucial role in the development of high-yield sugarcane varieties. Modern sugarcane cultivars are interspecific hybrids derived from crosses between *Saccharum officinarum* and *Saccharum spontaneum*, resulting in highly polyploid and aneuploid genomes (Yang et al., 2018; Luo et al., 2023). This genetic complexity has been harnessed to introduce agronomically useful traits such as high sucrose content, disease resistance, and stress tolerance. The use of molecular markers, such as simple sequence repeats (SSR) and single nucleotide polymorphisms (SNP), has facilitated the identification and selection of desirable traits in breeding programs (Thirugnanasambandam et al., 2018; Wu et al., 2019). For instance, SSR markers combined with high-performance capillary electrophoresis have been used to genotype sugarcane parental lines, aiding in the selection of the best parents for crossing and the evaluation of progeny (Wu et al., 2019). Additionally, genomic selection (GS) using SNP markers has shown promise in improving traits like cane yield and sugar content by providing a more robust estimation of genetic merit (Luo et al., 2023).

5.3 The role of polyploidy and genetic complexity in breeding programs

Polyploidy and genetic complexity are defining features of sugarcane that present both challenges and opportunities for breeding programs. The large, complex polyploid genome of sugarcane, with chromosome numbers ranging from 100 to 130, complicates traditional breeding efforts but also offers a rich source of genetic diversity (Luo et al., 2023). Advances in genomics and sequencing technologies have enabled the detailed characterization of sugarcane's genetic makeup, revealing the contributions of different progenitor species and the extent of linkage disequilibrium (Lu et al., 2004). These insights have informed breeding strategies aimed at leveraging the genetic diversity within sugarcane populations to develop improved cultivars. For example, the sequencing of sugarcane germplasm accessions has identified candidate genes associated with environmental adaptation and selection, providing valuable resources for breeding programs (Yang et al., 2018). Furthermore, the integration of genomic data with phenotypic information through high-throughput phenotyping and genomic selection holds the potential to accelerate the development of high-yield, stress-tolerant sugarcane varieties (Mahadevaiah et al., 2021; Luo et al., 2023).

6 Genomic and Molecular Breeding Approaches

6.1 Integration of genomic selection and marker-assisted breeding in sugarcane

The integration of genomic selection (GS) and marker-assisted breeding (MAB) has shown significant promise in accelerating genetic gains in sugarcane breeding programs. Traditional breeding methods in sugarcane are time-consuming, often requiring 10~14 years for varietal identification due to the complex polyploid nature of the crop and the extensive phenotyping required (Mahadevaiah et al., 2021). Genomic selection, which uses genome-wide markers to predict the genetic value of breeding candidates, can significantly reduce the breeding cycle length and increase the accuracy of selection for complex traits (Figure 1) (Yadav et al., 2020; Sandhu et al., 2022; Liang, 2024).

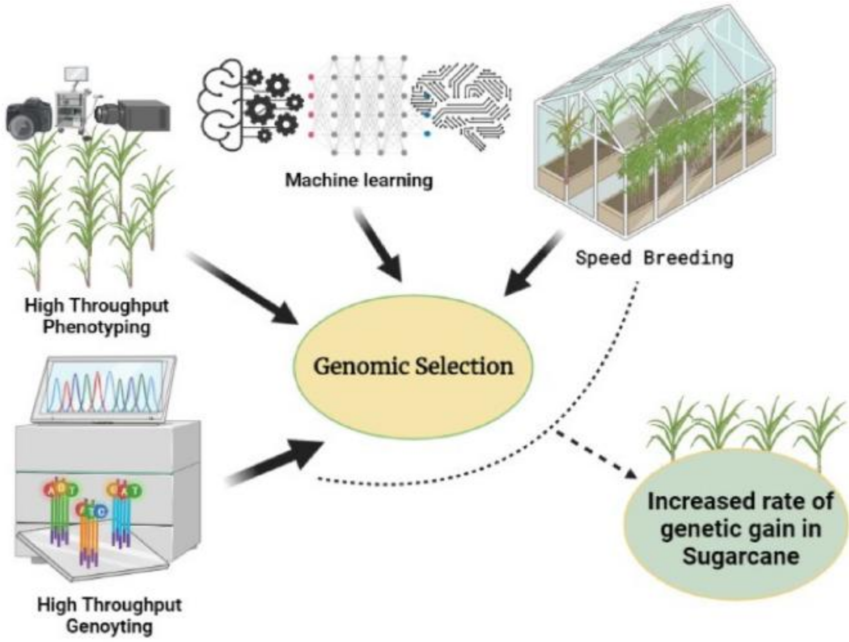

Figure 1 Various approaches which could be integrated in genomic selection in sugarcane for accelerated genetic gain (Adopted from Sandhu et al., 2022)

Marker-assisted selection (MAS) has been used to map and introgress genes for economically important traits, but its application in sugarcane has been limited by the crop's large and complex genome. However, the integration of high-throughput phenotyping and genotyping with GS can enhance the efficiency of breeding programs by enabling the rapid selection of superior genotypes and accelerating the breeding cycle (Sandhu et al., 2022). This integrated approach has the potential to overcome the challenges posed by the sugarcane genome's complexity and improve the rate of genetic gain (Sandhu et al., 2022; Luo et al., 2023).

6.2 Role of molecular tools

Molecular tools such as quantitative trait loci (QTL) mapping and gene editing have become essential in modern sugarcane breeding. QTL mapping helps identify genomic regions associated with important agronomic traits, facilitating the development of molecular markers for MAS (Barreto et al., 2019; Zan et al., 2020). For instance, genome-wide association studies (GWAS) have identified several markers linked to traits such as cane yield, sugar content, and disease resistance, which can be used to enhance breeding efficiency.

Gene editing technologies, such as CRISPR/Cas9, offer precise and targeted modifications of the sugarcane genome, enabling the introduction of desirable traits and the elimination of undesirable ones. These technologies can be used to improve sugarcane's tolerance to biotic and abiotic stresses, enhance sugar content, and increase biomass production (Shabbir et al., 2021). The combination of QTL mapping and gene editing provides a powerful toolkit for the genetic improvement of sugarcane, allowing breeders to achieve significant gains in a shorter time frame (Meena et al., 2022).

6.3 Genome-wide association studies (GWAS) and its application in sugarcane improvement

Genome-wide association studies (GWAS) have become a valuable tool in sugarcane breeding, enabling the identification of genetic variants associated with key agronomic traits. GWAS leverages the genetic diversity within sugarcane populations to detect marker-trait associations, providing insights into the genetic architecture of complex traits (Barreto et al., 2019; Zan et al., 2020). In sugarcane, GWAS has been used to identify loci associated with yield components, such as stalk height, stalk number, and cane yield, as well as quality traits like sugar content. These studies have revealed significant marker-trait associations that can be used to guide breeding decisions and improve the efficiency of selection. The application of GWAS in sugarcane breeding programs has the potential to enhance the precision of selection and accelerate the development of superior cultivars (Barreto et al., 2019; Zan et al., 2020).

7 Modern Cultivation Practices

7.1 Mechanized farming and its impact on sugarcane productivity

Mechanized farming has significantly transformed sugarcane cultivation, particularly in regions like China and Thailand. Fully mechanized cultivation (FMC) has been shown to increase the diversity and richness of endophytic microorganisms in sugarcane stems, which can potentially enhance plant health and yield. However, the overall cane growth, yield, and health were not significantly altered by FMC compared to conventional artificial cultivation (CAC) (Xiao et al., 2023). In Thailand, mechanized harvesting practices, such as using cutting machines, have been assessed for their greenhouse gas (GHG) emissions and costs. While mechanized harvesting has moderate GHG emissions, it incurs higher costs due to the need for specialized equipment. This has led some farmers to revert to traditional practices like burning cane, which is less costly but environmentally detrimental (Pongpat et al., 2017).

7.2 Precision agriculture and the use of technology in sugarcane fields

Precision agriculture (PA) is an emerging approach in sugarcane cultivation that involves the precise application of inputs to optimize yields and reduce costs. In developing countries, the adoption of PA techniques has been slow due to uncertainties and conflicting opinions. However, PA has the potential to significantly improve cane yield and quality by integrating affordable and effective technologies (Sanghera et al., 2020). In Mexico, the application of PA tools, such as remotely sensed yield estimation and agro-ecological zoning (AEZ), has shown that sugarcane fields have varying levels of land suitability. These tools help in identifying areas with high vulnerability to climate variability and in implementing agroecological management practices to increase yields (Aguilar-Rivera et al., 2018). Additionally, computational environments have been developed to support data-driven advances in sugarcane agricultural research, emphasizing the importance of spatial and temporal variations in soil attributes and crop yield (Driemeier et al., 2016).

7.3 Best practices for irrigation, pest management, and fertilization

Effective irrigation, pest management, and fertilization practices are crucial for optimizing sugarcane productivity. Fertigation, the application of fertilizers through irrigation systems, has been shown to significantly improve sugarcane productivity. For instance, the fertigation of nitrogen (N) and zinc (Zn) in sugarcane fields in Brazil resulted in a 38.90% increase in productivity for plant crops and a 13.70% increase for ratoon crops when treated with 180 kg ha^{-1} of N and 10 kg ha^{-1} of Zn (Cunha et al., 2020). Precision agriculture techniques can also aid in the efficient use of fertilizers, reducing nitrous oxide (N_2O) emissions, a significant greenhouse gas. Enhanced efficiency fertilizers (EEF) have been shown to reduce N_2O emissions by 38.6% compared to synthetic N fertilizers, highlighting the importance of innovative nutrient formulations in sustainable sugarcane cultivation (Yang et al., 2020).

8 Biotic and Abiotic Stress Management

8.1 Strategies for combating diseases and pests

Sugarcane is susceptible to a variety of biotic stresses, including diseases caused by fungi, bacteria, viruses, and insect pests. Modern biotechnological approaches have been pivotal in developing sugarcane varieties resistant to these biotic stresses. For instance, genetic engineering techniques have been employed to introduce genes that confer resistance to pests and diseases. The expression of modified genes such as *CEMB-Cry1Ac* and *CEMB-Cry2A* has shown significant resistance against cane borers, while glyphosate tolerance has been achieved through the expression of the CEMB-GTGene (Qamar et al., 2021). Additionally, transgene-free genome editing techniques, such as CRISPR/Cas, have been explored to create pest and disease-resistant sugarcane cultivars without the regulatory hurdles associated with transgenic plants (Krishna et al., 2023).

8.2 Breeding for resistance to abiotic stresses such as drought and salinity

Abiotic stresses, including drought and salinity, pose significant challenges to sugarcane cultivation. Recent advances in breeding and genomic approaches have been instrumental in enhancing sugarcane's tolerance to these stresses. Techniques such as molecular marker-assisted breeding, genome editing, and the use of omics technologies have identified key genes and regulatory elements responsible for abiotic stress tolerance (Meena et al., 2020; Shabbir et al., 2021). For example, the introgression of genes from wild species has led to the development of stress-tolerant varieties, and the use of CRISPR/Cas technology has enabled precise modifications to improve drought and salinity tolerance (Meena et al., 2020). Physiological interventions, such as inducing drought hardiness and managing soil salinity, also contribute to the resilience of sugarcane to abiotic stresses (Shrivastava et al., 2017).

8.3 Case studies on successful stress-resistant sugarcane varieties

Several case studies highlight the successful development of stress-resistant sugarcane varieties. One notable example is the development of transgenic sugarcane utilizing the *betA* gene, which imparts drought tolerance and has been commercialized for cultivation (Shrivastava et al., 2017). Another example is the creation of transgenic sugarcane lines expressing *CEMB-Cry1Ac* and *CEMB-Cry2A* genes (Figure 2), which have demonstrated complete resistance to cane borers and high tolerance to glyphosate spray in field conditions (Qamar et al., 2021). Additionally, the use of transcription factors such as WRKY, NAC, MYB, and AP2/ERF has been explored to regulate gene expression in response to abiotic and biotic stresses, providing important clues for engineering stress-tolerant cultivars (Javed et al., 2020). These advancements underscore the potential of modern breeding and biotechnological approaches in developing robust sugarcane varieties capable of withstanding various environmental stresses. By integrating these strategies, the sugarcane industry can enhance crop resilience, ensuring sustainable production in the face of increasing biotic and abiotic challenges.

Figure 2 Schematic presentation of all the steps involved in genetic modification of sugarcane (Adopted from Qamar et al., 2021)

Image caption: (A) Callus for Bombardment. (B) Homemade Biolistic machine. (C) Bombarded Callus after bombardment with DNA-coated tungsten particles. (D) Bombarded callus shifted on selection media with Kanamycime (50 mg/L) after 2 days. (E, F) Transformed callus regenerated on double selection (Kanamycine 50 mg/L+Glyphosate 40 mM) media, (G, H) Regenerated sugarcane plantlets on glyphosate selection media (45 mM), shifting on shoot multiplication media with Kanamycime (50 mg/L) and glyphosate (50 mM) selections. (I) Gus Assay for transgenic plant screening (abcd). (J) Transgenic plants for rooting. (K) Shifting on rooting media without any selection drug. (L, M) Acclimatization: Transgenic sugarcane plantlets in soil pots under green house conditions (Adopted from Qamar et al., 2021)

9 Case Study: Breeding and Cultivation Success in Brazil

9.1 Overview of Brazil as a leading sugarcane producer

Brazil stands as the world's largest producer of sugarcane, significantly contributing to the global supply of sugar and ethanol. In the 2019~2020 crop season, Brazil produced an impressive 642.7 million tons of sugarcane over an area of 8.44 million hectares. The country's leadership in sugarcane production is underpinned by a long history of breeding programs and the continuous release of superior cultivars, which have driven yield improvements over the past decades (Figure 3) (Cursi et al., 2021). Additionally, Brazil's sugarcane industry plays a crucial role in the global bioenergy market, with sugarcane being a major source of ethanol, a renewable biofuel (Bordonal et al., 2018).

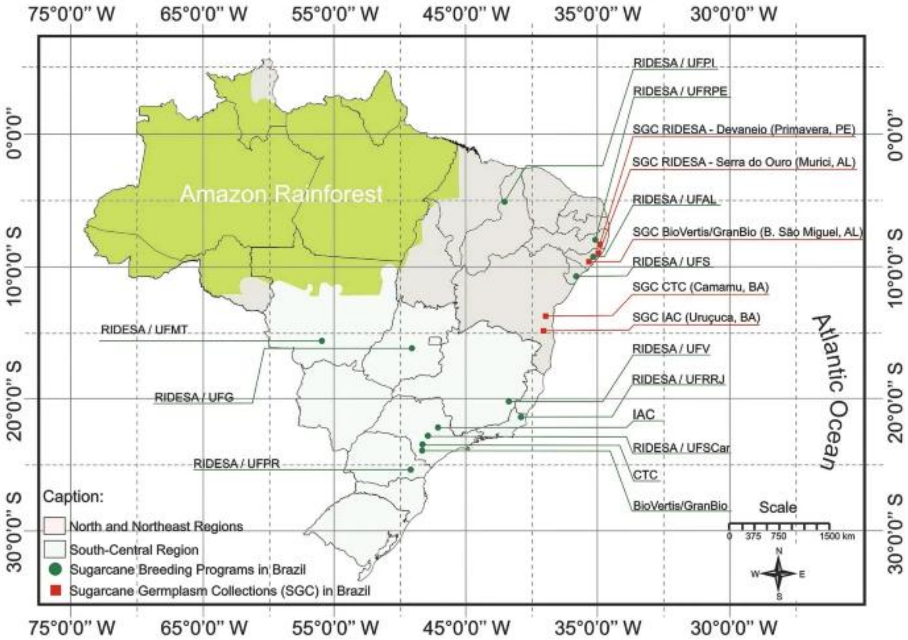

Figure 3 Sugarcane breeding programs and sugarcane germplasm collections in Brazil (Adopted from Cursi et al., 2021)

9.2 Strategies adopted in Brazilian sugarcane breeding programs

Brazilian sugarcane breeding programs have employed a variety of strategies to enhance productivity and sustainability. Traditional breeding methods have been complemented by modern biotechnological approaches, including molecular marker-assisted selection (MAS) and genomic selection (GS). These advanced techniques have enabled more precise and efficient breeding, leading to the development of cultivars with improved traits such as disease resistance, higher sugar content, and better adaptability to diverse environmental conditions (Yadav et al., 2020; Budeguer et al., 2021; Luo et al., 2023).

One notable strategy is the integration of high-throughput phenotyping and genotyping, which allows for the accurate selection of elite clones with desirable traits. This approach has been instrumental in overcoming the challenges posed by the complex polyploid genome of sugarcane (Luo et al., 2023). Additionally, the use of endophytic nitrogen-fixing bacteria has reduced the need for nitrogen fertilizers, further enhancing the sustainability of sugarcane cultivation in Brazil (Baldani et al., 2002).

9.3 Impact of modern breeding techniques on yield, sustainability, and biofuel production

The adoption of modern breeding techniques has had a profound impact on sugarcane yield, sustainability, and biofuel production in Brazil. Over the past 40 years, sugarcane breeding programs have contributed to an average annual increase of 155.7 kg/ha in sugar yield, with about half of this gain attributed to breeding efforts (Cursi et al., 2021). The implementation of genomic selection has the potential to further accelerate genetic gains by reducing breeding cycle lengths and increasing the accuracy of trait selection (Yadav et al., 2020; Mahadevaiah et al., 2021).

Sustainability has also been a key focus of Brazilian sugarcane breeding programs. The expansion of sugarcane cultivation on degraded pastures has minimized competition with food crops and prevented deforestation, while non-burning harvesting practices have improved soil health and reduced environmental impacts (Bordonal et al., 2018). Moreover, advancements in water management and nitrogen use efficiency have made sugarcane ethanol one of the most sustainable biofuel options available.

10 Future Prospects and Challenges

10.1 Emerging trends in sugarcane biotechnology

The field of sugarcane biotechnology is rapidly evolving, with significant advancements in genetic engineering and genome editing technologies. Modern biotechnologies, such as molecular marker-assisted breeding, sugarcane transformation, and multiple omics technologies, are being employed to improve sugarcane's tolerance to environmental stresses. These technologies offer promising solutions to the challenges posed by the crop's complex polyploid genome and susceptibility to various biotic and abiotic stresses (Budeguer et al., 2021; Shabbir et al., 2021). Additionally, the integration of high-throughput screening techniques and advanced transformation methods is expected to enhance the efficiency of sugarcane improvement programs (Kaur et al., 2020; Mohan et al., 2020).

10.2 Potential for CRISPR-Cas9 and gene editing technologies in sugarcane improvement

CRISPR-Cas9 and other gene editing technologies have shown immense potential in the genetic improvement of sugarcane. The CRISPR/Cas9 system, in particular, has been successfully employed to develop new sugarcane varieties with desired phenotypic and physiological traits (Haque et al., 2018; Hussin et al., 2022). This technology allows for precise modifications in the sugarcane genome, enabling the creation of cultivars with improved resistance to biotic and abiotic stresses (Chen et al., 2019; Krishna et al., 2023). The development of transgene-free genome editing techniques further enhances the commercial viability of these genetically edited crops by addressing regulatory concerns (Krishna et al., 2023). The application of CRISPR/Cas9 in sugarcane breeding is expected to revolutionize the field, making it faster, cheaper, and more efficient compared to traditional breeding methods (Haque et al., 2018; Ahmad, 2023).

10.3 Addressing sustainability issues through improved varieties

Improving the sustainability of sugarcane cultivation is a critical goal for future agricultural practices. The development of genetically modified sugarcane varieties with enhanced tolerance to environmental stresses, such as drought, salt, and temperature extremes, can significantly contribute to sustainable production (Budeguer et al., 2021; Shabbir et al., 2021). Additionally, the use of genome editing technologies to create climate-smart cultivars that can withstand changing environmental conditions is a promising approach (Haque et al., 2018; Krishna et al., 2023). These advancements not only ensure higher yields but also reduce the need for chemical inputs, thereby minimizing the environmental impact of sugarcane cultivation (Mahadevaiah et al., 2021; Shabbir et al., 2021).

10.4 Integration of bioenergy and bioproducts with sugarcane cultivation for future agricultural practices

The integration of bioenergy and bioproducts with sugarcane cultivation presents a significant opportunity for future agricultural practices. Sugarcane is a major source of biofuel, and advancements in genetic engineering can further enhance its biomass production and conversion efficiency (Mohan et al., 2020). The development of sugarcane varieties with improved traits for bioenergy production, such as higher sugar content and increased biomass yield, can contribute to the sustainable production of biofuels (Mahadevaiah et al., 2021). Additionally, the diversification of sugarcane applications beyond traditional uses, such as the production of bioplastics and other bioproducts, can create new economic opportunities and reduce reliance on fossil fuels (Mohan et al., 2020; Budeguer et al., 2021). The integration of these innovative approaches with traditional sugarcane cultivation practices is essential for the future of sustainable agriculture.

11 Concluding Remarks

The study of sugarcane diversity and cultivation has revealed significant advancements and challenges in both traditional and modern breeding techniques. Traditional breeding methods, while foundational, are labor-intensive and time-consuming due to the genetic complexity and low fertility of sugarcane. Modern biotechnologies, including genetic transformation and genomic selection, have shown promise in improving sugarcane's resistance to environmental stresses and enhancing economically important traits such as sucrose yield and biomass production. Despite these advancements, the genetic diversity of modern sugarcane cultivars remains narrow, necessitating efforts to broaden the genetic base through international collaborations and the use of molecular markers.

The future of sugarcane breeding lies in the integration of advanced genomic and phenomic approaches. The application of genomic selection (GS) and marker-assisted selection (MAS) has the potential to accelerate genetic gains by reducing breeding cycle lengths and increasing the accuracy of trait selection. However, the success of these methods depends on the development of reliable, high-throughput phenotyping techniques to accurately assess the genetic merit of sugarcane clones. Additionally, the creation of a comprehensive reference genome for sugarcane will be crucial in overcoming the current challenges posed by its complex polyploid genome. Collaborative efforts and the sharing of genetic resources across international borders will also play a vital role in enhancing the genetic diversity and resilience of future sugarcane cultivars.

Efforts should be made to broaden the genetic base of sugarcane cultivars by incorporating wild relatives and underutilized germplasm into breeding programs. This can be achieved through international collaborations and the use of molecular markers to identify and introgress valuable traits. Breeding programs should integrate modern biotechnologies such as genomic selection, marker-assisted selection, and genetic transformation to improve the efficiency and effectiveness of developing new sugarcane varieties. To support genomic selection and other advanced breeding techniques, it is essential to develop and implement high-throughput phenotyping methods that can accurately and cost-effectively assess the performance of large breeding populations.

Given the increasing impact of climate change, breeding efforts should prioritize the development of sugarcane varieties with enhanced tolerance to biotic and abiotic stresses, such as drought, salinity, and disease resistance. Continuous optimization of breeding programs, including the use of decentralized breeding networks and the incorporation of genomics and phenomics data, will be necessary to address the diverse agroclimatic conditions and improve the overall efficiency of sugarcane breeding. By following these recommendations, the sugarcane industry can achieve sustainable improvements in yield, resilience, and profitability, ensuring its continued contribution to global sugar and biofuel production.

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Conflict of Interest Disclosure
The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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