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Estimating the effect of biological nitrification inhibition-enabled sorghum on nitrogen fertilizer consumption, life cycle GHG emissions, farmer's benefit and fertilizer subsidy from Indian sorghum production

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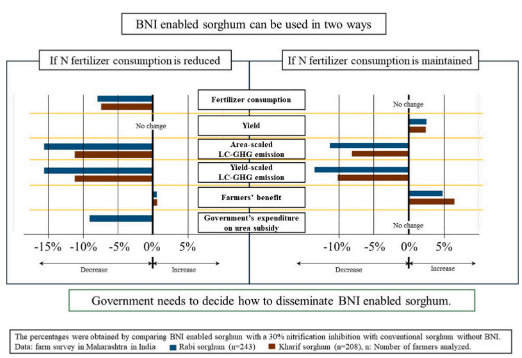
HIGHLIGHTS

- Biological nitrification inhibition enabled sorghum (BNIS) cultivar slows nitrifier activity.
- BNIS reduces nitrogen (N) loss and improves nitrogen use efficiency.
- BNIS can be used in two ways: reduce or maintain N fertilizer consumption.
- They reduce GHG emissions and improve farmers' benefits at different levels.
- Government needs to discuss dissemination ways before introducing BNIS to farmers.

GRAPHICAL ABSTRACT



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ABSTRACT

Biological nitrification inhibition (BNI) effectively curtails nitrogen (N) loss and enhances N utilization efficiency. BNI is increasingly important as a technology for mitigating greenhouse gas emissions and water pollution in countries with high N fertilizer consumption. This study aimed to evaluate the potential impacts of BNI-enabled sorghum varieties with a 30 % soil nitrification inhibition rate for a major sorghum-growing state (Maharashtra, India). We analysed the farm survey data collected for Rabi sorghum in 2020–2021 ($n = 250$) and for Kharif sorghum in 2022 ($n = 209$). Life cycle greenhouse gas (LC-GHG) emissions were estimated using a life cycle assessment with a cradle-to-farm gate perspective. The results showed that adoption of BNI-enabled sorghum reduced N fertilizer application in the Rabi and Kharif seasons by 8.0 % and 7.4 % and area-scaled/yield-scaled LC-GHG emissions by 15.6 % and 11.2 %, respectively, while increasing farmers' benefits slightly. These changes could reduce the government's expenditure on urea fertilizer subsidies by 9.1 %. However, many farmers indicated that they would not change N fertilizer application even if the yield per N fertilizer application increased. Even under these circumstances, area-scaled/yield-scaled LC-GHG emissions will be decreased by 11.3 % and 13.5 % in the Rabi season and 8.1 % and 10.2 % in the Kharif season, respectively. The yield and farmers' benefit will increase by 2.5 % and 4.9 % in the Rabi season and by 2.4 % and 6.5 % in the Kharif season, respectively, but the government's expenditure on fertilizer will not decrease. These results indicate that BNI-

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enabled sorghum can be introduced into countries where fertilizer use is low. This study shows the potential impacts of BNI-enabled sorghum under two scenarios; N fertilizer consumption is reduced or maintained. Discussions on the N fertilizer consumption under BNI-enabled sorghum are needed to establish a sustainable food system, especially in countries with high N fertilizer consumption.

1. Introduction

High nitrogen (N) fertilizer consumption has led to enhanced soil nitrifier activity and nitrification, which has reduced the nitrogen use efficiency (NUE) to 30–50 % (Tilman et al., 2002). An excess amount of N is partially lost into the environment, exacerbating groundwater pollution and increasing nitrous oxide (N_2O) emissions, contributing to climate change. By 2030, anthropogenic greenhouse gas (GHG) emissions, including N_2O emissions, must be reduced by 43 % from the 2019 level to achieve carbon neutrality by 2050 and limit global warming to 1.5 °C compared with preindustrial levels (Intergovernmental Panel on Climate Change (IPCC), 2023). Growing climate-resilient crops enables adaption to climate change and increases in food production in response to population increases projected for 2050.

Under these conditions, sorghum (*Sorghum bicolor* (L.) Moench) is becoming increasingly important due to its good performance even under input constraints and adverse climate conditions (Khalifa and Eltahir, 2023). Among cereal crops, sorghum ranks as the 5th largest harvested area and production worldwide (FAOSTAT, 2024). Sorghum is a major crop in South Asia and sub-Saharan Africa (Khalifa and Eltahir, 2023). Globally, sorghum yields increased by 61 % between 1961 and 2018 (FAOSTAT, 2024). The yield increase is attributed to hybrid improvement, nitrogen (N) fertilizer application, irrigation, and tillage (Assefa and Staggenborg, 2010). Total GHG emissions to produce one ton of biomass sorghum are estimated at 333 kg CO_2-eq to 361 kg CO_2-eq in Australia (Simmons et al., 2019) and at 88 kg CO_2-eq to 147 kg CO_2-eq (Glab and Sowiński, 2019) for sweet sorghum in Poland according to life cycle assessment (LCA) studies. These studies reported that more than half of the total GHG emissions from sorghum cultivation are attributed to N fertilizer production and soil N_2O emissions (Glab and Sowiński, 2019; Samarappuli and Berti, 2018; Simmons et al., 2019).

India was the world's sixth largest sorghum-producing country in 2022, third largest in 2021, and fourth largest in 2020 (FAOSTAT, 2024). Fertilizer consumption in India increased after the 'Green Revolution' (Shukula et al., 2022) and was the second highest in the world in 2018 (IFA, 2022); furthermore, it has been strengthened by fertilization subsidies (Narayan and Gupta, 1991). Excessive subsidies, especially for urea, have distorted the balanced application of fertilizers, degraded the environment, and increased stress on national finances (Kumar and Chandra, 2010). India's carbon emissions are the third largest in the world (Crippa et al., 2023). The cereal NUE in India is 21 %, with a decreasing trend due to high N consumption (Omara et al., 2019).

Biological nitrification inhibition (BNI) is becoming critical for reducing N pollution and mitigating climate change. BNI suppresses soil nitrifier activity and reduces nitrate formation and N_2O emissions (Coskun et al., 2017; Subbarao et al., 2015). BNI-enabled wheat with a 30 % soil nitrification inhibition rate was developed by the Japan International Research Center for Agricultural Sciences (JIRCAS) and the International Maize and Wheat Improvement Center (CIMMYT). Based on field experiments, the research team reported that BNI-enabled wheat increased production when using the same N fertilizer as conventional wheat (Subbarao et al., 2021).

Among field crops, sorghum, pearl millet, and ground nuts have detectable BNI capacities (Subbarao et al., 2007). Sorghum releases hydrophobic (not soluble in water) and hydrophilic (soluble in water) BNI compounds from its roots (Subbarao et al., 2013). Sorgoleone, which is one of the compounds among the hydrophobic BNI, is found mainly in rhizosphere soils and contributes to >85 % of the total hydrophobic BNI. The release of sorgoleone varies depending on the genotype (Sarr et al., 2020; Tesfamariam et al., 2014) and N status (NH_4^+ vs. NO_3^-, Subbarao et al., 2013) but is not influenced by soil pH (Di et al., 2018; Subbarao et al., 2013). Methyl 3-(4-hydroxyphenyl) propionate (MHPP) and sakuranetin (5,4′-dihydroxy-7-methoxyflavanone) are two of the compounds within hydrophilic BNI. They are released with water and move farther from the soils of the rhizosphere. Their release increases when the rhizosphere soil pH is ≤5.0 and the N form is NH_4^+ (Zhu et al., 2012). Reductions in nitrification are observed through incubation experiments (Subbarao et al., 2013; Tesfamariam et al., 2014), fields (Watanabe et al., 2015), and greenhouse pipe experiments (Sarr et al., 2020). The reductions in nitrification vary with the BNI release capacities of sorghum genotypes. For example, the nitrification rate was reduced by 40 % in one of the sorghum genotypes (GDLP34-5-5-3) with high sorgoleone release during the 30-day incubation period. In contrast, it was reduced by 12 % by another genotype (IS41245) with lower sorgoleone release (Tesfamariam et al., 2014). A reduction in annual N_2O emissions of 18.1 % and an increase in yield of 6.7 % were observed in vegetable fields when urea was applied with intercropping of sorghum, which was used as a source of BNI, compared with urea treatment (Zhang et al., 2015). Lower N_2O emissions and nitrification were reported for maize and sorghum intercropping compared to maize mono cropping (Zhang et al., 2023).

With the aim of achieving carbon neutrality by 2050, the JIRCAS and International Crops Research Institute for the Semiarid Tropics (ICRISAT) research team is currently developing BNI-enabled elite sorghum varieties with a 30 % reduction in soil nitrification (Subbarao and Serchinger, 2021). As BNI-enabled sorghum varieties require more time to develop, an evaluation prior to technology dissemination will help decision makers allocate limited resources to develop this technology further and facilitate its deployment (Thornton et al., 2003). A study of wheat with a high BNI capacity examined the potential impact of BNI-enabled wheat. It concluded that it could be part of mitigation strategies to limit GHG emissions from agricultural systems by reducing N fertilizer application rates (Leon et al., 2021). However, studies must estimate the potential influence of other BNI-enabled crops reflecting farmers' management. This work is the first to evaluate the BNI-enabled sorghum by addressing the changes in farmers' benefits and fertilizer subsidies, N fertilizer use, and LC-GHG emissions based on farm surveys. The present study aims to (1) estimate the potential impacts of BNI-enabled sorghum, (2) present potential factors influencing fertilizer application rates, and (3) present the potential effects of farmer decisions on BNI sorghum by using farm data for Rabi and Kharif sorghum to carry out analysis.

2. Materials and methods

2.1. Scenario description

Sorghum is one of the few field crops that has detectable BNI capacity (Subbarao et al., 2007); the BNI capacity varies according to genotype (Tesfamariam et al., 2014) and soil conditions (Subbarao et al., 2013). Therefore, the current sorghum varieties cultivated by farmers have been assumed not to have BNI capacity (a baseline scenario). The base scenario is conventional sorghum, and the alternative scenario is BNI-enabled sorghum with 30 % soil nitrification inhibition (an alternative scenario, Subbarao and Serchinger, 2021).

Moreover, BNI-enabled sorghum was hypothesized to reduce N loss, which is lost through N_2O emissions during nitrification/denitrification processes and nitrate leaching, when urea is applied as N fertilizer. This is because heavy urea consumption and distortion of the fertilizer balance are caused mainly by heavily subsidized urea (Kishore et al., 2021). BNI-enabled sorghum was also assumed to reduce N fertilizer application rates without penalizing sorghum yield (Subbarao et al., 2021).

2.2. Estimating changes in the N fertilizer application rate

Based on the study scenarios and assumptions (Section 2.1), the changes in the N fertilizer application rate were estimated by modifying two equations in the Intergovernmental Panel on Climate Change (IPCC) guidelines (Intergovernmental Panel on Climate Change (IPCC), 2019), following Leon et al. (2021). One equation expresses the relationship between N fertilizer application rates and loss through direct N_2O emissions. Another equation describes the relationship between N fertilizer application rates and loss through indirect N_2O emissions attributable to leaching and runoff (Intergovernmental Panel on Climate Change (IPCC), 2019). The emission factors in IPCC Guideline 2019 were used in this paper; these differ from those used by Leon et al. (2021), which were based on IPCC Guideline 2006. The details, including emission factors, are provided in Appendices A-1 and A-2.

2.3. A LCA case study of sorghum in India

2.3.1. Goal and scope

The LCA followed the ISO 14040 (International Organization for Standardization (ISO), 2006a) and 14044 (International Organization for Standardization (ISO), 2006b) guidelines. The present study aimed to estimate the potential impacts of BNI-enabled sorghum with 30 % soil nitrification inhibition on N fertilizer application rates, LC-GHG emissions, farmers' benefits, and government expenditures on urea fertilizer subsidies. The system boundary was a cradle-to-farm gate, which includes material production and sorghum cultivation stages (i.e., land preparation, sowing, fertilizer and pesticide applications, weeding, harvesting, drying and threshing). The functional units were defined as 1 kg of sorghum grain or 1 ha of sorghum cultivation per crop season.

2.3.2. Study area

Rabi (post-monsoon, dry season) sorghum grain is mainly used for food and stalk as fodder, and approximately half of Kharif (monsoon, rainy season) sorghum grain is used for animal feed and industry purpose (De Fries et al., 2023). We conducted the survey in Maharashtra state, which has the highest sorghum production in India, to obtain inventory data for Rabi sorghum in 2020–2021 and for Kharif sorghum in 2022. The survey regarding Rabi sorghum was carried out in the Pune, Kolhapur, Sangli, and Satara districts in Maharashtra. The survey

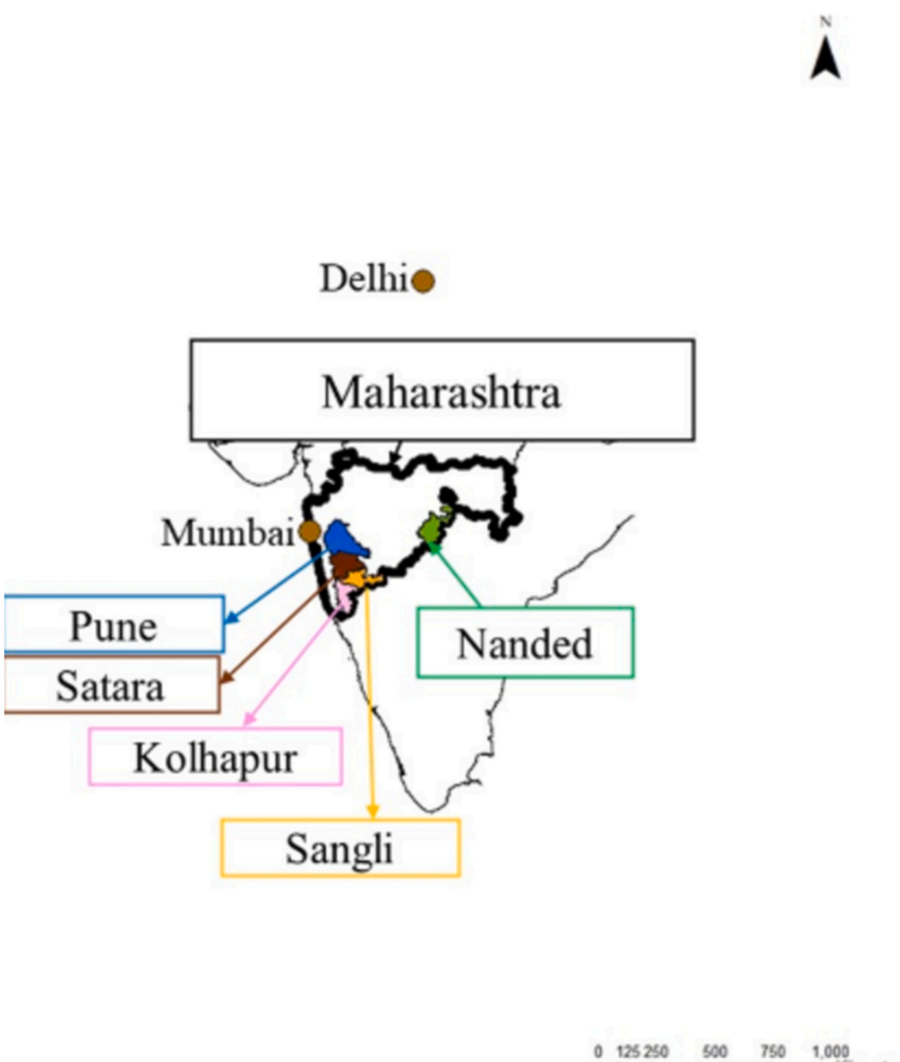

Fig. 1. Study area.

regarding Kharif sorghum was carried out in the Nanded and Satara districts (Fig. 1).

2.3.3. Inventory data collection

We used a structured pre-tested questionnaire to conduct the survey. Two hundred fifty farmers for the Rabi season and 209 for the Kharif season were randomly selected. Staff members of the ICRISAT selected the farmers and conducted the interviews. The following information was collected through the interviews as foreground data: dates of sowing and harvesting, operating hours and fuel consumption of machinery, sorghum seed rate and fertilizer, types of agrochemicals, irrigation frequencies, hours of irrigation, and sorghum yields. Background data that the authors did not collect, including agricultural inputs and machinery production, were obtained from the Ecoinvent database (version 3.0). When power, machinery weight, and fuel consumption data were missing, corresponding values were obtained from survey data or webpages for Indian machineries. When data for tractor power was missing, a corresponding value was obtained from the median power of the owned machinery in the survey data (45 HP for the Rabi season and 55 HP for the Kharif season). When tractor and attachment weight data were missing, corresponding values were obtained either from the database if provided in the surveys (e.g., 2000 kg for a 4-wheel tractor with 55 HPs in the Kharif season) or from the webpage if not provided (e.g., 2065 kg for a 4-wheel tractor with 45 HPs in the Rabi season). When data on the fuel consumption per hectare were missing, the corresponding values were obtained by multiplying the average ratio of fuel consumption (litre hr^{-1} ha^{-1}) by the number of operation hours of machinery (hr ha^{-1}). The average ratio was obtained from the survey data. Due to the lack of crops grown before sorghum, the N_2O emissions of crop residue from previous crops were not calculated. A nitrogen content of 0.5 % was used for compost (TNAU Agritech Portal, 2024).

2.3.4. Impact assessment

The present study evaluated the potential impacts of BNI-enabled sorghum on global warming, using the global warming potential (GWP) with a 100-year time horizon (Intergovernmental Panel on Climate Change (IPCC), 2013: CO_2:1, CH_4: 28, and N_2O:265). The GHG emissions of fossil fuels were obtained from MiLCA Ver. 2.3 software with the IDEA (version 2.3) database (JEMAI, Tokyo). The GHG emissions of the other inputs were obtained from Simapro 9.0 with ecoinvent (Version 3.0) using the method IPCC 2013 GWP 100 a. The emission factor for a pair of draught animals, 4.47 kg CO_2-eq hr^{-1}, was obtained from Gathorne-Hardy et al. (2013). The emission factor for electricity in India, 0.91 kg CO_2-eq kWh^{-1}, was obtained from the Institute for Global Environmental Strategies (Institute for Global Environmental Strategies (IGES), 2024). Soil N_2O emissions were calculated using the IPCC tier 1 method (Intergovernmental Panel on Climate Change (IPCC), 2019).

LC-GHG emissions were obtained by summing GHG emissions from N fertilizer production, soil N_2O emissions, fuel production and combustion, and other sources, including GHG emissions from the production of machinery, compost, P_2O_5, K_2O, and draught animal power, etc.

2.4. Calculating production costs

The production cost was obtained by summing the costs of seeds, fertilizer, manure, machinery, hired labour, draught animals, fuel, which were obtained from the survey. When farmers rented machinery, the cost included machinery, fuel, and operators. When farmers owned machinery, the cost of the machinery was obtained by multiplying the purchase price by the ratio of operation hours of machinery (hr ha^{-1}) to the machinery's lifetime. In calculating the production costs, family labour was not included. All the monetary prices were deflated/inflated with the consumer price index in India, with 2021 as the base year.

2.5. Calculating government subsidies

Subsidies for 1 kg of urea were derived by dividing the government's expenditure on urea consumption for agriculture. The government expenditures on subsidies for urea (9.5 E+11 Rupees) in 2020–2021 (India Budget, 2022) were used. The urea consumption in agriculture (3.5 E+10 kg) was obtained for 2020 (FAOSTAT, 2024) but not for 2022 since the data for 2022 have not yet been published. Using these data, the subsidy on 1 kg of urea is 27.17 Rupees: (9.5 E+11 Rupees)/(3.5 E+10 kg).

2.6. Statistical analysis

A regression approach was used to elucidate the factors controlling the N fertilizer application rate. This method can control potential observable selection bias. The factors controlled were as follows: season (Rabi or Kharif), amount of manure applied, off-farm income, age, education of the household head, the distance between the sorghum field and the house and livestock possession. Estimates were obtained using the following equation by ordinary least squares (OLS):

$$Y_i = \gamma + \beta x_i + \varepsilon_i \tag{1}$$

where Y_i is the dependent variable, such as the N fertilizer application rate; x_i is a vector of observable variables; and β is a parameter to be estimated. For the explanatory variables, we considered season, manure application rates, off-farm income, household head age and education, the distance between the sorghum field and the house and livestock possession. We created one dummy variable for farmers who earned both off-farm and agricultural incomes (the omitted category is farmers who earned only agricultural incomes); four dummy variables for household head education (no school, primary school, secondary school, high school, the omitted category is otherwise including college/university); and one dummy variable for livestock possession; and one dummy variable for season (season: Kharif season, the omitted category is the Rabi season). Heteroskedasticity-robust standard errors were used to derive the *p*-values. The model with the smallest AIC value was chosen as the best model.

2.7. Sensitivity analysis

Although BNI-enabled sorghum was hypothesized to reduce fertilizer consumption, yield was also hypothesized to increase when the same amount of N fertilizer was applied (Subbarao et al., 2021; Zhang et al., 2015), as N loss is reduced and more N is used by crops of BNI-enabled sorghum (Subbarao et al., 2021). This function of BNI-enabled sorghum will help farmers with low N fertilizer application rates, increasing soil fertility (FAO, 2016). Studies on synthetic nitrification inhibitors (SNIs), which slow the nitrification process like BNI, support this hypothesis. Meta-analyses of nitrapyrin (Wolt, 2004), one of the SNIs, and of other SNI_S (Qiao et al., 2015) reported reductions in N leaching and N_2O emissions and increases in grain yield. The decrease in N loss was estimated using the IPCC guidelines (Intergovernmental Panel on Climate Change (IPCC), 2019) described in Section 2.2 (Appendices A-1 and A-2). Then, the estimated reduction in N loss was added to the N application rate (Appendix A-3, Aeq. 12). The change in yield caused by a shift in available N was obtained by estimating the following equation by ordinary least squares:

$$\begin{aligned} Y_i = {} & \gamma + \alpha_1 N_i + \alpha_2 N_i^2 + \alpha_3 Age_i + \alpha_4 Fi_i + \alpha_5 No\ school_i \\ & + \alpha_6 Primary\ school_i + \alpha_7 Seconday\ school_i + \alpha_8 High\ school_i \\ & + \alpha_9 Season_i + \alpha_{10} Manure_i + \varepsilon_i \end{aligned} \tag{2}$$

where Y_i is yield, i is the i^{th} observation, N_i is nitrogen, N_i^2 is the square of N, Age_i is household head age, and $Manure_i$ is the application rate of manure. We created one dummy variable for farmers who earned both off-farm income and agricultural incomes (Fi_i: farmers who earned both off-farm income and agricultural incomes; the omitted category is farmers who earned only agricultural incomes), which may influence the purchase of agricultural inputs and may also influence working hours on the farm field; four dummy variables for household head education (no school, primary school, secondary school, high school, the omitted category is otherwise including college/university); and one dummy variable for season ($Season_i$: Kharif season, the omitted category is the Rabi season). Heteroskedasticity-robust standard errors were used to derive the *p*-values. Seven models were considered. The model with the smallest AIC was selected as the best model. We calculated the average of each explanatory variable, except for N and the square of N, in the selected model from the survey data for Rabi and Kharif to estimate yield. To calculate the value of N fertilizer under BNI-enabled sorghum, we added the estimated reduction in N loss to the average N application rate, following the assumption that BNI-enabled crops reduce the loss of N fertilizer, and thus the available N will increase (i.e., N used by crops will increase) for the same application rate under BNI-enabled crop.

3. Results

3.1. Farm household characteristics

The descriptive statistics of the farm household characteristics are summarized in Table 1 (Appendix B shows the detailed descriptive statistics). For Rabi sorghum, the average age of household heads was 55.8 years, and the average sorghum cultivated area was 0.36 ha. Over 40 % of their final education was secondary high school, followed by high school and primary school. Approximately 9 % of the farmers had off-farm income. For Kharif sorghum, the average age of the household head was 54.2 years, and the average cultivated area was 0.47 ha. A total of 31.4 % of their final education was secondary high school, and 30.9 % had no school education, followed by primary and high school. Approximately 35 % of the farmers had off-farm income.

3.2. Inventory data for field management

Table 2 shows the inventory data for the Rabi and Kharif sorghum cultivation. Appendix C-1 shows descriptive statistics of the inventory data. Appendix C-2 shows the weight and price of the machinery. The sowing of the Rabi sorghum was carried out mainly in November (57.9 %), followed by December (31.0 %). Harvesting was practised primarily in March (44.2 %) and April (53.3 %). Most farmers prepared land with a plough attached to a 4-wheel tractor, although some farmers used draught animals. Most farmers carry out fertilizer application, weeding, and harvesting manually. Agrochemicals were not used, and people stayed overnight in the fields to protect the sorghum from wild animals and birds. The sorghum grain was sun-dried. Threshing was carried out by threshing machinery attached to a 4-wheel tractor. In the Rabi season, 89.3 % of the farmers applied water to the field via an electric pump; the rest of the farmers depended on rainfall. Over 50 % of the farmers used the sorghum variety Maldandi and 20 % used Dagari. The average amount of urea and DAP used was 240.0 kg ha^{-1} and 88.1 kg ha^{-1}, respectively. The average yield was 1.6 t ha^{-1}. The yield-scaled GHG emissions were 1.4 kg CO_2-eq kg^{-1}, and the area-scaled GHG emissions were 2.3 t CO_2-eq ha^{-1}.

Kharif sorghum was mainly sown in June (80.2 %), followed by July (19.8 %), and it was harvested in October (56.5 %) and November (43.5 %). Many farmers cultivated hybrid sorghum varieties. Most farmers carry out fertilizer application, weeding, and harvesting manually. Agrochemicals were not used. After harvesting and sun drying the sorghum comb, threshing was carried out by a threshing machine. None of the farmers used irrigation; they all depended on precipitation. Average amounts of urea, DAP, and NPK compound fertilizers used were 170.5 kg ha^{-1}, 98.3 kg ha^{-1}, and 0.8 kg ha^{-1}, respectively. The average yield was 1.5 t ha^{-1}. The yield-scaled/area-scaled GHG emissions were 1.5 kg

Table 1
Descriptive statistics of farmer characteristics.

	Rabi season		Kharif season	
	Obs	Mean	Obs	Mean
Age	242	55.8	207	54.2
Area (ha)	243	0.36	209	0.47
No-school	243	0.03	207	0.31
Primary	243	0.24	207	0.18
Secondary	243	0.44	207	0.31
High school	243	0.25	207	0.15
College/University	243	0.05	207	0.04
Off-farm income	243	0.09	209	0.35

Table 2
Inventory data for Rabi and Kharif sorghum cultivation.

	Unit	Rabi (*n* = 243)		Kharif (n = 209)	
		Operation time (hour ha^{-1})	Amount used (kg ha^{-1})	Operation time (hour ha^{-1})	Amount used (kg ha^{-1})
Tractor 4 wheel	Piece	16.5	4.7	34.0	9.8
Tractor 2 wheel	Piece	0.1	0.0	0.0	0.0
Trolley	Piece	7.3	7.2	19.5	27.0
Plough	Piece	6.2	1.9	9.9	1.4
Rotary Harrow	Piece	1.7	0.7	1.1	0.3
Leveller	Piece	0.0	0.0	3.6	0.7
Seed cum fertilizer	Piece	3.1	0.8	8.8	0.8
Seed drill	Piece	1.5	0.1	5.4	0.7
Thresher	Piece	4.0	4.9	12.8	15.6
Animal	Piece	7.2	–	23.7	–
Pump	Piece	31.8	0.1	–	–
Seed	kg ha^{-1}	–	18.9	–	8.2
Diesel	Littre ha^{-1}	–	34.8	–	65.0
Electricity	kWh ha^{-1}	–	69.9	–	–
Total N	kg ha^{-1}	–	126.3	–	96.2
Urea	kg ha^{-1}	–	110.4	–	78.4
DAP	kg ha^{-1}	–	15.9	–	17.7
NPK	kg ha^{-1}	–	0.0	–	0.1
Total P_2O_5	kg ha^{-1}	–	40.6	–	45.3
DAP	kg ha^{-1}	–	40.5	–	45.2
NPK	kg ha^{-1}	–	0.1	–	0.1
K_2O	kg ha^{-1}	–	0.1	–	0.1
NPK	kg ha^{-1}	–	0.1	–	0.1
Manure	t ha^{-1}	–	4.3	–	4.3
Sorghum (Yield)	t ha^{-1}	–	1.6	–	1.5
Area-scaled GHG emissions (t CO_2-eq ha^{-1})		2.3		–	2.2
N-fertilizer production (t CO_2-eq ha^{-1})			0.4	–	0.3
Soil N_2O emissions (t CO_2-eq ha^{-1})			1.1	–	0.8
Fuel production/consumption (t CO_2-eq ha^{-1})			0.1	–	0.2
Other[a] (t CO_2-eq ha^{-1})			0.7	–	0.9
Yield-scaled GHG emissions (kg CO_2-eq kg^{-1})		1.4		–	1.5

[a] Other includes GHG emissions from the production of machinery, compost, P_2O_5, K_2O, and draught animal power, etc.

CO_2-eq kg^{-1} and 2.2 t CO_2-eq ha^{-1}, respectively.

3.3. Average production costs

Table 3 shows the average production costs and benefits of sorghum production (The details are shown in Appendix C-1). The fertilizer cost was the third and fourth highest of all items, contributing 14.8 % and 12.6 % to the total production cost in the Rabi and Kharif seasons, respectively.

3.4. Impacts of BNI-enabled sorghum

Fig. 2 shows the N application, soil N_2O emissions, area/yield-scaled LC-GHG emissions, and benefits of conventional sorghum and BNI-enabled sorghum when N is reduced (Appendix C-1 shows descriptive statistics). The present study estimated that BNI-enabled sorghum reduced N fertilizer consumption, soil N_2O emissions, area-scaled and yield-scaled LC-GHG emissions by 8.0 %, 29.6 %, and 15.6 %, in the Rabi season, respectively. In the Kharif season, BNI-enabled sorghum reduced N fertilizer consumption, soil N_2O emissions, area-scaled and yield-scaled LC-GHG emissions by 7.4 %, 27.7 %, and 11.2 %, respectively. The benefits to farmers increased by 0.46 % and 0.52 % in the Rabi season and in the Kharif season, respectively. Urea consumption and the government's expenditure on urea fertilizer subsidies were reduced by 9.1 %.

3.5. Factors influencing N application rates

The N application rates in the Kharif season were lower than those in the Rabi season at the 5 % level according to the *t*-test, and the cropping season had a significant effect ($p < 0.05$). The regression results indicated that fertilizer application is negatively influenced at the 5 % level by the Kharif season (a dummy variable for cropping season), the age of the household head and off-farm income (Table 4, Appendix D Model 1, Appendix D shows the estimated coefficients of seven models, standard errors, t-values, *p*-values, R^2 values, and AIC values).

3.6. Farmers' potential behaviour

Fifty-four percent of the farmers who cultivated sorghum in the Kharif season answered that they would maintain N fertilizer application rates to obtain a higher yield. The remaining farmers said they would reduce N fertilizer application to reduce fertilizer costs.

Table 3
Average production costs for sorghum (Rupees ha^{-1}).

	Rabi season		Kharif season	
	Obs	Mean	Obs	Mean
Manure	243	1548.65	209	2984.07
Plough	243	4138.05	209	5993.25
Sowing	243	2855.75	209	4355.91
Seed price	243	1146.00	209	1207.09
Fertilizer application	243	8.69	209	124.21
Fertilizer cost	243	3556.99	209	3387.58
Weeding	243	1739.74	209	1366.78
Harvest	243	2245.99	209	1918.33
Transport	243	1353.56	209	1702.35
Drying	243	8.14	209	78.07
Threshing	243	4487.86	209	3737.02
Water	243	1008.51	209	0.00
Total cost	243	24,097.93	208	26,888.01
Selling price (Rupees kg^{-1})	243	31.18	209	27.47
Revenue	243	50,672.04	208	43,300.12
Benefit	243	26,574.11	208	16,412.12

3.7. Sensitivity analysis

We evaluated the hypothesis that yield will increase even when the N fertilizer application rate is unchanged due to a reduction in N loss in BNI-enabled sorghum. The following equation with the smallest AIC was used to estimate yield (Appendix E shows the estimated coefficients of seven models, standard errors, t-values, p-values, R^2 values, and AIC values).

$$\begin{aligned}\text{Yield}_i = {} & 22.58 + 9.12\text{N}_i - 0.02\text{N}_i^2 + 10.25\text{Age}_i + 42.95\ \text{No school}_i \\ & - 29.67\ \text{Primari school}_i + 234.26\ \text{Seconday school}_i \\ & + 337.66\ \text{High school}_i + 140.60\ \text{Season}_i\end{aligned} \quad (3)$$

where N_i is nitrogen, N_i^2 is the square of N, and Age_i is household head age. No $school_i$, primary $school_i$, secondary $school_i$ and high $school_i$ (1 if household head education is no school, primary school, secondary school, and high school, otherwise 0) and Season (1 if the season is Kharif, 0 otherwise) are dummy variables.

Fig. 3 shows the yield, benefits, and area/yield-scaled LC-GHG emissions of conventional sorghum and BNI-enabled sorghum when N is maintained (Appendix C-1 shows descriptive statistics). According to the regression equation (eq. 3) used to estimate the change in yield caused by a shift in available N, the yield and revenue of BNI-enabled sorghum will increase by 2.5 % in the Rabi season and 2.4 % in the Kharif season compared with conventional sorghum. The farmers' benefits will increase by 4.9 % and 6.5 % in the Rabi and Kharif seasons, respectively. The area-scaled and yield-scaled LC-GHG emissions will decrease by 11.3 % and 13.5 %, respectively, in the Rabi season and by 8.1 % and 10.2 %, respectively, in the Kharif season.

4. Discussions

4.1. Comparison with previous studies and recommendations

Nitrogen is an essential nutrient for crop growth (McArthur and McCord, 2017). Its subsidy has contributed to increasing and stabilizing food production in India but has also increased environmental problems and caused imbalances in soil nutrients. The recent increase in global fertilizer prices is exacerbating the government's expenditure on subsidizing fertilizer: subsidies for urea increased by approximately 2.9 times from 2018–2019 (5.41 E+11 Rupees, India Budget, 2020) to 2022–2023 (1.55 E+12 Rupees, India Budget, 2024). The present study revealed heavy N application, especially urea, and imbalanced fertilizer application, as reported in previous studies (Gulati and Banerjee, 2015). Farmers applied N fertilizer above the recommendation of 80 kg N ha^{-1} for irrigated Rabi sorghum and Kharif sorghum (Indian institute of Millets Research, 2021). Although farmers applied P_2O_5 close to the recommendation (i.e., 40 kg P_2O_5 ha^{-1}), most farmers did not apply K_2O.

N fertilizer-induced GHG emissions (N fertilizer production and soil N_2O emissions) were the primary sources of LC-GHG emissions, consistent with previous studies (Samarappuli and Berti, 2018; Glab and Sowiński, 2019). However, even within this study, the contribution of N-derived GHG emissions to area-scaled LC-GHG emissions differed between Rabi (66.0 %) and Kharif (50.6 %) sorghum. The difference in the contribution of N-derived GHG emissions to area-scaled LC-GHG emissions can be explained by N fertilizer application rates, which were lower in Kharif than in Rabi season sorghum, and also by variations in agricultural management practices followed by the farmers. For example, GHG emissions from fuel production/consumption and other sources (Table 2) in the Kharif season were greater than those in the Rabi season. The higher Kharif season fuel consumption is attributed to longer operation hours for threshing due partly to incomplete drying, which may not influence the cost as the rental price is area-based. Moreover, the higher frequency of ploughing in the Kharif season than in the Rabi season can also explain the higher fuel consumption. Farmers

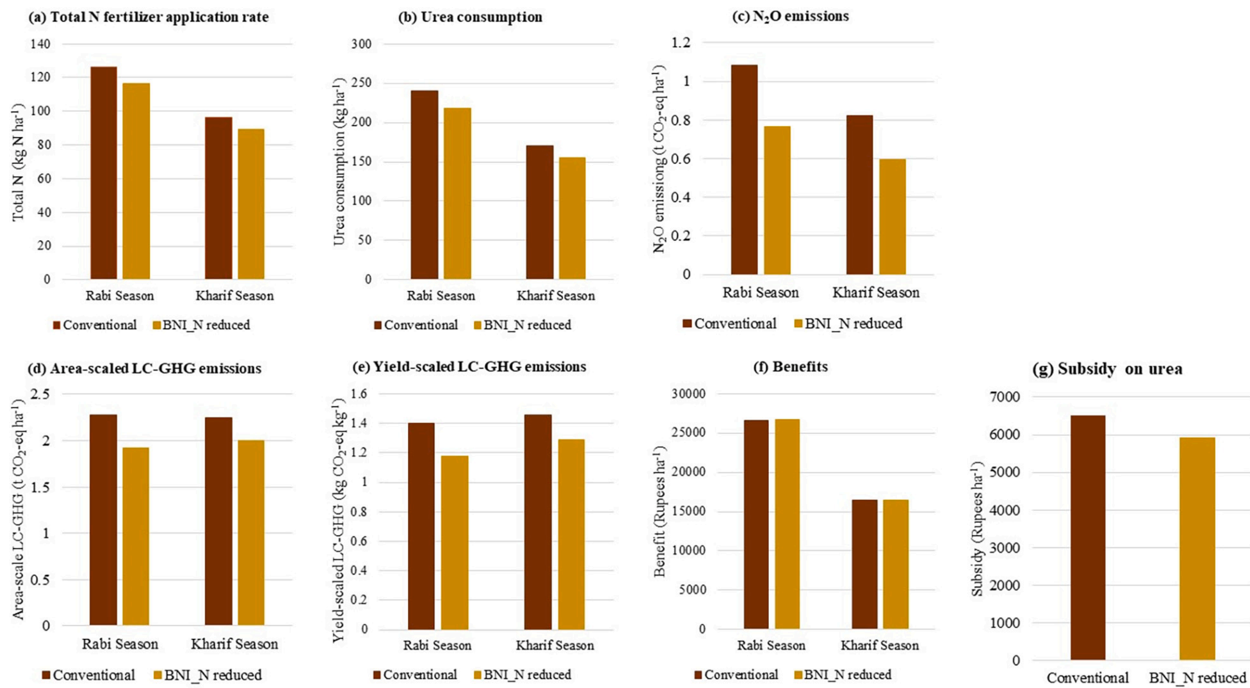

Fig. 2. (a) N fertilizer application rate, (b) urea consumption, (c) soil N_2O emissions, (d) area-scaled LC-GHG emissions, (e) yield-scaled LC-GHG emissions, (f) benefits, and (g) subsidy of conventional sorghum and BNI-enabled sorghum when N is reduced.

Table 4
Results of the multiple regression model for the nitrogen application rates.

	Coefficients	Std. Error	t-value	p-value
(Constant)	158.29	15.32	10.34	0.00
Age	−0.55	0.22	−2.49	0.01
No school	14.68	12.14	1.21	0.23
Primary	9.69	11.65	0.83	0.41
Secondary	−5.70	10.86	−0.52	0.60
High School	−3.01	11.52	−0.26	0.79
Season	−32.41	5.43	−5.97	0.00
Off-farm income	−13.02	5.45	−2.39	0.02

plough twice in the Kharif season: at the end of summer season and before sowing the crop. The higher Kharif GHG emissions are partly explained by the greater number of farmers who utilized bulls as draught animals compared with Rabi farmers. Using draught animals requires more operation hours (Phaniraja and Panchasara, 2009), which results in more GHG emissions than machinery (Aguielera et al., 2019; Gathorne-Hardy, 2016).

The estimated area-scaled LC-GHG (kg CO_2-eq ha^{-1}) emissions from Rabi and Kharif sorghum (Section 3.2, Table 2) were almost identical to those in previous studies, although direct comparison is impossible because of varying system boundaries, inventory databases, etc. (Zoli et al., 2021). That is, total GHG emissions for sweet sorghum varied between 1.5 and 2.6 t CO_2-eq ha^{-1} with fertilization treatment and between 2.1 and 2.4 t CO_2-eq ha^{-1} with grain sorghum cultivars, and the three-year average over the cultivar and fertilizer treatments was between 2.0 and 2.3 t CO_2-eq ha^{-1} (Glab and Sowiński, 2019). The total GHG emissions for forage sorghum were estimated to be 0.9 t CO_2-eq ha^{-1} (Samarappuli and Berti, 2018).

The production cost in this study (24,098 and 26,888 rupees ha^{-1} in the Rabi and Kharif seasons, respectively, Table 3) is within the ranges reported by previous studies: 21732 rupees ha^{-1} in 2013 in Maharashtra (Zalkuwi et al., 2015) and 28,491 rupees ha^{-1} in 2010 in Maharashtra (Zalkuwi et al., 2014, the costs were deflated/inflated with the consumer price index in India, with 2021 as the base year).

4.2. *Establishment of a sustainable agricultural system*

Mitigating both non-CO_2 emissions and CO_2 emissions, including

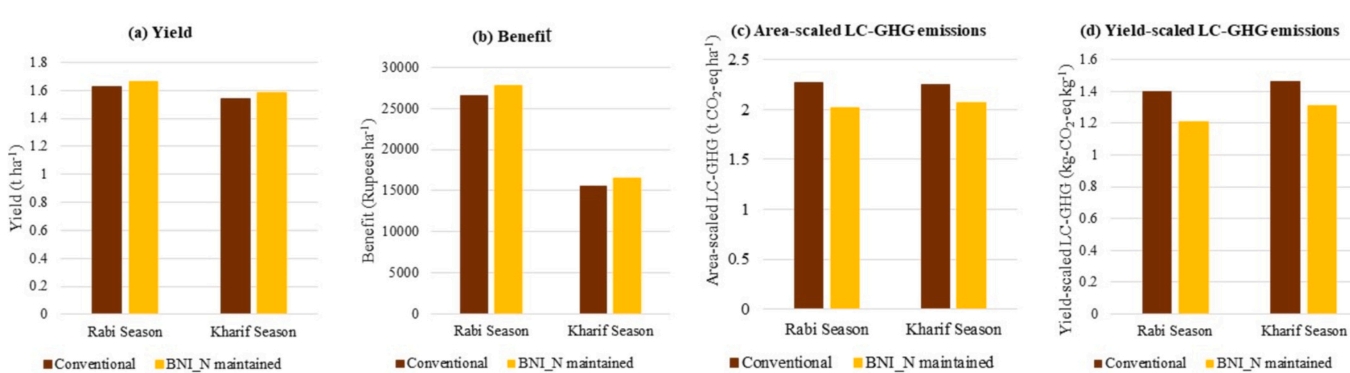

Fig. 3. (a) Yield, (b) benefits, (c) area-scaled LC-GHG emissions and (d) yield-scaled LC-GHG emissions of conventional sorghum and BNI-enabled sorghum when N is maintained.

N_2O emissions, is essential for achieving carbon neutrality by 2050 (Ou et al., 2021). Innovative technologies and new approaches are playing important roles. However, they might increase inputs or other GHG emissions while increasing yield and vice versa. To establish a sustainable agricultural system, the technologies and approaches are required to increase/maintain yield and reduce area-scaled and yield-scaled GHG emissions simultaneously (Leon, 2024). Nitrogen management must address at least two systems: a high-N application system and a low-N application system. Innovative technologies and new approaches for N management would be even more ideal if they provided tailored solutions to the two systems, as emphasized by Snapp et al. (2023), which advocated for differentiated N supply. To allow this, researchers at JIRCAS and ICRISAT are developing BNI-enabled sorghum to contribute to carbon neutrality by 2050 by lowering N consumption by farmers who overuse it and by improving yields where the N fertilizer application rate is currently deficient.

The present study, using the conclusion of a sensitivity analysis, showed that BNI-enabled sorghum could become a potential technology for establishing a sustainable agricultural system, satisfying the requirements described above by Leon (2024) and increasing farmers' benefits in both systems, with higher yields or the same yields with lower GHG emissions. That is, in the latter case, BNI-enabled sorghum will reduce N-fertilizer application rates, area-scaled and yield-scaled LC-GHG emissions, maintain yields, and increase farmers' benefits. In addition, BNI-enabled sorghum can provide a new solution to the problem of subsidies, allowing the government to reduce expenditures without increasing N fertilizer prices. The advantages and disadvantages of these subsidies have been discussed. Some studies have shown that reducing subsidies decreased fertilizer consumption, which negatively influenced agricultural production (Narayan and Gupta, 1991) and have recommended subsidizing farmers in different ways (FAO et al., 2021). One study reported that repurposing or reforming half of the subsidy could improve health and mitigate climate change (Springmann and Freund, 2022). Another study reported that a N credit system could be an alternative to internalized externalities. This system would collect funding from the beneficiaries of the reduction in reactive nitrogen (all N forms, except for N_2) to finance subsidies for farmers who implement better management practices (Gu et al., 2023).

The potential benefits of BNI-enabled crops are applicable to other countries, including South Asian countries where fertilizer is heavily subsidized by the government, such as Bangladesh, Nepal, and Sri Lanka (Kishore et al., 2021). In these countries, imbalanced fertilizer application is a problem, and subsidies have been repeatedly abolished and restored (Kishore et al., 2021). Introducing BNI-enabled sorghum, especially to farmers who grow Rabi sorghum, have only agricultural income, and have a young household head, can effectively reduce N fertilizer application rates (Section 3.5).

On the other hand, the present study showed that not all farmers will reduce N fertilizer application rates. Fifty-four percent of the farmers of Kharif sorghum in the present study answered that they would maintain the same N application rates, expecting a greater yield. These answers imply that farmers will be less likely to change N fertilizer applications under the BNI-enabled sorghum system, as fertilizer is the least expensive form of crop insurance for farmers (Bora, 2022). Farmers will compare the benefits of reducing and maintaining N fertilizer application rates under BNI-enabled sorghum. Farmers will increase N fertilizer application if the marginal product associated with fertilizer use is greater than the marginal cost (Hossain and Singh, 2000). According to the present study, most farmers would maintain the same N fertilizer consumption because the benefit to farmers will be more significant from increased yield (Fig. 3 (b)) than from N fertilizer reduction (Fig. 2 (f)). This is partly because farmers purchase subsidized N fertilizers, which discourages farmers from reducing N fertilizer application. Even when the assumption is changed (i.e., N fertilizer application is maintained), the sensitivity analysis showed that BNI-enabled sorghum would reduce area/yield-scaled LC-GHG emissions and increase yields and farmers' benefits, which is similar to the outcome under the other assumption.

These results indicate that BNI-enabled sorghum can be introduced into countries where fertilizer application rates are low, especially in Sub-Saharan African countries, to increase yield without increasing N fertilizer application rates and hence increasing farmers' benefit. Fertilizer application in 2019 was much lower in Middle Africa (8.64 kg ha^{-1}, FAO (2023)), Western Africa (17.32 kg ha^{-1}, FAO (2023)), Eastern Africa (24.99 kg ha^{-1}, FAO (2023)) than in other regions. In these regions, low fertilizer application is one of the factors that severely decreases soil fertility (FAO, 2016). In these countries, cost-effective measures to increase N use are paramount (Snapp et al., 2023), as N is a good indicator of yield change (Tonito and Ricker-Gilbert, 2016), and appropriate fertilization is one of the key elements to improving yield and ensuring sustainability under climate change. As sorghum is a main crop in Sub-Saharan Africa (Khalifa and Eltahir, 2023), introducing BNI-enabled sorghum could become a new cost-effective solution.

4.3. Uncertainties and limitations of this study

The performance of the BNI-enabled sorghum reported in this paper will vary depending on several factors. Firstly, this study did not consider the possible impact of the amount of BNI released from the root system on the nitrification inhibition rate of BNI-enabled sorghum. The amount of BNI release will vary depending on the genotype (Tesfamariam et al., 2014), growth stage (Subbarao et al., 2013), N status (Subbarao et al., 2013), clay content (Subbarao et al., 2012), and soil pH (Di et al., 2018; Subbarao et al., 2013), as described in the Introduction. Therefore, the results in this study might over/underestimate the impact of BNI-enabled sorghum.

Secondly, the results are limited to the study area. The benefit to farmers and the government of reducing N fertilizer application with BNI-enabled sorghum will vary depending on the country. In nonsubsidized countries, the benefit to farmers will be more significant than in this study since the farmers in this study bought subsidized N fertilizer in India. On the other hand, the benefit to the government from BNI-enabled sorghum in this study will be more significant than that in the other cases. Evaluating BNI-enabled sorghum for a country, or state will improve the evaluation accuracy.

Thirdly, we estimated the changes in N fertilizer application by modifying the equations with the default emission factors for soil N_2O emissions in the IPCC guidelines (Intergovernmental Panel on Climate Change (IPCC), 2019) due to the need for more data. Using the IPCC method may increase uncertainties in the estimate of changes in N fertilizer application. Soil N_2O emissions increase nonlinearly when the N application rate is high (Kim et al., 2013; Li et al., 2024), whereas it increases linearly in the IPCC methods. This could be one of the reasons why the reduction in soil N_2O emissions (Fig. 2(c): 29.6 % in the Rabi season, 27.7 % in the Kharif season) and the increase in yield (Fig. 3(a): 2.5 % in the Rabi season and 2.4 % in the Kharif season), which was estimated using the IPCC method (Sections 2.2 and 2.7, Appendices A-1, A-2 and A-3) in this study were smaller than those reported for meta-analyses of SNIs where field survey data were obtained from published literature: Yield increased by 7 % with nitrapyrin (Wolt, 2004) and 9 % with SNIs (Qiao et al., 2015) compared to without them; soil N_2O emissions were reduced by 38 % with nitrification inhibitors (Akiyama et al., 2010) and 44 % with SNIs (Qiao et al., 2015) compared with conventional fertilizer application.

Another reason for the differences in yields are partly explained by the differences between the data sources. The data for the meta-analysis were obtained from field experiment data where the management was well controlled and recorded. In contrast, the data for this study were based on farmers' management, and the data depended on farmers' memory recall. The low R^2 values ($R^2 = 0.16$, Appendix E) for the model to estimate yield imply a poor relationship between yield and the explanatory variables. Using a more extensive dataset could allow us to overcome this problem. Moreover, these estimations need to be replaced with field data.

Fourthly, this study did not consider a reduction in N loss when other than urea (e.g., DAP) is applied as N fertilizer (i.e., BNI-enabled sorghum was hypothesized to reduce N loss when urea is used as N fertilizer (Section 2.1)). This assumption may impact N loss, soil N_2O emissions, and benefits changes, and hence, including the other type of fertilizer will reduce the differences with respect to the published studies described above. However, the influence of DAP is relatively small. In particular, according to the present study, when not only urea but also DAP is applied, N and N_2O emissions will be reduced by 9.2 % and 33.8 %, respectively, in both the Rabi and Kharif seasons, whereas when only urea is applied N and N_2O emissions will be reduced by 8.0 % and 29.6 % in the Rabi season and 7.4 % and 27.7 % in the Kharif season, respectively.

5. Conclusions

The present study estimated the potential impacts of BNI-enabled sorghum varieties on N fertilizer application rates, LC-GHG emissions, yields, benefits to farmers, and benefits to the government via reduced fertilizer subsidy expenditures, using survey data from Maharashtra state, India.

The results revealed that BNI-enabled sorghum could become a potential technology for establishing a sustainable agricultural system with higher yields or the same yields with lower LC-GHG emissions and higher farmers' benefits. The latter approach (the same yields with lower LC-GHG emissions by decreasing N fertilizer) can reduce government fertilizer subsidy expenditures. The benefits of BNI-enabled sorghum are not limited to only Maharashtra states in India. BNI-enabled crops could be introduced to either reduce N fertilizer application in states with high N consumption or increase yield in states with low N consumption.

Farmers in countries with high N fertilizer consumption are less likely to reduce N fertilizer application rates. The present study suggests that each country's government should take measures to incentivize farmers to reduce N fertilizer application if they overuse it. Reforming and repurposing subsidies can increase the contribution of BNI-enabled sorghum to establish a sustainable food system (FAO et al., 2021).

CRediT authorship contribution statement

Ai Leon: Writing – original draft, Project administration, Methodology, Formal analysis, Conceptualization. **Swamikannu Nedumaran:** Data curation.

Declaration of competing interest

The authors declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.177385.

Data availability

Data will be made available on request.

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