Journal of Natural Resource Conservation and Management
Vol. 3, No. 2, pp 143-151, 2022
doi: 10.51396/ANRCM.3.2.2022.143-151

Rice straw compost: a sustainable residue recycling solution for soil health and productivity enhancement in the rice-wheat cropping system

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Received : November 06, 2022
Revised : December 21, 2022
Accepted : December 23, 2022
Published : December 31, 2022

ABSTRACT

The rice-wheat cropping system is the predominant crop rotation within the Indo-Gangetic Plain (IGP). A pressing concern in the region is the escalating issue of burning crop residues, coupled with the need to reduce the reliance on costly fertilizer inputs. A promising avenue to address both challenges lies in implementing integrated nutrient management (INM). An INM experiment was started at the Central Soil Salinity Research Institute (CSSRI) in Karnal to explore this solution in 2015. The experiment aimed to evaluate the effectiveness of eight distinct INM modules, namely: RS-F100, involving the *in situ* retention and incorporation of one-third of rice stubble along with 100% of the recommended fertilizers; RS-F150, similar to RS-F100 but with 150% of recommended fertilizers; WS-F100 and WS-F150, which same as the previous modules but pertain to wheat stubble; PSC-F50, utilizing 5 tons per hectare of Paddy Straw Compost (PSC) along with only 50% of recommended fertilizers; PSC+FYM-F50, combining 5 tons per hectare of PSC with an equal amount of Farmyard Manure (FYM), along with 50% of recommended fertilizers; GM+FYM-F50, involving Green Manuring with *Sesbania aculeata*, 5 tons per hectare of FYM, and 50% of recommended fertilizers; GM+PSC-F50, akin to the previous module but incorporating PSC instead of FYM. These modules were compared against F, representing 100% recommended fertilizer application, and O, signifying no fertilizer application (absolute control). The research finding revealed that grain yields and straw increased significantly under GM-PSC-F50 and GM-FYM-F50 INM modules. These INM modules make it possible to reduce chemical fertilizer usage by 50%. In cereal residue-based INM, including rice residue with 100% fertilizer led to a marginal yield reduction. However, this decrease could be effectively countered by adopting a 150% fertilizer application. The soil available N, P, K, and organic carbon was significantly improved under different INM modules. In conclusion, the promising INM modules are green manuring with *Sesbania aculeata* + Paddy straw compost, PSC @ 5 t ha^{-1} + only 50 % of recommended fertilizers (GM-PSC-F50), 1/3rd in situ wheat stubble retention and incorporation + 100 % recommended fertilizers (WS-F100), and 1/3rd rice stubble in situ retention and incorporation + 150 % recommended fertilizers (RS-F150).

Keywords: Integrated nutrient management, green manure, crop residue, paddy straw compost, fertilizer, rice-wheat system

INTRODUCTION

The rice-wheat cropping system plays a pivotal role in upholding India's food and nutritional security, primarily due to the extensive area it covers and its significance to the population. Rice and wheat are cultivated in a rotational pattern over an expansive 10.3 million-hectare expanse within India's Indo-Gangetic Plain (IGP), famously referred to as the "green revolution" region. This region's prominence is underlined by the provision of government-mandated minimum support prices for rice and wheat, rendering this cropping sequence exceptionally profitable and dominant. The era of the 1960s, known as the Green Revolution, witnessed a substantial surge in rice and wheat production, attributed to land availability, high-yielding semi-dwarf varieties, dependable irrigation practices, and a boom in fertilizer usage. Despite these transformative technological strides that considerably augmented food production in the preceding decades, the assurance of food security continues to encounter challenges stemming from various factors, notably climate change, water scarcity, escalating population pressures, and the accelerating pace of urbanization (Singh, 2016).

Numerous reports have raised concerns about the sustained viability of the rice-wheat cropping system due to diminishing factor productivity, the rapid decline of groundwater levels, and the deteriorating health of the soil within the region (Kumar and Sharma, 2020). Additionally, the combination of intensive tillage practices, challenges in labor and energy supply, absence of efficient crop residue disposal systems, and subsequent resort to residue burning have precipitated environmental contamination and soil health degradation. These issues have also impeded crucial ecosystem services and functions (Downing *et al.*, 2022).

Transplanted rice thrives optimally in submerged conditions, whereas wheat flourishes in well-pulverized soil featuring an appropriate balance of moisture, air, and temperature. The yearly soil transition between aerobic and anaerobic states constitutes a prominent characteristic of the rice-wheat farming system. Notably, the rice-wheat cropping system is inherently demanding regarding nutrients, and continuous cultivation without meticulous management can potentially erode soil fertility. This outcome can manifest as deficiencies in both macro and micronutrients, in addition to the degradation of soil quality attributed to the loss of organic carbon (Bhardwaj *et al.*, 2019). The stagnation or reduction in productivity within the rice-wheat system stems from a dual cause: the deterioration of soil quality and inefficient fertilizer management (Kumari *et al.*, 2017).

Fertilizers play a pivotal role in bolstering crop output and productivity. However, prolonged and imbalanced fertilizer application without adequate nutrient recycling can disrupt nutrient availability over time and degrade the physical condition of the soil, ultimately leading to a decline in crop yield (Dwivedi *et al.*, 2016). Reduced efficiency in nutrient utilization renders fertilizer application economically inefficient, triggers adverse impacts on soil microorganisms and enzyme activities, compromises groundwater quality, poses health hazards, and contributes to climate change. To enhance soil health, integrating a diverse array of nutrient sources, both inorganic and organic, proves beneficial. This approach curtails the reliance on synthetic chemical fertilizers, lowers cultivation expenses, and promotes environmental friendliness. As such, strategies for nutrient management that yield comprehensive impacts on the soil's physical, chemical, and biological attributes should form the bedrock of sustainable practices for maintaining soil productivity and fertility. Achieving this goal necessitates the harmonized utilization of organic manures and chemical fertilizers (Bhardwaj *et al.*, 2021).

The core principle that underpins integrated nutrient management (INM) revolves around conserving soil fertility, sustaining crop productivity, and augmenting farmers' net profits. This is achieved through a skillful and balanced amalgamation of chemical fertilizers, organic manures, and crop residues (Vashisht *et al.*, 2021). Crop waste, manures, and leguminous plants all serve as valuable organic sources to enhance soil quality and curtail the need for chemical fertilizers while maintaining crop yields. Organic sources gradually release nutrients into the soil solution in measured quantities, facilitating plant absorption. On the other hand, inorganic fertilizers swiftly release nutrients, potentially misaligning with the plant's requirements across the growth cycle (Bhardwaj *et al.*, 2020). Consequently, it's imperative to identify INM modules encompassing comprehensive solutions that are ecologically sound and economically viable. Potential organic choices within the rice-wheat system encompass green manure crops, farmyard manures, composts, and the residues of crops that farmers conventionally burn (Chejara *et al.*, 2021).

The rice-wheat combination generates a substantial volume of residue that, if effectively recycled, can serve as a significant nutrient source. Burning rice residues has been prohibited by law in the Indo-Gangetic Plain (IGP), compelling farmers to manage stubble through in situ retention in the field post-harvest, alongside incorporation or surface retention. Recycling crop residues is a valuable waste management strategy that contributes to augmenting soil fertility and preserving crop productivity (Chen *et al*., 2017).

Opting for suitable alternative fertilization methods, chiefly involving residues, green manure, and slow-release fertilizers, can yield improvements in yield and nitrogen utilization efficiency. These alternatives can, to some extent, replace conventional chemical fertilizers without compromising productivity. Retaining residues and employing farmyard manure (FYM) contribute to enhanced soil aggregation, along with increased carbon (C) and nitrogen (N) sequestration in the soil (Brar *et al*., 2013). When no organic inputs were introduced, the absence of organic amendments resulted in a substantial depletion of total C content (approximately 43 per cent) (Ghosh *et al*., 2012).

Incorporating leguminous green manure crops or grain legumes into the rice-wheat cropping system proves to be more advantageous than a simple rice-wheat sequence (Bhardwaj *et al*., 2020). Despite the recognized benefits of organic integration, such as manures and residues, comprehensive technology packages for integrated nutrient management (INM) tailored for adoption by rice-wheat farmers to achieve optimal economic gains and enhanced nutrient-use efficiency remain scarce. Long-term trials play a crucial role in uncovering less apparent benefits and drawbacks. As a result, this study, spanning the past six years, has assessed eight potential INM modules, aiming to maximize the productive utilization of crop residues and enhance crop productivity in the intensive rice-wheat systems of the IGP.

MATERIALS AND METHODS

Experimental site

In 2015, a research experiment focused on integrated nutrient management (INM) within the rice-wheat cropping system commenced at the ICAR-Central Soil Salinity Research Institute (CSSRI) in Karnal, India. The institute is positioned at 29.43º N latitude and 76.58º E longitude. The experiment was conducted on soil characterized as sandy loam in texture. During the commencement of the experiment, the soil's top layer (0-15 cm) exhibited a pH of 8.7, a bulk density of 1.43 Mg m^{-3}, a cation exchange capacity of 9.5 cmol(p^+)kg^{-1}, and an organic carbon content of 3.2 g kg^{-1}. The experimental site featured a semi-arid sub-tropical climate characterized by scorching summers, mild winters, and an annual average rainfall of 750 mm.

Experimental layout and treatment details

The experimental treatments encompassed a combination of various organic and inorganic inputs, designed to fulfill the nutrient demands of the rice (Oryza sativa L.)-wheat (Triticum aestivum) cropping system. These treatments were executed within plots measuring 9 m × 3.5 m, with three replications arranged in fully randomized plots. The experiment consisted of eight distinct integrated nutrient management (INM) modules, namely: RS-F100: Retention of rice stubble in situ + 100% recommended fertilizers, RS-F150: Retention of rice stubble in situ + 150% recommended fertilizers, WS-F100: Retention of wheat stubble in situ + 100% recommended fertilizers, WS-F150: Retention of wheat stubble in situ + 150% recommended fertilizers, PSC-F50: Application of Paddy Straw Compost @ 5 t ha^{-1} + only 50% of recommended fertilizers, PSC+FYM-F50: Application of Paddy Straw Compost @ 5 t ha^{-1} + Farmyard manure @ 5 t ha^{-1} + only 50% of recommended fertilizers, GM+FYM-F50: Green manuring with Sesbania aculeata + Farmyard manure @ 5 t ha^{-1} + only 50% of recommended fertilizers, GM+PSC-F50: Green manuring with Sesbania aculeata + paddy straw compost @ 5 t ha^{-1} + only 50% of recommended fertilizers, These modules were compared against F, representing the use of 100% recommended fertilizer, and O, representing the absolute control. The plots were organized in a completely randomized fashion. The management schedule followed for different treatments was as follows:

1) **O**: Rice followed by wheat was grown without any inorganic fertilizers or organic inputs
2) **F**: Rice (July-October) followed by wheat (November-April) was grown with 100% chemical fertilizer input. The fertilizer application was done in three equal splits at time = 0, 21, and 42 days after transplanting. No organic inputs were given.
3) **RS- F100**: 30 cm standing stubble (~1/3 of the total straw) was retained at the time of harvesting rice. It was dry plowed into the soil at the time of wheat sowing in the 2nd week of November. Rice was transplanted in July and

wheat was sown in November with 100 % of recommended fertilizer inputs.

4) **RS- F150**: 30 cm standing stubble (~1/3 of the total straw) was retained at the time of harvesting rice. It was dry plowed into the soil at the time of wheat sowing in the 2nd week of November. Rice was transplanted in July and wheat was sown in November with 150 % of recommended fertilizer inputs.
5) **WS- F100**: 30 cm standing stubble (~1/3 of the total straw) was retained at the time of harvesting wheat. It was dry plowed into the soil before soil puddling in July's first week. Rice was transplanted in July and wheat was sown in November with 100 % of recommended fertilizer inputs.
6) **WS- F150**: 30 cm standing stubble (~1/3 of the total straw) was retained at the time of harvesting wheat. It was dry plowed into the soil before soil puddling in July's first week. Rice was transplanted in July and wheat was sown in November with 150 % of recommended fertilizer inputs.
7) **PSC-F50:** In this system, rice straw from the previous year was used to make compost which was applied in the *Kharif* season just like farmyard manure at the time of rice planting. Compost was made by chopping rice straw into ~5 cm pieces using a hay chopper. The rice straw compost (RSC) preparation was initiated with the alternate piling of 5 layers (each ~10 cm thick) of chopped straw with fresh cattle dung @ 50 kg per 100 kg straw, on a hard floor. The cattle dung was diluted to 100% before application. During each layering, the diluted culture of *Trichoderma viride* was also sprayed on straw during layering to enhance decomposition. The decomposing culture of Trichoderma is used @ 1 liter per 100 kg straw. The paddy compost is left for maturation for at least 4 months (intermittently sprayed with water every month and mixed). Rice was transplanted in July and wheat was sown in November with reduced (~50 %) fertilizer inputs. The PSC was applied @ 5 t ha^{-1} at the time of puddling and rice transplanting.
8) **PSC+FYM-F50**: Paddy straw compost (PSC@ 5 t ha^{-1}) and farmyard manure (FYM) at the rate of 5 t ha^{-1} were incorporated into the soil just before soil puddling and transplanting of rice. Rice was transplanted in July and wheat was sown in November with reduced (~50 %) fertilizer inputs.
9) **GM+FYM-F50**: A green manure crop, *Sesbania aculeata*, was grown in the lean period between wheat and rice. The green manure crop was sown on or around the 20th of May every year after the wheat harvest. After 35-40 days of sowing, the green manure crop was incorporated into the soil using a power tiller along with added farmyard manure (FYM) at the rate of 5 t ha^{-1} just before rice transplanting. Rice was transplanted in July and wheat was sown in November with reduced (~50 %) fertilizer inputs.
10) **GM+PSC-F50:** A green manure crop, *Sesbania aculeata*, was grown in the lean period between wheat and rice. The green manure crop was sown on or around the 20th of May every year after the wheat harvest. After 35-40 days of sowing, the green manure crop was incorporated into the soil using a power tiller, and paddy straw compost (PSC) at the rate of 5 t ha^{-1} was incorporated into the soil just before rice transplanting. Rice was transplanted in July and wheat was sown in November with reduced recommended fertilizer inputs (~50 %).

The annual cropping regimen followed a pattern of cultivating rice (Oryza sativa L.) during the summer months (July-October), succeeded by wheat (*Triticum aestivum* L.) in the winter season (November-April). For the rice cultivation phase, the field preparation began with dry plowing carried out during the final week of June across all treatments. This was followed by puddling, performed under submerged conditions. In the initial week of July, rice seedlings (variety: Pusa 44), aged approximately 30 days, and raised in a nursery, were transplanted at the recommended row spacing of 20 cm within the plots. The fields were inundated for puddling, with around 10 cm of standing water maintained on the surface during the first month. For the subsequent month, the surface flooding was reduced to about 5 cm. During the third month, weekly irrigations were given, saturating the soil but not allowing standing water on the surface. Approximately two weeks before harvesting, all irrigation was ceased. During the wheat season, a distinct approach was taken. The soil was initially subjected to dry tilling using a power tiller, and subsequently, the seeds of the

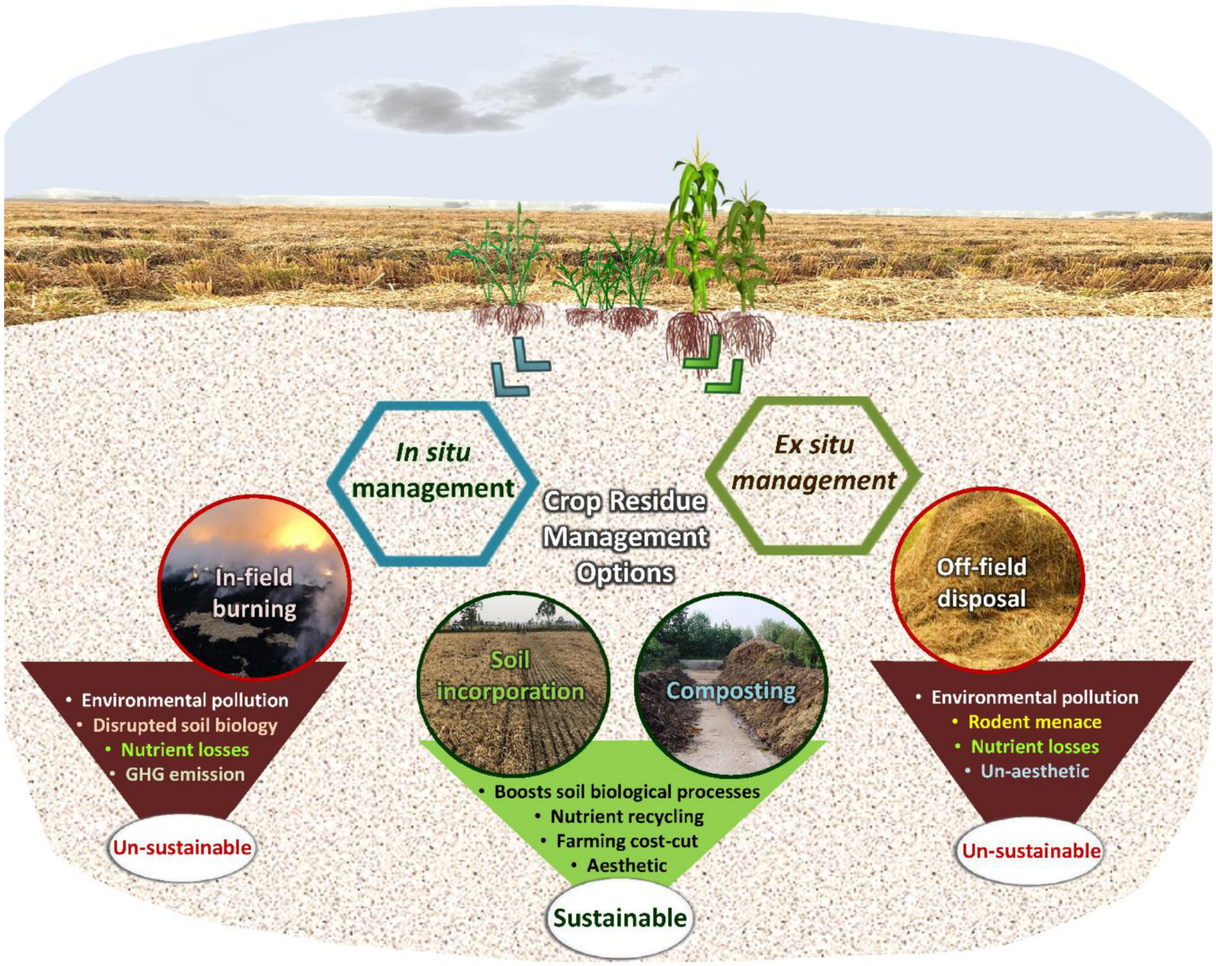

Fig. 1. Different crop residue management options in the rice-wheat system

HD2967 variety were sown in rows during the second week of November. This sowing process adhered to the recommended row spacing of 15 cm. Over the course of the season, the crops received nearly 3 to 4 surface irrigations, distributed at approximately 1-month intervals. For both rice and wheat, the recommended rates of inorganic fertilizers were as follows: 150 kg ha^{-1} for nitrogen (N), 26 kg ha^{-1} for phosphorus (P), and 42 kg ha^{-1} for potassium (K). Nitrogen was administered in three equal splits using urea, applied at intervals of t=0, 21, and 42 days after transplanting (for rice) or sowing (for wheat). On the other hand, full doses of phosphorus and potassium were introduced through diammonium phosphate (DAP) and muriate of potash (MOP), respectively, during the time of transplanting (for rice) or sowing (for wheat). The harvesting timeline for the crops was as follows: rice was harvested during the last week of October, while wheat harvesting was conducted in the first week of April, annually.

Soil Sampling and Chemical Analysis

After each year of wheat harvest in mid-April, representative soil samples were collected from the experimental field. Within each of the replicate plots, two samples were gathered from random locations and subsequently combined to create a composite sample. These composite samples were then air-dried under shade at room temperature, later pulverized using a wooden pestle and mortar, and sifted through a 2 mm stainless steel sieve. The analysis of these soil samples was conducted by established standard protocols. The determination of bulk density (g cm^{-3}) was carried out using a core sampler. Soil nitrogen (N) content was assessed through the alkaline potassium permanganate method (Subbiah and Asija, 1956). Soil phosphorus (P) was estimated using Olsen's method (Olsen *et al.*, 1954), while potassium (K) was extracted through neutral normal ammonium acetate and subsequently quantified via the flame photometer method (Hanway and Heidel, 1952). Oxidizable organic carbon (C) content was determined by employing the wet digestion method as outlined by Walkley and Black (1934). After the samples were dried, the soil pH was evaluated using a 1:2 (soil: water) suspension, measured with a digital multimeter (Eutech Instruments, Singapore; model PC510).

Crop yield

The rice and wheat crops were harvested and threshed plot-by-plot to accurately measure grain and straw yields, all standardized on a hectare basis.

Statistical analysis

The collected data underwent analysis of variance (ANOVA) and were evaluated using procedures for a completely randomized design. The initial year's data was excluded from the analysis, as it was considered a stabilization phase. The statistical analysis was conducted using JMP 9.0 software (SAS Inc., Cary, USA). The mean values of all parameters were subsequently subjected to the Tukey test for further evaluation. Correlation analysis was also undertaken to identify potential relationships among the measured parameters.

Unless explicitly specified, differences were deemed statistically significant only when they held at a significance level of $P \leq 0.05$. Graphical representation of the data was achieved using Origin v.8.5 software (Originlab Corporation, Northampton, USA).

RESULTS AND DISCUSSION

Grain and straw yield

The effect of different INM modules on grain and straw yield of rice and wheat crops is depicted in Fig. 2. Green manuring-based INM modules

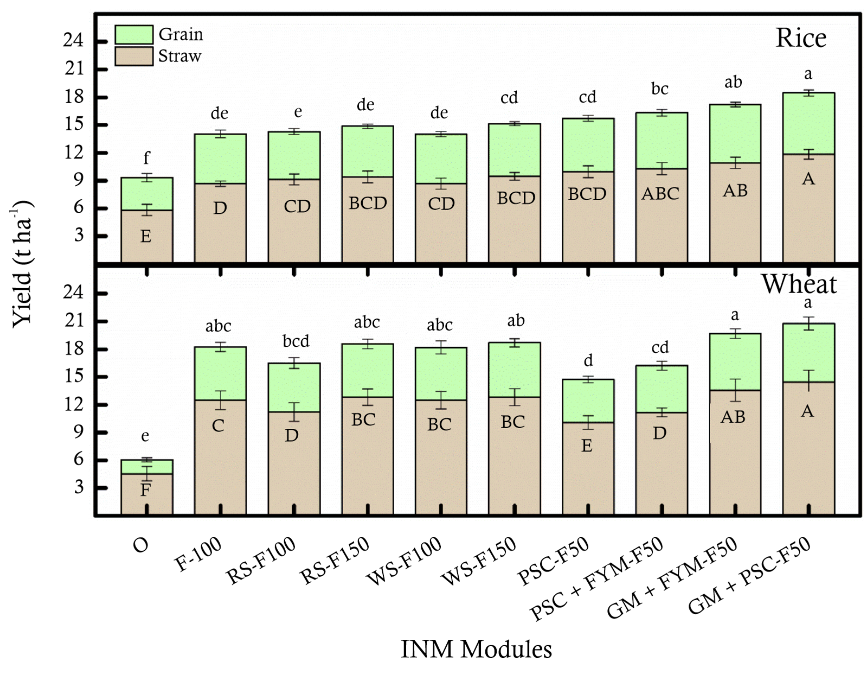

Fig. 2. Five years (2016-2021) average grain and straw yields (t ha^{-1}) of rice and wheat crops under different nutrient management modules. Module: O= absolute control, F= 100 % recommended fertilizer, RS-F100= in situ 1/3rd rice stubble retention and incorporation + 100 % recommended fertilizers, RS-F150= in situ 1/3rd rice stubble retention and incorporation + 150 % recommended fertilizers, WS-F100= in situ 1/3rd wheat stubble retention and incorporation + 100 % recommended fertilizers, WS-F150= in situ 1/3rd wheat stubble retention and incorporation + 150 % recommended fertilizers, PSC-F50=Paddy straw compost @ 5 t ha^{-1} + only 50 % of recommended fertilizers, PSC-FYM-F50= Paddy straw compost @ 5 t ha^{-1} + Farmyard manure @ 5 t ha^{-1} + only 50 % of recommended fertilizers, GM-FYM-F50= Green manuring with *Sesbania Aculeata* + Farmyard manure @ 5 t ha^{-1} + only 50 % of recommended fertilizers, GM-PSC-F50= Green manuring with *Sesbania Aculeata* + paddy straw compost @ 5 t ha^{-1} + only 50 % of recommended fertilizers. Error bars denote ± 1SD. Treatments with the same letters are not different significantly (P≤0.05)

with added compost/manure yet chemical fertilizers reduced to half (GM+FYM-F50, GM+PSC-F50) had the highest grain and straw yield among all treatments (~ 20 % increase over F100) for both rice and wheat crops. The in situ crop residue retention-based treatments, RS-F150 and WS-F100, performed statistically at par with F100. Rice stubble incorporation with 100 % recommended fertilizer (RS-F100) recorded a slight decrease in yield. The increase in yield can be attributed to a synergistic enhancement in the physical and chemical characteristics of the soil. Numerous studies in the past reported a positive effect of organic sources of nutrients on yield (Ali *et al.*, 2020). Integration of organics in nutrient management has advantages for both organic and inorganic fertilization systems, and it has been shown to have a consistent release of N throughout the growing season (Bhardwaj *et al.* 2020). Wheat residue retention has the highest potential to secure sustainable yield increment and good soil health by improving soil aggregation and soil organic carbon (SOC) sequestration in the rice-wheat cropping system (Chaudhary *et al.*, 2014). The return of both rice and wheat straw in a rice-wheat cycle can substantially enhance soil organic carbon (SOC), improve overall soil quality, and lead to marked improvements in productivity (Bhardwaj *et al.*, 2019).

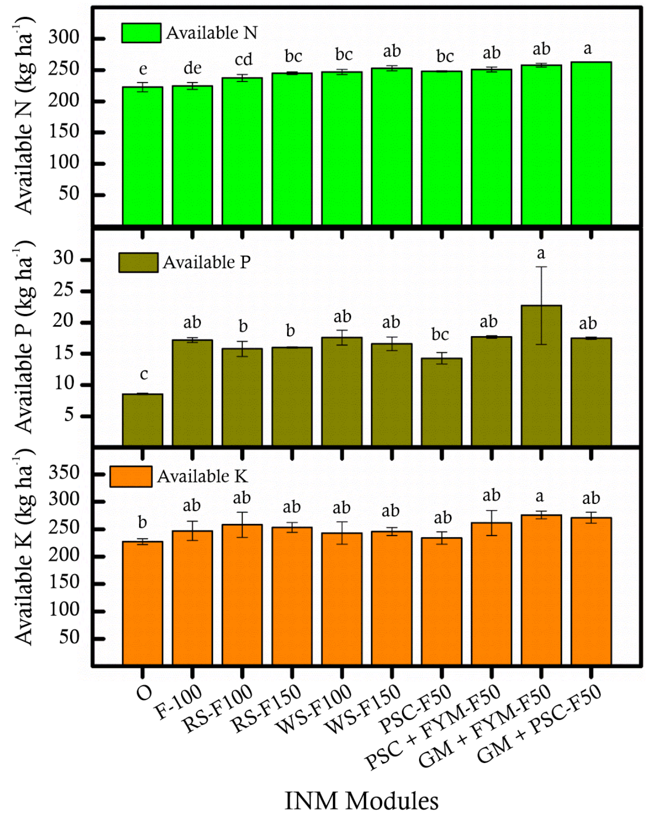

Fig. 3. Available nitrogen (N), Phosphorus (P), and Potassium (K) in soil under different INM modules in the rice-wheat system after 6 years of management. Refer to Fig. 2 for a description of treatments. Treatments with the same letters are not different significantly (P≤0.05)

Soil available N, P, and K

The effect of different integrated nutrient management (INM) modules on soil available nitrogen (N), available (P), and available (K) in the rice-wheat system after six years of study (Fig. 3; initial one year was considered as a stabilization period). There was a significant increase in soil available N under different INM modules, compared to F100 (100 % chemical fertilizer) and O (absolute control). The available N was significantly maximum in the GM + PSC- F50 INM module which was statistically at par with GM + FYM- F50, PSC + FYM-F50, and WS-F150. Similarly, all INM modules had higher available P and K compared to O (absolute control). Both P and K were maximum in the GM + FYM-F50 INM module. Green manuring can replace the required N, P, and K fertilizer applications in the second year to increase rice yield. Green manuring can elevate the soil's total N and K levels and decrease the base saturation. Green manure had the greatest contribution to total N, total P, zinc, iron, and manganese (Jha *et al.*, 2013).

Soil pH, bulk density, and organic carbon

The effect of different integrated nutrient management (INM) modules on soil pH, bulk density, and soil organic carbon in the rice-wheat system is presented in Fig. 4.

There was a significant decrease in soil pH and bulk density under different INM modules, compared to F100 (100 % chemical fertilizer) and O (absolute control).

Though small but significant buildup of organic carbon was noted for INM modules, especially a combination of paddy straw compost (PSC) and FYM along with 50 % chemical fertilizer application (PSC+FYM-F50), and green manuring-based management (GM+FYM-F50, GM+PSC-F50). Flooding soil is a powerful driver of the changes in fertility and nutrient availability via the two most important determinants of soil fertility-pH and redox potential (Eh) (Sahrawat, 2015). The drop of Eh under submerged soil influences the stability and availability of nutrients to the rice

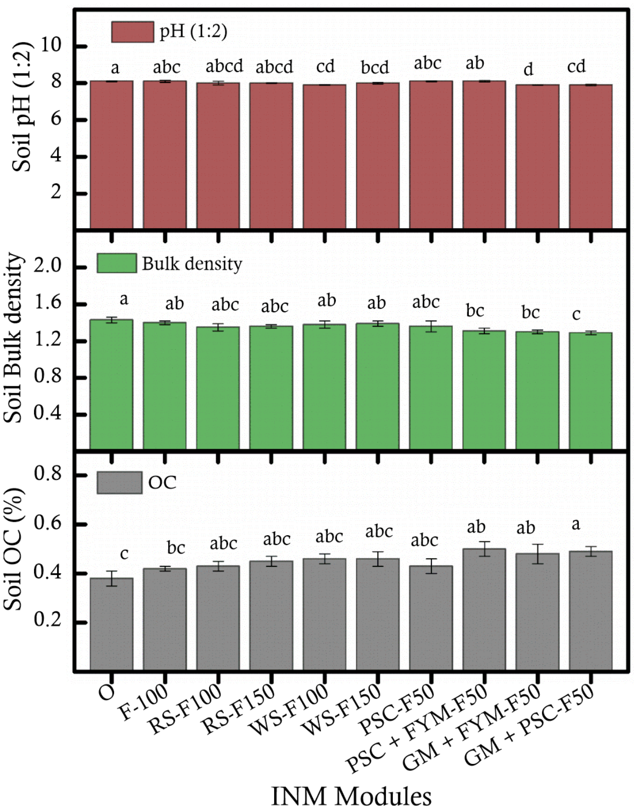

Fig. 4. Soil pH, bulk density, and organic carbon under different INM modules in the rice-wheat system after 6 years of management. Refer to Fig. 2 for a description of treatments. Treatments with the same letters are not significantly different (P≤0.05).

plant. Integrated nutrient management (INM) is a widely recognized tool to ensure sustainable crop productivity while preserving soil fertility. Dhaliwal *et al.*, 2021 reported that the organic source and inorganic fertilizers improved the water holding capacity, total porosity, soil respiration, microbial biomass C, microbial biomass N, and potentially mineralizable N. However, pH, EC, and bulk density of soil decreased with the addition of FYM, coupled with chemical fertilizers.

CONCLUSION

The green manuring with *Sesbania aculeata* along with paddy straw compost @ 5 t ha^{-1} + only 50 % of recommended fertilizer, *in situ* wheat stubble retention and incorporation with 100 % recommended fertilizer, and *in situ* rice stubble retention with 150% of recommended fertilizer performed the best in terms of crop yield and improvements in soil fertility among all INM modules. For the rice-wheat system, composting paddy straw using the study's composting techniques or *in situ* stubble retention for rice and wheat with 100% recommended fertilizer application with wheat stubble and 150% with rice stubble are both workable options.

ACKNOWLEDGEMENT

This work was financially supported by the ICAR-Central Soil Salinity Research Institute and the NICRA project (ICAR-DARE-NICRA-03).

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