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Economic evaluation of maize- wheat cropping system under natural and organic farming practices with drip irrigation- an GHG angle

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ABSTRACT

Global agriculture faces the challenge of meeting food demand while minimising environmental impacts such as greenhouse gas (GHG) emissions. The maize-wheat cropping system, vital for food security in South and East Asia, traditionally involves intensive fertiliser use and flood irrigation that exacerbate GHG emissions and degrade soil health. This study evaluated the effectiveness of integrated nutrient management (INM), organic, natural, and chemical nutrient practices combined with surface and subsurface drip irrigation on GHG emissions, crop productivity, and economic returns. Results demonstrated that INM coupled with drip irrigation significantly reduced CO_2 and N_2O emissions while improving nutrient use efficiency and maximising yields. Economic analysis indicated that INM and natural farming treatments maintained higher benefit-cost ratios (up to 1.59) and lower total annual costs (as low as ₹85,057) compared to organic and chemical treatments. Although chemical fertilisation resulted in higher incomes, it incurred elevated emission costs, reflecting negative externalities that reduce sustainability. The findings support the adoption of integrated nutrient and water management strategies for the sustainable intensification of maize-wheat systems, balancing productivity, profitability, and environmental stewardship. The study faced challenges related to the accurate quantification of GHG fluxes under field conditions, high initial investment costs of drip systems, and site-specific variability in soil–climate interactions. Despite these constraints, this work contributes robust field-based evidence on the energy–water–carbon nexus and provides a scalable framework for integrating drip irrigation with climate-smart nutrient management for sustainable intensification of maize–wheat systems.

Keywords: *Benefit Cost Ratio, GHG emission, Maize, Nutrient Management, Irrigation, Sustainability, Wheat.*

Introduction

Global agriculture is under increasing pressure to meet food demand while reducing its negative effects on the environment, particularly greenhouse gas (GHG) emissions, making the transition to sustainability a pressing goal. The productivity and resource efficiency of the maize-wheat cropping system make it highly valued in many areas and serve as the foundation for food security, particularly in South and East Asia [1,2]. However, conventional agriculture—characterised by intensive tillage, higher rates of application of fertiliser, especially N, and flood irrigation—has contributed to elevated GHG emissions and declining soil health in Indian Agriculture [3,4].

Combining different nutrient sources according to crop demand maximises fertiliser use, increases nutrient use efficiency, and lowers carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions [5,6]. Several studies have shown that, in comparison to conventional fertiliser regimes, the integrated application of fertilisers in maize-wheat systems under drip irrigation significantly lowers GHG emissions [4,7]. For instance, maize cultivation with INM reduced cumulative N_2O emissions by over 20% relative to synthetic fertiliser-only treatments [3]. Likewise, enhanced soil organic carbon sequestration and lower emission intensity when Integrated Nutrient Management (INM) with precision irrigation practices [4]. These integrated approaches promote soil health and reduce nutrient loss pathways contributing to GHG emissions. The field-based life cycle evaluations confirm that the total carbon footprint of maize-wheat cropping systems is decreased by optimising nitrogen and water management through INM and drip irrigation, respectively [10].

The economic benefits of INM with drip irrigation are significant; these methods typically lower fertiliser costs and water use while stabilising yields, offering improved net returns for farmers [2,6]. Moreover, diversified nutrient inputs within INM mitigate risks of nutrient imbalances and long-term soil degradation seen in mono-fertiliser systems, further supporting sustainability [7]. The diversification of cropping system combined with INM practices enhances resilience to climate variability, decreases GHG emissions, and contributes to more sustainable agroecosystems [9].

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Despite these proven benefits, adoption of INM and drip irrigation faces challenges, including upfront investment and knowledge barriers. However, policy and extension support can improve adoption rates and translate into substantial environmental and economic enhancement [4,10]. Therefore, a field experiment was conducted to identify a sustainable nutrient management option and evaluate it under different irrigation systems in the maize-wheat cropping system. All these nutrient management strategies,in conjunction with the drip irrigation system, need to be evaluated in terms of GHG emissions.

Materials and Methods

The field study was conducted during the 2023–24 agricultural year at the Water Technology Centre of the Indian Agricultural Research Institute (ICAR) in New Delhi, India. This study site is 241 meters above mean sea level and is located at 28°37'48" N latitude and 77°09'40" E longitude. The semi-arid subtropical monsoonal climate prevails in the experiment site. The experimental site had an annual precipitation of 115.7 cm, a total annual evaporation of 122.9 mm, and peak and minimum mean monthly temperatures of 36.8°C and 17.1°C, respectively, during the study period.

The study evaluated the impact of different irrigation methods and nutrient management strategies on greenhouse gas emissions in maize and wheat crops, respectively, using a randomised block design (RBD) with three replications. A range of treatment combinations was used in the trial, including surface drip irrigation (SDI) and subsurface drip irrigation (SSDI), which were applied at 80% crop evapotranspiration (ETc).

Multiple nutrient management options, including natural, conventional chemical fertiliser, organic, and integrated fertiliser, were used to provide the necessary nutrient dose (Table 1). The results were contrasted with the control, which involved flooding and the recommended dosage of NPK.

Nutrient management treatments were tailored for each approach: chemical plots received fertigation at the recommended dose (maize: 150:75:60 NPK kg/ha; wheat: 150:60:60 NPK kg/ha); integrated treatments combined 50% RDF with 5 t/ha farmyard manure and 2.5 t/ha vermicompost before sowing. Organic plots were amended with 10 t/ha FYM and 5 t/ha vermicompost. Natural farming used seed treatment with *beejamruta*, field application of *jeevamruta* at 15-day intervals, and mulching with 2 t/ha crop residue (see Table 1).

Table 1. Nutrient Management Strategies and Irrigation method employed for different treatments in the Mazie-Wheat cropping system

Treatments	Irrigation method	Nutrient management strategy
T_1	SSDI	Chemical
T_2		Organic
T_3		Integrated
T_4		Natural
T_5	SDI	Chemical
T_6		Organic
T_7		Integrated
T_8		Natural
T_9	Flood Irrigation	100% RDF

Note: Treatments were expressed as T_1, T_2, T_3 and so on. SSDI, SDI – Surface and Sub-surface drip irrigation.

GHG samples collection and analysis

GHG samples were collected using static acrylic chambers placed above the root zone for maize and over the crop canopy for wheat [11]. Airtight 50 ml syringes drew gas samples at 0 and 60 minutes via a silicone stopper. CO_2 and N_2O concentrations were analysed with gas chromatography using flame ionisation and electron capture detectors, respectively [12]. Methane was excluded due to negligible emissions in these aerobic systems [13,14]. GWP was calculated in CO_2-equivalent using IPCC (2021) factors [15].

Cost and Income Calculations

Annual total costs included both variable and fixed expenses for each input, with fixed costs covering drip system infrastructure (pipes, filters, valves, etc.) and annualised using the capital recovery factor (CRF) at a 10% interest rate. This provided the annual fixed cost (AFC), ensuring a precise estimate of annual financial requirements based on asset depreciation and investment life. Operational, maintenance, and cultivation expenses such as land preparation, seeds, fertilisers, chemicals, irrigation, labour, and energy (costed at ₹10/kWh)—formed the variable costs, calculated yearly to capture all recurrent expenditures involved in maize and wheat production.

Gross income was determined by multiplying market prices by harvested grain and straw/stover yields, reflecting all monetary returns from both crops. Net income was computed as the difference between gross income and total variable costs, giving a direct measure of profitability for each treatment. Economic efficiency was further evaluated using the discounted benefit-cost ratio (BCR), which compared the present value of benefits (gross returns) to costs, incorporating a 7% opportunity cost to account for alternative investments and the time value of money, thereby assessing the relative financial viability of each production approach.

In the Indian context, the voluntary carbon credit prices range between ₹200 and ₹400 (approximately USD 2.5 to 5) per ton of CO_2 equivalent, with the anticipated compliance market prices expected to rise to ₹800–₹1,000 (approximately USD 10 to 12) per ton (PIB) [15]. This pricing framework reflects India's commitment under the Paris Agreement to achieve a 45% reduction in GHG intensity by 2030 and net-zero emissions by 2070, supporting sustainable development and fostering green investments. According to the 2025 Global Carbon Accounts report by I4CE (Institute for Climate Economics), effective carbon prices in major jurisdictions range between USD 40–80 per tCO_2eq., to sufficiently incentivise emissions reductions [16]. In our study, we have taken the minimum anticipated prices of 10 USD to calculate the negative externality of GHG emissions.

The overall cost of production for each treatment was increased due to the negative externality costs of greenhouse gas emissions from the maize and wheat crops. The adjusted net income values were then calculated by deducting the total expenses from the total income received under each of the different treatments. The economic feasibility of each treatment was then assessed by computing an adjusted benefit-cost ratio, which takes into consideration the net financial gains after deducting the costs of greenhouse gas emissions.

Statistical analysis

Statistical analysis was conducted in R with ANOVA and DMRT via the GRAPES facility [17,18].

Results

Greenhouse Gas Emissions

The cumulative global warming potential (GWP) of CO_2 and N_2O was calculated separately for maize and wheat, with N_2O converted using a factor of 273 kg CO_2 per kg N_2O.

Significant differences were observed among treatments. In maize, the Global Warming Potential (GWP) associated with maize production exhibited clear differentiation across irrigation and nutrient management strategies. Surface irrigation registered a GWP of 4756.4 kg CO_2-eq ha^{-1}, which consistently exceeded the values observed under SSDI. Relative to surface irrigation, SSDI paired with chemical, organic, integrated and natural nutrient management reduced GWP by 8.9%, 102.2%, 49.8% and 25.9%, respectively, underscoring the substantial mitigation potential of subsurface drip systems, particularly when combined with organic inputs. Under SDI, organic, integrated and natural nutrient options also conferred notable reductions in GWP, lowering emissions by 26.0%, 57.4% and 18.3%, respectively. However, SDI coupled with chemical fertilisation (4899.85 kg CO_2-eq ha^{-1}) exhibited a GWP statistically comparable to that of surface irrigation, suggesting that the benefits of micro-irrigation on emission reduction may be diminished under high mineral-N conditions. In wheat, surface irrigation recorded the highest GWP (2736.12 kg CO_2-eq ha^{-1}), while all SSDI treatments produced notably lower emissions, with reductions of 8.0–39.6% depending on the nutrient source. SDI also lowered GWP substantially, with organic, integrated and natural nutrient options reducing emissions by 44.7%, 19.0% and 13.1%, respectively. Unlike maize, SDI combined with chemical fertilisation (2138.97 kg CO_2-eq ha^{-1}) also reduced GWP, registering a clear decrease relative to surface irrigation, indicating that SDI was consistently effective across nutrient sources in wheat.

Economic Evaluation

Input costs and gross income varied noticeably across irrigation–nutrient combinations, contributing to the clear differences in BCR in both maize and wheat. In maize, SSDI- and SDI-based systems generally incurred lower operational costs (particularly under natural nutrient management) while sustaining moderate to high gross income, resulting in higher BCR values ranging from 1.49 to 1.59. SSDI-Natural and SDI-Natural produced the most favourable economic outcomes due to the combined effect of reduced annual cost and reasonably high-income levels. In contrast, organic nutrient management increased total annual costs substantially, while generating comparatively lower income, leading to the lowest BCR across both drip systems. Surface irrigation exhibited higher costs with only marginally higher income, leading to a moderate BCR (1.53). Wheat followed a similar trend: SSDI-Chemical and SSDI-Integrated recorded the highest gross income and maintained competitive input costs, yielding BCR values of 1.54 and 1.47, respectively. Organic nutrient management again generated higher costs and lower income, sharply reducing BCR (1.10–1.25). Overall, the analysis shows that micro-irrigation, especially when combined with integrated or chemical nutrient strategies, optimises input costs and enhances gross returns, making it economically superior to surface irrigation.

These values demonstrate that while natural management can be cost-effective, its lower income potential may impact profitability in initial years. The income from natural nutrient management is anticipated to increase over time, as reported by [19,20].

Impact of Negative Externality and Adjusted BCR

Incorporating the external cost of GHG emissions further strengthened the advantage of micro-irrigation. Treatments such as SSDI-Natural, SDI-Natural, and SSDI-Integrated in maize—already characterised by lower input cost and moderate income benefited from their lower emission costs, resulting in the highest adjusted BCR values (1.51–1.53). Conversely, SDI-Chemical and surface irrigation accumulated higher emission costs due to elevated GWP values, increasing total annual expenditure and reducing adjusted BCR. In wheat, although absolute emission costs were lower, the trend remained consistent: SSDI-Chemical, SSDI-Integrated, SDI-Chemical and SDI-Integrated maintained high adjusted BCR values because their gross income remained high while emission-related penalties were relatively small. Organic nutrient treatments, despite emitting less, still produced the lowest adjusted BCR because of high production costs and poor gross returns, indicating that environmental benefits do not fully compensate for economic limitations.

Overall, chemical nutrient management, despite raising productivity and incomes, contributed to higher negative externalities in the form of greenhouse gas emissions and costs, ultimately diminishing economic efficiency relative to more sustainable integrated and natural nutrient management practices combined with water-saving irrigation. Notably, the results align with findings that the inclusion of emission costs highlights the financial impact of agricultural negative externalities and can substantially evaluate the sustainability of different nutrient management options [20,21,22].

Table 2. Response of different nutrient management options and irrigation methods on GHG emission in the Mthe aize crop

Maize				
Method of Irrigation	**Nutrient Options**	**CO_2 (Kg ha^{-1})**	**N_2O (Kg ha^{-1})**	**GWP (CO_2 eq. Kg ha^{-1})**
SSDI	Chemical	3976.46±294.89^{a}	1.44±0.05^{de}	4368.73±165.39^{bc}
	Organic	1976.3 ±123.42^{b}	1.38±0.07^{de}	2352.58±84.82^{f}
	Integrated	2734.8±222.88^{c}	1.61±0.07^{a}	3175.24±48.51^{e}
	Natural	3405.15±123.42^{b}	1.37±0.07^{de}	3778.48±188.92^{d}
SDI	Chemical	4375.11±260.75^{a}	1.92±0.04^{cd}	4899.85±149.69^{a}
	Organic	3376.34±231.501^{b}	1.46±0.03^{b}	3774.27±152.53^{d}
	Integrated	2573.37±575.0^{c}	1.64±0.06^{e}	3021.86±92.32^{e}
	Natural	3398.86±136.12^{b}	2.28±0.06^{c}	4022.31±152.28^{cd}
Control	Flood irrigation and Broadcasting	4423.21±236.34^{a}	1.22±0.05^{cd}	4756.4±357^{ab}
SE(m)		167.83	0.07	145.75
Wheat				
Method of Irrigation	**Nutrient Options**	**CO_2 (Kg ha^{-1})**	**N_2O (Kg ha^{-1})**	**GWP (CO_2 eq. Kg ha^{-1})**
SSDI	Chemical	1928.87±70.90^{ab}	2.21±0.08^{cd}	2533.4±82.57^{ab}
	Organic	1503.98±58.93^{ab}	1.67±0.08^{b}	1960.41±170.75^{d}
	Integrated	1872.84±97.47^{ab}	1.78±0.04^{e}	2358.87±66.38^{bc}
	Natural	1949.45±50.77^{c}	1.51±0.06^{cd}	2360.59±81.25^{bc}
SDI	Chemical	1511.36±77.76^{a}	2.3±0.10^{a}	2138.97±82.31^{cd}
	Organic	1408.00±50.77^{c}	1.77±0.06^{cd}	1890.38±114.84^{d}
	Integrated	1765.01±147.92^{ab}	1.96±0.06^{de}	2298.79±94.05^{bc}
	Natural	1970.87±60.78^{c}	1.65±0.08^{de}	2420.07±70.93^{bc}
Control	Flood irrigation and Broadcasting	2053.94±53.92^{b}	2.5±0.06^{c}	2736.12±50.66^{a}
SE(m)		82.76	0.08	88.67

Note- Data presented in table are mean values of three replications along with ± standard error (SE). Mean values followed by alphabets in superscript shows significant levels at 5% level. SDI and SSDI- Surface and Sub-surface drip irrigation. SE(m) means Standard error of mean.

Table 3. Gross income, Net income and Benefit Cost ratio of different nutrient management options and irrigation methods

Maize				
Method of Irrigation	**Nutrient Options**	**Total Annual cost (₹/ha)**	**Total Income (₹/ha)**	**Benefit Cost Ratio**
SSDI	Chemical	96934.11± 466.83^{a}	150888.25± 1767.58^{ab}	1.56±0.009^{ab}
	Organic	105345.61±707.32^{a}	146990.36± 2026.02^{ab}	1.39± 0.005^{b}
	Integrated	100608.11±1785.38^{ab}	157784.14± 1440.45^{a}	1.57± 0.006^{ab}
	Natural	85057.61±490.11c	134940.17± 1996.34 ^{b}	1.59± 0.010^{a}
SDI	Chemical	97784.15±1259.34^{a}	145267.53 ± 537.29 ^{ab}	1.49± 0.006 ^{ab}
	Organic	106195.65±1177.06^{d}	141966.54± 1984.65^{ab}	1.34± 0.006^{b}
	Integrated	101458.15 ±1232.65^{ab}	150689.37± 1117.75^{ab}	1.49± 0.004 ^{ab}
	Natural	85907.65±1333.68^{c}	136812.84 ± 854.85 ^{b}	1.59± 0.001^{a}
Control	Flood irrigation and Broadcasting	103769.03± 2529.89^{ab}	158583.16± 1042.71^{a}	1.53± 0.010 ^{ab}
SE(m)		**1220.25**	**1418.63**	**0.066**
Wheat				
Method of Irrigation	**Nutrient Options**	**Total Annual cost (₹/ha)**	**Total Income (₹/ha)**	**Benefit Cost Ratio**
SSDI	Chemical	91964.41±1195.5^{b}	141551.61 ±1840.17^{a}	1.54±0.002^{a}
	Organic	102045.9±889.61^{a}	127355.96 ±907.35^{bc}	1.25±0.009^{b}
	Integrated	98630.16±615.90^{ab}	145293.28 ±1110.26^{a}	1.47±0.001^{a}
	Natural	80989.91±353.02^{c}	106933.07 ±466.11^{c}	1.32± 0.006^{a}
SDI	Chemical	92814.45±245.56^{b}	127589.93 ±337.57^{a}	1.38±0.003^{a}
	Organic	102896±861.52^{a}	113418.92 ±1151.15^{bc}	1.10±0.007^{b}
	Integrated	99480.2±642.50^{ab}	132923.98 ±713.24^{a}	1.34±0.116^{a}
	Natural	81839.95±536.60^{c}	108768.28 ±708.30^{c}	1.34±0.087^{a}
Control	Flood irrigation and Broadcasting	93229.03±493^{ab}	131509.94± 695.88^{ab}	1.41± 0.075^{a}
SE(m)		**648.13**	**881.11**	**0.063**

Note- Data presented in table are mean values of three replications along with ± standard error (SE). Mean values followed by alphabets in superscript shows significant levels at 5% level. SDI and SSDI- Surface and Sub-surface drip irrigation. SE(m) means Standard error of mean.

Table 3. Negative Externality due to Emissions, Cost of GHG emissions, Adjusted Benefit Cost Ratio (BCR) under different nutrient management options and irrigation methods

Maize				
Method of Irrigation	**Nutrient Options**	**Cost of Emission (₹/ha)**	**Total Annual cost including Emission cost (₹/ha)**	**Adjusted BCR for Emission cost**
SSDI	Chemical	3639.15±290.60^{b}	100573.26±1285.61 ^{a}	1.50±0.19^{ab}
	Organic	1959.70±254.76^{f}	107305.30±937.87 ^{a}	1.36±0.11^{b}
	Integrated	2644.98±343.85^{d}	104247.26±651.02 ^{a}	1.51±0.09^{ab}
	Natural	3147.47±60.13 ^{c}	88205.08 ±372.77^{b}	1.52±0.06^{a}
SDI	Chemical	4081.09±122.8 ^{a}	100928.12±267.30 ^{a}	1.44±0.03^{ab}
	Organic	3143.97±408.72^{c}	110157.74±687.93 ^{a}	1.29±0.08^{b}
	Integrated	2517.21±327.24^{de}	103975.37±565.82 ^{a}	1.44±0.12^{ab}
	Natural	3349.74±473.09^{ef}	89257.40 ±900.45 ^{b}	1.53±0.10^{a}
Control	Flood irrigation and Broadcasting	3962.08±515.07^{a}	106414.01±563.09^{a}	1.49±0.08^{ab}
SE(m)		**94.232**	**692.43**	**0.064**
Wheat				
Method of Irrigation	**Nutrient Options**	**Cost of Emission (₹/ha)**	**Total Annual cost including Emission cost (₹/ha)**	**Adjusted BCR for Emission cost**
SSDI	Chemical	1667.79±205.22 ^{c}	93632.20±1216.05 ^{b}	1.51± 0.19^{a}
	Organic	1637.13±212.83 ^{c}	1043683.04± 906.80 ^{a}	1.22± 0.10^{b}
	Integrated	1969.89±256.08 ^{a}	100600± 628.24 ^{ab}	1.44± 0.09 ^{a}
	Natural	1971.33±256.27^{a}	82961.24± 354.07 ^{c}	1.28± 0.05 ^{ab}
SDI	Chemical	1786.26±232.21 ^{b}	94600.71± 249.89 ^{b}	1.34± 0.03 ^{a}
	Organic	1578.66±163.22 ^{c}	104474.61± 655.21 ^{a}	1.08± 0.07 ^{b}
	Integrated	1919.72±249.56 ^{a}	101399.9± 878.14 ^{ab}	1.31± 0.11 ^{a}
	Natural	2021.00±262.73 ^{a}	83860.95± 538.35 ^{c}	1.29± 0.09 ^{a}
Control	Flood Irrigation and Broadcasting	1779.08±189.32 ^{b}	95008.11± 502.77^{ab}	1.38± 0.07 ^{a}
SE(m)		**53.906**	**658.84**	**0.062**

Note- Data presented in the table are mean values of three replications along with ± standard error (SE). Mean values followed by alphabets in superscript show significant levels at 5% level. SDI and SSDI- Surface and Sub-surface Drip Irrigation. SE(m) means Standard error of mean.

Discussion

About 18% of India's gross national emissions come from agriculture, making it the country's second-largest source of greenhouse gas emissions. Reducing agriculture's contribution to overall GHG emissions requires finding high-yield, low-emission routes for the nation's cereal production [11,19,23]. India recently announced a voluntary objective to reduce its GDP's emission intensity by 35% by 2030 compared to 2005 levels (India's NDC submitted to UNFCCC).

Irrigation, Nutrient Management Options and GHG emissions

Our field experiment exhibits that soil CO_2 and N_2O fluxes are interactively determined by fertiliser management and irrigation technique, resulting in complex patterns in overall GWP. While N_2O emissions showed treatment- and irrigation-specific responses, integrated and organic nutrient systems frequently enhanced CO_2 fluxes and GWP in comparison to conventional treatment. Notably, for the identical nutrient management options (e.g., SSDI-Chemical vs. SDI-Chemical in maize), surface and subsurface drip irrigation yielded significantly different CO_2 and GWP values, highlighting the strong interaction between irrigation method and nutrient management technique.

The results are consistent with earlier research demonstrating that drip irrigation often alters N_2O fluxes by changing soil moisture microsites, and that organic manures can increase soil respiration (CO_2) while the effect on N_2O depends on mineralisation and moisture dynamics [24, 25].

Change in Benefit-Cost Ratio due to the negative Externality of GHG emissions.

Greenhouse gas (GHG) emissions significantly increase the cost of crop cultivation and reduce the income levels by increasing the costs related to environmental degradation. The Benefit Cost Ratio of various treatments in our research has undergone changes due to negative externality caused by GHG emissions in both maize and wheat crops. A higher degree of reduction in the benefit-cost ratio was observed in conventional chemical nutrient management options in both maize and wheat. Whereas, the natural and integrated nutrient management options showed a lesser change in BCR after deducting the emission cost. This clearly shows that the integrated nutrient management and natural farming practices result in reducing the environmental costs due to the emission of greenhouse gases [30].

For calculating emission cost, we considered the minimum cost of ($10. The reduction in income from crops due to the factor of greenhouse gas emission was also reported by various research experiments [26, 27, 28]. The research experiment counted only the direct emission of GHG from crops for calculating the economic cost of the emission, whereas the indirect costs due to emission from field operations like land preparation, irrigation, pesticide application, harvesting use of mechanised equipment, which uses conventional energy sources such as diesel engines, etc., may also be taken into account.

Conventional chemical fertilisers play a crucial role in boosting agricultural yields and ensuring food security for the growing population, especially in intensive cropping regions like the Indo-Gangetic Plain (IGP). However, the overuse of such fertilisers increases production costs for farmers and contributes significantly to environmental pollution through greenhouse gas emissions and nutrient leaching [30]. Therefore, balanced and site-specific fertiliser use—such as through the Soil Health Card Scheme and *Paramparaghat Krishi Vikas Yojana*—has become essential for maximising crop productivity while minimising environmental cost. Reduction in conventional nutrient sources combined with balanced fertiliser application not only enhances crop yields and farmer incomes but also serves as a key mitigation strategy to reduce GHG emissions in Indian agriculture [29].

Conclusions

The experiment demonstrates that integrated nutrient management (INM) and conservation agriculture practices can effectively reduce greenhouse gas emissions from maize and wheat crops compared to conventional chemical fertiliser application, without compromising farmers' income. Moreover, natural farming practices have the potential to increase productivity over time due to the beneficial residual effects of organic inputs and enhanced microbial activity in the soil. Therefore, the judicious use of fertilisers combined with integrated nutrient application and water conservation measures plays a crucial role in minimising agricultural emissions. Although Indian agriculture contributes relatively low per capita emissions from crop production, adopting these conservation practices can significantly improve the sustainability of farming systems while maintaining steady income levels for farmers.

Future scope of the study

Future studies should emphasize long-term quantification of GHG emissions and soil carbon dynamics under integrated nutrient and drip irrigation systems across diverse agro-ecological zones. Integration of life cycle assessment (LCA), sensor-based irrigation scheduling, and carbon credit valuation will strengthen environmental and economic sustainability assessments. There is also scope to develop site-specific climate-smart management packages for large-scale adoption in maize–wheat systems.

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Author contributions

All the authors contributed intellectual input and research assistance to this study and manuscript preparation. G.S., M.K. and A.S. Conceptualisation; G.S., M.K., A. B., K.L., and A.S Investigation; G.S., M., A.B, A.S., K.L., M.K., A.D, V.P., and A.A. Methodology, validation, formal analysis and data curation; G.S., A.S., M., V.P., A.B. and A.D. writing; G.S., M.K., A.S., M., K.L., A.B., A.B., V.P., A.A., review and editing; M.K., supervision

Conflict of interest

The authors declare no conflicts of interest

Data Availability Statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

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