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Evaluating the Potential of Biological Nitrification Inhibition (BNI) in Sorghum Using an Ex-Ante Crop Modeling Approach with DSSAT

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Cover photo: African boy with sorghum grain

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Contents

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Abstract

Nitrogen (N) is a critical input for crop production, yet nitrogen use inefficiencies result in substantial economic losses and environmental externalities, including nitrate leaching and greenhouse gas emissions. Biological Nitrification Inhibition (BNI) is a plant-mediated mechanism that suppresses soil nitrification via root-secreted compounds, thereby improving nitrogen retention in agroecosystems. This working paper evaluates the potential agronomic and environmental benefits of incorporating BNI activity into sorghum using an ex-ante crop simulation approach. The DSSAT crop system model was applied for a representative irrigated post-rainy (Rabi) sorghum system in Ahmednagar district, Maharashtra, India, using the widely cultivated sorghum hybrid CSH-5. Virtual sorghum cultivars with varying BNI efficiency were assessed, and duration was evaluated by modifying the DSSAT fertilizer parameter file in accordance with recommended nitrogen management. Results indicate that high-efficiency, long-duration BNI scenarios can increase sorghum yields by up to 7%, reduce nitrogen losses, and lower cumulative CO_2-equivalent greenhouse gas emissions by up to 12% over the crop season. The findings provide robust ex-ante evidence supporting BNI-enabled sorghum as a climate-smart, resource-efficient innovation for dryland and irrigated cereal systems.

1. Introduction

Nitrogen (N) is a central driver of crop productivity and global food security, underpinning yield gains achieved over the past half-century. However, the efficiency with which applied nitrogen is converted into harvested grain remains low in many cereal-based production systems, particularly in the tropics and subtropics. A substantial proportion of applied nitrogen is lost through leaching, runoff, denitrification, and ammonia volatilization, resulting in economic inefficiencies and significant environmental externalities, including groundwater contamination and nitrous oxide (N_2O) emissions, a potent greenhouse gas (O'Hara et al., 2002; Butterbach-Bahl et al., 2013).

Conventional approaches for improving nitrogen use efficiency have largely focused on fertilizer management strategies, including split applications, enhanced-efficiency fertilizers, and precision nutrient management. While these interventions can reduce nitrogen losses, their effectiveness is often constrained by cost, management complexity, and variable farmer adoption, particularly in smallholder-dominated systems (Akiyama et al., 2010). As a result, increasing attention has turned toward plant-based solutions that can intrinsically regulate nitrogen transformations in the soil–plant system.

Biological Nitrification Inhibition (BNI) represents a novel and promising plant-mediated mechanism through which crops can influence soil nitrogen cycling. BNI refers to the capacity of certain plant species to release inhibitory compounds from their roots that suppress the activity of ammonia-oxidizing microorganisms, thereby slowing the conversion of ammonium (NH_4^+) to nitrate (NO_3^-) (Subbarao et al., 2007; Subbarao et al., 2015). Maintaining nitrogen in the ammonium form for longer periods, BNI can reduce nitrate leaching and denitrification losses, improve synchronization between nitrogen supply and crop demand, and mitigate N_2O emissions.

Experimental studies have demonstrated substantial variation in BNI capacity among plant species and genotypes, with particularly strong effects observed in sorghum (*Sorghum bicolor*) and tropical forage grasses such as *Brachiaria* (Subbarao et al., 2009; Subbarao et al., 2013). In sorghum, BNI activity has been linked to specific root exudates and has been shown to suppress soil nitrification under both controlled and field conditions, thereby improving nitrogen retention in the rhizosphere. These findings have positioned sorghum as a leading candidate crop for integrating BNI traits into breeding programs to improve nitrogen use efficiency and environmental performance.

Despite growing physiological and biochemical understanding of BNI, several important knowledge gaps still remain. First, most existing evidence is derived from plot-level experiments or short-term measurements of nitrification rates and N_2O fluxes, which do not fully capture system-level outcomes such as seasonal yield response, cumulative nitrogen losses, and whole-crop greenhouse gas emissions. Second, the performance of BNI-enabled genotypes under contrasting soil types, management regimes, and production environments remains insufficiently explored. Third, empirical evaluation of BNI across multiple environments is time- and resource-intensive, underscoring the need for complementary analytical tools that can support early-stage prioritization.

Crop system models provide a powerful ex-ante framework to address these gaps by integrating crop growth, soil nitrogen processes, and environmental outcomes within a unified analytical platform (Antle et al., 2017). The DSSAT (Decision Support System for Agrotechnology Transfer) modeling framework, in particular, offers flexibility to represent fertilizer behavior, nitrification inhibitors, and soil–crop interactions, enabling simulation of BNI effects without altering core model structure. Parameterizing plausible ranges of BNI efficiency and duration, crop models can be used to explore potential agronomic and environmental impacts prior to large-scale breeding, field testing, or deployment.

Against this backdrop, the objective of this study is to evaluate the potential productivity, nitrogen-use, and greenhouse gas mitigation benefits of incorporating BNI activity into sorghum using an ex-ante crop modeling approach. Using DSSAT, we simulated virtual sorghum cultivars with varying BNI efficiency and duration under a representative irrigated post-rainy (Rabi) sorghum production system in western India. Specifically, the study aims to: (i) quantify the potential yield benefits of BNI-enabled sorghum; (ii) assess changes in nitrogen dynamics and losses; (iii) estimate implications for N_2O and CO_2-equivalent greenhouse gas emissions; and (iv) examine how these effects vary across contrasting soil types. By providing system-level evidence under realistic management conditions, this study seeks to inform sorghum breeding strategies, agronomic research, and policy discussions on climate-smart and resource-efficient cereal production.

2. Methodological Framework

2.1. Crop Simulation Model

The DSSAT v4.8 crop simulation framework was used to simulate sorghum growth, soil nitrogen dynamics, and greenhouse gas emissions. The CERES-Sorghum module was applied to represent crop phenology, biomass accumulation, and yield formation under irrigated post-rainy season conditions.

2.2. Study Location and Cropping System

Simulations were conducted for Ahmednagar district, Maharashtra, India, representing a major sorghum-growing region under irrigated Rabi (post-rainy) season conditions.

Key system characteristics include:

- Location: Ahmednagar, Maharashtra, India
- Season: Rabi (October–February)
- Water management: Fully irrigated
- Production environment: Semi-arid tropical

Daily weather data of the Ahmednagar environment were used to drive simulations.

2.3. Sorghum Cultivar and Crop Duration

The simulations were based on the sorghum hybrid CSH-5, a widely cultivated variety in India, with:

- Crop duration: ~120 days
- Phenology: Medium-duration Rabi sorghum

The baseline genetic coefficients were retained across all scenarios to ensure that yield and environmental differences arose exclusively from nitrogen-process modifications associated with BNI, rather than varietal differences.

2.4. Crop and Nutrient Management

Fertilizer Management

Nitrogen fertilizer application followed recommended agronomic practices for irrigated Rabi sorghum in the region:

- Recommended nitrogen rate: **150 kg N ha^{-1}**
- **Split application**:
    - 75 kg N ha^{-1} at sowing
    - 75 kg N ha^{-1} at 35 days after sowing

This split application was consistently applied across all BNI and non-BNI scenarios.

Other crop management practices (planting date, irrigation scheduling, and crop husbandry) were held constant across scenarios.

2.5 Representation of Biological Nitrification Inhibition (BNI)

Biological nitrification inhibition was simulated by modifying fertilizer nitrification inhibitor parameters within the DSSAT fertilizer parameter file (FERCH048.SDA) located in the DSSAT standard data directory. BNI effects were represented through changes in:

- **NIEFF**: Nitrification inhibition efficiency (% reduction in nitrification)
- **NIDUR**: Duration of nitrification inhibition (days)

Five scenarios were simulated:

Scenario	NIEFF (%)	NIDUR (days)
Normal sorghum (no BNI)	0	0
High efficiency – long duration	80	40
Medium efficiency – long duration	60	40
High efficiency – medium duration	80	25
Medium efficiency – medium duration	60	25

These scenarios were designed to reflect plausible ranges of BNI expression reported for BNI-enabled genotypes, without altering fertilizer rates or application timing.

2.6 Calibration and Scenario Evaluation Approach

An **ex-ante calibration strategy** was adopted, appropriate for evaluating hypothetical BNI-enabled genotypes. Model performance was assessed through:

1. **Baseline realism checks**, ensuring simulated yields for CSH-5 under irrigated Rabi conditions fell within observed regional ranges;

2. **Relative impact assessment**, with results expressed as percentage changes relative to the non-BNI baseline; and

3. **Nitrogen mass balance verification**, confirming consistency among ammonium, nitrate, plant uptake, and nitrogen loss pathways.

No site-specific calibration of BNI parameters was conducted, as the objective was to assess relative system-level responses.

2.7 Greenhouse Gas Emissions Accounting

Daily nitrous oxide (N_2O) emissions simulated by DSSAT were aggregated over the 120-day crop duration. Seasonal cumulative emissions were converted to **CO_2-equivalent emissions** using IPCC 100-year global warming potential factors. Emission results are presented as relative mitigation potential under BNI scenarios compared with the non-BNI baseline.

3. Results

3.1 Effects on Sorghum Yield

Simulated results show that virtual sorghum cultivars with **high BNI efficiency (80%) and long duration (40 days)** achieved the highest yield gains, with an average increase of 7.0% relative to the non-BNI baseline.

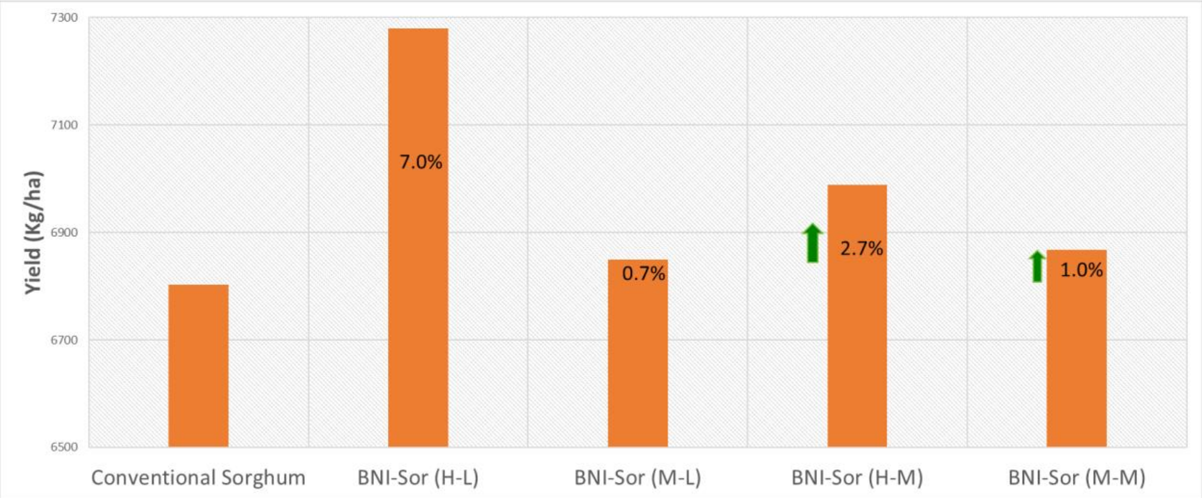

Figure 1. Simulated sorghum yield under alternative BNI scenarios

3.2 Nitrogen Dynamics and Loss Reduction

BNI scenarios resulted in:

- Reduced daily inorganic nitrogen availability in soil solution
- Lower nitrate formation and leaching potential
- Improved synchronization between nitrogen supply and crop demand

These effects contribute to **improved nitrogen use efficiency and reduced system-level nitrogen losses.**

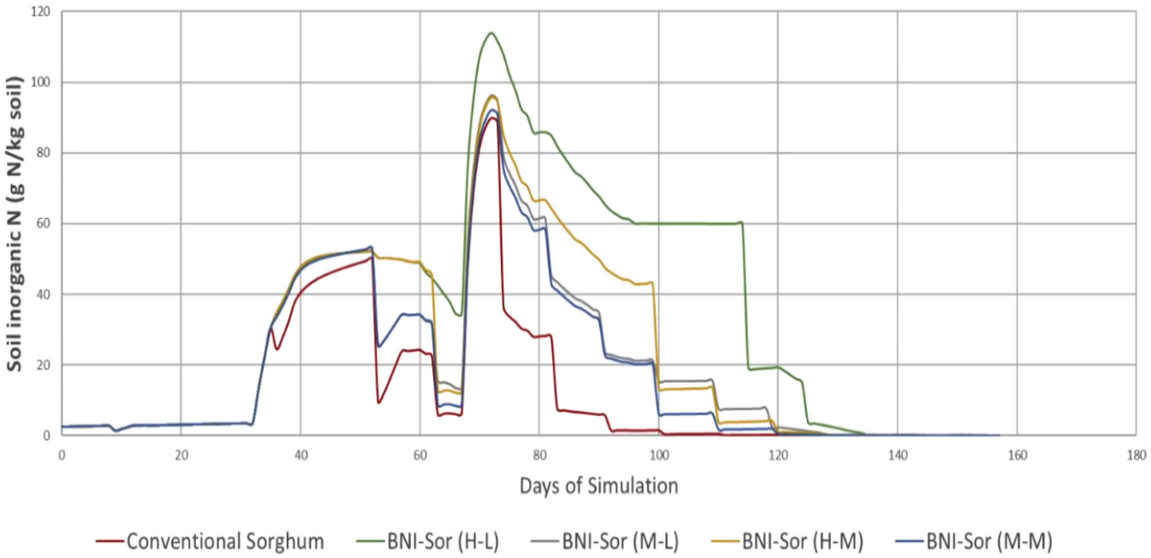

Figure 2. Daily soil inorganic nitrogen dynamics under BNI and non-BNI scenarios

3.3 Greenhouse Gas Emissions

BNI incorporation significantly reduced daily and cumulative N_2O emissions. Across the cropping period, total CO_2-equivalent **greenhouse gas emissions declined by up to 12%** compared to the baseline scenario.

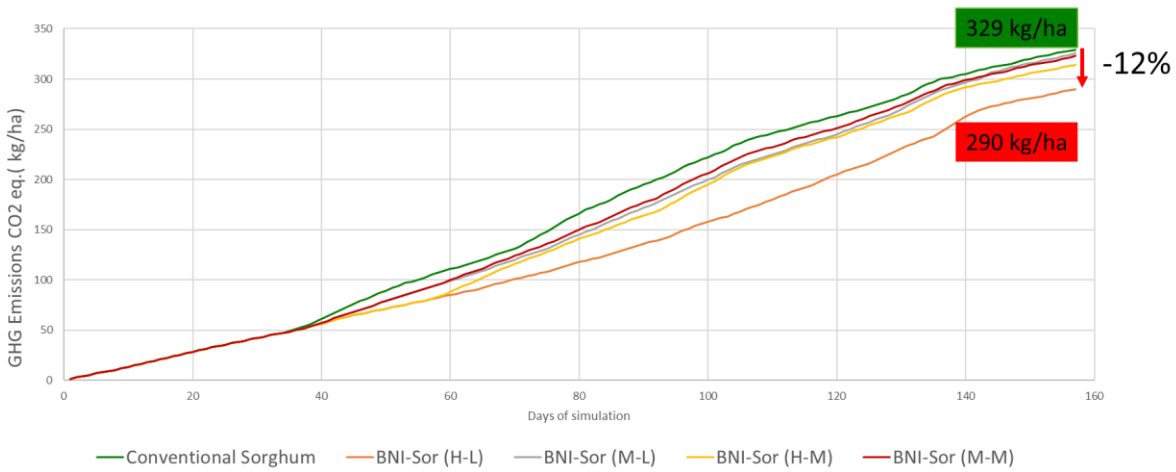

Figure 3. CO_2-equivalent emissions across scenarios

3.4 Soil-Specific Responses

BNI impacts varied across soil types:

- Yield advantage was greater in **Alfisols (6.8%)** than in **Vertisols (3.0%)**
- Absolute GHG mitigation was higher in **Vertisols (≈503 kg CO_2 eq)** compared with **Alfisols (≈396 kg CO_2 eq)**

These differences underscore the importance of soil-specific targeting of BNI-enabled cultivars.

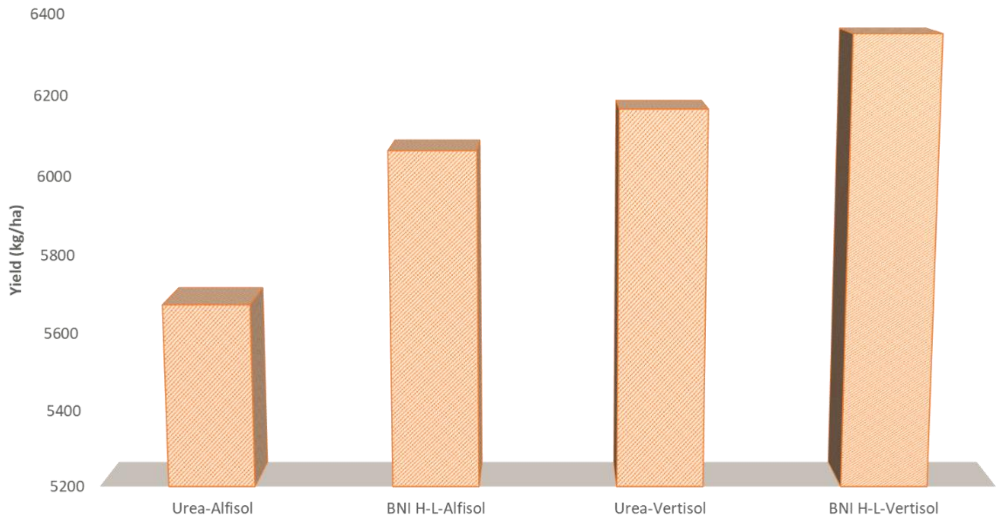

Figure 4. Yield effects of BNI across soil types

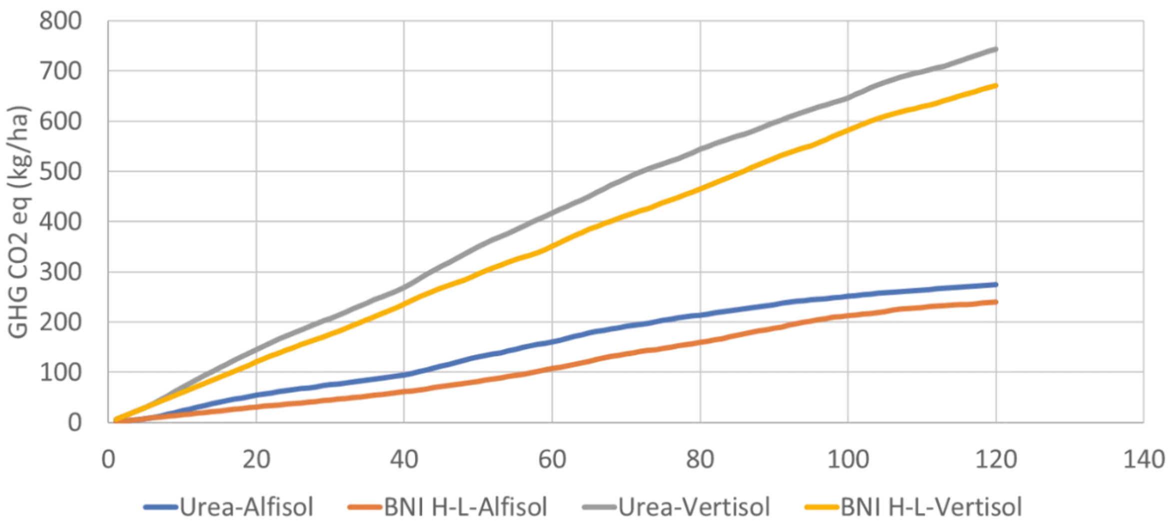

Figure 5. GHG mitigation effects of BNI across soil types

4. Discussion

Biological Nitrification Inhibition (BNI) has gained increasing attention as a plant-mediated strategy to improve nitrogen use efficiency and reduce environmental nitrogen losses in agricultural systems (Subbarao et al., 2007; Subbarao et al., 2015). Experimental studies, particularly in sorghum and tropical forage grasses such as *Brachiaria*, have demonstrated that root-released allelochemicals can substantially suppress soil nitrification by inhibiting ammonia-oxidizing microorganisms, thereby altering nitrogen transformation pathways in the rhizosphere (Subbarao et al., 2013; Byrnes et al., 2017). Despite these advances, quantitative evidence on the **system-level agronomic and environmental impacts of BNI under realistic management and soil conditions** remains limited. This study addresses this gap through an ex-ante, crop-system modeling assessment.

The simulated yield gains associated with high-efficiency, long-duration BNI scenarios (up to 7%) are consistent with the theoretical and experimental understanding that BNI improves synchronization between nitrogen availability and crop nitrogen demand. By slowing the conversion of ammonium to nitrate, BNI reduces early-season nitrogen losses when plant uptake capacity is still limited, resulting in greater nitrogen retention within the root zone (Subbarao et al., 2015; Rao et al., 2017). Field experiments in sorghum have reported improved nitrogen recovery and, in some cases, yield benefits associated with high-BNI genotypes, particularly under conditions prone to nitrate leaching (Subbarao et al., 2009). The present modeling results extend this evidence by showing that BNI-related yield benefits can persist even under **irrigated, high-input Rabi sorghum systems**, where fertilizer losses are often assumed to be less constraining.

A major contribution of this study is the explicit quantification of greenhouse gas mitigation benefits associated with BNI. Nitrous oxide (N_2O) emissions are closely linked to nitrification and denitrification processes, and reductions in nitrification rates have been shown to lower N_2O emissions in both controlled and field conditions (Akiyama et al., 2010; Subbarao et al., 2013). The modeled reduction of up to 12% in cumulative CO_2-equivalent emissions aligns with experimental observations reporting lower N_2O fluxes in high-BNI systems (Byrnes et al., 2017). Importantly, these mitigation gains were achieved **without reducing nitrogen application rates**, highlighting BNI as a genetic and biological mitigation pathway that complements agronomic nutrient management rather than substituting for it. This characteristic makes BNI particularly attractive in contexts where fertilizer reduction is constrained by yield risk or food security objectives.

The soil-specific responses observed in this study further reinforce earlier research's findings, emphasizing the context-dependent nature of BNI effectiveness. Greater yield gains in Alfisols likely reflect their higher susceptibility to nitrate leaching due to lighter texture and faster drainage, conditions under which suppression of nitrification more directly translates into improved nitrogen availability for crop uptake (Rao et al., 2017). In contrast, the larger absolute greenhouse gas mitigation observed in Vertisols is consistent with their higher denitrification potential associated with greater clay content, water retention, and periodic anaerobic conditions (Butterbach-Bahl et al., 2013). These results suggest that BNI-enabled cultivars may deliver **different dominant benefits, yield stability versus emission mitigation, depending on soil type**, underscoring the importance of targeted deployment strategies.

From a methodological perspective, representing BNI through nitrification inhibitor parameters within DSSAT provides a pragmatic and transparent approach for ex-ante evaluation. While this approach simplifies complex biological processes such as dynamic root exudation, microbial adaptation, and spatial heterogeneity in the rhizosphere, it captures the first-order effects of nitrification suppression on nitrogen cycling and crop performance (Antle et al., 2017). The relative-impact focus adopted here is consistent with best practices in ex-ante impact assessment of emerging traits and provides credible evidence to inform breeding prioritization, research investment, and policy dialogue. Future work should integrate field-based measurements with modeling to refine parameterization, explore interannual variability in BNI expression, and assess longer-term system feedbacks.

Overall, the findings position BNI-enabled sorghum as a **strategic innovation at the intersection of productivity enhancement, nutrient-use efficiency, and climate mitigation**. Unlike input-intensive mitigation options, BNI represents a biologically embedded trait that can be scaled through breeding and seed systems, making it particularly relevant for smallholder-dominated cereal systems. By providing system-level evidence under realistic management conditions, this study strengthens the empirical and conceptual basis for integrating BNI into sorghum improvement programs and climate-smart agriculture strategies.

5. Conclusions and Policy Relevance

This study provides robust ex-ante evidence that BNI-enabled sorghum has the potential to improve yields by up to 7%, substantially reduce nitrogen losses and N_2O emissions, and lower CO_2-equivalent greenhouse gas emissions by up to 12%. The magnitude of benefits is strongly influenced by soil context, emphasizing the need for location-specific targeting. Overall, BNI represents a promising pathway to advance climate-smart, resource-efficient cereal production systems. These findings support investments in BNI-oriented sorghum breeding, field validation, and scaling as part of climate-smart and resource-efficient dryland agriculture strategies aligned with national and global sustainability goals.

6. Limitations

As the study adopts a simulation-based, ex-ante framework to explore the potential impacts of biological nitrification inhibition in irrigated Rabi sorghum systems, BNI effects were represented using a step-function inhibitor approach within DSSAT. This representation does not explicitly capture dynamic root exudation processes or soil microbial feedbacks. In addition, multi-season carryover effects of BNI on soil nitrogen dynamics were not evaluated, as simulations were limited to a single crop cycle. These limitations may affect the absolute magnitude of simulated impacts but do not affect relative comparisons between BNI and non-BNI scenarios, which are the primary focus of this analysis.

7. Future Research Directions

Future work should focus on field-level validation of modeled BNI effects, integration of BNI traits into sorghum breeding pipelines, economic and welfare impact assessment of BNI adoption, and long-term system simulations under climate change scenarios. The reproducible DSSAT-based modeling framework developed in this study, with documented input files and parameter modifications, enables replication and extension of the analysis across locations and scenarios.

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About

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is a pioneering, international non-profit scientific research for development organization, specializing in improving dryland farming and agri-food systems. The Institute was established as an international organization in 1972, by a Memorandum of Agreement between the Consultative Group on International Agricultural Research and the Government of India. ICRISAT works with global partners to develop innovative science-backed solutions to overcoming hunger, malnutrition, poverty, and environmental degradation on behalf of the 2.1 billion people who reside in the drylands of Asia, sub-Saharan Africa, and beyond.

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