Field Crop 2024, Vol.7, No.4, 191-200
http://cropscipublisher.com/index.php/fc

Review Article Open Access

Sustainable Sugarcane Cultivation: The Impact of Biological Nitrogen Fixation on Reducing Fertilizer Use

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Field Crop, 2024, Vol.7, No.4 doi: 10.5376/fc.2024.07.0019
Received: 03 May, 2024
Accepted: 14 Jun., 2024
Published: 05 Jul., 2024

Preferred citation for this article:
Liang K.W., 2024, Sustainable sugarcane cultivation: the impact of biological nitrogen fixation on reducing fertilizer use, Field Crop, 7(4): 191-200 (doi: 10.5376/fc.2024.07.0019)

Abstract Sustainable sugarcane cultivation is critical for reducing environmental impacts and enhancing agricultural productivity. This study examines the role of biological nitrogen fixation (BNF) in reducing the reliance on synthetic nitrogen fertilizers in sugarcane farming; synthesizes findings from multiple studies to evaluate the effectiveness of BNF in improving nitrogen use efficiency (NUE), soil health, and crop yields. Key insights include the potential of legume cover crops to enhance soil nitrogen storage and microbial biomass, the genetic variability in BNF among sugarcane progenitors, and the influence of endophytic nitrogen-fixing bacteria on nitrogen metabolism in sugarcane. Additionally, this study highlights the environmental benefits of optimized water-fertilizer management and the synergistic effects of intercropping with legumes. The findings underscore the importance of integrating BNF strategies into sugarcane cultivation to achieve sustainable agricultural practices and reduce greenhouse gas emissions.
Keywords Biological nitrogen fixation; Sugarcane; Nitrogen use efficiency; Sustainable agriculture; Soil health

1 Introduction

Sugarcane is a critical agricultural commodity with a significant role in the global economy, providing raw material for sugar production and biofuels, among other products (Li, 2024). It accounts for 80% of global sugar production and is the second-largest bioenergy crop worldwide (Yang et al., 2020). Major producers like Brazil have seen their sugarcane production more than double in recent decades to meet the increasing global demand for bioenergy, which helps reduce crude oil dependency and mitigate climate change (Bordonal et al., 2018). However, the intensive cultivation practices, including high nitrogen (N) fertilizer inputs, have significant environmental impacts, such as increased nitrous oxide (N_2O) emissions, which contribute to greenhouse gas effects (Bordonal et al., 2018; Yang et al., 2020).

The rapid expansion of sugarcane cultivation has raised concerns about its sustainability, particularly regarding its environmental footprint. Therefore, optimizing the production performance and adaptability of sugarcane will not only enhance its economic value, but is also an important factor in the continued improvement of the global environment (Liang, 2024). Sustainable agriculture aims to balance the need for food and bioenergy production with the preservation of environmental quality and natural resources. In the context of sugarcane, this involves optimizing agricultural practices to reduce negative impacts such as soil degradation, water consumption, and greenhouse gas emissions (Bordonal et al., 2018). The adoption of best management practices, including the use of organic amendments and precision agriculture, is crucial for enhancing the sustainability of sugarcane production (Bordonal et al., 2018; Yang et al., 2020).

Biological Nitrogen Fixation (BNF) is a natural process where atmospheric nitrogen (N_2) is converted into a form usable by plants through the action of symbiotic bacteria. This process can significantly reduce the need for synthetic N fertilizers, which are a major source of N_2O emissions when used in sugarcane cultivation (Medorio-García et al., 2020; Yang et al., 2020). The integration of legume cover crops, which facilitate BNF, has shown promise in increasing soil nitrogen storage and reducing the dependency on synthetic fertilizers, thereby enhancing the sustainability of sugarcane production (Tenelli et al., 2021).

This study evaluates the impact of Biological Nitrogen Fixation (BNF) on reducing fertilizer use in sugarcane cultivation; assesses current practices and challenges related to nitrogen use in sugarcane cultivation, with a particular focus on understanding the limitations and inefficiencies in existing approaches. Additionally, this study examines the role of BNF in enhancing soil nitrogen levels, thereby reducing the dependency on synthetic fertilizers; involves evaluating the environmental benefits of integrating BNF into sugarcane cultivation, particularly concerning the reduction of greenhouse gas emissions. Based on these findings, this study provides recommendations for best management practices that promote sustainable sugarcane production through the utilization of BNF.

2 Biological Nitrogen Fixation in Sugarcane

2.1 Mechanisms of nitrogen fixation

Biological nitrogen fixation (BNF) is a microbial-mediated process where atmospheric nitrogen (N_2) is converted into ammonium (NH_4^+), which plants can readily absorb. This conversion is facilitated by the enzyme nitrogenase, which is present in diazotrophic bacteria. These bacteria can either live freely in the soil or form symbiotic relationships with plant roots, often resulting in the formation of specialized structures called nodules (Soumare et al., 2020; Aasfar et al., 2021). In sugarcane, diazotrophic bacteria have been found to colonize plant tissues without causing any visible anatomical changes or disease symptoms, promoting root growth and increasing plant yield (Carvalho et al., 2022).

2.2 Key microbial players in BNF

Several diazotrophic bacteria are known to play crucial roles in BNF within sugarcane. Notable among these are species of *Azotobacter*, which are free-living nitrogen fixers and have been highlighted for their potential as biofertilizers due to their ability to enhance plant nutrition and soil fertility (Figure 1) (Aasfar et al., 2021). Additionally, endophytic diazotrophic bacteria, which live inside plant tissues, have shown significant potential in improving sugarcane yield and nitrogen content (Antunes et al., 2019; Pereira et al., 2020). Inoculation with a mixture of diazotrophic bacteria strains has been demonstrated to increase nitrogen accumulation and plant growth in sugarcane (Martins et al., 2020).

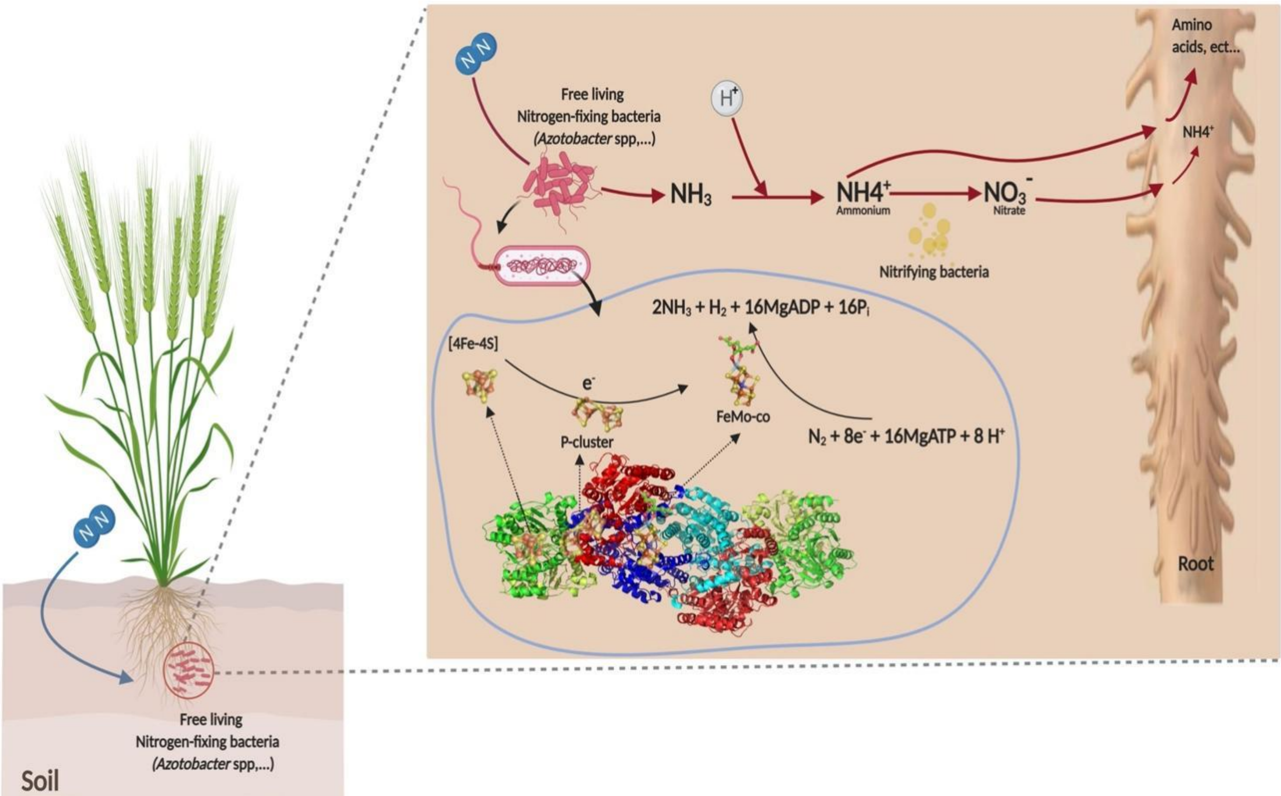

Figure 1 Mechanism of non-symbiotic fixation of atmospheric nitrogen by *Azotobacter* sp. (Adopted from Aasfar et al., 2021)

Aasfar et al. (2021) illustrates the non-symbiotic nitrogen fixation process carried out by free-living nitrogen-fixing bacteria, specifically *Azotobacter* species, in soil. The process begins with the conversion of atmospheric nitrogen (N_2) into ammonium (NH_4^+) via the nitrogenase enzyme complex. The key components of this enzyme, including the Fe-protein (4Fe–4S cluster) and MoFe-protein (P-cluster and FeMo-co), are essential for electron transfer and ATP hydrolysis, which drive the reduction of nitrogen. The NH_4^+ produced is subsequently taken up by plants and converted into nitrates (NO_3^-) and amino acids, supporting plant growth. This mechanism underscores the critical role of non-symbiotic nitrogen fixation in enhancing soil nitrogen availability and reducing dependency on synthetic fertilizers.

2.3 Benefits of BNF in agriculture

The benefits of BNF in agriculture are manifold. Primarily, BNF reduces the dependency on synthetic nitrogen fertilizers, which are associated with environmental issues such as nitrate pollution and greenhouse gas emissions (Mahmud et al., 2020; Soumare et al., 2020). In sugarcane, BNF has been shown to contribute significantly to the plant's nitrogen needs, with some studies reporting that over 60% of the nitrogen in sugarcane can be derived from BNF (Martins et al., 2020). This not only enhances the sustainability of sugarcane cultivation but also improves soil health by maintaining a natural nitrogen cycle (Mahmud et al., 2020). Furthermore, BNF-associated bacteria can promote plant growth through other mechanisms, such as phytohormone production and protection against phytopathogens (Aasfar et al., 2021).

2.4 Factors influencing BNF efficiency in sugarcane

Several factors influence the efficiency of BNF in sugarcane. Nutrient availability, particularly nitrogen and phosphorus, plays a critical role. Excessive nitrogen fertilization can inhibit BNF, while phosphorus addition can have variable effects depending on the type of nitrogen fixation (symbiotic or free-living) (Santachiara et al., 2019; Zheng et al., 2019). Environmental conditions such as water stress, temperature, and flooding also significantly impact BNF efficiency. For instance, water stress and flooding have been shown to reduce BNF activity, especially during the vegetative stage of plant growth (Santachiara et al., 2019). Additionally, genetic factors, such as the specific sugarcane genotype, can influence BNF efficiency. Different sugarcane genotypes exhibit varying levels of BNF, which can be attributed to differences in nitrogen metabolism, hormone regulation, and microbial recognition pathways (Carvalho et al., 2022; Luo et al., 2023).

In conclusion, optimizing BNF in sugarcane involves understanding the complex interactions between microbial players, plant genetics, and environmental factors. This optimization is crucial for enhancing the sustainability of sugarcane cultivation and reducing the reliance on synthetic fertilizers.

3 Impact on Reducing Fertilizer Use

3.1 Current fertilizer practices in sugarcane cultivation

Sugarcane cultivation traditionally relies heavily on synthetic nitrogen (N) fertilizers to achieve high yields. However, the efficiency of nitrogen use in sugarcane is relatively low, leading to significant environmental concerns such as nitrate leaching and ammonia volatilization (Castro et al., 2019; Junior et al., 2023). Current practices often involve the application of high rates of N fertilizer, sometimes exceeding 150 kg N ha^{-1}, which can result in diminishing returns and increased production costs (Castro et al., 2019). Additionally, the timing of fertilizer application plays a crucial role in optimizing yields, with studies showing that earlier applications can significantly enhance both stalk and sugar yields (Castro et al., 2019).

3.2 Role of BNF in reducing chemical fertilizer dependency

Biological nitrogen fixation (BNF) offers a promising alternative to reduce dependency on synthetic N fertilizers in sugarcane cultivation. BNF involves the conversion of atmospheric nitrogen into a form that plants can use, facilitated by nitrogen-fixing bacteria. Research has shown that endophytic diazotrophs, such as those found in various Saccharum species, can significantly contribute to the nitrogen needs of sugarcane (Figure 2) (Singh et al., 2022; Soumare et al., 2022). For instance, the use of legume cover crops has been demonstrated to increase soil nitrogen storage and microbial biomass carbon, thereby reducing the need for additional inorganic fertilizers (Tenelli et al., 2021). Moreover, certain sugarcane varieties and their wild progenitors exhibit high BNF capacity, which remains resilient even under varying nitrogen conditions (Luo et al., 2023).

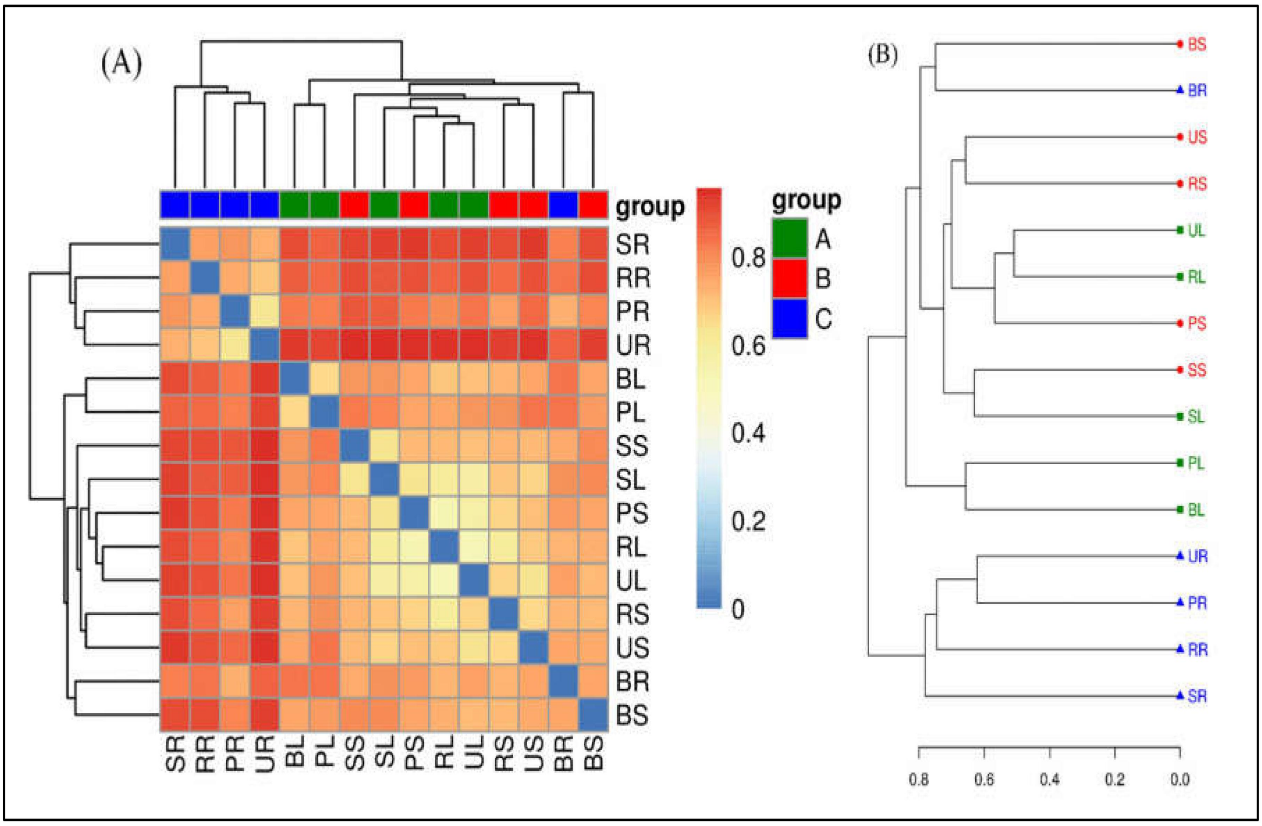

Figure 2 Beta-diversity analysis. (A) Matrix heat map of UniFrac; Beta-diversity matrix heatmap visualizes the Beta-diversity data and graphically clusters the samples and samples with similar beta diversity are clustered together to reflect similarities between samples. (B) UniFrac multi-sample similarity tree assessment; the distance matrix derived from Unifrac analysis is used in a wide range of analysis methods. The non-weighted group averaging method unweighted pair group method with arithmetic mean (UPGMA) in hierarchical clustering is used to construct graphical visualization processing such as a phylogenetic tree, that can visually show the similarity and differences in microbial evolution in different environmental samples (Adopted from Singh et al., 2022)

Singh et al. (2022) analyzes the beta-diversity of endophytic bacterial communities across different tissues (roots, stems, leaves) of various sugarcane species. The results, visualized through a heat map and hierarchical clustering dendrogram, reveal distinct microbial community structures associated with specific tissue types. Roots from different sugarcane species tend to cluster together, indicating similar microbial compositions, while leaves and stems form separate clusters. This suggests that endophytic bacterial communities are tissue-specific and may be influenced by the unique environmental conditions and physiological functions of each tissue. The clear separation between the microbial communities in roots compared to other tissues highlights the complexity and diversity of endophytic bacteria in sugarcane, with potential implications for crop health and productivity.

3.3 Economic and environmental benefits

The integration of BNF into sugarcane cultivation can lead to substantial economic and environmental benefits. Economically, reducing the reliance on synthetic N fertilizers can lower production costs and increase profitability for farmers. For example, the use of cover crops has been shown to provide an annual N fertilizer replacement of 9 to 15 kg ha^{-1}, translating to significant cost savings (Tenelli et al., 2021). Environmentally, BNF can mitigate the adverse effects of excessive fertilizer use, such as greenhouse gas emissions and soil degradation. Studies have highlighted that optimizing BNF can reduce nitrous oxide emissions, a potent greenhouse gas, thereby contributing to climate change mitigation (Yang et al., 2020). Additionally, the use of organic amendments and biofertilizers can enhance soil health and biodiversity, promoting sustainable agricultural practices (Soumare et al., 2022; Junior et al., 2023).

3.4 Challenges and limitations

Despite the potential benefits, there are several challenges and limitations associated with the widespread adoption of BNF in sugarcane cultivation. One major challenge is the variability in BNF efficiency among different sugarcane varieties and environmental conditions. Genetic and environmental factors can influence the effectiveness of nitrogen-fixing bacteria, necessitating further research to identify and develop high-BNF sugarcane varieties (Singh et al., 2022; Luo et al., 2023). Additionally, the establishment and maintenance of beneficial microbial communities in the rhizosphere can be complex and may require specific management practices (Guo et al., 2023). There are also practical considerations, such as the initial costs and labor associated with implementing cover crops or biofertilizers, which may deter some farmers from adopting these practices (Tenelli et al., 2021; Junior et al., 2023). Finally, there is a need for more comprehensive studies to fully understand the long-term impacts of BNF on soil health and crop productivity.

In conclusion, while BNF presents a viable strategy to reduce chemical fertilizer dependency in sugarcane cultivation, addressing the associated challenges and limitations is crucial for its successful implementation. Continued research and development, along with farmer education and support, will be essential to harness the full potential of BNF for sustainable sugarcane production.

4 Case Study

4.1 Description of the study area

The study area for this case study is located in a region known for its extensive sugarcane cultivation. The soil types in this area include both sandy and clayey soils, which are representative of the diverse agricultural conditions under which sugarcane is grown. The climate is tropical, with distinct wet and dry seasons, providing a suitable environment for sugarcane growth and the implementation of Biological Nitrogen Fixation (BNF) techniques.

4.2 Implementation of BNF techniques

In this study, various BNF techniques were implemented to assess their impact on reducing the need for synthetic nitrogen fertilizers in sugarcane cultivation. One approach involved the use of legume cover crops, such as *Crotalaria spectabilis*, during the renovation period of sugarcane fields. This method aimed to enhance soil nitrogen content through the natural nitrogen-fixing abilities of the legume plants (Tenelli et al., 2021). Another technique included the inoculation of sugarcane with diazotrophic bacteria, which are known to fix atmospheric nitrogen and make it available to the plants. Different strains of these bacteria were tested to evaluate their effectiveness in promoting sugarcane growth and nitrogen uptake (Martins et al., 2020; Pereira et al., 2020).

4.3 Outcomes and observations

The implementation of BNF techniques yielded several notable outcomes. The use of legume cover crops resulted in increased soil nitrogen storage and microbial biomass carbon, which contributed to higher sugarcane yields. Specifically, cover crops increased sugarcane yield by 9% in sandy soils and 15% in clayey soils compared to bare fallow fields (Tenelli et al., 2021). Inoculation with diazotrophic bacteria also showed promising results, with some treatments leading to a 15% increase in sugarcane yield and an 18% increase in nitrogen content in the shoots (Pereira et al., 2020). Additionally, the contribution of BNF to the total nitrogen uptake by sugarcane was significant, with some studies reporting that BNF accounted for up to 47% of the nitrogen supply in sugarcane (Monteiro et al., 2021).

4.4 Lessons learned and future directions

The case study highlights the potential of BNF techniques to reduce the reliance on synthetic nitrogen fertilizers in sugarcane cultivation, thereby promoting more sustainable agricultural practices. Key lessons learned include the importance of selecting appropriate legume cover crops and diazotrophic bacterial strains to maximize nitrogen fixation and crop yield. Future research should focus on optimizing these techniques for different soil types and environmental conditions to enhance their effectiveness. Additionally, exploring the genetic diversity of sugarcane and its wild relatives, such as *Saccharum spontaneum*, may provide insights into developing high-BNF sugarcane varieties with improved nitrogen use efficiency (Carvalho et al., 2022; Luo et al., 2023). Further studies should also investigate the long-term impacts of BNF techniques on soil health and greenhouse gas emissions to fully understand their environmental benefits (Santos et al., 2019; Soumare et al., 2022).

5 Comparative Analysis with Other Sustainable Practices

5.1 Comparison with organic fertilizers

Biological nitrogen fixation (BNF) and organic fertilizers both aim to reduce the reliance on synthetic nitrogen (N) fertilizers, but they operate through different mechanisms. BNF involves the conversion of atmospheric nitrogen into a form usable by plants through symbiotic relationships with nitrogen-fixing bacteria, while organic fertilizers, such as chicken litter, provide nitrogen through the decomposition of organic matter.

Studies have shown that the use of organic fertilizers like chicken litter can be as effective as mineral nitrogen (MN) fertilizers in promoting sugarcane growth and yield. For instance, the application of chicken litter increased sugarcane yield and improved plant growth metrics such as height and tiller number, comparable to the effects of ammonium nitrate (Junior et al., 2023). Additionally, organic fertilizers contribute to soil health by enhancing soil organic carbon (SOC) and microbial biomass, which are crucial for long-term soil fertility (Tenelli et al., 2021).

5.2 Comparison with integrated nutrient management

Integrated Nutrient Management (INM) combines the use of organic and inorganic fertilizers to optimize nutrient availability and improve crop yields sustainably. INM practices often include the use of cover crops, crop rotations, and the strategic application of fertilizers to enhance nutrient use efficiency (NUE).

Research indicates that INM can significantly improve sugarcane yields and reduce environmental impacts. For example, the use of legume cover crops in sugarcane fields has been shown to increase soil nitrogen storage and microbial biomass, leading to higher yields without the need for additional synthetic N fertilizers (Tenelli et al., 2021). Similarly, adjusting the timing and rate of N fertilizer application can enhance NUE and reduce nitrogen losses, as demonstrated by increased sugarcane yields when N was applied at optimal times (Castro et al., 2019).

5.3 Long-term sustainability and yield impacts

The long-term sustainability of sugarcane cultivation practices is a critical consideration. BNF offers a sustainable alternative by reducing the need for synthetic N fertilizers, which are associated with greenhouse gas emissions and environmental pollution. Studies have shown that BNF can maintain or even increase sugarcane yields over multiple harvests, contributing to long-term soil fertility and sustainability (Figure 3) (Tenelli et al., 2021; Luo et al., 2023).

Luo et al. (2023) illustrates the substantial genetic variation observed in *Saccharum spontaneum* accessions for traits such as shoot length, stalk number, and brix percentage. The analysis reveals significant variability among the different genotypes, with some accessions demonstrating superior performance in one or more traits. For instance, accession G152 showed the highest BNF activity, while others like G103 performed poorly. Similarly, shoot length, stalk number, and brix content also exhibited considerable variation, although the range was less pronounced compared to BNF activity. The results underscore the genetic diversity within *S. spontaneum* and highlight the potential for selecting and breeding specific clones with desirable traits for improving sugarcane cultivation and productivity. This genetic variability is crucial for enhancing crop resilience and yield.

In comparison, organic fertilizers also support long-term sustainability by improving soil health and reducing dependency on synthetic inputs. However, the effectiveness of organic fertilizers can vary based on the type and rate of application. For instance, the application of mill mud, an organic fertilizer, has been shown to reduce dissolved inorganic nitrogen (DIN) losses in runoff, thereby protecting aquatic ecosystems (Vilas et al., 2021).

INM practices, which integrate both organic and inorganic fertilizers, offer a balanced approach to sustainable sugarcane cultivation. By optimizing nutrient inputs and enhancing soil health, INM can improve crop yields and reduce environmental impacts over the long term. For example, the strategic use of organic and inorganic fertilizers in combination with cover crops has been shown to enhance sugarcane yields and soil fertility (Tenelli et al., 2021; Vilas et al., 2021).

In conclusion, while BNF, organic fertilizers, and INM each have their unique advantages, integrating these practices can provide a comprehensive approach to sustainable sugarcane cultivation. By leveraging the strengths of each method, it is possible to achieve high yields, improve soil health, and reduce environmental impacts.

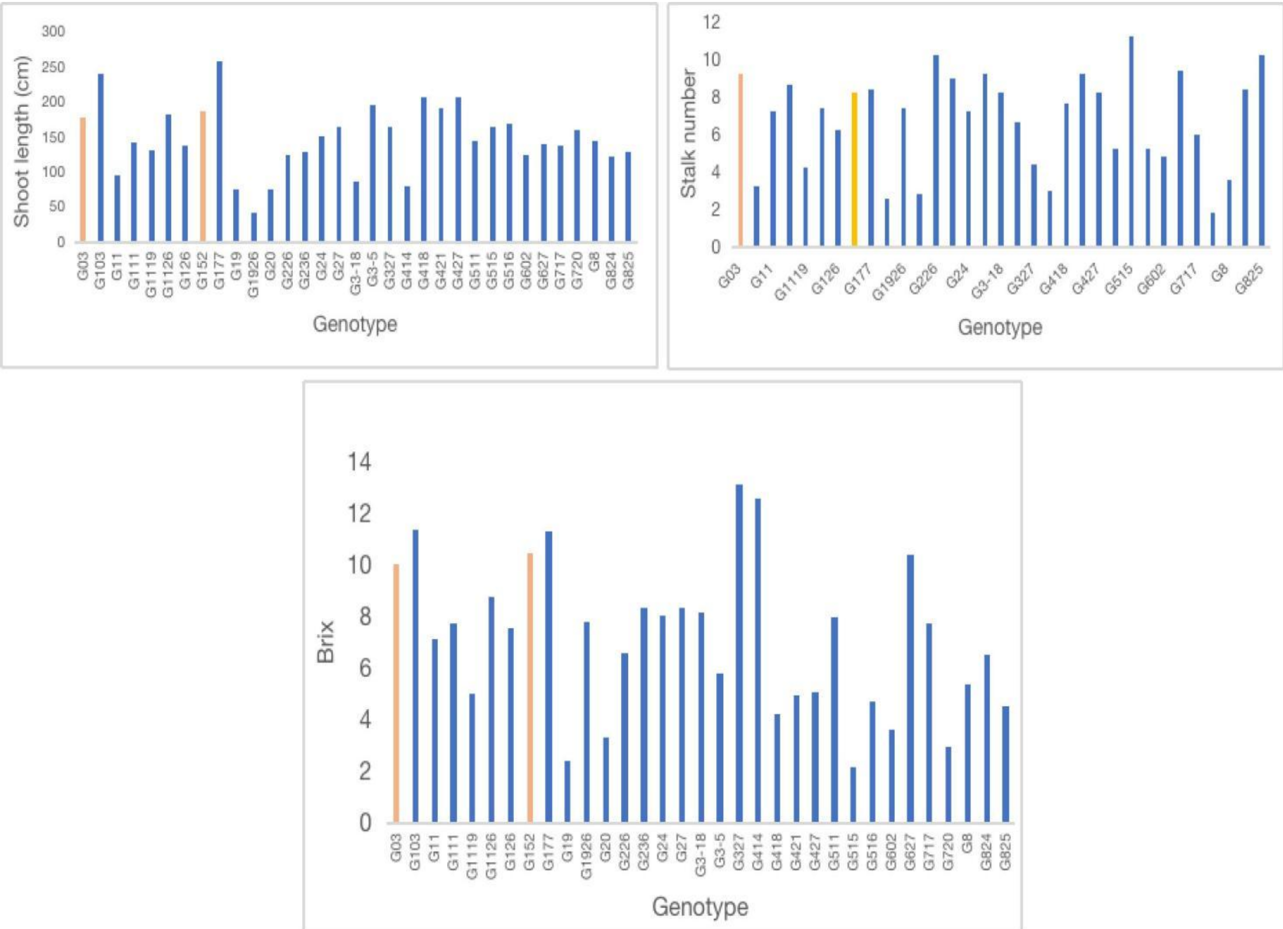

Figure 3 Variation in shoot length, stalk number per stool and brix (%) of *S. spontaneum* accessions Values are mean of 6 independent measurements; shoot length l.s.d. 15.4, $p < 0.001$; shoot number l.s.d. 1.2, $p < 0.001$; brix l.s.d. 1.09, $p < 0.001$ (Adopted from Luo et al., 2023)

6 Policy and Management Implications

6.1 Encouraging BNF adoption in sugarcane cultivation

The adoption of Biological Nitrogen Fixation (BNF) in sugarcane cultivation can significantly reduce the dependency on synthetic nitrogen fertilizers, thereby promoting sustainable agricultural practices. Research has shown that inoculating sugarcane with diazotrophic bacteria can enhance nitrogen acquisition and improve crop yields (Martins et al., 2020; Pereira et al., 2020). Additionally, the use of legume cover crops has been demonstrated to increase soil nitrogen storage and microbial biomass, which in turn boosts sugarcane yields without the need for additional synthetic fertilizers (Tenelli et al., 2021). To encourage the adoption of BNF, it is essential to educate farmers about the benefits of using nitrogen-fixing microorganisms and provide them with access to high-quality biofertilizers.

6.2 Government policies and subsidies

Government policies and subsidies play a crucial role in promoting sustainable agricultural practices. To support the adoption of BNF in sugarcane cultivation, governments can offer financial incentives for farmers who use biofertilizers and adopt nitrogen-fixing cover crops. Subsidies for research and development of efficient nitrogen-fixing microorganisms can also accelerate the commercialization of these biofertilizers (Soumare et al., 2020). Additionally, policies that promote the use of environmentally friendly agricultural practices, such as reducing synthetic fertilizer use, can further encourage the adoption of BNF (Luo et al., 2023).

6.3 Training and extension services for farmers

Training and extension services are vital for the successful implementation of BNF in sugarcane cultivation. Farmers need to be educated on the benefits of BNF, the proper use of biofertilizers, and the management practices required to optimize nitrogen fixation. Extension services can provide hands-on training, demonstrations, and technical support to farmers, helping them to adopt and integrate BNF into their farming systems (Santachiara et al., 2019). Collaborations between research institutions, agricultural extension agencies, and farmer organizations can facilitate the dissemination of knowledge and best practices related to BNF (Singh et al., 2022).

6.4 Future research directions

Future research should focus on identifying and developing more efficient nitrogen-fixing microorganisms that can be used as biofertilizers in sugarcane cultivation. Studies should explore the genetic and molecular mechanisms underlying BNF to enhance the nitrogen-fixing capacity of these microorganisms (Monteiro et al., 2021; Luo et al., 2023). Additionally, research should investigate the long-term effects of BNF on soil health, crop yields, and environmental sustainability. Understanding the interactions between nitrogen-fixing microorganisms and sugarcane plants at the physiological and molecular levels can provide insights into optimizing BNF for improved crop performance (Pereira et al., 2020; Singh et al., 2022). Finally, research should also address the challenges and limitations of transferring nitrogen fixation capacity to non-leguminous plants, which can further expand the application of BNF in agriculture (Soumare et al., 2020).

7 Concluding Remarks

The research on sustainable sugarcane cultivation has highlighted the significant potential of biological nitrogen fixation (BNF) in reducing the reliance on synthetic nitrogen (N) fertilizers. Several studies have demonstrated that integrating legume cover crops and intercropping with nitrogen-fixing plants can enhance soil nitrogen content and improve sugarcane yields. For instance, the use of legume cover crops like *Crotalaria spectabilis* has been shown to increase soil nitrogen storage and microbial biomass carbon, leading to a 9%-15% increase in sugarcane yield compared to bare fallow. Similarly, intercropping sugarcane with soybean under reduced nitrogen input has been found to enhance phosphorus acquisition and overall system P-use efficiency, contributing to sustainable sugarcane production.

Moreover, optimizing nitrogen fertilization practices, such as the timing and amount of application, can significantly improve nitrogen use efficiency (NUE) and reduce environmental impacts. Studies have shown that applying nitrogen fertilizer at specific times (e.g., 45 days after harvest) can increase sugarcane yield and sugar content. Additionally, the genetic base-broadening of sugarcane using high-BNF *Saccharum spontaneum* accessions has shown promise in developing nitrogen-efficient varieties.

The future of sustainable sugarcane cultivation lies in the continued exploration and integration of biological nitrogen fixation strategies. Research should focus on identifying and utilizing high-BNF sugarcane varieties and optimizing intercropping systems with legumes to maximize nitrogen fixation and improve soil health. Additionally, advancements in molecular and physiological understanding of BNF mechanisms in sugarcane and its wild relatives can pave the way for breeding programs aimed at enhancing nitrogen efficiency.

Furthermore, sustainable water-fertilizer management practices, such as drip irrigation combined with optimal fertilization levels, should be promoted to reduce greenhouse gas emissions and maintain soil health. The development of eco-friendly nitrogen application strategies that minimize the use of chemical fertilizers while maintaining high yields is crucial for the long-term sustainability of sugarcane cultivation.

In conclusion, the integration of biological nitrogen fixation into sugarcane cultivation presents a viable pathway to reduce the dependency on synthetic nitrogen fertilizers, thereby enhancing the sustainability of sugarcane production. The findings from various studies underscore the importance of adopting legume cover crops, intercropping systems, and optimized fertilization practices to improve nitrogen use efficiency and soil health. Future research should continue to explore innovative approaches to harness the potential of BNF and develop sustainable agricultural practices that can mitigate environmental impacts and ensure the long-term viability of sugarcane cultivation.

By leveraging the benefits of biological nitrogen fixation and sustainable management practices, the sugarcane industry can move towards a more environmentally friendly and economically viable future, contributing to global efforts in sustainable agriculture and climate change mitigation.

Acknowledgments
Author thanks to the reviewers for their constructive feedback, which has contributed to the improvement of this study.

Conflict of Interest Disclosure
Author affirms 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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