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Influence of 36 years of integrated nutrient management on soil carbon sequestration, environmental footprint and agronomic productivity of wheat under rice-wheat cropping system

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A long-term field experiment was conducted to study the effects of different combinations of integrated nutrient management (INM) on carbon sequestration and wheat yield in a rice-wheat cropping system. The experiment consisted of 11 treatments that were replicated three times. The organic manures used in the study included farmyard manure (FYM), wheat straw (WS), and green manure (GM) with *Sesbania aculeata*. The results of the experiment revealed that the application of 50% of the recommended dose of fertilizers (RDF) along with 50% nitrogen (N) through FYM during rice cultivation, and RDF during wheat cultivation, led to a significant increase in soil organic carbon (SOC). Specifically, the SOC content was enhanced by 46.4% (18.29 Mg ha^{-1}) compared to RDF in rice and wheat, resulting in a C sequestration rate of 0.22 Mg ha^{-1} year^{-1}. These increases were higher in treatments that combined organic and inorganic inputs. Additionally, the application of 50% RDF and substituting 50% of the nitrogen with FYM during wheat cultivation resulted in a 24.7% increase in grain yield compared to RDF in rice and wheat. The INM treatments, showed significantly ($p \leq 0.05$) higher agronomic efficiency (AE) of nitrogen (N), phosphorus (P) and potassium (K), partial factor productivity (PFP) of N, P and K, and carbon pool index (CPI) compared to the application of inorganic fertilizers at the recommended dose. Moreover, the INM treatments also exhibited lower greenhouse gas (GHG) emission intensity. Application of neither chemical fertilizers nor organic manure (T_1) resulted in maximum GHG emission intensity (328.1 kg CO_2 eq Mg^{-1} yield). Based on these findings, it can be concluded that the combined use of inorganic fertilizers and organic manures significantly increased crop yield and soil organic carbon sequestration while reducing GHG emissions in a rice-wheat cropping system in the eastern Indo-Gangetic Plains (EIGP) of India.

KEYWORDS

carbon pool index, FYM, GHG emission intensity, SOC sequestration, wheat

Introduction

Wheat (*Triticum aestivum* L.) is a major cereal crop and a staple diet for around one-third of the world's population. It is grown in an area of 225.62 Mha with a production of 750 Mt and productivity of 3322 kg ha^{-1} (FAO, 2020). However, in India, it is cultivated over an area of approximately 32 Mha, with production and productivity of 109 Mt and 3420 kg ha^{-1}, respectively (USDA, 2021). Wheat cultivation areas cannot be expanded beyond certain limits; the only choice is to optimize production per unit area while preserving soil fertility (Sharma and Dhaliwal, 2019). Due to years of intensive farming and unbalanced fertilizer usage, the soil has become deficient in several nutrients and low in organic matter content (Chauhan et al., 2018). The long-term sustainability of agricultural systems is a major concern, and soil degradation is a key factor that affects crop productivity (Singh et al., 2018). This degradation is primarily caused by imbalanced chemical fertilizer and pesticide use and inadequate application of organic manures. In India, there is a significant nutrient imbalance, with an annual requirement of 28 Mt of nitrogen (N), phosphorus (P), and potassium (K), but only 18 Mt being provided from various sources, resulting in a negative primary nutrient balance of 10 Mt (Dhiman et al., 2019). This negative balance indicates a deterioration in soil health due to intensive cultivation practices and excessive use of chemical fertilizers over time (Shambhavi et al., 2018; Sandhu et al., 2020).

To address these issues and enhance crop productivity and sustainability, an integrated approach that recognizes the importance of soil as a storehouse of essential nutrients and promotes its efficient management is necessary (Weih et al., 2018; Parven et al., 2020). Integrated nutrient management (INM) practices aim to ensure both food security and environmental sustainability. Implementing INM practices in the long term has positive impacts on soil properties and helps reduce greenhouse gas (GHG) emissions (Bhatt et al., 2016; Puniya et al., 2019). But it is not universal that INM always reduces the GHG emission and lowers global warming potential (Lenka et al., 2017). Also, the declining soil health and environmental pollution associated with rice-wheat cropping systems highlight the need for sustainable solutions. One strategy to improve soil health and mitigate climate change is soil organic carbon (SOC) sequestration. Long-term fertilizer experiments (LTFE) may be considered valuable tools for assessing the impact of varied cropping systems on SOC sequestration, carbon pool index (CPI), and GHG emissions in rice-wheat systems (Saha et al., 2018).

The present study has taken into account the various combinations of conventional inorganic sources along with varied organic sources including farmyard manure (FYM) and green manure (GM) in different proportions to find out the better combination towards reducing environmental footprints through carbon sequestration and ultimately reducing the global warming potential. In earlier studies, only certain organic or inorganic sources were studied individually without making the appropriate combined study.

Therefore, an experiment has been framed to validate the effect of conventional RDF in contradiction to various INM practices to investigate the effects of long-term INM on agronomic production, potential improvements in SOC stock, and the minimization of environmental footprints under rice-wheat cropping system in eastern Indo-Gangetic Plains (EIGP) of India.

Materials and methods

Experimental site details

The field experiment was initiated in 1984 at the Research Farm of Bihar Agricultural University in Sabour, Bihar, India (coordinates: 25°15′4″N and 78°2′45″E, with an elevation of 86.6 m above sea level). The geographical location of the study site is presented in Figure 1. The experiment was conducted under the network project research program of the Project Directorate on Farming System Research, Modipuram. The initial (of the year 1984) soil physicochemical properties have been presented in Table 1.

The region has a humid subtropical climate, and the monsoon season typically begins in the first week of June and lasts until October. The average annual rainfall in the area is 1280 mm, with approximately 75%–80% of the rainfall occurring between mid-June and mid-October. In May, the average monthly temperature ranges from 35°C to 39°C, while in January, it varies from 5°C to 10°C.

Weather during crop growth period and crop management

The study was conducted on wheat during the winter season of the year 2020–2021. During the study period, the total rainfall recorded at the Sabour, Bhagalpur study site was 0.4 mm. The weather during the crop growth period was characterized by bright sunshine and cold temperature typical of the dry season. The maximum temperature ranged from 19.9°C to 34.4°C, while the minimum temperature varied between 7.7°C and 21.9°C during the winter season of 2020–2021. The average minimum relative humidity ranged from 79.7% to 98.9%, while the maximum relative humidity ranged from 38.3% to 80.7% (Figure 2).

The wheat cultivar 'HD-2967' was sown at the rate of 100 kg ha^{-1} on 15 November 2020 and harvested on 5 April 2021. Three irrigations that are pre-sowing irrigation of 5.0 cm followed by two irrigations depending on prevailing weather conditions were provided. All the required cultural practices were followed consistently to bring the wheat crop to maturity.

Treatment details

The field experiment consisted of 11 treatments that were replicated three times. Each plot had dimensions of 8.10 m × 4.20 m. The experimental design used was a randomized block design (RBD), and the treatments were designed based on various combinations of inorganic and organic nutrient sources, as outlined in Table 2. The control treatment (T_1) received no fertilizer or organic manure. The recommended dose of fertilizers, including urea, single super phosphate, and muriate of potash, was applied at a ratio of N: P_2O_5: K_2O as 120-60-40 kg ha^{-1}, respectively. During the study period of wheat cultivation, half of the N and full P_2O_5 and K_2O were applied at the time of sowing and the remaining N was top dressed equally at 30 days after sowing (DAS) and 60 DAS as per the treatments.

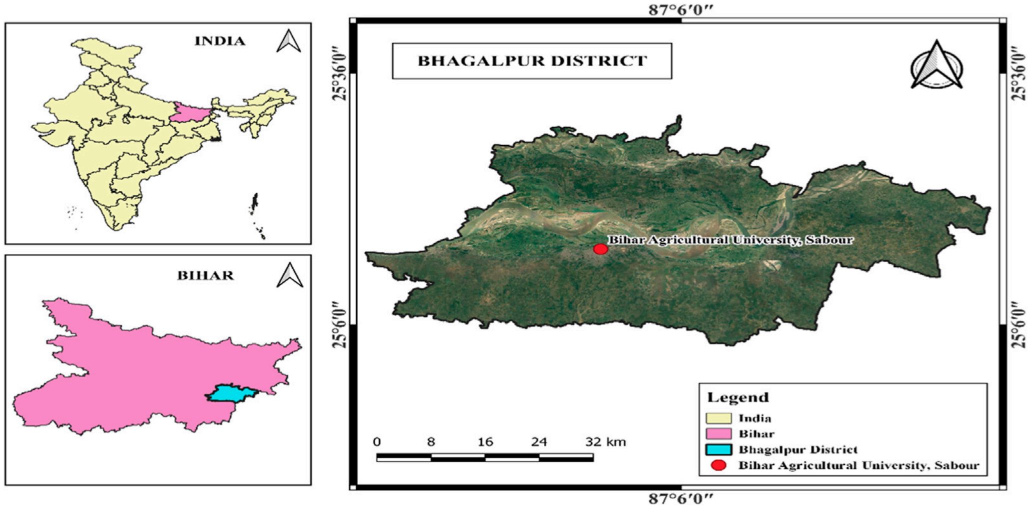

FIGURE 1
The geographical location map of the study area.

TABLE 1 Physical and chemical properties of soil of experimental plot in the year of initiation (1984).

Particulars	Value	Method used	References
Sand (%)	47.4	Bouyoucos Hydrometer	Piper (1966)
Silt (%)	32.6		
Clay (%)	19.6		
Texture	Sandy loam	Textural Diagram	Black (1965)
Bulk density	1.49 Mg m^{-3}	Core sampler	Black (1965)
Soil pH (1:2.5 soil water suspension)	7.4	Potentiometric	Jackson (1973)
Electrical conductivity	0.29 dS m^{-1}	Potentiometric	Jackson (1973)
Organic carbon	10.30 Mg ha^{-1}	Walkley and Black rapid titration method	Jackson (1973)
Available nitrogen (N)	194 kg ha^{-1}	Alkaline $KMnO_4$	Subbiah and Asija (1956)
Available phosphorus (P)	23 kg ha^{-1}	Olsen's method	Olsen et al. (1954)
Available potassium (K)	155 kg ha^{-1}	1N neutral ammonium acetate method	Jackson (1973)

Grain yield

For grain yield estimation of wheat, a 2.0 m^2 area was selected from each plot and the harvested bundles were threshed and winnowed separately. After cleaning, the grain was sun-dried on the threshing floor and the weight was recorded and converted into Mg ha^{-1} at 12% moisture content.

Soil sampling and processing

Soil samples were collected after harvesting wheat (05 April 2021) using a core sampler (15 cm height and 7.6 cm diameter) from 0 to 15 depth from each plot. Samples were air-dried under shade after collection, ground, and sieved to pass through a 5 mm sieve and kept for further analysis.

Soil analysis

The soil sample (0–15 cm) was collected and bulk density (BD) was determined using a core sampler. For the organic C estimation, the Walkley and Black (Jackson, 1973) method was used for all the samples. The C sequestration capability of soil was calculated using the SOC obtained from different treatments [Eqs. 1–3 (Pathak et al., 2011; Nayak et al., 2012). As the initial SOC for topsoil of the experimental plot (0–15 cm) was known, the C sequestration capacity of topsoil alone was

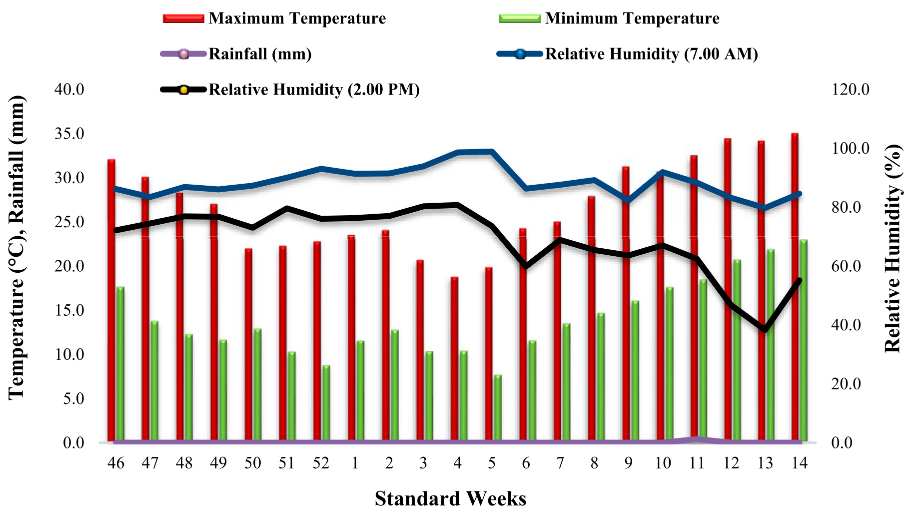

FIGURE 2
Details of weather condition during the experimental period.

TABLE 2 Treatment details of experimental plot.

Treatments	Rice	Wheat
T_1	Control (No fertilizer, no organic manure)	Control (No fertilizer, no organic manure)
T_2	50% RDF	50% RDF
T_3	50% RDF	100% RDF
T_4	75% RDF	75% RDF
T_5	100% RDF	100% RDF
T_6	50% RDF +50% N through FYM	100% RDF
T_7	75% RDF +25% N through FYM	75% RDF
T_8	50% RDF +50% N through wheat straw (WS)	100% RDF
T_9	75% RDF +25% N through wheat straw (WS)	75% RDF
T_{10}	50% RDF +50% N through GM	100% RDF
T_{11}	75% RDF +25% N through GM	75% RDF
Recommended dose	N = 80 kg ha^{-1}, P_2O_5 = 40 kg ha^{-1}, K_2O = 20 kg ha^{-1}	N = 120 kg ha^{-1}, P_2O_5 = 60 kg ha^{-1}, K_2O = 40 kg ha^{-1}

FYM: Farmyard manure, GM: Green manure (*Sesbania aculeata*).

calculated. Different C sequestration related parameters were calculated using the given formula:

$$\textbf{SOC Stock}\ (\textbf{Mg ha}^{-1}) = \text{SOC} \times \text{BD} \times \text{D} \times 10 \qquad (1)$$

where, SOC represents the SOC content (Mg ha^{-1}); BD is the soil bulk density (Mg m^{-3}); D represents the soil depth (m), which was 0.15 m in this study; and 10 represents the conversion coefficient

$$\textbf{C sequestration rate}\ (\textbf{Mg ha}^{-1}\textbf{year}^{-1})$$

$$= \text{SOC–SOC}_{\text{initial}} / \text{ Years of experimentation} \qquad (2)$$

$$\textbf{C sequestered}\ (\textbf{Mg ha}^{-1}) = \text{SOC} - \text{SOC}_{\text{initial}} \qquad (3)$$

where, SOC represents the SOC of each long-term nutrient management treatment (Mg ha^{-1}) and SOC$_{\text{initial}}$ represents the initial SOC (Mg ha^{-1}) of the long-term experiment in 1984.

Carbon pool index (CPI) was calculated following (Blair et al., 1995):

$$\textbf{Carbon pool index}\ (\textbf{CPI}) = \text{sample SOC} / \text{ reference SOC} \qquad (4)$$

where, sample SOC represents SOC of each treatment (Mg ha^{-1}) and reference SOC represents SOC of the unfertilized control treatment (Mg ha^{-1}).

Nutrient use efficiency (NUE) of N, P, and K were calculated as per the formulae given below (Dobermann, 2007; Fixen et al., 2015):

$$\textbf{Agronomic efficiency}\ (\textbf{AE, kg kg}^{-1}) = (\text{GY}_{\text{F}} - \text{GY}_{\text{UF}}) / \text{F}$$

$$\textbf{Partial factor productivity}\ (\textbf{PFP, kg kg}^{-1}) = \text{GY} / \text{F}$$

where, GY$_{\text{F}}$ is Grain yield of the fertilized plot; GY$_{\text{UF}}$, is grain yield of the unfertilized plot; GY is the grain yield and F is the amount of nutrients applied.

TABLE 3 Effect of long-term fertilization on grain yield, soil organic carbon, soil bulk density and carbon pool index (CPI).

Treatment	Grain yield (Mg ha^{-1})	Organic carbon (Mg ha^{-1})	Bulk density (Mg m^{-3})	Carbon pool index (CPI)
T_1	0.96	8.06	1.49	1.06
T_2	2.33	9.26	1.48	1.22
T_3	3.58	10.15	1.47	1.33
T_4	2.90	10.83	1.47	1.42
T_5	3.44	12.62	1.47	1.66
T_6	4.29	18.29	1.37	2.40
T_7	3.76	17.02	1.39	2.24
T_8	3.80	17.25	1.39	2.26
T_9	3.29	16.20	1.40	2.13
T_{10}	3.92	17.02	1.39	2.24
T_{11}	3.66	16.28	1.40	2.14
SEm (±)	0.16	0.21	0.01	0.03
LSD ($p \leq 0.05$)	0.49	0.62	0.03	0.08

T_1, Control (no fertilizer no organic manure); T_2, 50% recommended dose of fertilizers (RDF) to both rice and wheat; T_3, 50% RDF, to rice and 100% RDF, to wheat; T_4, 75% RDF, to both rice and wheat; T_5, 100% RDF, to both rice and wheat, T_6, 50% RDF +50% N through farmyard manure (FYM) to rice and 100% RDF, to wheat; T_7, 75% RDF +25% N through FYM, to rice and 75% RDF, to wheat; T_8, 50% RDF +50% N through wheat straw to rice and 100% RDF, to wheat; T_9, 75% RDF +25% N through wheat straw to rice and 75% RDF, to wheat; T_{10}, 50% RDF +50% N through green manure (GM) to rice and 100% RDF, to wheat; T_{11}, 75% RDF +25% N through GM, to rice and 75% RDF, to wheat.

Greenhouse gas emission estimation

The estimation of GHG emissions for wheat was conducted using the Climate Change, Agriculture and Food Security-Mitigation options tool (CCAFS-MOT), developed by the United States Department of Agriculture (USDA) in collaboration with the University of Aberdeen (Feliciano et al., 2017). This tool assesses the performance of production systems in terms of GHG emissions, considering land-use efficiency and efficiency per unit of output. The tool calculates the global warming potential (GWP) by converting all GHGs generated by the production systems into CO_2-equivalents (CO_2-eq) using the global warming potential (over 100 years) values of 34 for CH_4 and 298 for N_2O. The GHG emission intensity of each crop was determined by dividing the total GWP by the grain yield.

Statistical analysis

The field experiment data was analyzed using “Analysis of Variance” (ANOVA) in RBD as suggested by Gomez and Gomez (1984). To compare the differences between treatments, the standard error of mean (SEm) and least significant difference (LSD) at a significance level of 5% were calculated for each variable. Statistical analysis was performed using SPSS version 16.0 (SPSS Inc., Chicago, United States of America), while Microsoft Excel 2016 (Microsoft Corporation, United States of America) was utilized for graphing purposes. The heat map was created in R software version 4.2.2 using the “ggplot” package (R Core Team, 2023).

Results

Soil bulk density and organic carbon

The combination of 50% recommended dose of fertilizer (RDF) and 50% N through FYM followed by RDF in wheat (T_6), resulted in the most significant reduction in BD (1.37 Mg m^{-3}) compared to the initial value (1.49 Mg m^{-3}). No change in BD was observed in the control plot compared to the initial value (Table 3).

The addition of organic matter proved effective in increasing the SOC content throughout the experiment. Among various organic sources such as FYM, wheat straw (WS), and GM with *Sesbania aculeata*, FYM exhibited higher efficiency in significantly accumulating higher levels of SOC in the soil. The organic carbon content increased from 10.30 Mg ha^{-1} in the first year (1984) to 18.29 Mg ha^{-1} with the application of 50% RDF and 50% N applied through FYM in rice, and RDF in wheat (T_6). This treatment resulted in a 44.9% increase in soil organic carbon content in comparison to the RDF treatment (T_5) (Table 3). The plots which received no fertilizer or organic manure (T_1), 50% RDF through inorganic fertilizers for both crops (T_2) and 50% RDF in rice and RDF in wheat (T_3), showed a decrease in SOC content from the initial value.

Soil organic carbon stock and sequestration rate

The integration of organic inputs and chemical fertilizers resulted in significantly higher SOC stock. After 36 cycles of the rice-wheat sequence, SOC stocks ranged from 8.05 to

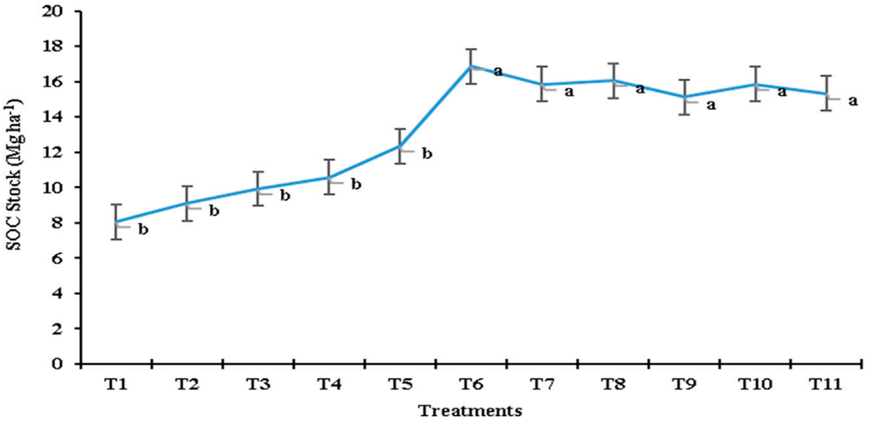

FIGURE 3
SOC stock (Mg ha^{-1}) under different treatments after 36 years of experiment. Means of different treatments followed by the different lower-case letters are significantly different at $p \leq 0.05$ levels of significance according to Duncan's multiple range test.

16.85 Mg ha^{-1} (Figure 3). The application of 50% RDF + 50% N through FYM in rice and RDF in wheat (T_6) yielded the highest SOC stock of 16.85 Mg ha^{-1}. On the other hand, the unfertilized control (T_1) had the lowest SOC stock of 8.05 Mg ha^{-1}, which was significantly lower than the initial stock of 10.28 Mg ha^{-1}. The addition of FYM, WS, or GM along with reduced doses of RDF contributed to an enhancement in SOC stock. Compared to the application of RDF in both crops, there was a maximum increase of 36.43% and 29.9% in SOC stock with the use of 50% RDF +50% N through FYM in rice and RDF in wheat (T_6), and 50% RDF +50% N through WS in rice and RDF in wheat (T_8), respectively.

The amount of C sequestered ranged from −2.24 to 8.07 Mg ha^{-1} (Figure 4A). The integrated nutrient management (INM) treatments significantly increased both the quantity and potential of soil C sequestration compared to the treatment with no manures and fertilizers. The highest C sequestration (8.07 Mg ha^{-1}) was observed with the application of 50% RDF +50% N through FYM in rice and RDF in wheat (T_6), followed by 50% RDF +50% N through WS in rice and RDF in wheat (T_8) (6.95 Mg ha^{-1}). The data also indicated the C sequestration rate, which ranged from −0.06 Mg ha^{-1} year $^{-1}$ under the unfertilized control (T_1) to 0.22 Mg ha^{-1} year $^{-1}$ with 50% RDF +50% N through FYM in rice and RDF in wheat (T_6) (Figure 4B). The CPI varied from 1.06 to 2.40, with the highest value observed with the application of 50% RDF +50% N through FYM in rice and RDF in wheat (T_6) (Table 3).

Crop yield and nutrient use efficiency

The grain yield of wheat at maturity for each treatment was analyzed statistically, and the results are summarized in Table 3. The study found that integrated nutrient management practices in rice had a significant impact on wheat grain production. Among the treatments, the highest grain yield of 4.29 Mg ha^{-1} was achieved with the application of 50% RDF and 50% N through FYM in rice, followed by RDF in wheat (T_6). Conversely, the control plot (T_1) had the lowest grain yield of 0.96 Mg ha^{-1}.

The AE of N in wheat ranged from 20.65 to 31.06 kg kg^{-1}. For P and K, the AE ranged from 94.58 to 142.23 kg kg^{-1} and 74.96 to 112.73 kg kg^{-1}, respectively (Figures 5–7). Generally, the organic treatment plots showed relatively higher AE values compared to the RDF treatment, except for the treatment involving 50% recommended dose of fertilizers (T_3), which still had a reasonably higher value compared to the RDF treatment. The organically treated plots outperformed the solely inorganic plots. The treatment with the highest AE involved 25% N substitution through FYM in rice and 75% RDF in wheat (T_7), followed by 25% N substitution through GM in the rice growing season and 75% RDF in wheat (T_{11}). The treatment with the lowest AE utilized RDF for both rice and wheat (T_5).

Regarding PFP of N, the values ranged from 28.68 to 41.76 kg kg^{-1}. The PFP range for P and K varied from 131.33 to 191.24 kg kg^{-1} and 104.09 to 151.57 kg kg^{-1}, respectively (Figures 5–7). The plots with organic substitutions exhibited higher PFP values compared to the RDF treatment but lower than the treatments where only inorganic fertilizers were applied at different rates.

GHG emission intensity

In the study, it was observed that the combined organic-inorganic treatments had lower GHG emission intensities compared to the sole application of chemical fertilizers. The treatment with the minimum GHG emission intensity (206.6 kg CO_2-eq Mg^{-1} yield) involved the application of 75% RDF and 25% N through FYM in rice, followed by 75% RDF in wheat (T_7). Application of neither chemical fertilizer nor organic manure (control, T_1) accounted highest GHG emission intensity, i.e. 328.1 kg CO_2-eq Mg^{-1} yield. Besides control, the treatment with the maximum GHG emission intensity (286.9 kg CO_2-eq Mg^{-1} yield) used RDF in both rice and wheat (T_5) (Figure 8).

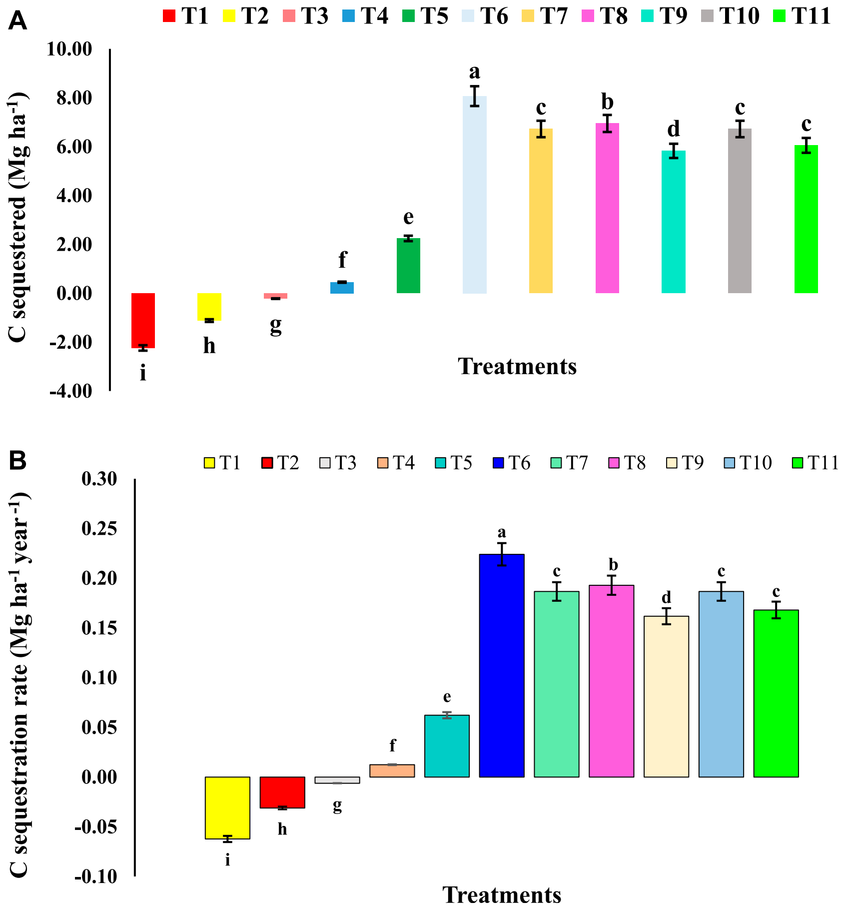

FIGURE 4
(A) C sequestered (Mg ha^{-1}) and **(B)** C sequestration rate (Mg ha^{-1} year $^{-1}$) under different treatments after 36 years of experiment. Means of different treatments followed by the different lower-case letters are significantly different at $p \le 0.05$ levels of significance according to Duncan's multiple range test.

Discussion

Effect of long-term fertilization on bulk density and organic carbon

Among the three organic sources (FYM, WS, and GM), FYM was found to be more effective in increasing the soil organic carbon content. Due to the additive effect of inorganic and organic sources of nutrients, as well as the interactions between them, FYM, WS, and GM complemented with chemical fertilizer increased soil organic carbon content in comparison with inorganic fertilizer alone (Zhang et al., 2022). This can be explained by the higher concentration of SOC in FYM treated plots as a result of increased root production and plant residues, along with the application of organic carbon through FYM (Meena et al., 2019). Organic matter in various forms had a significant impact on the organic carbon status, which can be attributed to the improved soil properties (Trivedi et al., 2020; Gogoi et al., 2021).

The INM treatments resulted in lower bulk density compared to the use of solely inorganic fertilizers. The inclusion of organic sources such as FYM, WS, and GM with *Sesbania aculeata* contributed to increased porosity, leading to a decrease in bulk density (Ram et al., 2020). This is because organic sources, which are primarily composed of fibrous agricultural wastes, enhance soil volume while reducing bulk density (Randhawa et al., 2021). However, in all the treatments involving only chemical fertilizers, bulk density increased at the soil surface due to reduced porosity and decreased SOC (Bhardwaj et al., 2019). The decrease in BD over the years could be attributed to the addition of root and plant biomass and the conversion of some micro-pores into macro-pores as a result of the cementing action of organic acids and polysaccharides formed during the decomposition of organic residues by higher microbial activities (Parihar et al., 2018; Jat et al., 2019).

Impact of long-term INM on carbon stock and sequestration rate

The increase in SOC stock in plots amended with manure can be attributed to improved aggregation and encapsulation of carbon

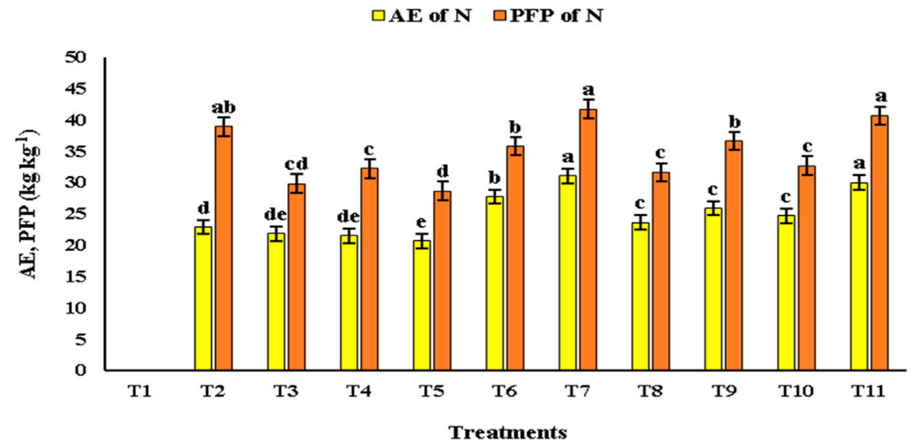

FIGURE 5
Agronomic efficiency (AE) and partial factor productivity (PFP) of applied nitrogen (N) of wheat as affected by different nutrient management strategies under rice-wheat cropping system. Means of different treatments followed by the different lower-case letters are significantly different at $p \leq 0.05$ levels of significance according to Duncan's multiple range test.

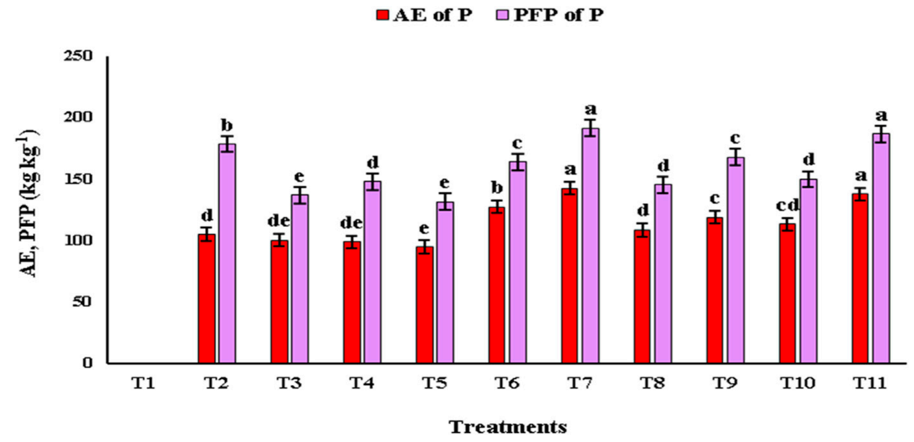

FIGURE 6
Agronomic efficiency (AE) and partial factor productivity (PFP) of applied phosphorus (P) of wheat as affected by different nutrient management strategies under rice-wheat cropping system. Means of different treatments followed by the different lower-case letters are significantly different at $p \leq 0.05$ levels of significance according to Duncan's multiple range test.

within soil aggregates (Bhattacharyya et al., 2013). The highest total SOC stock observed in plots treated with 50% RDF and 50% N through FYM in rice, followed by RDF in wheat (T_6), may be a result of the combined effect of increased carbon inputs and enhanced biomass production (Duval et al., 2018). Chemical fertilizers combined with FYM not only improved crop yield, but FYM as a good source of organic matter contributed significantly to the carbon pool index. This might be attributed to enhanced plant growth, root biomass, and CO_2 fixation through balanced NPK fertilizers and carbon inputs through organic manure (FYM) in soil with NPK and organic manure application (He et al., 2020).

The combination of organic manure with synthetic fertilizers promotes crop production and improves the soil capacity to store SOC for long-term sustainability (Zhang et al., 2018; Srinivasarao et al., 2019). This finding supports the positive impact of integrated nutrient management on SOC-derived CO_2 through mineralization (Zhao et al., 2018). Pathak et al. (2011) observed the mean carbon-sequestration rates of Indian soils from 26 long-term nutrient management trials across the subcontinent with varying cropping patterns were 0.33 and 0.16 Mg C ha^{-1} year^{-1} for NPK + FYM and FYM alone, respectively. Similarly, pooled analysis of 28 long-term fertilizer experimental trial data in China showed that NPK + manure sequestered more carbon (0.67 Mg C ha^{-1} year^{-1}) than NPK (0.30 Mg C ha^{-1} year^{-1}) (Zhou et al., 2016). Conversely, long-term application of inorganic fertilizer can activate humus mineralization, which can negatively affect soil quality and lead to issues such as nitrogen leaching and the accumulation of toxic metals from fertilizer impurities (Jat et al., 2019).

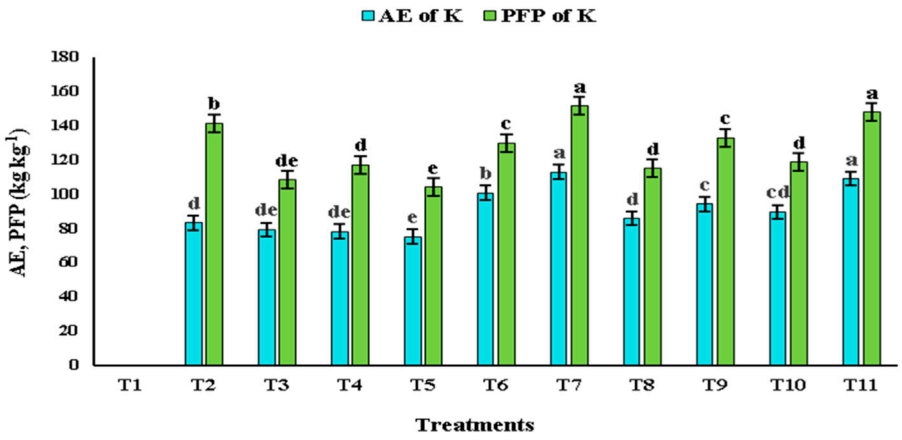

FIGURE 7
Agronomic efficiency (AE) and partial factor productivity (PFP) of applied potassium (K) of wheat as affected by different nutrient management strategies under rice-wheat cropping system. Means of different treatments followed by the different lower-case letters are significantly different at $p \leq 0.05$ levels of significance according to Duncan's multiple range test.

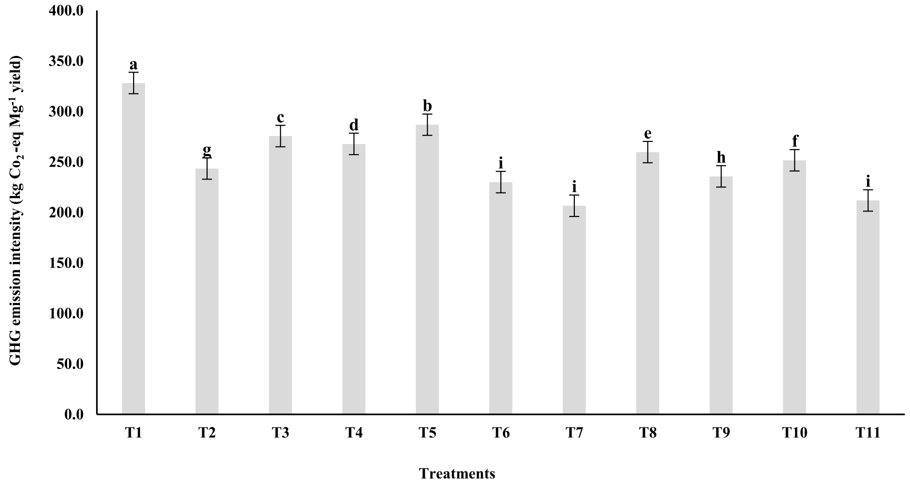

FIGURE 8
GHG emission intensity of wheat under rice-wheat system with different fertilizer management strategies after 36 years of experiment. Means of different treatments followed by the different lower-case letters are significantly different at $p \leq 0.05$ levels of significance according to Duncan's multiple range test.

Long-term fertilization effects on yield and nutrient use efficiency

Yield

The application of organic sources plays a crucial role in optimizing nutrient utilization and achieving a balance between growth and yield attributes. Among the various organic sources, FYM offers distinct advantages over WS and GM, as discussed in detail in the analysis of growth parameters (Ghaley et al., 2018). FYM has a higher organic matter content, which enhances the physical and biological properties of the soil compared to WS and GM (Datta et al., 2018). It is also rich in highly humified organic matter, particularly fulvic acid, and provides greater availability of macro and micronutrients, thereby improving the soil's physical and chemical properties (Alam et al., 2020). These beneficial effects of FYM, in comparison to WS and GM, likely contribute to higher yields in treatments where 50% of inorganic N is substituted with FYM, along with the application of 50% recommended dose of fertilizers in rice, followed by RDF in wheat (T_6) (Ghosh et al., 2018).

Nutrient use efficiency

Agronomic efficiency (AE) is an important indicator of the impact of applied nutrients on productivity. Higher AE values indicate a direct effect of incorporating FYM and other organic materials along with mineral fertilizers, suggesting that N mineralization from organics aligns with nutrient supply and crop demand. Organic manures improve fertilizer use efficiency and serve as alternative nutrient sources. The combined use of organic manure and N fertilizer ensures a continuous N supply, minimizes losses, and enhances the efficient utilization of N. Additionally, organic nutrient sources act as slow-release fertilizers, synchronizing nutrient release from the labile soil pool and applied sources with plant nutrient demand in terms of timing and spatial distribution (Dwivedi et al., 2016).

Plots treated with inorganic fertilizers and exhibiting higher partial factor productivity (PFP) values indicate suboptimal N use or potential nutrient supply limitations, while lower values suggest less responsiveness or excessive nutrient application (Dobermann, 2007; Fixen et al., 2015). In LTFE, nitrogen use efficiency, calculated in terms of PFP, significantly increased in the INM treatments compared to the application of fertilizer NPK at recommended rates (Mondal et al., 2016).

Higher AE and PFP values reflect the utilization of P at lower rates, indicating increased yield but less efficient P utilization. The lower AE of P in FYM-treated plots may be attributed to limited P mobilization from FYM during the crop growth period, resulting in increased P availability and higher yield. Substituting 50% of N with organics in rice and application of RDF to wheat (T_6) resulted in lower PFP compared to substituting 25% of N in rice and applying 75% recommended dose of fertilizer to wheat (T_7, T_9 and T_{11}).

The results showed that the residual effect of applied organics in rice was evident in wheat, where all organic-treated plots exhibited better AE and PFP values for K compared to the plot receiving RDF. Additionally, lower K application in organic-treated plots resulted in higher K use efficiency. The high K use efficiency in plots treated solely with inorganic fertilizers indicates nutrient depletion over the years, leading to nutrient deficiency and lower yield. Overall, lower K use efficiency values in plots incorporating WS may be attributed to the higher K content in straw compared to other nutrients, as continuous K solubilization over the years increased soil K levels, ultimately resulting in higher crop uptake (Singh et al., 2010). Improved management of crop residues and organic waste helps prevent K depletion, and retaining crop residue enhances crop K requirements, thereby improving K use efficiency (Singh et al., 2018; Dhillon et al., 2019).

GHG emission intensity

In recent years, the environmental impact of agricultural practices like nutrient management practices has garnered significant attention due to concerns related to climate change and GHG emissions (Menegat et al., 2022; Hemingway et al., 2023). Various studies have indicated the discrepancy that inorganic fertilizers tend to emit more GHGs than organic manures mainly attributed to multiple factors, including nutrient composition (Walling and Vaneeckhaute, 2020), application methods, microbial activity (Jannoura et al., 2014; Tripathi et al., 2020; Yu et al., 2022), and soil management practices (Van Kessel et al., 2013). The highest GHG emission intensity was attributed to the control treatment because of its reduced yield. The T_5 which comprises the inorganic fertilizers fully for both crops is characteristically composed of synthetically produced N, P, and K compounds that have a high solubility, allowing for rapid nutrient availability to plants (Jain et al., 2016). However, excess nutrients can be lost through various pathways, leading to increased GHG emissions and in turn to GHG emission intensity. To the contrary, organic manures contain lower nutrient concentrations, which are gradually released through microbial decomposition and mineralization processes, resulting in reduced nutrient losses as well as GHG emission which was well reflected in the T_7 where 25% (from both rice and wheat) inorganic fertilizer application was reduced and supplemented by FYM.

On the other hand, the generally followed application methods for inorganic fertilizers lead to N losses through volatilization and denitrification. This leads to the release of GHGs like nitrous oxide (N_2O) and carbon dioxide (CO_2) significantly impact GHG emissions and emission intensity. However, organic manures like FYM and green manure are generally applied in lower doses and mixed with the soil, facilitating better nutrient retention and minimizing GHG emissions which supplements the decrease in emission intensity of T_7 and T_{11}. Similarly, the inorganic fertilizers, being highly soluble and readily available, can stimulate microbial activity, particularly nitrification and denitrification processes, which generate N_2O (De Rosa et al., 2018), a potent GHG like in T_2, T_3, T_4, and T_5. However organic substrates like WS and green manuring crops provide a diverse range of organic matter, promoting the growth of beneficial soil microorganisms that enhance nutrient cycling, potentially reducing GHG emissions. Green manuring crops and incorporation of WS contribute to improved soil health and structure, enhancing the ability of the soil to retain water and nutrients which tends to reduce leaching and runoff (Menegat et al., 2022), minimizing the loss of nutrients and subsequent GHG emissions corroborating with the results of T_{11}. Green manure (T_{11}) increased the retention capacity of nutrients than WS (T_9) so resulting in lesser emission intensity. In contrast, the excessive and imbalanced application of inorganic fertilizers can negatively affect soil health, resulting in increased GHG emissions through nutrient runoff and leaching (Hemingway et al., 2023). Thereby, by adopting sustainable practices that promote the use of organic manures such as FYM and GM, farmers can reduce GHG emissions intensity (Gorjian et al., 2022) and mitigate the negative environmental impact of agricultural activities.

Correlation study

Analysis of the data revealed a strong positive correlation between SOC stock and grain yield (r = 0.82) (Figure 9). A positive association between the PFP of N with grain yield (r = 0.74) was observed. Similarly, grain yield exhibited strong positive linear relationships with CPI (r = 0.81). The results from the regression analysis indicated that there is a significant influence of SOC stock and PFP of N on grain yield, each recording a change of 0.2341 (**$y = 0.2341x + 0.1812$)** and 0.0606 (**$y = 0.0606x + 1.3454$)** units, respectively for one unit change in SOC stock and PFP of N respectively. Long-term application of organic materials through various C sources improved the C stock and CPI (Ozlu and Sandeep, 2018).

GHG emission intensity was negatively correlated with the grain yield ($r = -0.667$). The negative correlation between grain yields with

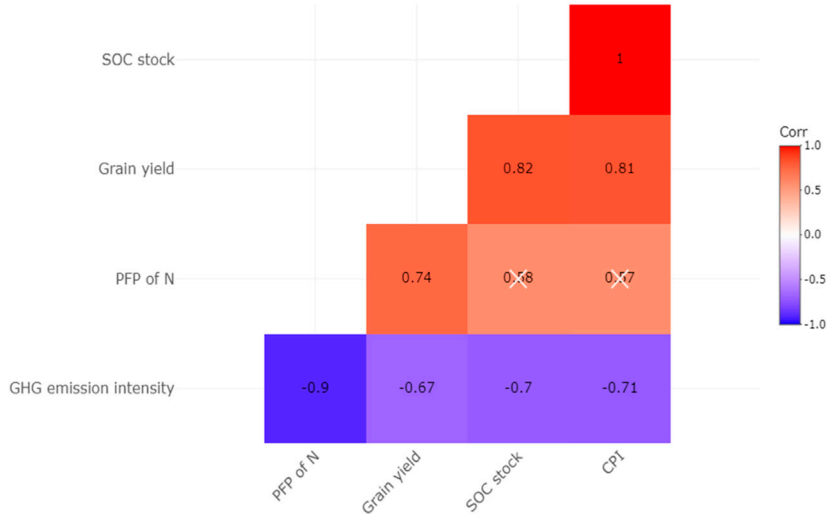

FIGURE 9
Heatmap of correlation coefficient between different parameters after 36 years of LTFE (white colour cross-mark visualizes non-significance at $p \leq 0.05$ and rest are significant).

GHG emission intensity showed that organic and inorganic combined practices resulted in low GHG emission intensity (Figure 9). These strong correlations may be because the benefits of proper management of nutrients (right dose, organic + inorganic) in soil are significant and improve soil health (Jat et al., 2021).

Conclusion

The 36 years old permanent manurial experimental soil provided an opportunity to assess the long-term consequences of nutrient management adoptions on carbon sequestration, yield and GHG emission intensity. Continuous application of organic manure with balanced chemical fertilizers significantly increased the SOC sequestration and yield, as well as reduced the emission intensity under an intensive rice-wheat cropping system. However, our study suggests that carbon management in this system is just above the threshold level, and it has to be increased to restore soil health and productivity. The in-depth knowledge of soil carbon dynamics and GHG emission with INM under the rice-wheat cropping system is scant in the EIGP of India. By conducting comprehensive research in these areas, scientists and policymakers can gain a complete understanding of the effects of long-term INM implementation on maintaining agricultural production while promoting environmental sustainability. This knowledge can help form better agricultural practices and policies to address food security and environmental challenges in the EIGP of India.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

SR framed the notion and was overall in charge of this manuscript preparation. SR, SK, SKD, SS, and SRP collected literature, analyzed data, and drafted the manuscript. SRP did preparation of heat map and SR and SS did preparation of study area location map. PD, SS, DKR, DN, KB, and VB edited the manuscript. All contributors discussed the outcomes and added to the final document. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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