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RESEARCH

Sustainability Assessment of Rice-Wheat System Through Organic Fertilizers and Green Manuring in Sub-Tropical Humid Climate

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Abstract

The improved crop varieties and inorganic fertilizers played a key role in bringing the revolutionary change from insufficient to surplus food grains production. In the era of self-reliant in food grains production, the noxious impacts of long-term sole application of inorganic fertilizers on natural resources are being observed critically and climate vagary and its threat to agriculture sector makes such studies of prime importance. The present study was undertaken with a hypothesis to substitute the inorganic N (either partial or fully) with farm yard manure (FYM) in at least one crop under rice-wheat system. The experiment was conducted in a two-factorial randomized complete block design with different levels of FYM (0, 10 and 30 t ha^{-1}) in each crop to study the yield, soil health, quality, profitability and sustainability with a comparison to recommended dose of conventional inorganic fertilizers (CIFs). In all treatments, green manuring was done through the incorporation of *Sesbania aculeata (Willd.) Pers* crop prior to rice translating. The results of pooled analysis of seven-year data (2013–2014 to 2019–2020) revealed that application of 30 t ha^{-1} FYM produced statistically similar ($p > 0.05$) rice yield but with a decline of 19.21% in wheat yield as compared to CIFs. The continuous application of FYM @30 t ha^{-1} increased organic carbon content of soil to 1.24% in the upper soil layer which was 74.6% higher than that under CIFs. The substitution of CIFs with FYM brought significant ($p < 0.05$) increase in available N, P and K in the top layer of the soil. The available N was significantly higher ($p < 0.05$) along with slight improvement ($p > 0.05$) in organic carbon in the top layer of the soil under control treatment associated with *Sesbania aculeata (Willd.) Pers* incorporation over CIFs. The application of 30 t ha^{-1} FYM produced similar net return and wheat equivalent yield as with CIFs. However, benefit-cost (B:C) ratio in CIFs (2.16) was significantly ($p < 0.05$) higher than those with FYM application (1.75–1.90) due to increase in transportation and labour cost in handling bulky FYM. The substitution of CIFs with FYM produced statistically similar sustainability value index (SVI) which indicates the similar stability of rice-wheat system and its sustainable nature as with CIFs. The results of present study suggest that CIFs can be substituted by green manuring + FYM application @30 t ha^{-1} in rice crop under rice-wheat cropping system without any penalty on crop productivity and profitability while providing the multifarious benefits on soil health, which has been deteriorated through intensive cultivation of rice-wheat system, and overdosed and imbalanced inorganic fertilizers application in Indo Gangetic plains. Further, assured premium price of organic rice can escalate the adoption of such alternative fertilizers; however, high cost of FYM amidst declining cattle, increased transportation and labour cost in handling bulk volume of such fertilizers seems to be challenging factors.

Keywords Farm yard manure · Organic carbon · Soil properties · Yield · Profitability · Sustainability

Introduction

In the sub-tropical humid environment, the predominant cropping system is puddled transplanted rice (*Oryza sativa* L.), followed by intensively tilled wheat (*Triticum aestivum* L.) which serves food to the millions of people in South Asia. But, the intensive cultivation of rice-wheat rotation has led to the stagnant yield due to reduced

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quantity and quality of soil organic carbon (Bhatt et al., 2019; Chaudhury et al., 2005; Saurabh et al., 2021), imbalanced and injudicious application of fertilizers and pesticides (Jat et al., 2019), multi-nutrients (N, P, K, S, Zn and B) deficiency (Bhatt et al., 2019; Hazra et al., 2019) and ill effects of puddling such as sub-surface compaction and migration of clay particles, restricting the root growth of subsequent crop (Singh et al., 2005; Chauhan et al., 2012). The intensive cereal-cereal production system, imbalanced fertilization and nil or inadequate recycling of biomass into soil led to not only reduced productivity but also declined soil fertility, inadequate response of crops to applied fertilizers, reduced fertilizer use efficiency, higher nutrient losses, increased environmental emissions, reduced factor productivity and imbalanced agro-ecosystem.

The application of only mineral fertilizers (urea, diammonium phosphate and muriate of potash) for longer period deteriorates pore structure of soil through changes in pore morphology and network structure, which can influence other important soil processes and properties (Lu et al., 2019). The trend of synthetic nitrogen application in India is shown in Fig. 1 . The annual use of synthetic nitrogen sharply increased from 10.92 million tonnes (Mt) in 2000 to 17.63 Mt in 2018. It caused direct N_2O and in-direct N_2O (from leaching and volatization) emissions to the tune of 277 and 90 kilo tonnes, respectively. The adverse effects of conventional inorganic fertilizers (CIFs) can be evaded through continuous application of organic matter to soil in various forms such as farm yard manure (FYM), green manure, crop residues, etc., either in partial substitution or as a supplement due to improvement in micro nutrients, carbon addition and increased activities of bacteria (Rajasulochana & Rao, 2021).

The partial substitution or supplementation of CIFs with organic fertilizers provides several beneficial effects such as slow release of multiple macro and micro nutrients essential for plant growth (Verma et al., 2020); better soil aeration, aggregate stability, pore development and increased soil biological activities and improved soil structure (Roba, 2018; Shaji et al., 2021); and reduced phosphorus losses (Mitran et al., 2018; Singh et al., 2019a, b); increased soil carbon (18.3%), nitrogen (17.5%) and soil microbial biomass C (49.3%) over base treatment with conventional inorganic fertilizers (Yu et al., 2020; Lu et al., 2019) recommended the use of manure for improving the soil pore structure. Similarly, Mishra et al., (2006) suggested to apply organic manures for sustained supply of Zn and Cu to soils under rice-wheat system. The other approaches namely green manuring, inclusion of legume in crop rotation and crop residue incorporation also enhance the soil fertility and crop productivity (Tripathi et al., 2019, 2021); improve the soil microbial population, increase the soil enzyme activities (Bhatt et al., 2019); provide higher yield, more net return and save the expenditure on inorganic fertilizers besides improving the overall soil health (Sah, 2020; Singh et al., (2019a, b; Tripathi et al., (2021); Das et al., (2014a) reported better soil aggregation, structural stability and water retention capacity with 25% N substitution through organic material (FYM, sulphitation press mud, green gram or rice/wheat residue) in rice-wheat system. The treatment having green gram residue in rice and FYM in wheat increased C content in macro-aggregates over mineral fertilizer application. Mazumdar et al., (2015) concluded that integrated nutrient management involving 50% NPK + 50% N through FYM in rice and 100% NPK in wheat increased soil organic carbon to 7.7 g kg^{-1} along with higher mean weight diameter and macro-aggregate fractions over control and sole inorganic fertilization

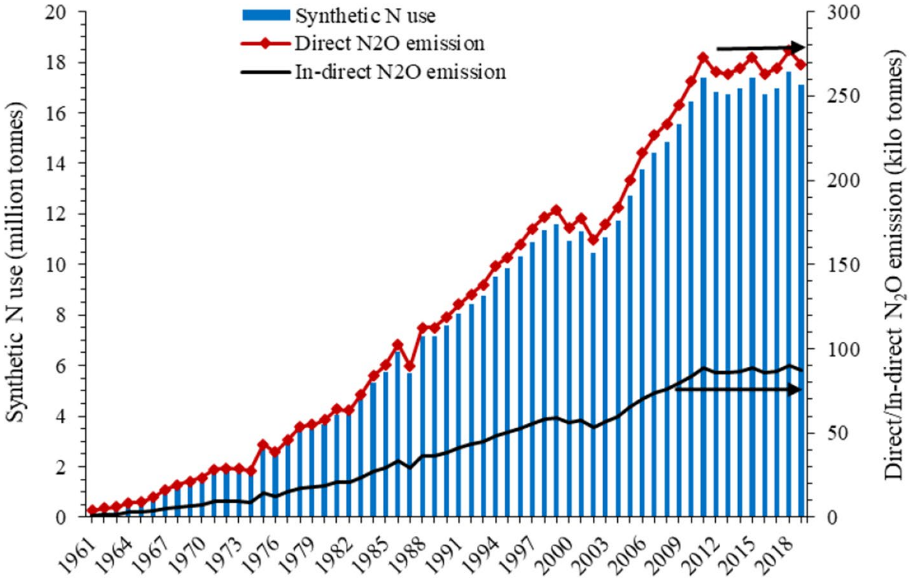


Fig. 1 Use of synthetic nitrogen and associated direct and in-direct N_2O emissions in India over the years *(Source: FAOSTAT 2022)*

and thus helps in mitigation of global warming. Benbi et al., (2016) also noted higher macro-aggregates, organic carbon and carbon sequestration rate under 100% NPK application with 15 t ha^{-1} FYM in rice-wheat cropping sequence. In a different study, Mitran et al., (2018) concluded that long-term organic input (either as FYM, green manure or wheat/rice straw) provides structure rejuvenation i.e., transformation of micro-aggregates to macro-aggregates and reduces phosphorus losses, leading to a sustainable farming. Further, Sandhu et al., (2020) reported that replacing 50% N of conventional inorganic fertilizers with organic sources only in summer (rice) not in winter (wheat) led to significant decline in bulk density and soil strength along with improved infiltration rate, higher hydraulic conductivity, increased level of soil macro- and micro-nutrients and higher soil organic carbon over CIFs alone in rice-wheat rotation.

In addition to improvement in soil properties, the yield aspect plays crucial role in the adoption of alternate crop production system. The application of FYM with recommended dose of NPK is must for sustaining the productivity and profitability of rice-wheat cropping system in long-term (Singh et al., 2019a; Gami et al., 2001) reported significant decline in rice and wheat yield with sole application of FYM or substituting 50% N with FYM or wheat straw over standard practice of inorganic fertilization. However, treatment receiving organic input increased soil carbon and nitrogen from 18 to 15% to 62 and 48%, respectively, over mineral fertilization along with buildup of phosphorus in the soil. In a different study, Pathak et al., (2002) concluded that substituting the farmers' practice of applying nitrogen (typically 240 kg urea ha^{-1}) to urea (60 kg N ha^{-1}) + FYM (60 kg N ha^{-1}) and urea (108 kg N ha^{-1}) dicyandiamide (12 kg N ha^{-1}) reduced NO_2-N emission from 1570 g ha^{-1} to 1415 and 1096 g ha^{-1}, respectively, without any significant difference in crop yield of rice-wheat system. Rasool et al., (2007) reported slightly higher yield of rice (7.92 t ha^{-1}) and wheat (4.83 t ha^{-1}) and more uptake of nutrients with FYM application @20 t ha^{-1} over standard practice mineral NPK fertilization (120, 30 and 30 kg ha^{-1}, respectively). Klepper et al., (2010) concluded that inorganic N need to be applied to the soil periodically despite soil is fertilized through manure with moderate or large application rate due to imbalanced nutrients in manure with respect to plant demand. The combination of high rate application of manure once per 3 or 4 years and inorganic N enhanced the yield of forage crops (sorghum and triticale) and nutrient recovery with lesser dissolved nutrient losses. Das et al., (2014b) reported from long-term (28 years) experiments that yield of both rice and wheat crops declined under sub-optimal fertilizer application (50–75% of recommended dose). Treatments with organic supplements (either as FYM, green manure or wheat straw) indicated positive yield trend but with a net depletion of K, which need to be balanced to improve nitrogen and phosphorus use efficiency and crop yield in long-term. In a different study, Bhatt et al., (2016) reported more yield, enhanced microbial biomass, better soil enzyme activities and overall improved soil biological properties with 100% NPK + FYM @15 t ha^{-1} over all other treatments. Similarly, Singh et al., (2018) found higher yield, soil organic carbon and net return in rice-wheat system with FYM application @5 t ha^{-1} in combination with recommended dose of NPK.

In recent time, grain quality and net-return of crop to environment have been used as important indicators from human health from climate change point of view. Bhardwaj et al., (2019) conducted long-term study to assess the effect of different nutrient management systems (control, 100% inorganic fertilizer and 55% inorganic fertilizer with wither legume crop, green manure, FYM, wheat stubbles or rice stubbles) on soil organic carbon, its fractionalization and yield responses under rice-wheat system. The maximum amount of carbon (as the percentage of C assimilated in the system) was credited to soil with green manure (36%) followed by rice stubble (34%), wheat stubble (33%), legume crop (24%) and FYM (21%) over control (15%) and inorganic fertilization (15%). However, legume-based carbon input favored more soil C sequestration and biological productivity. From a long-term (20 years) study, Singh et al., (2019a) found the maximum yield of rice, wheat and rice-wheat system, when 75% of recommended dose of inorganic fertilizer was applied in combination with organic fertilizer (IPNS). The inclusion of legumes every third year in rice-wheat with IPNS treatment, replacing rice, reduced NO_3–N losses, soil bulk density while improved soil organic carbon. The cost of cultivation was maximum with the least economic net return through the sole application of organic fertilizer, however; economic net return was maximum with lesser cultivation cost under IPNS treatment.

Green manuring, inclusion of legume in crop rotation, FYM application and crop residue methods have also been used to supply organic matter to soil and to enhance the soil fertility and crop productivity. Green manuring through *Sesbania aculeate* holds the potential ability for partial substitution of inorganic fertilizers and improved soil health and productivity of rice-wheat system (Sah, 2021). However, green manuring alone seems to be less efficient in improving the aggregate stability (Bandyopadhyay et al., 2010). The aggregation of carbon was higher and more stabilized with FYM input than treatments having paddy straw and green manuring.

It is evident from above mentioned literature that supply of biomass either as FYM, green manure or crop residue to soil in combination with mineral fertilizer provides multifold benefits on soil characteristics. However, long-term yield aspect of rice-wheat system under the sole application of FYM has been rarely explored and no clear recommendation is available as per the best knowledge of the authors.

Therefore, this study was undertaken to investigate the effect of FYM levels along with *Sesbania aculeata (Willd.) Pers* incorporation on yield, soil health, profitability and sustainability of rice-wheat cropping system.

Materials and Methods

Study Site

A field experiment was conducted for seven consecutive years, commencing from 2013−14 to 2019−20 at research farm of ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana, India (29°43′ N, 76°58′ E and 245 m MSL). The experimental soil was classified as inceptisol with sandy loam in texture (14.8% clay), low in available N (127.9 kg ha^{-1}), medium in organic carbon (0.70%), available P (13.39 kg ha^{-1}) and available K (124.3 kg ha^{-1}), alkaline in nature (pH 7.46) and low in electrical conductivity (0.15 dS m^{-1}).

Weather

The month-wise weather parameters (temperature and rainfall) during the study years are depicted in Figs. 2 and 3. The minimum temperature in February, March and April, representing the wheat grain filling period, was quite higher than long term average (LTA) during 2013 and 2015 and in August, September, October and November, representing rice growth and maturity period, was reasonably higher than LTA during 2019 and 2020. In other years, the minimum

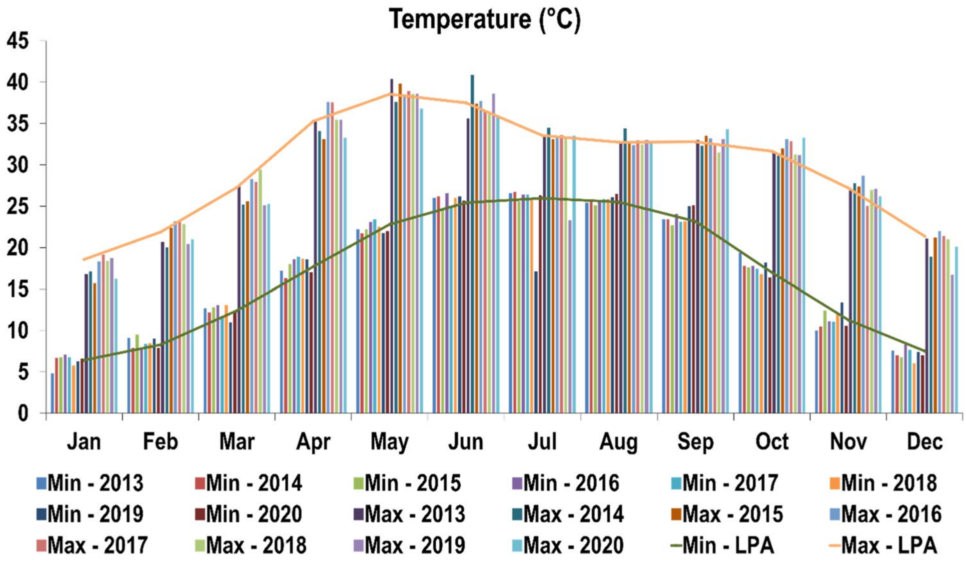


Fig. 2 Month-wise distribution of minimum and maximum temperature during 2013–2020

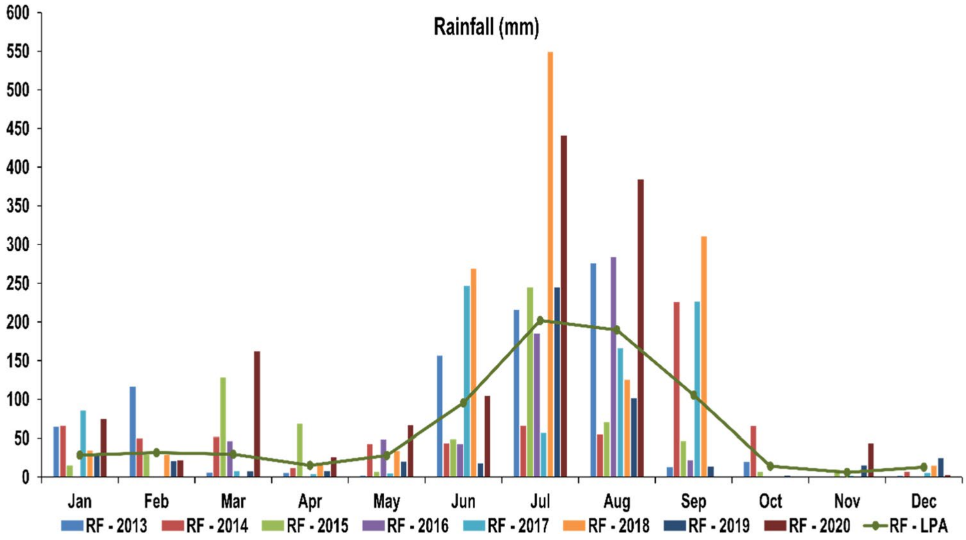


Fig. 3 Month-wise distribution of rainfall during 2013–2020

temperature was either similar or lower than LTA. In the month of July 2019, the minimum temperature was about 9 ℃ lesser than LTA. The maximum temperature in March 2013 and April 2013, 2016 and 2017, representing the wheat maturity period, was quite higher than LTA. In rice growing period, the maximum temperature was above to LTA in August 2014; and in September and October months of 2020. During the wheat growing period, the precipitation was higher than LTA in February 2013, March and April of 2015, January 2017, and March and November of 2020. Whereas in rice season, precipitation in July 2018 and in September, 2020 was higher than LTA. In rest of the study years, the precipitation was below to LTA.

Experimental Design and Treatments

The experiment was conducted in a two-factorial randomized complete block design with four replications with the treatments of different FYM levels (0, 10, 20 and 30 t ha^{-1}) vis-à-vis CIFs. Each experimental plot was having a size of 8 × 1.8 m as a fixed plot all throughout the study period. The seeds of high yielding wheat (*Triticum aestivum*) variety, 'HD2967' of 150–160 days duration were obtained from ICAR-IIWBR, Karnal, Haryana, India. In case of rice, popular variety 'PB 1509' was used under this study. A well decomposed FYM (containing 0.51% N, 0.27% P and 0.52% K on dry weight basis) was applied before rice transplanting and wheat sowing during each year. In the control plot, neither any fertilizer nor any FYM was applied throughout the experimental years. In all the plots irrespective of the treatment, *Sesbania aculeata (Willd.) Pers* was grown after wheat harvest and it was incorporated into the soil after attaining the age of 45–50 days (dry biomass 600–800 g m^{-2}). In CIFs treatment, 150:60:40 N:P_2O_5:K_2O kg ha^{-1} was applied to the soil in rice as well as in wheat. One third of recommended dose of nitrogen i.e., 50 kg N ha^{-1} in the form of urea, full dose of phosphorus (60 kg P_2O_5 ha^{-1}) in the form of single superphosphate and full dose of potassium (40 kg K_2O ha^{-1}) in the form of potash was applied to the soil as basal dose well before sowing/transplanting of crop. The remaining, two-third N was applied after 20 and 40 days after transplanting in rice in equal dose. In case of wheat, one-third N was applied at DC 31 (first node visible) and remaining one-third nitrogen was applied at DC 35 (Zadoks et al., 1974).

Crop Management

Rice nursery was grown during the first week of June on seed bed during each year and 25–30 days old seedlings (one per hill) were transplanted during the first week of July with plant to plant distance as 10 cm at a row spacing of 20 cm. Before transplanting, the field was prepared with two passes of cultivator, cross harrowing, planking and then puddling the soil after irrigation. In rice, irrigations were applied as per crop requirement whereas wheat received six irrigations at different stages viz. DC 20, 29, 37, 65, 75 and 85 (Zadoks et al., 1974). Wheat field was also prepared by two passes of cultivator, cross harrowing and one planking operation followed by seeding the wheat with mechanised seed drill by maintaining the row to row distance as 20 cm. Seed rate in wheat was kept at 250 viable seeds m^{-2} whereas for rice nursery, it was taken as 30 kg ha^{-1}. The weeds in rice crop under CIFs condition were controlled by applying butachlor at the rate of 1.0 kg ha^{-1} in 400 L of water at 3–4 days after rice transplanting. In case of wheat, narrow and broad leaves weeds were controlled by applying sulfosulfuron at the rate of 25 g ha^{-1} and metsulfuron at the rate of 4 g ha^{-1}, respectively, in 400 L of water at 30–35 days after sowing. In treatments having organic fertilizers, weeds were controlled by two mechanical operations with hand hoe in wheat and manual uprooting of weeds in case of rice. Insect-pests in both the crops were controlled by using bio originated pesticides like *bioneem* and *neemol* at the rate of 1000 ml ha^{-1} as and when required. Approximately 7–10 days after physiological maturity, net plot of 9.8 m^2 was harvested manually with the help of sickles by excluding the border rows and crop grown in half meter length at both the ends in longitudinal direction of plot. All the other recommended packages of practices were adopted in both the crops. All the yield and yield attributing characters were obtained by using methods as described by Bell & Fischer (1994).

Observations

Observations were recorded on grain yield, biomass and its component characters for rice and wheat crops. Grain yield was recorded at 14% moisture content and biomass yield was determined after oven-drying the straw samples at 70 °C till constant weight was observed and expressed in dry-weight basis. Harvest index (HI) in rice and wheat was calculated by taking the ratio of grain yield and biomass. The number of spikes or panicles per meter row length were counted at the physiological maturity from two places in the plot, averaged and converted into wheat-spike number m^{-2} and rice-panicle number m^{-2}. Grain samples were randomly collected for thousand grain weight and it was calculated by counting the seeds using Contador electronic seed counter (make: Pfeuffer, Germany) and then weighing these seeds on electronic weighing balance. In both the crops, the number of grains per panicle or spike and number of grains per m^2 were calculated by the method described by Bell & Fischer (1994). The protein content in grain of rice and wheat was determined by using near infrared spectroscopy (NIR-S) on yearly basis (Salgó & Gergely, 2012).

Wheat Equivalent Yield

Wheat equivalent yield (WEY) was calculated by taking the total return of each product and by-product on pooled basis and dividing it by the price of one tonne of wheat.

Sustainability Value Index

Sustainability value index (SVI) was calculated as per procedure described by Singh et al., (1990).

$$\mathrm{SVI} = (\mu - \delta)/\mathrm{Y}_{\max}$$

Where, μ is mean of particular treatment in monetary terms, δ is standard deviation of particular treatment in monetary terms and Y_{max} is potential maximum monetary returns (by converting potential maximum yield in monetary terms) over the years.

Economics

For calculation of returns, the price of basmati rice,organic wheat and wheat straw was taken as 400 $ t^{-1}, 256.6 $ t^{-1}33.33 $ t^{-1}, respectively, and all three were added to get the gross return. The cost of cultivation was calculated by taking the price of inputs viz., fertilizer, FYM, seed, irrigation, tillage operation, transportation charges, management charges, rental value of land, interest on fixed capital, depreciation cost of implements and farm buildings into consideration. The net return was calculated by subtracting the cost of cultivation from gross returns. Benefit to cost ratio was calculated as the ratio of gross returns and cost of cultivation.

Soil Parameters

At the start of experiment and end of 7 crop cycles, the soil samples from different depths (0–15, 15–30, 30–45 and 45–60 cm) were taken with cone auger followed by air drying in shadow for 10 days and then oven drying at 105 ℃ for 6 h. The soil samples were then cooled, grinded in wooden mortar and pestle, sieved through 80 mesh sieve and analysed for organic carbon (Walkley & Black, 1934), available N (Jackson, 1958), available P (Olsen, 1954), available K (Merwin & Peech, 1951), EC and pH (1:2.5 soil: water solution).

Statistical Analysis

Analysis of variance (ANOVA) and ranking of treatments was completed using Tukey's Range test at 5% level of significance (α = 0.05). The General Linear Model (GLM) Procedure in SAS®9.3 version 6.1.7061 for Windows (Cary, NC, SAS Institute Inc., 2012) was used for statistical analysis. Fertilization practices and study year were included as fixed factors in the model and replications were treated as random effects. The design used was randomised block design where treatments were compared. Correlation coefficient (r) was used to indicate the interaction amongst the traits studied.

Results

Effect of Study year and Fertilizer on Yield and Yield Attributes

The effect of FYM on yield and yield attributes of rice and wheat crops was studied through analysis of variance at 5% level of significance. It was observed that study year, fertilizer practices and their interaction in both rice and wheat crops produced significant effect on all yield and yield attributing parameters except the effect of fertilizer practices on thousand grain weight of rice as presented in Table 1. This showed that study year and type and amount of fertilizer used significantly affected the yield and yield attributing traits of both rice and wheat crops.

The variation of grain yield of both crops with the years of study is depicted in Fig. 4. It was observed that mean yield of wheat was within 4.3–4.5 t ha^{-1} range during the study years of 2016–2017, 2017–2018, 2018–2019 and 2019–2020 without any significance difference ($p > 0.05$). The lowest wheat yield of 3.37 t ha^{-1} was noticed during the first year of study period. In case of rice, yield was similar without any significant difference during the study years of 2014-17. The maximum rice yield of 6.54 t ha^{-1} was observed in study year of 2019 while it was lowest as 4.44 t ha^{-1} in the year of 2018.

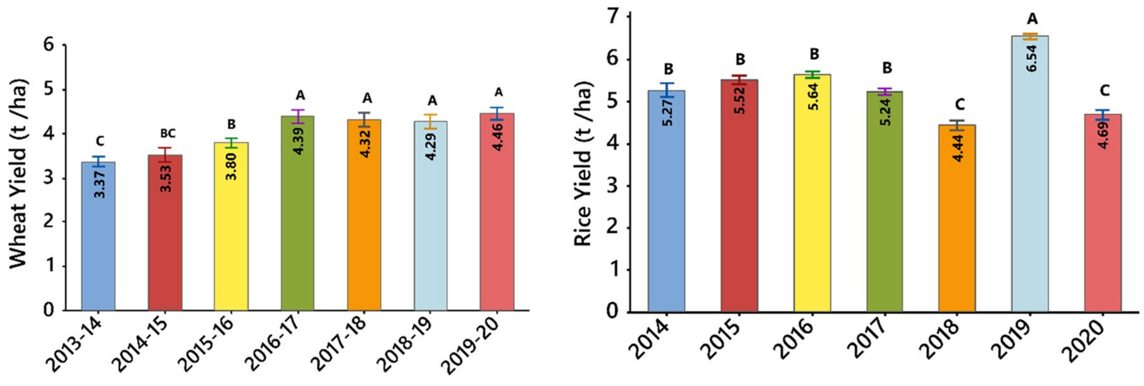
Yield Components and Grain Protein

The analysis of pooled data of study years revealed that all fertilizer practices (type and amount of fertilizer) introduced significant effect on all yield attributing traits of wheat and these were higher with CIFs over other treatments except for TGW (38.4 g) and protein content (10.6%). The grain

Table 1 Wheat and rice yield components as affected by the FYM levels across 7 years

Treatment	BM (t ha^{-1})	GY (t ha^{-1})	HI	EHPMS	TGW (g)	GrPEH	Gr.PMS	GrProt (%)	PHT (cm)	EHL (cm)
Wheat										
Control + S	6.7 ± 0.1^{e}	2.5 ± 0.0^{e}	0.37 ± 0.003^{c}	279.1 ± 5.4^{d}	41.0 ± 0.2^{b}	22.6 ± 0.6^{d}	6074 ± 83^{e}	9.4 ± 0.1^{d}	81.4 ± 0.7^{d}	8.2 ± 0.11^{d}
FYM.10 + S	9.2 ± 0.2^{d}	3.6 ± 0.1^{d}	0.39 ± 0.004^{b}	323.4 ± 5.4^{c}	42.4 ± 0.3^{a}	26.4 ± 0.5^{c}	8428 ± 139^{d}	10.2 ± 0.1^{c}	89.8 ± 0.8^{c}	8.7 ± 0.11^{c}
FYM.20 + S	10.3 ± 0.2^{c}	4.0 ± 0.1^{c}	0.39 ± 0.004^{b}	324.5 ± 6.3^{c}	42.5 ± 0.2^{a}	29.6 ± 0.5^{b}	9425 ± 151^{c}	10.5 ± 0.1^{b}	92.1 ± 0.8^{b}	8.8 ± 0.11^{bc}
FYM.30 + S	11.4 ± 0.2^{b}	4.5 ± 0.1^{b}	0.39 ± 0.003^{b}	351.3 ± 5.8^{b}	42.4 ± 0.2^{a}	30.5 ± 0.5^{b}	$10{,}642 \pm 196^{b}$	11.0 ± 0.1^{a}	92.9 ± 1.0^{b}	9.0 ± 0.10^{b}
CIF + S	13.4 ± 0.2^{a}	5.6 ± 0.1^{a}	0.41 ± 0.003^{a}	408.2 ± 5.1^{a}	38.4 ± 0.3^{c}	35.9 ± 0.5^{a}	$14{,}599 \pm 210^{a}$	10.6 ± 0.1^{b}	97.0 ± 0.8^{a}	9.5 ± 0.08^{a}
ANOVA										
Main effects										
Study year (SY)	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Fertilization practices (FP)	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Interaction effects										
SY * FP	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Rice										
Control + S	13.9 ± 0.31^{c}	4.6 ± 0.13^{d}	0.30 ± 0.003^{ab}	299.7 ± 5.9^{c}	28.76 ± 0.17^{a}	55.18 ± 1.76^{a}	$16{,}112 \pm 439^{d}$	9.63 ± 0.05^{d}	83.02 ± 1.87^{b}	27.363 ± 0.17^{c}
FYM.10 + S	17.1 ± 0.34^{b}	5.1 ± 0.10^{c}	0.29 ± 0.003^{b}	327.6 ± 5.1^{b}	28.84 ± 0.17^{a}	54.66 ± 1.13^{a}	$17{,}716 \pm 351^{c}$	10.17 ± 0.07^{c}	87.75 ± 1.90^{ab}	28.188 ± 0.17^{b}
FYM.20 + S	17.9 ± 0.37^{b}	5.3 ± 0.09^{bc}	0.30 ± 0.003^{ab}	322.7 ± 4.7^{b}	28.93 ± 0.17^{a}	57.71 ± 1.05^{a}	$18{,}456 \pm 333^{bc}$	10.36 ± 0.07^{bc}	89.06 ± 1.85^{ab}	28.46 ± 0.16^{ab}
FYM.30 + S	19.5 ± 0.36^{a}	5.7 ± 0.10^{ab}	0.30 ± 0.004^{b}	335.4 ± 4.5^{b}	28.95 ± 0.17^{a}	59.60 ± 1.28^{a}	$19{,}716 \pm 346^{ab}$	10.65 ± 0.07^{a}	91.01 ± 1.89^{a}	28.785 ± 0.14^{a}
CIF + S	19.6 ± 0.42^{a}	5.9 ± 0.09^{a}	0.31 ± 0.004^{a}	360.2 ± 6.2^{a}	28.75 ± 0.23^{a}	58.54 ± 1.17^{a}	$20{,}707 \pm 345^{a}$	10.49 ± 0.09^{ab}	88.53 ± 1.71^{ab}	28.527 ± 0.14^{ab}
ANOVA										
Main effects										
Study year (SY)	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Fertilization practices (FP)	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.080$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Interaction effects										
SY * FP	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

Alphabet(s) following the mean values is based on Tukey’s test of significance. For each trait, mean values followed by different letters (without any common letter) indicate significant difference at 5% level of significance



Individual standard error of mean values are used to draw error bars.

Fig. 4 Wheat and rice grain yield fluctuation during the years of study, Alphabet(s) following the mean values is based on Tukey's test of significance. For each treatment mean values followed by same letters are not significantly different at 0.05 probability level

protein and TGW were maximum under the treatment of 30 t ha^{-1} FYM application. The sole application of green manuring resulted in the lowest yield of wheat (2.5 t ha^{-1}) which consistently increased with inclusion of FYM amount. The maximum grain yield of wheat (5.6 t ha^{-1}) was recorded under CIFs treatment followed by 4.5 t ha^{-1} with 30 t ha^{-1} FYM application. The wheat grain yield with the highest rate of FYM (30 t ha^{-1}) used in the study was 19.6% lower than that under CIFs application.

In case of rice, the application of 30 t ha^{-1} FYM produced statistical similar values of all yield attributing traits as with CIFs except for harvest index and earheads per m^2. The rice grain yield with 30 t ha^{-1} FYM application was found to be 5.7 t ha^{-1} as compared to 5.9 t ha^{-1} with CIFs.

Pearson Correlation

Correlation study was performed to prepare the correlation heatmap and to understand the relationship between the studied traits. In case of rice, GY had a strong and significant correlation with GrPMS (0.953, $p<0.001$), GrPEH (0.629, $p<0.001$), EPMS (0.379, $p<0.001$), Protein (as shown in Fig. 5. On the contrary, a significant negative correlation (– 0.354, $p<0.001$) was found between BM and HI. In case of wheat, GY was significantly and positively correlated with BM (0.953, $p<0.001$), GrPEH (0.629, $p<0.001$), EHPMS (0.379, $p<0.001$), TGW (0.147, $p>0.01$), EHL (0.131, $p<0.001$), and HI (0.116, $p<0.05$) as presented in Fig. 4.

Soil Chemical Properties

In the present study, the effect of type and rate of fertilizer used on chemical properties of soil was also investigated and details are given in the following subsections.

pH

The pH of soil taken from different layers (0–15, 15–30, 30–45 and 45–60 cm depth) was measured and it was observed that soil pH increased significantly from initial levels in all four soil layers as evident from Fig. 6. The top layer of soil (0–15 cm) was found to have the lowest pH among all four layers of soil used in the present study. The type and rate of fertilizer used in both rice and wheat crops didn't introduce any significant change in soil pH among themselves in the soil layer at 30–45 and 45–60 cm depth. The continuous application of 20 and 30 t ha^{-1} FYM brought a significant decline in pH level of soil at 0–15 and 15–30 cm depths over control, CIFs and 10 t ha^{-1} FYM applications.

EC

The results of the pooled data revealed that top layer of soil (0–15 cm depth) had higher EC than other soil layer depths and it successively deceased with deeper depth as evident from Fig. 6. In all soil layers other than top layer, FYM and CIFs application exhibited similar levels of EC without any significant difference. The application of FYM @30 t ha^{-1} resulted into the maximum value of EC in the top layer of soil compared to other treatments except 20 t ha^{-1} application. It was noticed that soil EC was close to initial level event after seven years of CIFs application in all the soil layers.

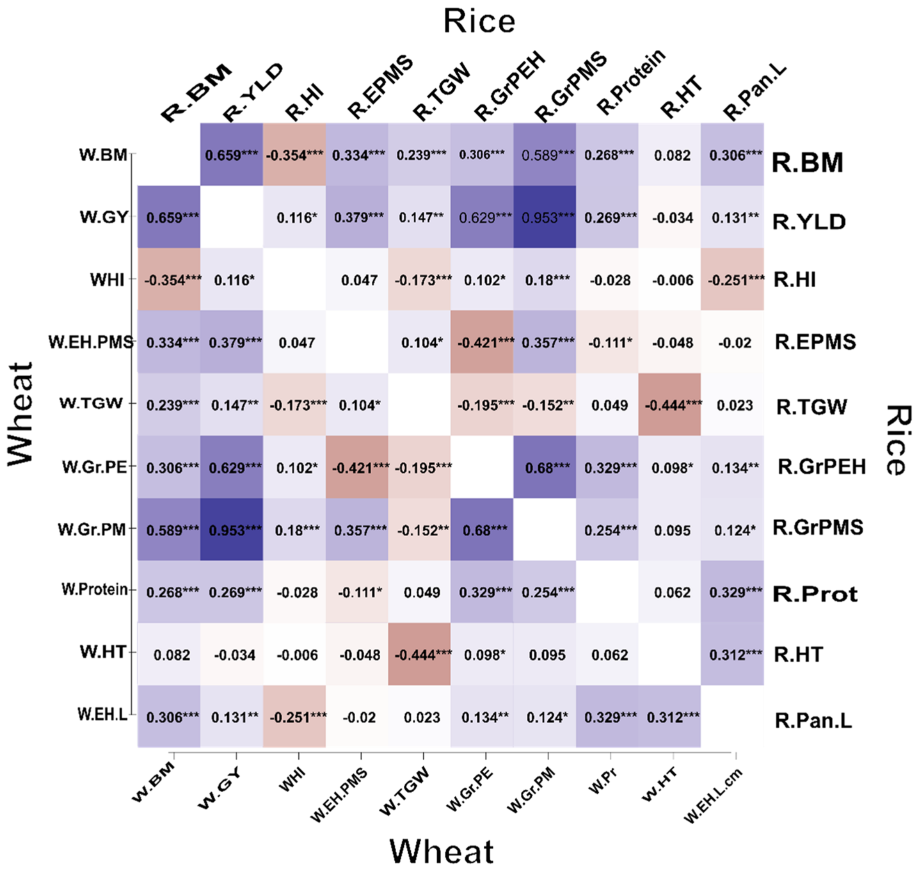


Fig. 5 Correlation heatmap showing relationship among different traits of wheat and rice with significance levels expressed by asterisks (***for p-value ≤ 0.001, **for p-value ≤ 0.01, *for p-value ≤ 0.05)

Organic Carbon

The organic carbon of soil consistently declined ($p < 0.05$) with increase in soil depth for all treatments as details given in Fig. 6. The mean soil organic carbon in top layer (0–15 cm) across all treatments was found to be 0.97%, which was 61.7, 136.6 and 223.3% higher than organic carbon present in 15–30, 30–45 and 45–60 cm depths, respectively. In the subsurface soil layers (30–45 cm and 45–60 cm), any fertilizer treatment could not make significant change in organic carbon from its initial level. In the soil layer of 15–30 cm depth, the sole application of green manuring (control) and green manuring + FYM application exhibited higher organic carbon of soil than its initial level and value under CIFs application. In this soil layer, control and all FYM treatments exhibited in the top layer of soil (0–15 cm), the continuous application of CIFs could not improve the soil organic carbon. The organic carbon marginally increased with the sole application of green manuring but the difference was not significant. The control treatment (green manuring) and FYM application up to 20 t ha^{-1} showed statistically similar levels of organic carbon ($p > 0.05$) in the top layer of soil. The maximum value of organic carbon was observed to be 1.24% in the top layer of soil (0–15 cm) with the application of 30 t ha^{-1} FYM. However, organic carbon of soil top layer with 30 t ha^{-1} FYM application was statistically similar ($p > 0.05$) to those with 10 and 20 t ha^{-1} FYM application. The application of 30 t ha^{-1} FYM substituting CIFs increased the soil organic carbon of top layer by 74.6%.

Available N

The results presented in Fig. 6 indicate the maximum availability of nitrogen as 251.6 kg ha^{-1} as compared 107.5, 79.3 and 77.8 kg ha^{-1} in 15–30, 30–45 and 45–60 cm depths, respectively. In the deeper layer of 45–60 cm depth, available N was significantly higher with treatment of 20 t ha^{-1} FYM than other treatments except control and 30 t ha^{-1} FYM application. The soil layer of 30–45 cm depth showed similar availability of N with control, FYM and CIFs application but these were significantly more than initial value. The continuous application of 30 t ha^{-1} FYM significantly improved the organic carbon of soil in 15–30 cm depth as compared to initial

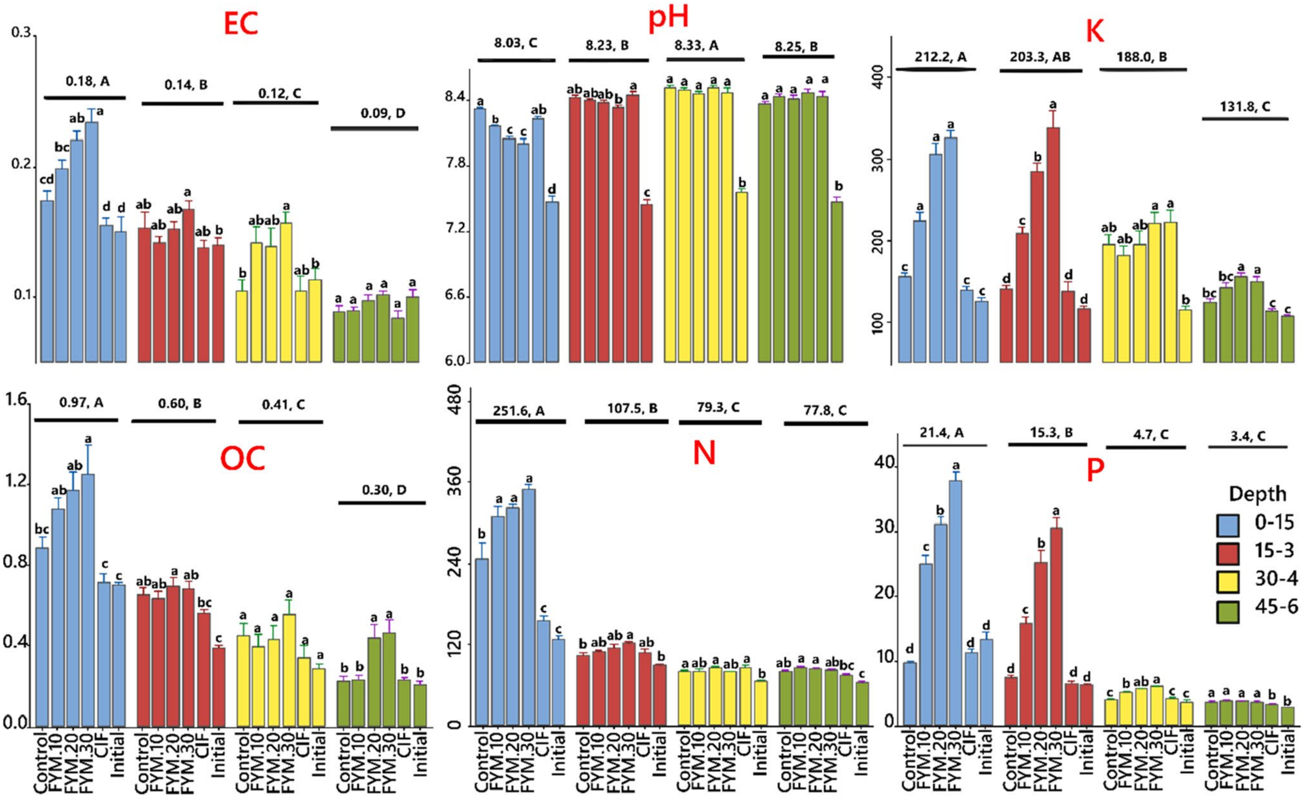


Fig. 6 Soil fertility at different level of FYM application at various depths

value and CIFs application. In the top soil layer, FYM applications determined non-significant ($p > 0.05$) differences among themselves for available N content; however, registered significantly ($p < 0.05$) higher than other treatments of control and FIFs application. The sole application of green manuring increased N availability in top soil layer by 58.7 and 92.4% over CIFs application. The maximum soil N availability was observed with 30 t ha^{-1} FYM (with statistically similar under 10 and 20 t ha^{-1} FYM), which was much higher than initial level of soil N availability and that under CIFs application.

Available P

The soil availability of phosphorus was also the maximum (21.4 kg ha^{-1}) in the top layer which decreased significantly with increase in soil depth as shown in Fig. 6. In deeper soil layers (15–30, 30–45 and 45–60 cm depth), available P significantly improved with all FYM applications (being maximum with 30 t ha^{-1} FYM) over initial level and CIFs treatment. The available P in the top layer of soil consistently increased with rise in FYM dose. All FYM treatments exhibited significantly higher levels of available P in top soil layer over initial level, control and CIFs application. Overall, the application of 30 t ha^{-1} FYM increased available P significantly ($p < 0.05$), which was 237.5, 369.2, 43.9 and 16.1% higher than those under CIFs application in 0–15, 15–30, 30–45 and 45–60 cm, respectively.

Available K

The results given in Fig. 6 suggest that available K content in the soil layer of 0–15 and 15–30 cm depths was statistically similar but available K in the top soil layer (212.2 kg ha^{-1}) was significantly higher than those under 30–45 (188.0 kg ha^{-1}) and 45–60 cm (131.8 kg ha^{-1}) depths. In the deepest soil layer of 45–60 cm depth, FYM

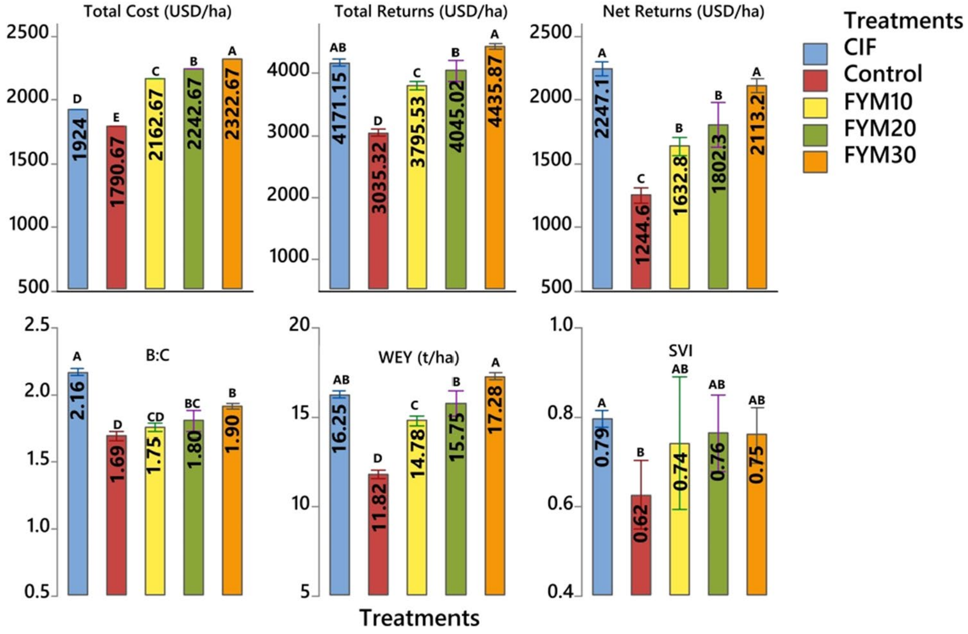


Fig. 7 Seven years effect of different treatments on economics, WEY, SVI of rice-wheat

application at the rate of 20 and 30 t ha^{-1} brought a significant rise in available K over all other treatments. In the soil layer at 30–45 cm depth, control, FYM application and CIFs treatments indicated similar levels of available K but available K with 30 t ha^{-1} and CIFs application were significantly higher than its initial level. The amount of FYM added into soil consistently increased the available K in 15–30 cm soil depth. In 0–15 cm soil depth, different rates of FYM application caused non-significant effect ($p > 0.05$) on available K among themselves but these were significantly ($p < 0.05$) higher over control, initial and CIFs treatment.

Economics

The economic analysis of rice-wheat under various fertilizer treatments was done based on pooled data and it was found that total return and net return in rice-wheat cropping system with 30 t ha^{-1} FYM and CIFs application were statistically similar ($p > 0.05$) as presented in Fig. 7. The input cost varied with each treatment and it was the maximum with 30 t ha^{-1} FYM application while being the lowest for control treatment. The continuous application of 30 t ha^{-1} FYM produced the highest total return (without significant difference from CIFs) but managed with slightly lesser net return than CIFs (without significant difference) due to increased transportation and handling cost in the case of former. The benefit-cost (B:C) ratio was found to be maximum as 2.16 with CIFs application which was significantly higher than all other treatments. The application of FYM @30 t ha^{-1} demonstrated B:C ratio as 1.90 as compared to 1.69 for control treatment.

Wheat Equivalent Yield (WEY)

The application of 30 t ha^{-1} FYM resulted into the maximum WEY (17.28 t ha^{-1}) which was significantly higher than all other treatments except CIFs as shown in Fig. 7. The successive increase in FYM dose made significant increase in WEY. The application of 30 t ha^{-1} FYM led to 6.3 and 46.2%% increase in WEY over to CIFs application and control treatment, respectively.

Sustainability Value Index (SVI)

The sustainability value index with all treatments except control was statistically similar and ranged from 0.74 to 0.79 as presented in Fig. 7. The sole application of green manuring exhibited SVI statistically similar to those with FYM application but it was significantly lesser than CIFs application. The results suggest the sustainability of rice-wheat system under green manuring with *Sesbania aculeata (Willd.) Pers* + FYM applications as an alternative to CIFs application.

Discussion

Yield Components and Grain Protein

The intensive cultivation of rice-wheat, imbalanced and overdosed inorganic fertilization particularly N, and inadequate residue recycling in northern Indian plains led to soil health deterioration and stagnant crop productivity (Kumar et al., 2017, 2021; Singh et al., 2021). To address these critical challenges, a long-term field experiment was started in sandy loam soil of northern Indian plains to study the potential of FYM and green manuring as an alternative option to inorganic fertilization. According to the envisioned hypothesis, FYM and green manuring may replace inorganic fertilization in at least one crop under rice-wheat cropping system. The inorganic fertilizers are generally high in concentration which makes them advantageous in terms of transportation, handling and application and are applied in smaller amount to meet out the recommended doses, making little alteration in the soil medium after application as compared to over organic sources based fertilizers. Contrary, application of organic fertilizers like FYM in large amount causes changes in soil medium and biological activities. The slow release of nutrients from FYM associated with slow decomposition rate makes the inadequate supply of nutrients to the plants, which seems to be prominent reason for low wheat yield especially during the initial years of this study, which increased in the subsequent years. In case of rice, only little variation in yield during the initial years of study may be associated with faster decomposition of FYM due to repeated wet tillage operation (puddling) and additional nutrients available from FYM applied in previous wheat crop. It was supplemented by green manuring of *Sesbania aculeata (Willd.) Pers* prior to rice transplantation, which has nitrogen fixation properties and contains about 3.5% N, 0.6% P and 1.2% K (on dry weight basis) and its above ground parts are decomposed within four weeks (Kurdali et al., 2019). The results of present study suggest that rice yield as with CIFs can be achieved with 30 t ha^{-1} FYM application post attaining the nutrient stabilization stage after few years of commencement of study. The rise in rice yield for all treatments during 2019 could be due to increased minimum temperature in the month of September and October, coinciding with grain filling period of rice crop. The yield attributes of rice with 30 t ha^{-1} FYM application were similar to those under CIFs except earheads per m^2 and harvest index. The findings of this study suggest that wheat yield continued to suffer with FYM application even after several years possibly due to nutrients exhaustive crop (rice) and unavailability of green manuring prior to sowing of wheat crop besides slow release of nutrients in FYM treatments. In previous studies, Martinez et al., (2017) also highlighted the slow mineralization of N and failure of synchronization of organic N with crop demand and recommended to apply the manure in combination with chemical fertilizer. In the present study, the application of 30 t ha^{-1} FYM to each crop of rice and wheat could not fulfil complete nutrients requirement of wheat crop. This is accompanied by slow mineralization of organic N associated with low temperature during initial phase of wheat growing period. A good observation to make in yield attributes of wheat that grains were bolder with FYM application over CIFs, which is suitable for better germination and seed production programme. The alternative fertilization practice i.e. FYM offers equal or advantageous opportunities in terms of grain protein for both rice and wheat crops. Ali et al., (2020) also reported higher grain protein in bread wheat with combined application of vermicompost and FYM over the base treatment.

Effect of FYM on Soil Properties

The alteration in fertilizer practice also makes the changes in the chemical properties of soil. The continuous application of FYM and CIFs to soil increased its pH as compared to its initial status. The availability of organic matter and other cations are generally high in the top layer of soil and therefore high pH of soil in the top layer with control treatment could be associated with lesser organic matter content. The continuous application of FYM makes amendments in the soil medium through replenishment of soil with basic cations, thereby raising the soil pH in top and subsurface layers of soil (Shiwakoti et al., 2020; Kumar et al., 2017) also reported decline in soil pH with the continuous application of FYM to soil in long-term under rice-rice cropping system. Liang et al., (2012) reasoned the presence of organic acid in manure for decline in soil pH in long-term application. The increase in soil EC of top layer with the amount of FYM added to soil was probably due to dissolved salts present in the manure. The result of present study are supported by the findings of Ozlu & Kumar (2018) who reported 120% increase in soil EC of top layer (2.01 dS m^{-1}) with manure application over soil EC (0.66 dS m^{-1}) under chemical fertilization in maize-soybean cropping system. The major changes in terms of nutrients availability and soil other properties with alternation in fertilizer practice are experienced in the top layer of soil. The combined application of green manuring of *Sebania aculeata* and 30 t ha^{-1} FYM application in long-term was effective to improve the status of available N in top layer from low (127.9 kg ha^{-1}) to medium category (349 kg ha^{-1}). The organic sources based fertilizer application also introduced positive impact on nitrogen availability at subsurface layers, which may be helpful for crops under fertilizer deficit conditions. Another advantage of organic sources based fertilizer application lies in fixing of P and K nutrients which consistently increases with the amount of FYM added to the soil. One interesting thing to note that continuous application of CIFs for seven years could not make any positive change and only sustained the same status of P and K nutrients. Mitran et al., (2018) concluded that application of organic amendments to soil promotes the transformation of micro aggregates to macro aggregates resulting in lesser phosphorus losses. In a different study, Bhardwaj et al., (2020) reported that integration of organics through green manuring with *Sesbania*, biomass incorporation of leguminous crop and crop residue incorporation can substitute 50% inorganic N in rice crop. Also, daily N mineralization rate was consistently higher (1.6-2.0 µg cm^{-2}) with organic input over mineral fertilization in rice-wheat system. The results of this study suggest that researchers and farming communities need to think from soil perspective and substitute CIFs through FYM + green manuring in rice crop for long-term sustainability of rice-wheat system without any penalty on system productivity and profitability. The slow mineralization of N in organic sources based fertilizers may not be beneficial to the crop immediately but definitely it would create a nutrient bank in the soil useful for succeeding crops in a long-term.

A drastic positive change was observed in organic carbon of soil especially top layer on substituting the CIFs with green manuring + FYM application. The amount of carbon added to the soil through FYM application and green manuring helps in buildup of OC. The sole application of green manuring also helped in improving the OC of soil due to carbon added through the incorporation of *Sesbania aculeata (Willd.) Pers* and low yield level. The build-up of OC in the subsurface layers of soil through organic sources based fertilization would be helpful in sustaining the proper functioning of soil and better crop performance under inadequate recycling of organic matter and fertilizer deficit conditions. The results of present study are in-line with findings of Ramdas et al., (2017) who observed that higher soil OC with FYM application over other treatments of inorganic fertilization, vermicompost, green manuring and straw incorporation in the rice crop. It is well understood that OC build-up in soil is a continuous process, which requires regular supply of carbon and fertilizers to soil likewise continuous production of crops is done it. Mustafa et al., (2020) found more accumulation rate of manure derived OC in macro-aggregates (> 250 µ) which decreased with aggregate size. Hicks et al., (2019) concluded that excess supply of N to soil than that required for potential yield had a positive priming effect and increased soil OC. The slow mineralization and slow N-mining in FYM for long-term results in build-up of carbon stock in the soil and increased OC status of soil.

Economics

The alternative fertilization practice by means of green manuring + FYM application offered similar profitability and sustainability indices as with CIFs. However, lower B:C ratio with FYM application over CIFs remains a down point due to increased cost occurred during the transportation, handling and application of such bulky material to meet the similar N demand as with CIFs. In a previous study, Sarma et al., (2017 also reported higher B:C ratio (8.3) with mineral fertilizer over FYM (6.1) in okra crop. It is to accept that lower B:C ratio with FYM over CIFs may challenge the large scale acceptability of FYM by the farmers. However, there are possibilities to reduce the expenditure on transportation and improve B:C ratio for FYM application, when such practices are adopted by the farmers who have their animals and fields adjoining to their houses. A large number of farming communities falls under this category in India. The integrated approach of green manuring + FYM application in rice crop is a potential alternative to inorganic fertilization under rice-wheat system, which provides the multifarious benefits in long-term without compromising the system productivity and profitability in a sustainable manner. These alternative organic fertilization practices may be beneficial to rice growing famers having their own animals and adjoining fields in the region of northern Indian plains, where crop productivity and sustainability of rice-wheat system are facing serious challenges.

Conclusion

The present study was undertaken to find out the possibility of substituting CIFs through FYM and green manuring in at least one crop under rice-wheat cropping system. The experiment on graded doses of FYM (0, 10, 20 and 30 t ha^{-1}) and CIFs in both rice and wheat crops continued for seven years under rice-wheat system. The application of green manuring + FYM application @30 t ha^{-1} produced similar rice yield as with CIFs but with a penalty of 19.21% in wheat yield. The soil fertility parameters such as organic carbon, available N, P_2O_5 and K_2O improved tremendously in the top soil layer (0–15 cm) along with improvement in P_2O_5 and K_2O status of soil up to 30 cm soil depth on substituting CIFs with green manuring + 30 t ha^{-1} FYM application. The profitability and suitability indices of rice-wheat with FYM application are comparable with CIFs but with a lesser B:C ratio due to higher transportation and handling cost of bulky material. Therefore, the continuous application of such alternative organic sources based fertilizers in rice crop can be beneficial in improving the soil health and sustainability of rice-wheat system with lesser noxious impact on the environment. Availability of FYM in huge quantity and its transportation is a problem for large farmers whereas for small and marginal farmers in India, which constitute about 85% of total farmers who keep animals as a practice on their farm will be an added advantage. However, nutrient and pest-dynamics needs to be studied under organic fertilization practices in future for large scale adoption.

Author Contributions Subhash Chander conducted experiment and recording of data, S C Tripathi and Neeraj Kumar drafted and edited the MS, Karnam Venkatesh analysis of data and edited MS, R P Meena and Nidhi Kamboj reviewed the literature, R S Chhokar edited MS, Nitesh Kumar formatted the references, all authors reviewed and approved the MS for publication.

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Data Availability All the data will be available if request is made.

Code Availability Project No. CRSCIIWBRSIL201500800189.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No potential conflict of interest was reported by the authors.

Ethics Approval All authors approve ethical responsibilities related with this manuscript.

Consent to Participate Not applicable.

Consent for Publication All authors give their consent for publication in International Journal of Plant Production.

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