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Residue recycling options and their implications for sustainable nitrogen management in rice–wheat agroecosystems

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Abstract

Background In the Indo-Gangetic Plain, rice–wheat is the most extensively practiced crop rotation. The escalating issue of crop residue burning, particularly rice straw, and the necessity to lower the exorbitant expenses associated with fertilizer inputs stand out as significant challenges for farmers in the region. A well-suited integrated nutrient management (INM) strategy that focuses on recycling crop residues can serve as a solution to address these issues. Such a strategy not only mitigates air pollution resulting from residue burning but also helps combat water pollution due to nitrate losses from agroecosystems. Field experiments were used to evaluate the suitability of eight INM-modules that included various combinations of inorganic fertilizer rates (50%, 100%, 150% of recommended dose), crop residues (wheat and rice stubble retention at 30 cm standing stubble equivalent to 1/3 the straw yield), rice straw compost (RSC), farmyard manure (FYM), and green manuring (GM), compared to 100% recommended dose of fertilizers (F) and no fertilizer application.

Results There was a considerable improvement in nitrogen mineralization, grain yields, and nitrogen use efficiency under GM + RSC-F50 and GM + FYM-F50. These INM modules would permit a 50% reduction in the use of chemical fertilizers. There was a little yield penalty with in situ rice residue incorporation at 100% F; however, this could be overcome with 150% F fertilizer application. In situ retention of wheat straw with a full application of fertilizer resulted in steadily rising crop yields over time. Changes in the redox potential, soil pH, and soil organic carbon best accounted for the observed trajectories in nitrogen use efficiency.

Conclusion The most promising INM modules for adoption by farmers in the Indo-Gangetic Plain to judiciously use crop residues and curtail chemical fertilizer inputs are green manuring with *Sesbania aculeata* + rice straw compost at 5 t ha^{-1} + only 50% of recommended dose of fertilizers (GM + RSC-F50), and green manuring with *Sesbania aculeata* + farmyard manure at 5 t ha^{-1} + only 50% of recommended dose of fertilizers (GM + FYM-F50). Sole incorporation of crop residues without nitrogen augmentation from other sources might not help curtail chemical fertilizer use. Composting rice straw, which otherwise is widely burnt, proved a useful nitrogen source and a vital component of INM. Waste rice straw composting at the community scale and its application as a nutrient source can help achieve sustainable nitrogen management in the agroecosystems of Indo-Gangetic Plain.

Keywords Rice–wheat, Nitrogen use efficiency, Sustainable nitrogen management index, Crop residue, Rice straw compost

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Background

Nutrient management via fertilizer application is a very important practice in rice–wheat systems to maintain profitability and sustainability (Cheng et al. 2022). To achieve a significant crop yield, nitrogen (N) fertilizers are commonly used as a vital input for proper plant growth (Leghari et al. 2016). Nitrogen stands as an essential macronutrient for growth and metabolism, and the application of N fertilizers is a common practice adopted by farmers to achieve higher yields (Park et al. 2023). The rice–wheat system is the preferred production system by the farming community in Asia, and N fertilizer consumption has increased substantially in this cropping system after the green revolution (Harwood 2019). The contribution of N fertilization in enhancing food security cannot be overlooked since N is the most yield-limiting nutrient element. In India, N fertilizer consumption increased from 0.21 million tonnes in the 1960s to 17.0 million tonnes in 2018 (FAI 2018). However, 50% of N fertilizer is either left unused or lost, causing water pollution through nitrate (NO_3^-) discharge to surface waters and leaching into groundwater, and contributing to air quality issues and acid rain through transformations to nitrogen oxides (NO, N_2O, NO_2) (Ruan et al. 2016; Zheng et al. 2019). Due to these losses, the use efficiency of N is low, and therefore farmers often apply nitrogen in excessive amounts to rice–wheat to get maximum profit. The nitrogen loss from fertilizers through leaching and denitrification processes raises concerns for both air and water quality (Luo et al. 2023). Some reactive forms of nitrogen viz; nitrite (NO_2^-), nitrogen oxides (NOx), ammonia (NH_3), and nitrous oxide (N_2O) can be harmful to human beings, plants, microbes as well as animals (Aziz et al. 2022). Nitrate can contaminate groundwater and cause eutrophication of surface waters. Methemoglobinemia and other health problems can result from drinking water that contains nitrates (Hu et al. 2018). Furthermore, ammonia volatilization not only contributes to acid rain but also serves as a secondary origin of nitrous oxide, which contributes to ozone layer depletion, thereby expediting the processes of climate change and global warming (Rutting et al. 2018).

Excessive and inefficient utilization of N fertilizers increases crop production expenses. Excess N fertilizer application does not increase yield significantly but causes serious environmental problems due to low N use efficiency (Anas et al. 2020). The apparent recovery efficiency (the percentage of N fertilizer accumulated in aboveground plant biomass at the end of the cropping period) of N fertilizers is low (Garnett et al. 2009). Worldwide, utilization of N fertilizer has surged to 108 Tg N yr^{-1}, whereas the N use efficiency (NUE) of permanent crops ranges between 30 to 50% for total N recovery (Khalsa et al. 2020). In field crops, NUE hardly surpasses 40%, while the rest of the added N is lost via various means viz: runoff, leaching, volatilization, and denitrification (Dwivedi et al. 2016). Rice crop grows in flooded (anaerobic) conditions and wheat crop grows in dry (aerobic) conditions. The alternate soil wetting and drying cycle moving from anaerobic to aerobic between rice and wheat crops is also a challenge for enhancing N conservation (Xu et al. 2022). Ammonia volatilization due to oxygen shortage during anaerobic conditions, and nitrate leaching during aerobic conditions are substantial N losses in the cropping sequence (Farooq et al. 2022). NUE is a complex attribute affected by multiple factors, but it is regarded as a performance indicator of any crop production system. There are different types of NUE assessment parameters viz: N uptake efficiency, agronomical NUE, and N assimilation efficiency which vary depending on the purpose of use (Han et al. 2015). Growing constraints necessitate enhancing the NUE in agricultural farming systems.

Management has a significant impact on NUE. The sole application of chemical fertilizers deprived of nutrient recycling degrades soil fertility, resulting in secondary and micronutrient deficiency in the long term (Dwivedi et al. 2016). Increasing costs of inorganic sources of N, and mismatch in N supply-crop demand are major challenges in crop production systems (Lobell 2007). It is important to have knowledge-based strategies that improve crop N demand–supply synchronization. Balanced N application is important to meet the crop requirement as well as to curtail nutrient losses from the field (Dhawan et al. 2022). Therefore, to improve NUE, it is a prerequisite that the overdosing of chemical fertilizers be reduced and the availability in soil be synchronized with crop demand. Future improvements in rice–wheat system productivity are expected only by increased nutrient use efficiency (Nadeem et al. 2022). Including organic sources in nutrient management is the best option to cut down excessive fertilizer use yet fulfilling the crop's nutritional demand at the same time can be challenging (Singh and Saini 2022). The integration of inorganic and organic sources of nutrients has been noted to improve soil fertility (Gogoi et al. 2021). The common organic sources include farmyard manure, residue compost, crop residues, and cover crops (Sharma et al. 2019; Bhardwaj et al. 2021a). Integrated nutrient management (INM) is the best alternative for enhancing soil health and sustaining the rice–wheat system productivity (Bhardwaj et al. 2019).

The N mineralization is the main reaction, which governs the availability of N in soil solution. Nitrogen mineralization in the soil is a biological reaction in which soil organic N is chemically transformed to plant-available inorganic forms (NH_4^+ and NO_3^-) in the presence of microbial activity (Grzyb et al. 2020). However, the transformation of N in available forms is largely governed by the organic matter composition (Ukalska-Jaruga et al. 2020). The organic matter having a lower C/N ratio releases extra nitrogen (Drost et al. 2020), while the higher C/N ratio releases less nitrogen due to immobilization (Cao et al. 2021). Because organic sources are vital components of INM, knowledge of their biochemical composition, breakdown, and N mineralization rate is crucial. The potential options for organics integration in the rice–wheat system are green manure, farmyard manure, legume cropping, crop residues of preceding crops, and various cover crops (Saha et al. 2018). The rice–wheat systems' productivity highly depends upon enhancements in soil fertility through best nutrient management and use of crop residues. Rice–wheat crop rotation is practiced nearly on about 13.5 Mha in Indo-Gangetic Plain (IGP) of South Asia, out of which 10.3 Mha was present in Indian IGP (Bhatt et al. 2016). Annual production of rice crop residue was 156.8 Mt and wheat crop residue was 149 Mt (Venkatramanan et al. 2021). Most of the wheat straw is utilized for dry fodder purposes, while rice straw is not suitable as nutritious feed for cattle because of the high content of silica. Farmers generally adopt the practice of paddy straw burning before sowing wheat as an easy and cheap option, but it results in a huge loss of organic carbon and N, loss of other major nutrients, adverse health impacts, and environmental pollution (Thorat et al. 2015). Integrating crop residues in nutrient management helps to minimize the environmental pollution concerns due to residue burning, curtail huge nutrient losses from fertilizers, and reduce commercial fertilizer use. The byproducts of wheat and rice straws are carbon-rich energy sources that contain N, phosphorus, potassium, and other nutrients that are required for plant growth and development (Xue et al. 2014). Crop residue addition enhances soil organic carbon and nutrient levels as well as aggregate stability. Crop residue incorporation alters the soil physicochemical environment, affects soil microbial activity, and ultimately influences nutrient cycling (Ramteke and Vashisht 2023). Long-term crop residue recycling might increase the amount of easily mineralized soil organic N, lowering the need for additional fertilizer N in succeeding crop years (Bhardwaj et al. 2020, 2021b).

Recent studies on the integration of organics in nutrient management pointed out the need for more efficient INM modules as the insufficiency of N fulfillment may lead to yield penalties, particularly during the initial years of in situ crop residue incorporation (Bhardwaj et al. 2019, 2022). Composting of rice straw and its application in combination with green manuring can be a viable option as it improves the C/N ratio and provides adequate N to meet crop requirements. Therefore, the current experiment was undertaken to study eight innovative INM modules based on N mineralization trends and use efficiency for crop residue integration in rice–wheat systems.

Materials and methods

Experimental site

In 2015, a research experiment was initiated at ICAR-Central Soil Salinity Research Institute (CSSRI) in Karnal, India, situated at coordinates 29.43° N latitude and 76.58° E longitude. The experiment focused on INM in the rice–wheat cropping system. The texture of the soil in the experimental field was sandy loam. At the initiation of the experiment, the soil in the 0–15 cm depth range exhibited the following characteristics: a pH of 8.7, cation exchange capacity of 9.5 cmol (P+) kg^{-1}, bulk density of 1.43 g cm^{-3}, and an organic carbon content of 3.2 g kg^{-1}. The experimental site had a semi-arid sub-tropical environment with hot summers, moderate winters, and 750 mm of annual rainfall on average.

Experimental layout and treatment details

The nutritional requirements of the rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system were fulfilled by a combination of organic and inorganic inputs in the treatments. The treatments were employed in three replications in completely randomized 9 m × 3.5 m plots. The experiment consisted of eight INM modules viz: RS-F100 = Rice stubble retention (in situ) + 100% recommended fertilizers, RS-F150 = Rice stubble retention (in situ) + 150% recommended fertilizers, WS-F100 = Wheat stubble retention (in situ) + 100% recommended fertilizers, WS-F150 = Wheat stubble retention (in situ) + 150% recommended fertilizers, RSC-F50 = Rice straw compost at 10 t ha^{-1} + only 50% of recommended fertilizers, RSC + FYM-F50 = Rice straw compost at 5 t ha^{-1} + Farmyard manure at 5 t ha^{-1} + only 50% of recommended fertilizers, GM + FYM-F50 = Green manuring with dhaincha (*Sesbania aculeata*) + Farmyard manure at 5 t ha^{-1} + only 50% of recommended fertilizers, GM + RSC-F50 = Green manuring with dhaincha + Rice straw compost at 5 t ha^{-1} + only 50% of recommended fertilizers, compared to F = 100% recommended fertilizer, and O = absolute control. The following management schedule was used for different treatments:

i. O: The cultivation of rice (July–October) followed by wheat (November–April) involved the exclusion of both inorganic fertilizers and organic inputs. Rice was transplanted in the first week of July after soil preparation and puddling in flooded conditions with a power tiller. It was harvested in the last week of October. It was followed by wheat which was row sown under dry-tilled conditions in the first week of November and harvested in the first week of April.

ii. F: Rice followed by wheat was grown with 100% recommended chemical fertilizer inputs. No organic inputs were applied. Rice was transplanted in the first week of July after soil preparation and puddling in flooded conditions with a power tiller. It was harvested in the last week of October. It was followed by wheat which was row sown under dry-tilled conditions in the first week of November, and harvested in the first week of April.

iii. RS-F100: The 30 cm standing stubble which is approximately 1/3 of the total straw, was retained at the time of rice harvesting. At the time of wheat sowing, it was dry plowed into the soil in the first week of November. The rice crop was transplanted in the first week of July and the wheat crop was sown in the first week of November with 100% of recommended chemical fertilizer inputs for both crops.

iv. RS-F150: The 30 cm standing stubble which is approximately 1/3 of the total straw, was retained at the time of rice harvesting. At the time of wheat sowing, it was dry plowed into the soil in the first week of November. The rice crop was transplanted in the first week of July and the wheat crop was sown in the first week of November with 150% of recommended chemical fertilizer inputs for both crops.

v. WS-F10**0**: The 30 cm standing stubble that is approximately 1/3 of the total straw was retained at the time of wheat harvesting. It was dry plowed into the soil during soil preparation/puddling operation in the first week of July. Rice was transplanted immediately after puddling, in the first week of July month, with recommended (100%) fertilizer inputs. Rice was followed by wheat which was sown in the first week of November with recommended (100%) fertilizer inputs.

vi. WS-F150: The 30 cm standing stubble that is approximately 1/3 of the total straw was retained at the time of wheat harvesting. It was dry plowed into the soil during soil preparation/puddling operation for rice transplanting in the first week of July. Rice was transplanted immediately after puddling, in the first week of July, with increased (150%) fertilizer inputs. Rice was followed by wheat which was sown in the first week of November with increased (150%) fertilizer inputs.

vii. RSC-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 at 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* was used at 1 L per 100 kg straw. The rice compost is left for maturation for at least 4 months (intermittently sprayed with water every month and mixed). During soil preparation/puddling, 10 t ha^{-1} of rice straw compost (RSC) was added to the soil. Rice was transplanted immediately after puddling, in the first week of July month, with reduced (50%) fertilizer inputs. Rice was followed by wheat which was sown in the first week of November with reduced (~ 50%) of recommended fertilizer inputs.

viii. RSC + FYM-F50: During soil preparation/puddling, 5 t ha^{-1} of rice straw compost (RSC) and 5 t ha^{-1} of farmyard manure (FYM) were added to the soil. Rice was transplanted immediately after puddling, in the first week of July, with reduced (50%) fertilizer inputs. Rice was followed by wheat which was sown in the first week of November with reduced (50%) of recommended fertilizer inputs.

ix. GM + FYM-F50: Between the harvests of wheat and rice, a green manure crop, *Sesbania aculeata*, was grown. Every year, after the wheat harvest, the green manure crop was sown on or around May 20. A power tiller was used to mix the green manure crop into the soil after 35–40 days of sowing along with farmyard manure (FYM) at a rate of 5 t ha^{-1}, at soil preparation/puddling for rice transplanting. During soil preparation, organic materials were dry-tilled into the soil with a power tiller followed by puddling under flooded conditions. Rice was transplanted immediately after puddling, in the first week of July, with reduced (50%) fertilizer inputs. Rice was followed by wheat which was sown in the first week of November with reduced (~ 50%) fertilizer inputs.

x. GM + RSC-F50: Between the harvests of wheat and rice, a green manure (GM) crop, *Sesbania aculeata*, was grown. Every year, after the wheat harvest, the green manure crop was sown on or around May 20. A power tiller was used to mix the GM crop into the soil after 35–40 days of sowing along with rice straw compost (RSC) at a rate of 5 t ha^{-1}, at soil preparation/puddling for rice transplanting. During soil preparation, organic materials were dry-tilled into the soil with a power tiller followed by puddling under flooded conditions. Rice was transplanted immediately after puddling, in the first week of July, with reduced (50%) fertilizer inputs. Rice was followed by wheat which was sown in the first week of November with reduced (50%) fertilizer inputs.

The yearly crop rotation involved the cultivation of rice during the summer (July–October) and subsequent cultivation of wheat during the winter (November–April). In all treatments, the field was prepared for rice cultivation by practicing dry plowing during the last week of June, followed by puddling under water-flooded conditions. 30-day-old nursery-raised rice seedlings (var. Pusa 44) were transplanted at recommended row spacing (20 cm) in all plots. The fields were initially flooded for puddling, and subsequently, a layer of approximately 10 cm of standing water was maintained on the surface for the first month. During the second month, the surface flooding was maintained to approximately 5 cm. In the third month, weekly irrigations were provided only for saturating the soils without maintaining any standing water on the soil surface. Irrigations were stopped two weeks before the harvest. However, in the wheat season, the soil was initially prepared through dry tilling using a power tiller. Subsequently, the seeds of variety HD2967 were sown in rows during the second week of November at a recommended row spacing (15 cm) in all plots. Approximately 3–4 surface irrigations were provided at intervals of 1 month. For both crops, the recommended quantities of inorganic fertilizers were 150 kg ha^{-1}, 26 kg ha^{-1}, and 42 kg ha^{-1} for nitrogen (N), phosphorus (P), and potassium (K), respectively. The nitrogen doses were applied in three equal splits using urea, with the first split application at the time of transplanting (rice)/sowing (wheat), followed by the next two split applications at 21 and 42 days. Full doses of P and K were applied at the time of transplanting (rice)/sowing (wheat) using diammonium phosphate (DAP) and muriate of potash (MOP), respectively. Every year, rice was harvested in the last week of October, and wheat was harvested in the first week of April.

Soil sampling and chemical analysis

After the wheat harvest in mid-April each year, soil samples were collected from the experimental field at a depth of 0–15 cm. For each of the replicates, two samples were collected at random spots within a plot, and subsequently mixed. The composite samples were air-dried in the shade at room temperature, then ground using a ceramic pestle and mortar, and finally sieved through a 2 mm stainless steel sieve. The soil samples were analyzed following standard procedures. Available nitrogen in soil was determined by the alkaline potassium permanganate method described by Subbiah and Asija (1956).

Estimation of nitrogen in amendments and crop plants

Biomass samples were taken for all amendments at the time of their application. Rice straw compost (RSC) and farmyard manure (FYM) samples were taken during their application to the soil while preparing it for rice transplanting. Samples for green manure crops (*Sesbania aculeata*) were acquired at the time of its incorporation into the soil. Rice stubble was sampled right after the rice harvest, and wheat stubble was sampled at the wheat harvest. The sampled amendments underwent the Kjeldahl N determination to determine their N concentrations.

At harvest of each crop, the biomass samples from each treatment were collected. The grains and straw were segregated and placed into paper bags, left to air dry for 24 h, and subsequently subjected to oven drying at 65 °C for 48 h. The dried samples were then ground separately using a grinder. The total N determinations were done in the grain and straw samples for each treatment using Kjeldahl N determination method.

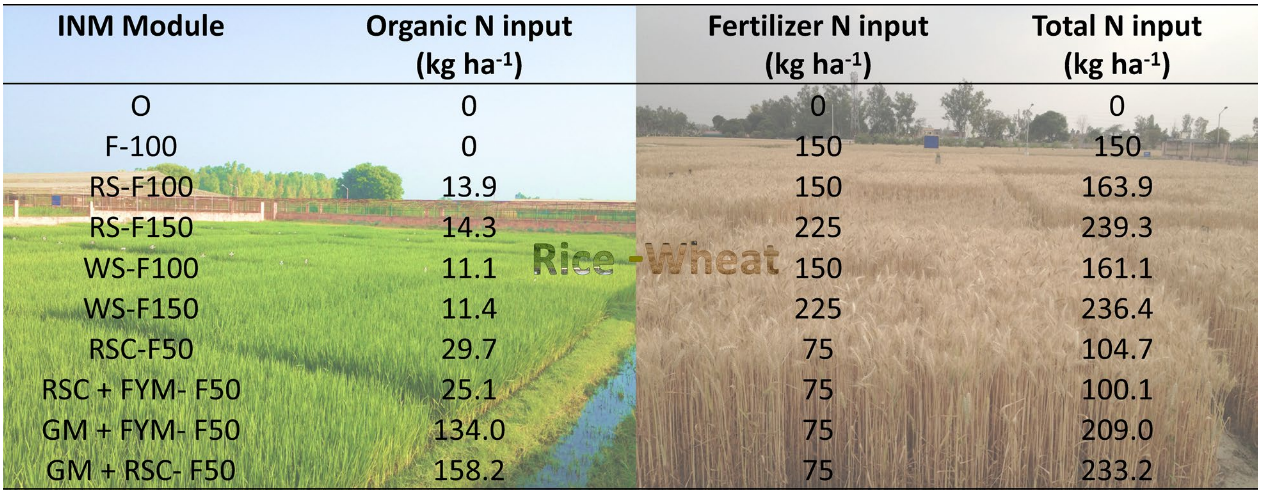
For the determination of N content (%), a finely ground sample weighing 1 g was subjected to digestion in 250 ml digestion tubes containing concentrated H_2SO_4 and catalysts (K_2SO_4, $CuSO_4$, and selenium). The samples underwent digestion for 2–3 h within a temperature range of 360 to 420 °C until the sample displayed a light blue coloration. Subsequently, the digestion tubes were placed into the Kjeldahl distillation system. Through a programmed Kjeldahl N Analyzer (Pelican Equipments, Chennai, India), 10 ml of distilled water and 40 ml of 40% NaOH were added. The steam distillation released ammonia was captured within a 20 ml solution of boric acid (4%). The titration process was executed using 0.1 N H_2SO_4 to quantify the total N content (%) present in the boric acid solution.

Rice straw compost (RSC) and FYM had an N concentration (w/w) of 0.81% and 0.56%, respectively. The green manure crop, *Sesbania aculeata*, had an N concentration of 2.65% at the time of adding to soil. Wheat stubble had 0.27%, and rice stubble had 0.46% N concentration. The total N inputs (5-year average) into different INM modules are summarized in Table 1.

Estimation of nitrogen harvested

The N concentration in the straw was multiplied by the total straw yield (t ha^{-1}), and the N concentration in the grains was multiplied by the total grain yield (t ha^{-1}) to obtain the N yield for each replication in a particular treatment.

Table 1 The nitrogen inputs under different integrated nutrient management (INM) modules in rice–wheat cropping system.



INM Module	Organic N input (kg ha^{-1})	Fertilizer N input (kg ha^{-1})	Total N input (kg ha^{-1})
O	0	0	0
F-100	0	150	150
RS-F100	13.9	150	163.9
RS-F150	14.3	225	239.3
WS-F100	11.1	150	161.1
WS-F150	11.4	225	236.4
RSC-F50	29.7	75	104.7
RSC + FYM- F50	25.1	75	100.1
GM + FYM- F50	134.0	75	209.0
GM + RSC- F50	158.2	75	233.2

Nitrogen mineralization in soil

During the growing season, nitrogen availability (net mineralization) in soils was assessed using ion exchange resin (IER) membranes. From big commercially available sheets, membrane strips measuring 2.5 cm by 10 cm were cut out (cation and anion separately) (General Electricals, Watertown, MA, USA). The strips were charged by immersing and stirring them in 0.5 mol L^{-1} HCl for 1.2 h, followed by an additional 5 h of immersion and stirring in 0.5 mol L^{-1} $NaHCO_3$. Afterward, the strips were rinsed using deionized water. Subsequently, vertical slots were cut into the treated soils, and the resin strips were carefully inserted, and securely closed, ensuring that the strips made direct contact with the soil. Both cation and anion strips were positioned 5 cm apart, and left undisturbed for 15 days, and the old strips were removed, and replaced with new strips. This procedure was repeated consistently throughout the entire cropping season. Once removed from the soil, the strips were thoroughly rinsed with deionized water to remove any remaining soil particles. Both cation and anion strips were carefully preserved and transported in a vial for further analysis. In the laboratory, to extract NH_4^+-N and NO_3^--N, 70 mL of KCl (2 mol L^{-1}) was added to the vial containing the strips, which was agitated for 1 h before being carefully decanted into a scintillation vial. The extracted solution was tested for NH_4^+-N and NO_3^--N using the Kjeltec 2200 analyzer (Foss, Hillerod, Denmark).

Nitrogen use efficiency (NUE) indicators

Two different approaches were used to quantify nitrogen use efficiencies (NUEs), the N difference approach and the N balance approach (Quan et al. 2021).

NUE with nitrogen difference approach (NUE$_{diff}$)

The N difference approach (NUE$_{diff}$) is calculated by dividing the difference between the N harvested in the fertilized treatment (NH$_t$) and the N harvest in the non-fertilized control (NH$_o$) treatment, with N fertilizer (organic + inorganic) inputs (F$_{input}$).

$$\mathrm{NUE_{diff}} = \frac{\mathrm{NH_t - NH_O}}{\mathrm{F_{inputs}}} \tag{1}$$

The main emphasis of NUE$_{diff}$ assessment is on the fertilizer N recovery efficiency during a crop-growing season with no concern for legacy effects.

Nitrogen balance approach (NUE$_{bal}$)

The N difference approach (NUE$_{bal}$) is calculated by dividing the N harvested in any treatment (NH$_t$) by all N inputs (including all fertilizer inputs (F$_{inputs}$) and non-fertilizer inputs (NF$_{input}$)). We considered the N inputs from fertilizer (organic + inorganic) for calculating F$_{inputs}$, and N deposition (Mishra and Kulshrestha 2022) for calculating NF$_{inputs}$.

$$\mathrm{NUE_{bal}} = \frac{\mathrm{NH_t}}{\mathrm{F_{inputs} + NF_{inputs}}} \tag{2}$$

When evaluating NUE$_{bal}$, the use efficiency of all N inputs and the proportion of N inputs lost are given the most consideration. It is assumed that there is no change in the soil N status, and it is in a quasi-steady state (Quan et al. 2021). In the current long-term experimental study, the average change in soil N stock from season to season was minimal compared to the N inputs during the growing seasons.

Sustainable nitrogen management index

The sustainability of nitrogen management for different nutrient management strategies was calculated using the Sustainable Nitrogen Management Index (SNMI) developed by Zhang et al. (2022). The index integrates the performance in N crop yield and NUE, considering the requirement for food production as well as for environmental preservation. In the standard SNMI assessment, the reference yield was set at a constant value of 90 kg ha^{-1} (Taking into account a worldwide averaged yield target for meeting food demand in the year 2050), and the reference NUE at 1.0 (considered to be the optimal NUE). The agricultural SNMI merged two crucial efficiency metrics, NUE and land use efficiency (crop yield), into a unified ranking score. SNMI calculates the geometric distances of normalized NUE (*NUE**) and normalized yield (*NYield**) from a reference point in a two-dimensional graphic.

Briefly, the *NUE* is determined by dividing NUE by a reference NUE ($NUE_{ref}=1$), and NUE > 1 are adjusted downward to prevent inflating the score due to excessive soil N depletion. The normalized crop yield is calculated by dividing the crop yield by a reference crop yield ($NYield_{ref}=90$ kg ha^{-1}). SNMI values close to zero indicate sustainable N management, as both yield and NUE approach their respective targets. Mathematically, SNMI is defined as the Euclidean distance from an ideal point aimed at achieving optimal NUE and yield. The equations used for its calculation are as follows:

$$SNMI = \sqrt{\left(1 - NYield^{*}\right)^{2} + \left(1 - NUE^{*}\right)^{2}} \qquad (3)$$

where,

$$NYield^{*} = \begin{array}{l|l} NYield/NYield_{ref} & (NYield \le NYield_{ref}) \\ 1 & (NYield > NYield_{ref}) \end{array} \qquad (4)$$

$$NUE^{*} = \begin{array}{ll} NUE/NUE_{ref} & (NUE \le NUE_{ref}) \\ 1 & (NUE_{ref} < NYield_{ref} \le 1) \\ 1 - (\text{NUE - 1}) & (1 < \text{NUE} \le 2) \\ 0 & (\text{NUE} > 2) \end{array} \qquad (5)$$

Crop yield

Plot-wise harvesting and threshing of both rice and wheat crops were done to record grain and straw yields.

Statistical analysis

Analysis of variance (ANOVA) and completely randomized design approaches were used to analyze the data. The first year of data was not included in the analysis as it was considered as treatment stabilization period. The statistical analysis of experimental data was done using the software JMP 9.0 (SAS Inc., Cary, USA). The significant difference between the treatment means was compared by using Tukey's Honest Significant Difference test. We used correlation analysis to find correlations between the variables we measured. Unless otherwise pointed out, the threshold for determining statistical significance was set at $P \le 0.05$. The graphical demonstration was done using Origin v.8.5 software (Originlab Corporation, Northampton, USA). The curve fitting for all the management/treatment was done with instrumental weighing in the Origin software. The standard errors are used as weights in instrumental weighing, and the weight formula was $w_i = 1/\sigma_i^2$, where σ_i is the error/standard deviation.

Results

All INM modules had significantly ($P < 0.05$) similar availability of ion exchange resin (IER)-sorbed N availability during rice season (Fig. 1). During rice growing season, most IER-sorbed N represented net mineralized N was in the form of NH_4^+-N (~ 75%) and was significantly higher in INM treatments compared to F100. There were significant differences in quantified NH_4^+-N and NO_3^--N, at different stages due to the management effects (Fig. 1). Up to 45 days after transplanting (DAT), most of the N in soil solution (> 60% of total-N) was available in the form of NH_4^+-N with an average value of 3.1, 2.6, 1.3 and 1.0 µg cm^{-2} day^{-1} at 0–15, 15–30, 30–45 and 45–60 DAT, when rice crop was under anaerobic conditions due to flooding with frequent irrigation plus rainfall. Soil solution NH_4^+ availability was drastically altered when irrigation patterns changed from flooding to an alternating wetting and drying cycle. At 60–75 DAT and 75–90 DAT the quantity of NH_4^+-N available in soil solution was decreased by 43% and 57%, respectively, from the average values for continuous flooding in the prior period (0–60 DAT). On the other hand, near withdrawal of irrigation during the 90–105 DAT phase, again detected an increase in NH_4^+-N in the soil solution. Crop-stage wise, for 0–15 DAT (early tillering) rice straw compost (RSC) based INM management (RSC-F50, RSC + FYM-F50, GM + RSC-F50) had significantly higher N availability in soil solution, compared to other managements. During the maximum tillering stages (15–30 and 30–45 DAT), these RSC-based managements along with the crop-residue-based management (RS, WS) had significantly similar availability which was comparable to F100. Beyond this stage, the total available N significantly decreased until the grain-filling stage. For 45–60

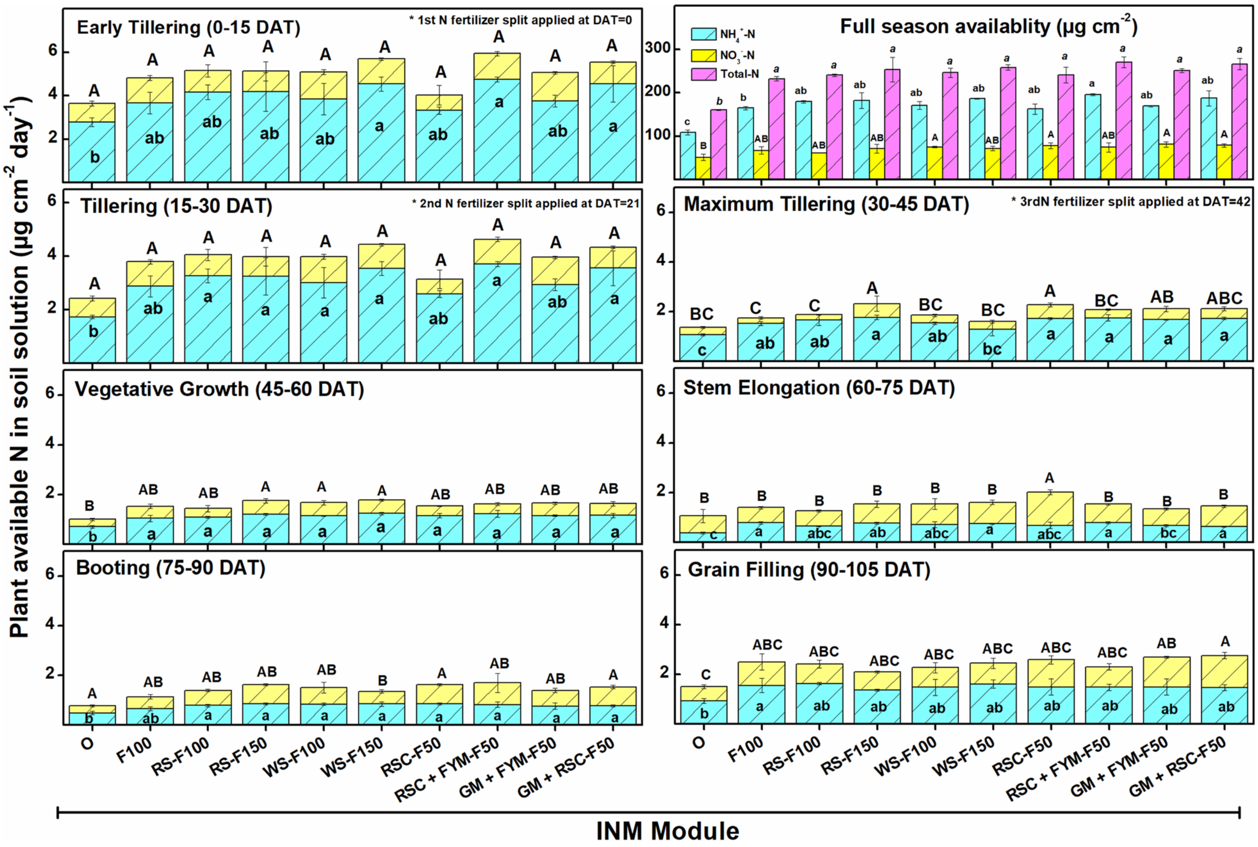


Fig. 1 Full season and stage-wise differences in plant available NH_4^+-N, NO_3^--N, and total-N in soil solution during the rice growing season (average for two cropping years). Lowercase letters denote differences for NH_4^+-N, capital letters for NO_3^--N, and lowercase italic letters for total-N. 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, RSC-F50 = rice straw compost at 5 t ha^{-1} + only 50% of recommended fertilizers, RSC-FYM-F50 = rice straw compost at 5 t ha^{-1} + farmyard manure at 5 t ha^{-1} + only 50% of recommended fertilizers, GM-FYM-F50 = green manuring with *Sesbania aculeata* + farmyard manure at 5 t ha^{-1} + only 50% of recommended fertilizers, GM-RSC-F50 = green manuring with *Sesbania aculeata* + rice straw compost at 5 t ha^{-1} + only 50% of recommended fertilizers. Error bars denote ± 1SD. Treatments with the same letters are not different significantly ($P < 0.05$)

DAT, not much difference was noted between any of the managements. The concentration of NO_3^--N was the same in all managements for up to 60 DAT. Beyond 60 DAT, the N concentration in form of NO_3^--N and NH_4^+-N was at almost similar levels.

For wheat crop, green manuring with compost application (GM + FYM-F50 and GM + RSC-F50) followed by wheat-stubble-incorporation-based management (WS-F100 and WS-F150) had the maximum net mineralized N availability, compared to all other managements. In comparison to NH_4^+-N, NO_3^--N was often more abundant. Plant-available N, as measured by ion exchange resin strips, varied significantly throughout wheat crop development phases and management practices (Fig. 2). During the shoot initiation period (0–30 DAS), WS-F150 and rice-straw-compost-based management (RSC + FYM-F50, GM + FYM-F50, and GM + RSC-F50) had the maximum N availability which continued to early tillering. From 30–45 DAS, crop-residue-based management (RS, WS) lagged behind other managements in N availability in soil. Beyond this stage, up to 90 DAS, there was a continuous decline in N availability and it was significantly lower in the case of RS-F100. From heading until ripening stages (beyond 90 DAS), all INM modules maintained significantly higher N availability in soil. The IER-determined available N in soil-solution related well to the total applied N (inorganic N plus the organic N added via the organic amendments in the rice season) during the wheat season only ($R^2 = 0.81$, $P = 0.0009$) while it related significantly to the soil N during both seasons ($R^2 = 0.71$, $P = 0.004$, and $R^2 = 0.48$, $P = 0.03$ in rice and wheat, respectively) (Fig. 3).

During 6 years of study, for rice grain yield, a decreasing trend in rice grain yield was noted over the years for rice

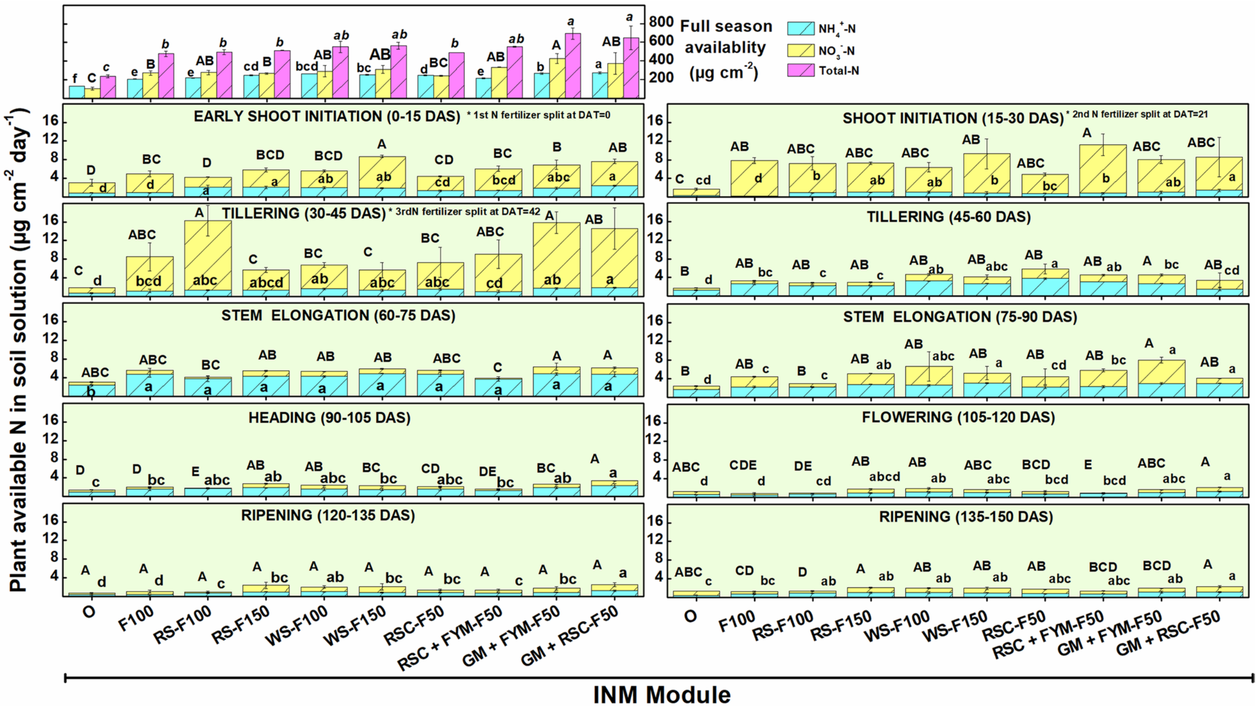


Fig. 2 Full season and stage-wise differences in plant available NH_4^+-N, NO_3^--N, and total-N in soil solution during the wheat growing season (average for two cropping years). Lowercase letters denote differences for NH_4^+-N, capital letters for NO_3^--N, and lowercase italic letters for total-N. Error bars denote ± 1SD. Treatments with the same letters are not different significantly ($P < 0.05$). Refer to this figure for a description of treatments

straw compost with only 50% fertilizer application (RSC-F50: $R^2 = 0.86$, $P = 0.02$) as well as for absolute control (O: $R^2 = 0.84$, $P = 0.02$) treatments (Fig. 4). For wheat grain yield, an increasing trend was noted for the wheat stubble based management (WS-F100 and WS-F150) indicating the residual impacts of N mineralized from stubble incorporated in previous wheat seasons. Significantly higher yields were obtained in both rice and wheat for green manuring with compost/manure-based management (GM + RSC-F100 and GM + FYM-F100) but it was also similar to crop residue (RS, WS) and sole fertilizer (F100) based management in wheat. Similar trends were noted for averaged straw yields (Fig. 5). For straw yield, over the years, increasing trends were visible for wheat-stubble-based management (WS-F100 and WS-F150) for both rice and wheat straw yields. Rice-stubble-based management with increased fertilizer application (RS-F150) also showed increasing trends for rice straw yields, while RSC-F50 showed slight yet significant decreasing trends.

For both rice and wheat crops, WS-F100 showed increasing trends in NUE_{diff} as well as NUE_{bal} (Fig. 6). For rice crop, rice-stubble-based integration (RS-F100 and RS-F150), RSC-F50 and GM + RSC-F50 also showed significantly increasing trends in N use efficiency while for wheat WS-F150 also showed significantly increasing N use efficiency with years (Fig. 6). The averaged value of SNMI for 6 years of different management modules indicated the significantly higher performance for rice straw compost based integrated management (RSC-F50 and RSC + FYM-F50), for both rice and wheat crops. In rice crop, the most sustainable N management was provided by RSC-based integration (RSC-F50, PS + FYM-F50) followed by green manuring with RSC/FYM-based integration (GM + RSC-F100, GM + FYM-F100) (Fig. 7). The in situ residue incorporation based management provided less sustainable N management option compared to F100. For wheat, both wheat-stubble-based integrations (WS-F100 and WS-F150) showed increasing trends in NUE over the years (Fig. 8).

The correlation analysis between several soil parameters, yield, N use efficiency parameters (NUE_{diff}, NUE_{bal}, N yield, and SNMI), and N mineralization characteristics at different critical stages of rice (Table 2) and wheat (Table 3) was analyzed. The analysis indicated that the soil pH ($r = -0.64^{**}$), soil organic C ($r = 0.88^{***}$), and soil N availability at all stages except at 60–75 DAT ($r = 0.68^{**}$, 0.74^{**}, 0.66^{**}, 0.77^{***}, 0.71^{**}, and 0.88^{***} at 0–15, 15–30, 30–45, 45–60, 75–90, and 75–90 DAT, respectively) were all highly significantly correlated with rice grain yield. The asterisks (*, **, ***) indicate a significant difference between management at $P < 0.05$,

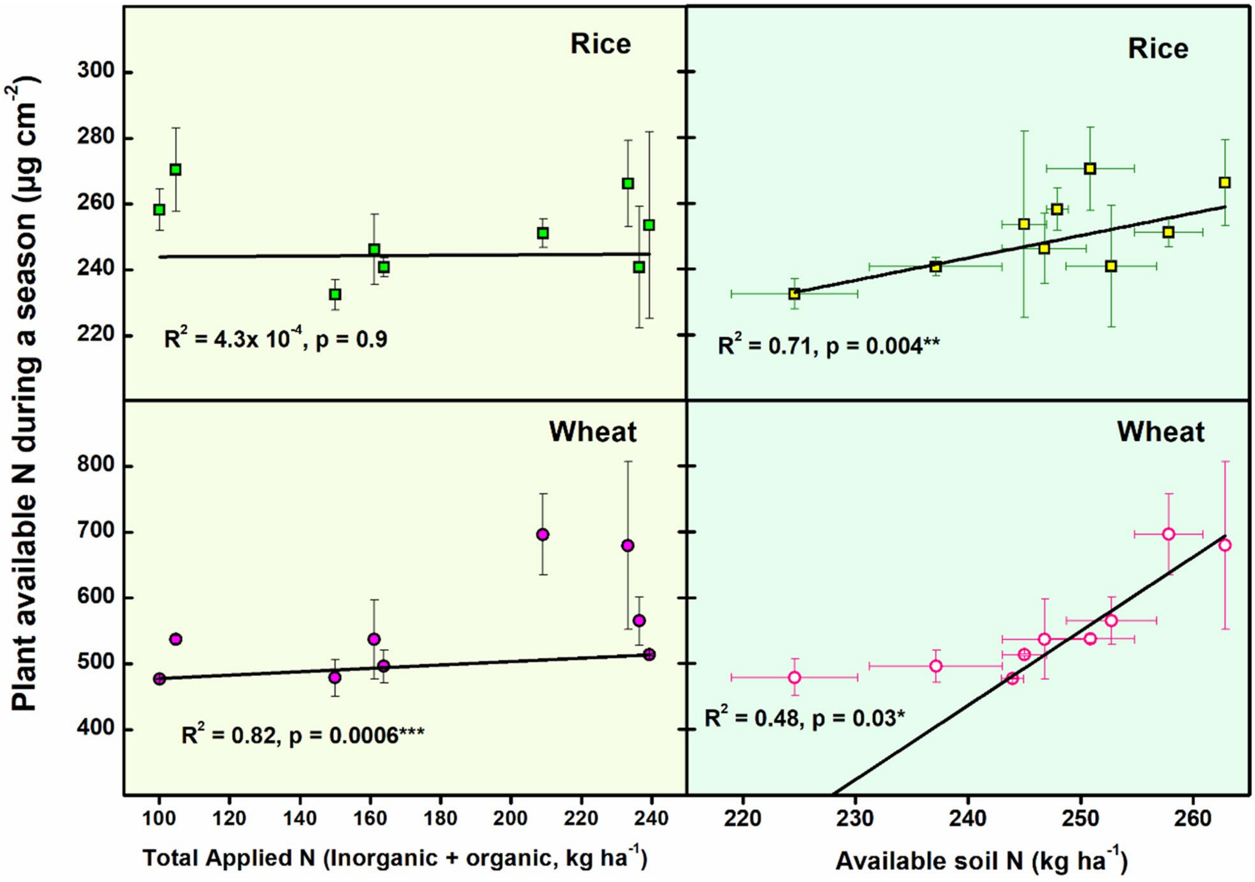


Fig. 3 Relationship between nitrogen (N) availability in soil solution with total applied N (including both sources, organic and inorganic) and with available soil N during rice and wheat growing season. Error bars denote ± 1 SD. Refer to Fig. 2 for a description of treatments

$P<0.01$, and $P<0.001$, respectively. However, all N use efficiency parameters (NUE_{diff}, NUE_{bal}, N yield, and SNMI) significantly correlated to the N mineralization only at 0–15 ($r=0.71^{**}$) and 15–30 DAT ($r=0.71^{**}$). Soil organic C also correlated well to IER-based soil N availability at most stages ($r=0.65^{**}$, 0.73^{**}, 0.62^{*}, 0.81^{***}, and 0.65^{**} at 15–30, 30–45, 45–60, 75–90, and 75–190 DAT, respectively). Similarly for the wheat crop as well, the soil pH ($r=-\ 0.76^{**}$), soil organic C ($r=0.68^{**}$), and soil N availability at most stages ($r=0.72^{**}$, 0.77^{***}, 0.58^{*}, 0.79^{***}, 0.58^{*}, 0.69^{**}, and 0.67^{**} at 0–15, 15–30, 30–45, 60–75, 75–90, 90–105, and 120–135 DAT, respectively) were all highly significantly correlated with rice grain yield (Table 3). The N use efficiency parameters (NUE_{diff}, NUE_{bal}, N yield, and SNMI) significantly correlated to the N mineralization only at 45–60 DAT ($r=0.66^{**}$). Besides soil organic C, soil pH also seems to have a good correlation with N availability in the case of wheat. Soil organic C also correlated well to IER-based soil N availability at most stages ($r=0.75^{**}$, 0.79^{***}, 0.66^{*}, and 0.65^{**} at 0–15, 60–75, and 120–135 DAT, respectively).

Discussion

The rice–wheat cropping system's seasonal soil transition from aerobic to anaerobic and back is its most distinctive feature. Rice–wheat cultivation necessitates a significant amount of labor and energy and is becoming less lucrative owing to resource constraints, particularly expensive fertilizers (Bhatt et al. 2016). The fertilizer management is particularly skewed towards highly subsidized N fertilizers leading to their indiscriminate N application and low use efficiency without a significant gain in productivity. Burning of crop residues by farmers (particularly rice straw but also other crops recently) has aggravated pollution problems and also wastes precious nutrient resources. Combining rice and wheat yields a lot of residues (8–10 t ha^{-1} yr^{-1}). Rice straw's high silica concentration deters farmers from feeding it to cattle. In recent years, wheat straw is also being burned, mainly in the western IGP. Due to constraints, farmers have not completely adopted many technology innovations and diversification options to address diminishing system production and residue issues. Integrating residues into

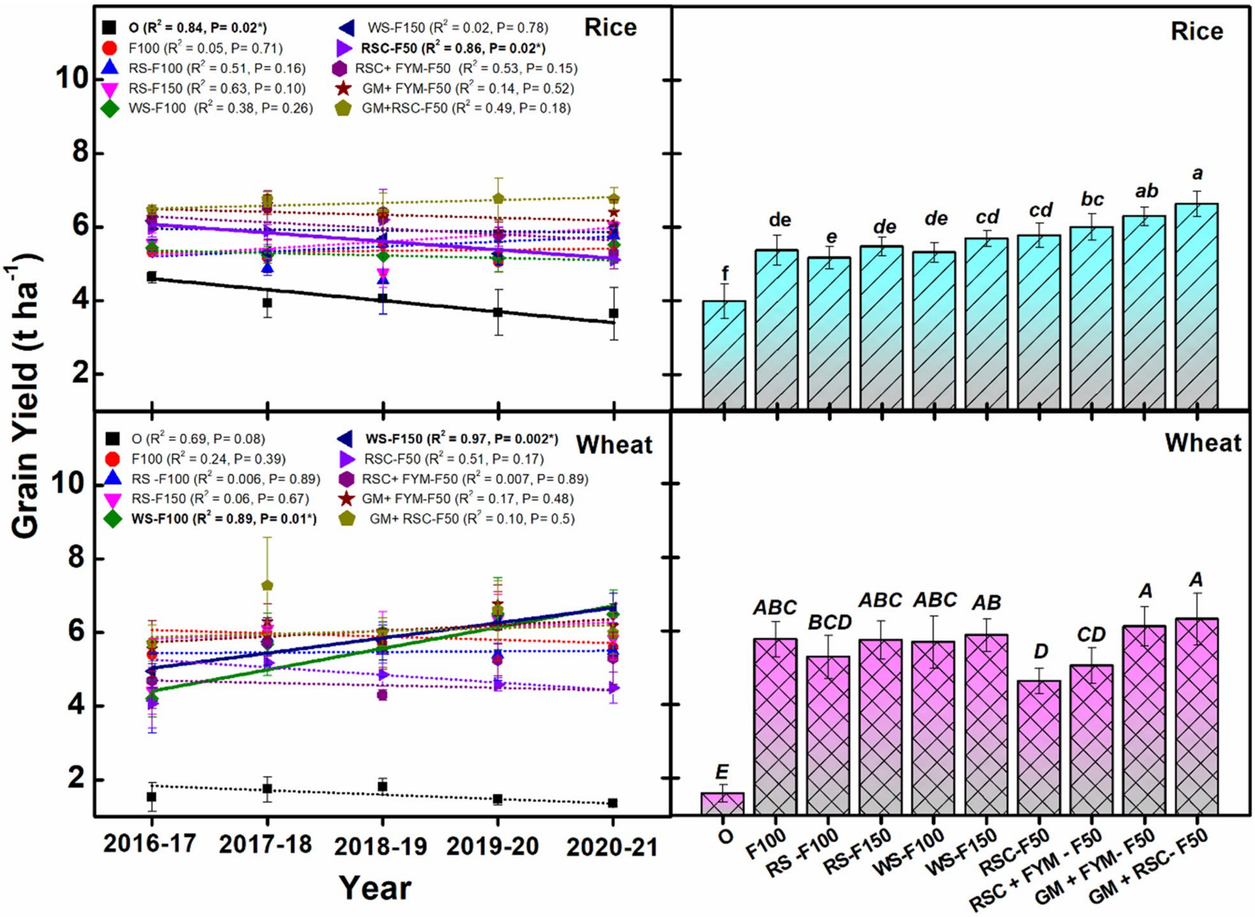


Fig. 4 Five years (2016–2021) average as well as trends in grain yields (t ha^{-1}) of rice and wheat crops under different nutrient management modules. Error bars denote ± 1SD. Treatments with the same letters are not different significantly ($P < 0.05$). Refer to Fig. 2 for a description of treatments

crop nutrient management can take care of some of these issues.

Previous studies suggest that if crop residue incorporation is needed to address critical issues like residue burning, then cutting down the rate of inorganic fertilizer application may not be a good idea (Bhardwaj et al. 2020, 2021b). Instead, this kind of management should be supplemented with quickly decomposable inputs (like compost, farmyard manure, or green manuring) or with approved quantities of fertilizers to speed the breakdown of resistant organic materials (like rice stubble). The eight INM modules for integration of rice–wheat crop residue in nutrient management of this cropping system indicated that productivity gains can be achieved while saving chemical fertilizers, and N use efficiency can also be increased at the same time by careful combinations of feasible options. While the green manuring along with the rice-straw-compost (RSC) based module provided maximum productivity gain, and RSC-based modules provided maximum N use efficiency, in situ rice–wheat stubble incorporation based INM modules (RS-F150 and WS-F100) also yielded similar to F100 with better sustainable N management index (SNMI) during the wheat season, indicating that all integrated management options are more sustainable. Over five years, rice straw compost with 50% fertilizer (RSC-F50) had a minor decline in grain output, while cereal-based INM modules (WS-F100; WS-F150) had an upward trend in wheat grain yield. However, the experiment conducted by Huang et al. (2023) to study the rice crop response under different combinations of paddy straw compost with chemical fertilizer reported that 10% replacement of chemical fertilizer with paddy straw compost resulted in higher rice yield and also increased microbial diversity compared to 100% chemical fertilizer. Bhatt et al. (2023) also reported significantly higher sugarcane yield and quality parameters under 25% higher than the recommended dose of fertilizer + 5.5 quintal paddy straw compost ha^{-1} in sandy loam N-deficient soils

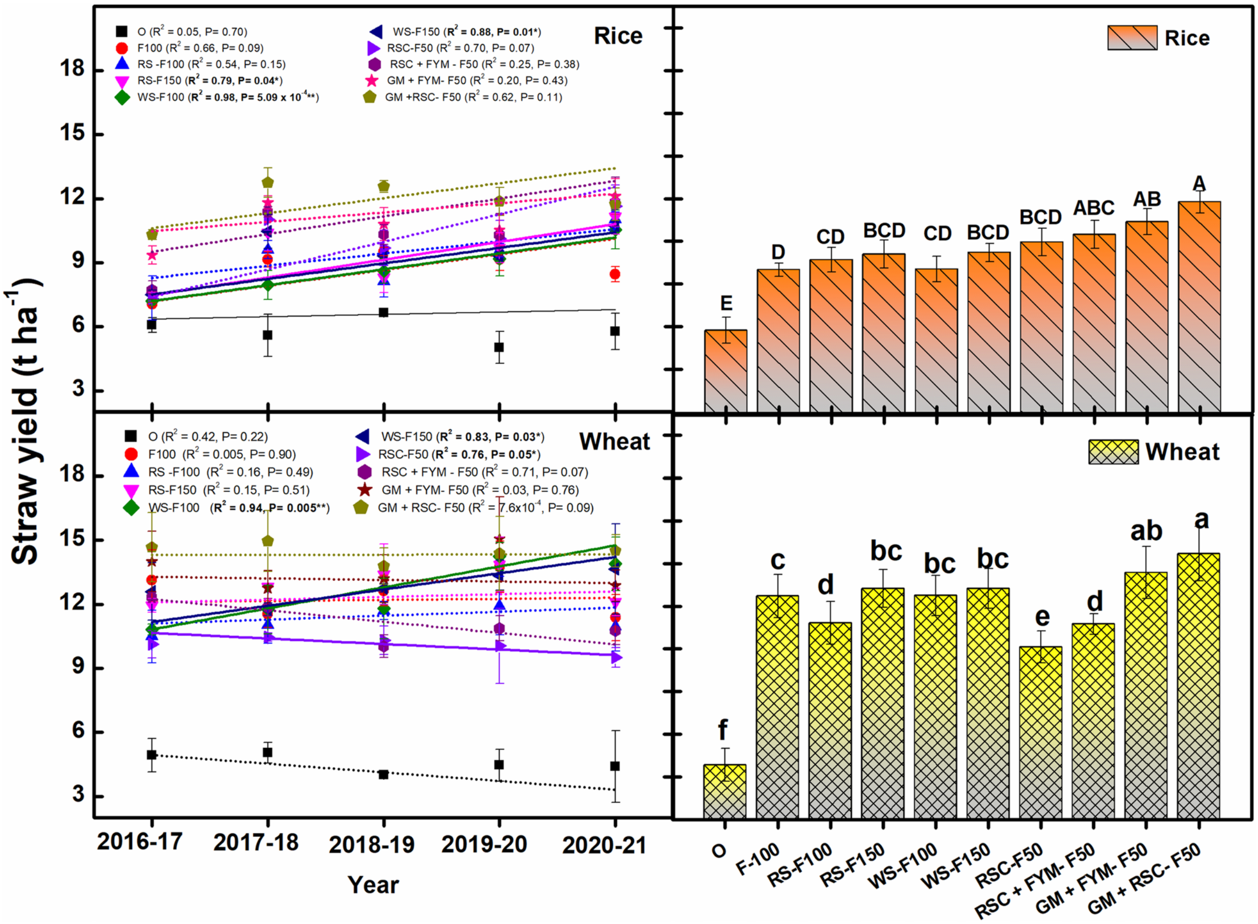


Fig. 5 Five years (2016–2021) average as well as trends in straw yields (t ha^{-1}) of rice and wheat under different nutrient management modules. Error bars denote ± 1 SD. Treatments with the same letters are not different significantly ($P < 0.05$). Refer to Fig. 2 for a description of treatments

of Kapurthala district of Punjab, India. On the other hand, Byeon et al. (2023) revealed that soil organic carbon was highest in the NPK + rice straw compost at 30 t ha^{-1} treatment compared to NPK alone treatment. However, with an increase in compost application, the exchangeable K and Ca of the soil increased, and the exchangeable K and Ca were higher than the optimum range in NPK + rice straw compost at 22.5 t ha^{-1} and NPK + rice straw compost at 30 t ha^{-1} treatments. Sharma et al. (2023) revealed that rice straw retention along with green manuring significantly increased rice and wheat yields compared to conventional tillage without green manuring. Irfan et al. (2023) observed that the sole application of recommended dose of fertilizer (RDF100) showed the lowest recovery efficiency of NPK while press mud (PM) + RDF50 revealed a higher recovery efficiency of NPK. The results suggested that INM could be a sustainable approach to enhance wheat productivity and nutrient efficiency in alkaline calcareous soils. In addition, PM along with RDF100 NPK fertilizers proved superior in improving root traits and nutrient accumulation thereby increasing wheat grain yield. Paramesh et al. (2023) reported that the crop yield was significantly increased with the adoption of INM over conventional nutrient management. With the integration of organic manure and residue retention in INM, there was a significant improvement in soil aggregates and microbiota. Nutrient use efficiency and net mineralized N correlated positively and significantly with rice and wheat grain yield. The influence of N mineralization and availability at different critical stages has been demonstrated in many studies (Bhardwaj et al. 2019; Ali et al. 2020). Consistent N release throughout the growing season is one of the advantages of including organics in nutrition management (Bhardwaj et al. 2020). Wheat residue retention in a rice–wheat cropping system promotes productivity and soil health by enhancing soil aggregation and SOC sequestration (Choudhury et al. 2014). In a rice–wheat cycle, rice and wheat straw may increase SOC, soil quality, and production (Zhu et al. 2015; Bhardwaj et al. 2019).

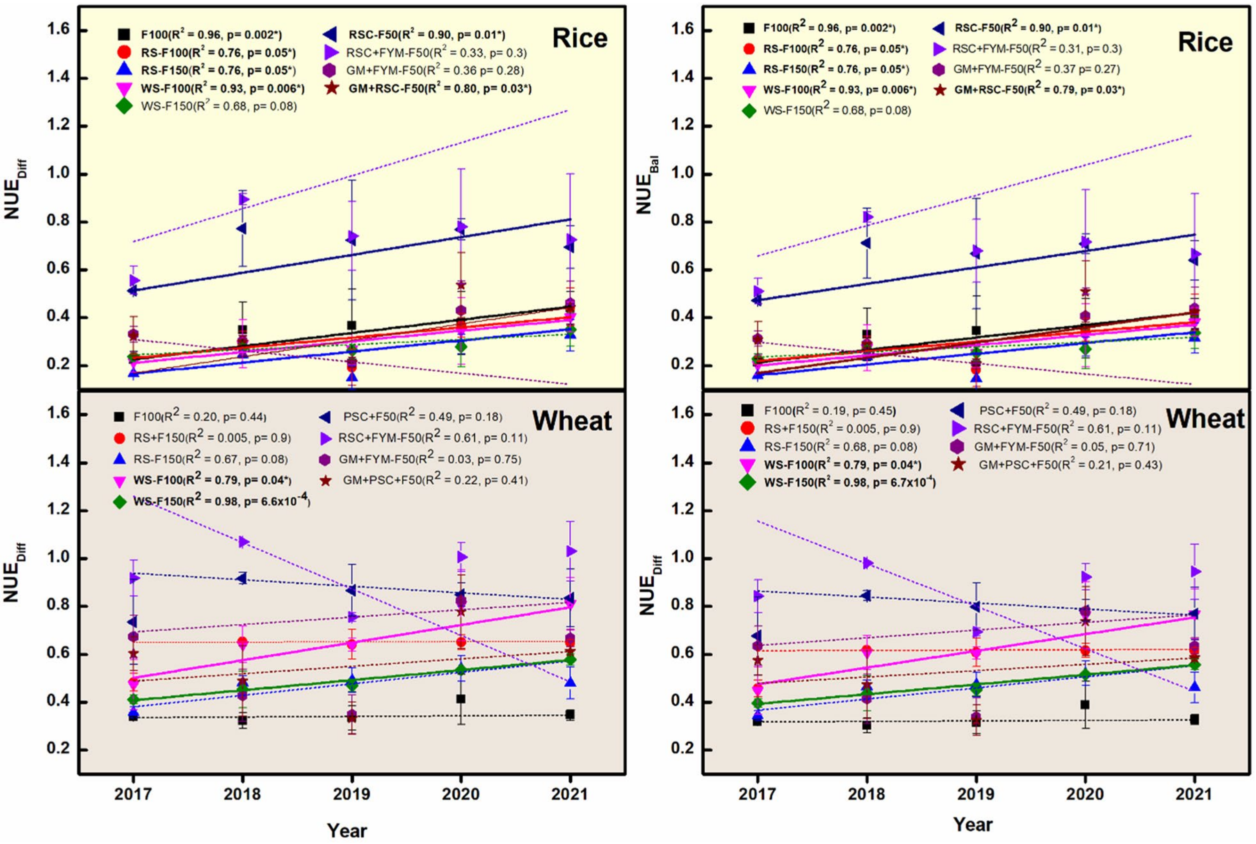


Fig. 6 Trends in nitrogen use efficiency (both NUE_{diff} and NUE_{bal}) for rice and wheat during 5 years (2016–2021) under different integrated nutrient management modules. Error bars denote ± 1SD. Refer to Fig. 2 for a description of treatments

To maximize the rice–wheat system's yield potential and sustainability, crop responsiveness to N application and N use efficiency must be assessed. Nitrogen is the most necessary plant nutrient, severely restricts crop growth, and N deficiency lowers agricultural yield significantly (Bhardwaj et al. 2020). Developing innovative soil and plant management strategies and understanding the underlying mechanisms that improve N efficiency is vital for achieving sustainability in agricultural production systems. Recent crop-production system NUE studies have stressed the need for increased synchronization between crop N demand and N supply from all sources throughout the growing season (Bhardwaj et al. 2021b). Ion exchange resin (IER) membranes in direct contact with soil might measure N fluxes into soil solution dynamically (net N mineralization). Since plants take up ionic forms of nutrients from the soil solution, these assessments are more relevant than extractant-based soil nutrient assessments. The method measures plant available N and soil N supply capacity accurately (Qian and Schoenau 2005; Nyiraneza and Snapp 2007; McSwiney et al. 2010). All management had unique NH_4^+-N and NO_3^--N availability dynamics. The slow yet constant release is essential to match plant needs throughout the season. 100% inorganic fertilizers straight away loose here due to their quick dissolution characteristics, but crop residues alone may also not meet plant demand at critical stages.

For rice crop, at all stages, the N mineralization and availability, as determined with the IER method revealed a significantly better scenario with integrated management. Particularly in the modules where RSC was combined with either FYM or GM, the availability was significant to meet the crop requirement even with the reduced (50%) rate of chemical fertilizers. Rice–wheat crop residues alone may not meet the critical N content requirement of 1.8–2.0% which is needed by the microbes and therefore it may lead to N immobilization (Snapp et al. 1998). Rice straw compost (RSC) and FYM had N concentrations of 0.81 and 0.56% (dry weight basis), respectively, and therefore these may also be not able to cross the critical limits when used alone in the quantities tested (5 t ha^{-1}). Green manure crop (*Sesbania aculeata*) has a high concentration of 2.5% N and has been noticed to provide a good option for utilizing a fallow 45 days period after wheat season and incorporation of its green

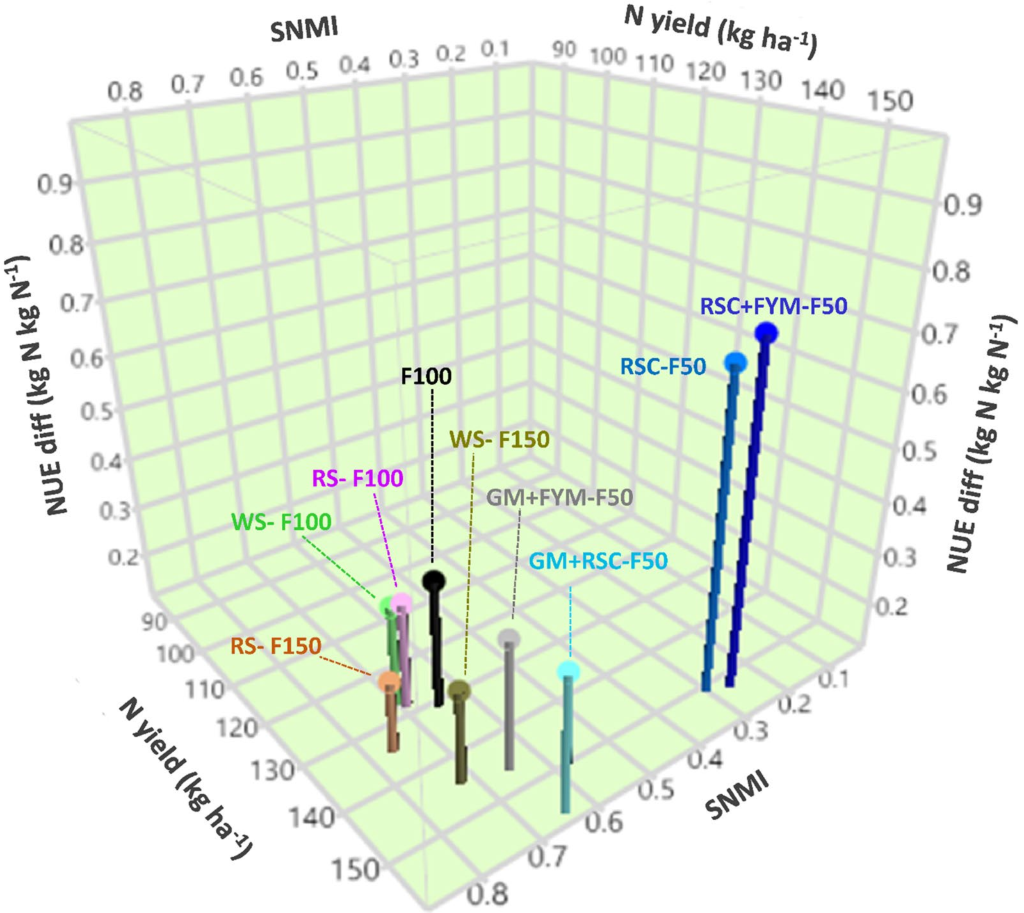


Fig. 7 Five years (2016–2021) averages for sustainable nitrogen management index (SNMI), nitrogen use efficiency (NUE$_{diff}$), and N yield (kg N ha^{-1} season^{-1}) for rice under different integrated nutrient management modules

matter at the time of rice transplanting (Bhardwaj et al. 2020, 2021a). A combination of these options can provide enough N to meet the needs of crops for high N at critical stages, even with reduced rates of fertilizers. The INM modules with the combination of RSC/FYM with GM particularly showed its impact during the following wheat season (after incorporation in rice season) where almost double availability at many critical stages (shoot initiation and tillering) could be noted, compared to F100 (100% of recommended N through chemical fertilizers). Plants can rapidly absorb and use the nitrogen in the soil that has been amended with compost or legume residue because of the latter's narrower C/N ratio and higher N concentration (Bhardwaj et al. 2020). With an annual release as high as 5–10% per year, the effects have been observed to continue for extended periods, even years, benefiting future crops (Fillery 2001; Peoples et al. 2009; Khakbazan et al. 2014; St. Luce et al. 2015). The N mineralization synchronization with the crop demand at critical stages can help achieve better NUE. The INM modules tested in the study provided immense benefits in terms of NUE and SNMI, especially in wheat crop. Previous studies have indicated lesser use efficiency in wheat crop compared to rice, under business as usual (Bhardwaj et al. 2022). A similar study by Dwivedi et al. (2016) found that increasing NUE with INM has the potential to boost rice–wheat system production.

The correlations between soil carbon (C) and N mineralization at different stages of both rice and wheat crops suggested that organic C improvement through the integration of organic sources of nutrients has an influence on the N release characteristics and therefore should contribute to NUE. Organic C had significant relations with grain yield, straw yield, and N yield (amount of N harvested) as well. Studies have indicated that soil labile (active pool) organic C fractions boost NUE, especially for wheat crops. Active/labile soil C fractions affect fertilizer profitability, as recently discovered (Chamberlin

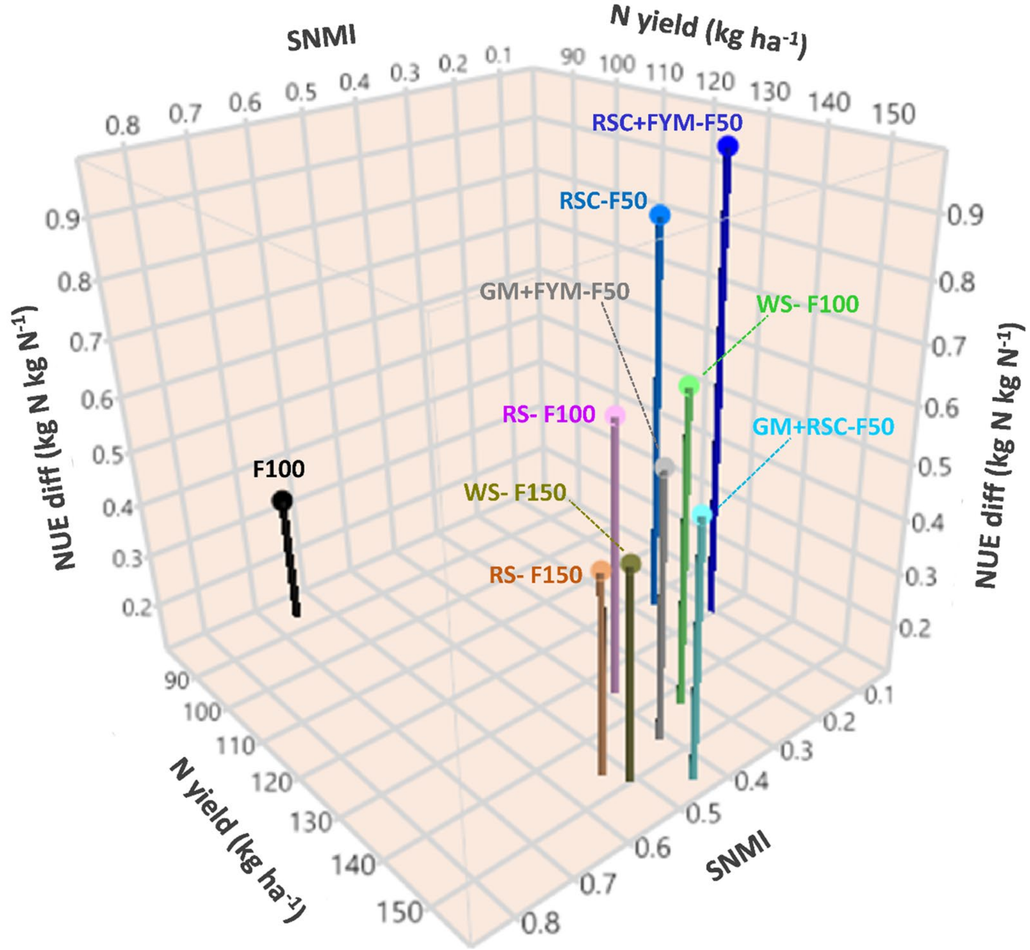
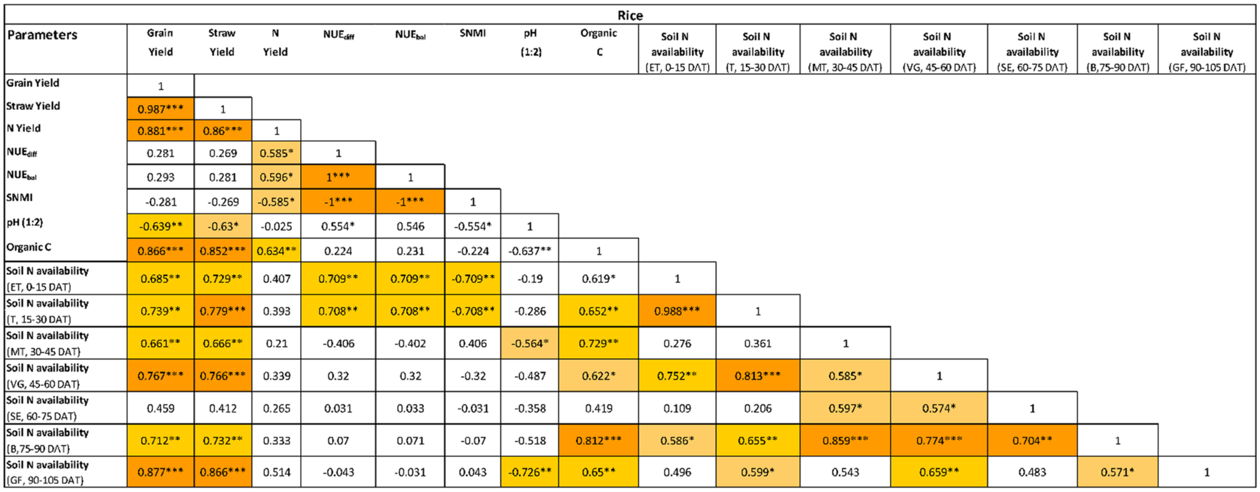


Fig. 8 Five years (2016–2021) averages for sustainable nitrogen management index (SNMI), nitrogen use efficiency (NUE_{diff}), and N yield (kg N ha^{-1} $season^{-1}$) for wheat under different integrated nutrient management modules

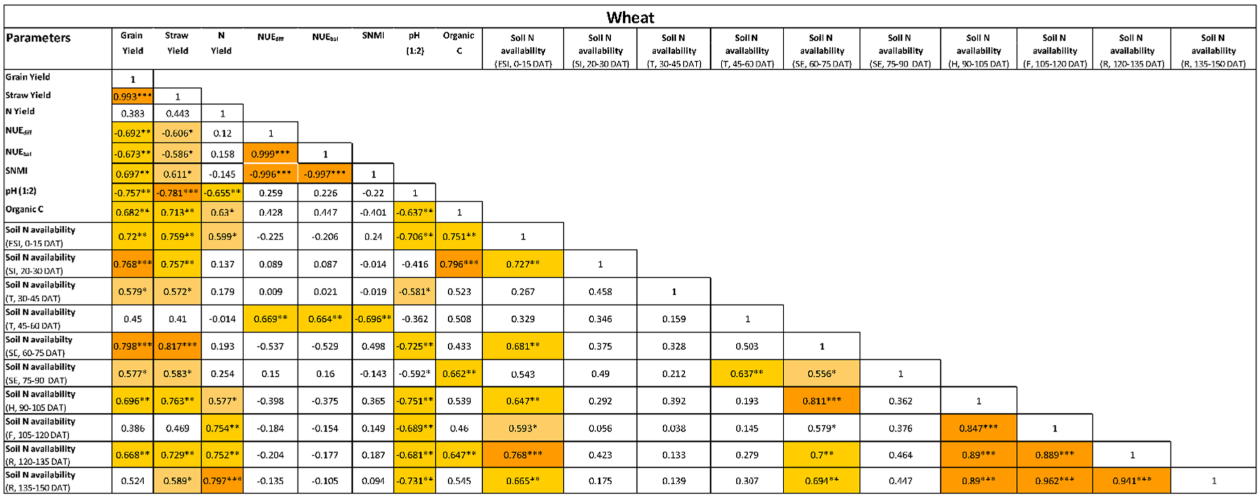
Table 2 Correlation matrix of soil N availability at different time intervals and chemical properties with grain yield, and nitrogen use efficiency parameters (N use efficiency-NUE, sustainable N management index-SNMI, N-yield) recorded under different integrated nutrient management modules in rice crop



	Rice														
Parameters	Grain Yield	Straw Yield	N Yield	NUE_{diff}	NUE_{bal}	SNMI	pH (1:2)	Organic C	Soil N availability (ET, 0-15 DAT)	Soil N availability (T, 15-30 DAT)	Soil N availability (MT, 30-45 DAT)	Soil N availability (VG, 45-60 DAT)	Soil N availability (SE, 60-75 DAT)	Soil N availability (B,75-90 DAT)	Soil N availability (GF, 90-105 DAT)
Grain Yield	1														
Straw Yield	0.987***	1													
N Yield	0.881***	0.86***	1												
NUE_{diff}	0.281	0.269	0.585*	1											
NUE_{bal}	0.293	0.281	0.596*	1***	1										
SNMI	-0.281	-0.269	-0.585*	-1***	-1***	1									
pH (1:2)	-0.639**	-0.63*	-0.025	0.554*	0.546	-0.554*	1								
Organic C	0.866***	0.852***	0.634**	0.224	0.231	-0.224	-0.637**	1							
Soil N availability (ET, 0-15 DAT)	0.685**	0.729**	0.407	0.709**	0.709**	-0.709**	-0.19	0.619*	1						
Soil N availability (T, 15-30 DAT)	0.739**	0.779***	0.393	0.708**	0.708**	-0.708**	-0.286	0.652**	0.988***	1					
Soil N availability (MT, 30-45 DAT)	0.661**	0.666**	0.21	-0.406	-0.402	0.406	-0.564*	0.729**	0.276	0.361	1				
Soil N availability (VG, 45-60 DAT)	0.767***	0.766***	0.339	0.32	0.32	-0.32	-0.487	0.622*	0.752**	0.813***	0.585*	1			
Soil N availability (SE, 60-75 DAT)	0.459	0.412	0.265	0.031	0.033	-0.031	-0.358	0.419	0.109	0.206	0.597*	0.574*	1		
Soil N availability (B,75-90 DAT)	0.712**	0.732**	0.333	0.07	0.071	-0.07	-0.518	0.812***	0.586*	0.655**	0.859***	0.774***	0.704**	1	
Soil N availability (GF, 90-105 DAT)	0.877***	0.866***	0.514	-0.043	-0.031	0.043	-0.726**	0.65**	0.496	0.599*	0.543	0.659**	0.483	0.571*	1

(* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$)

Table 3 Correlation matrix of soil N availability at different time intervals and chemical properties with grain yield, and nitrogen use efficiency parameters (N use efficiency-NUE, sustainable N management index-SNMI, N-yield) recorded under different integrated nutrient management modules in wheat crop



	Wheat																	
Parameters	**Grain Yield**	**Straw Yield**	**N Yield**	**NUE_{diff}**	**NUE_{bal}**	**SNMI**	**pH (1:2)**	**Organic C**	**Soil N availability (ESI, 0-15 DAT)**	**Soil N availability (SI, 20-30 DAT)**	**Soil N availability (T, 30-45 DAT)**	**Soil N availability (T, 45-60 DAT)**	**Soil N availability (SE, 60-75 DAT)**	**Soil N availability (SE, 75-90 DAT)**	**Soil N availability (H, 90-105 DAT)**	**Soil N availability (F, 105-120 DAT)**	**Soil N availability (R, 120-135 DAT)**	**Soil N availability (R, 135-150 DAT)**
Grain Yield	1																	
Straw Yield	0.993***	1																
N Yield	0.383	0.443	1															
NUE_{diff}	-0.692**	-0.606*	0.12	1														
NUE_{bal}	-0.673**	-0.586*	0.158	0.999***	1													
SNMI	0.697**	0.611*	-0.145	-0.996***	-0.997***	1												
pH (1:2)	-0.757**	-0.781***	-0.655**	0.259	0.226	-0.22	1											
Organic C	0.682**	0.713**	0.63*	0.428	0.447	-0.401	-0.637**	1										
Soil N availability (ESI, 0-15 DAT)	0.72**	0.759**	0.599*	-0.225	-0.206	0.24	-0.706**	0.751**	1									
Soil N availability (SI, 20-30 DAT)	0.768***	0.757**	0.137	0.089	0.087	-0.014	-0.416	0.796***	0.727**	1								
Soil N availability (T, 30-45 DAT)	0.579*	0.572*	0.179	0.009	0.021	-0.019	-0.581*	0.523	0.267	0.458	1							
Soil N availability (T, 45-60 DAT)	0.45	0.41	-0.014	0.669**	0.664**	-0.696**	-0.362	0.508	0.329	0.346	0.159	1						
Soil N availabilty (SE, 60-75 DAT)	0.798***	0.817***	0.193	-0.537	-0.529	0.498	-0.725**	0.433	0.681**	0.375	0.328	0.503	1					
Soil N availability (SE, 75-90 DAT)	0.577*	0.583*	0.254	0.15	0.16	-0.143	-0.592*	0.662**	0.543	0.49	0.212	0.637**	0.556*	1				
Soil N availability (H, 90-105 DAT)	0.696**	0.763**	0.577*	-0.398	-0.375	0.365	-0.751**	0.539	0.647**	0.292	0.392	0.193	0.811***	0.362	1			
Soil N availability (F, 105-120 DAT)	0.386	0.469	0.754**	-0.184	-0.154	0.149	-0.689**	0.46	0.593*	0.056	0.038	0.145	0.579*	0.376	0.847***	1		
Soil N availability (R, 120-135 DAT)	0.668**	0.729**	0.752**	-0.204	-0.177	0.187	-0.681**	0.647**	0.768***	0.423	0.133	0.279	0.7**	0.464	0.89***	0.889***	1	
Soil N availability (R, 135-150 DAT)	0.524	0.589*	0.797***	-0.135	-0.105	0.094	-0.731**	0.545	0.665**	0.175	0.139	0.307	0.694**	0.447	0.89***	0.962***	0.941***	1

(* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$)

et al. 2021). Active soil C fractions are more strongly associated with soil functions such as nitrogen cycling, soil aggregation, and soil quality (Benbi et al. 2015). Bhardwaj et al. (2019) also found that soil C sequestration boosted crop resilience. Carbon mineralization, like N mineralization, strongly affects plant growth and output (Culman et al. 2013). Many studies have shown that N mineralization and C mineralization are linked, which improves crop performance (Vahdat et al. 2010; Sherrod et al. 2012; Culman et al. 2013). Organic C inputs and their effect on the moderation of pH also play an important role in NUE as evident from a significant correlation of these parameters with N mineralization and availability during different stages (Bhardwaj et al. 2019, 2022). Iqbal et al. (2019) studied the combined effects of cattle manure, poultry manure, and chemical fertilizer on soil properties, growth, and grain yield of rice crop and reported that the integration of 30% N from cattle manure, poultry manure with 70% N from conventional urea had significantly higher grain yield. Improvement in grain yield and NUE was associated with improved soil properties, viz: bulk density, soil porosity, soil organic carbon, and total N. Ranjan et al. (2023) reported that the application of organic manures along with chemical fertilizers reduced bulk density and soil pH. Soil organic carbon and available soil nutrients (N, P, and K) were found to be maximized in INM treatment as compared to control. Moreover, a highly positive and significant correlation was also witnessed between soil organic carbon and available soil N, P, and K.

Conclusion

The ability of an agroecosystem to maximize its nitrogen use efficiency (NUE) is dependent on the degree to which agronomic management influences changes in soil conditions that govern N transformations, which in turn govern N availability to plants and the rate at which those plants grow. Enhancing NUE in rice–wheat cropping envisages targeting soil conditions, inundated with water during the rice season to create anaerobic conditions and tilled dry during the wheat season to reverse to aerobic conditions. Green manuring with *Sesbania aculeata* augmented with rice straw compost or farmyard manure at 5 t ha^{-1} afforded cutting down inorganic fertilizers to 50%. These INM modules would permit a 50% reduction in the use of chemical fertilizers with substantial gains in productivity. These are promising INM modules for adoption by farmers in the north-western IGP to productively use crop residues and improve crop yield. However, the sole use of RSC or FYM or a combination may not suffice to afford cutting down fertilizer use due to evident adverse effects on yield, especially in wheat. Meeting the critical N levels to avoid immobilization while increasing NUE seems to play a crucial role in selecting practices with an optimum balance of productivity and NUE. Composting rice straw, which otherwise is widely burnt, proved a useful nitrogen source and a vital component of INM. Changes in the N mineralization and availability, organic matter induced changes in soil pH and soil redox during rice, and soil carbon during wheat season related best to the yield responses. Waste rice straw composting at community scale and its application as nutrient source can help achieve sustainable nitrogen management in the agroecosystems of IGP.

Abbreviations

IGP	Indo-Gangetic Plain
INM	Integrated nutrient management
N	Nitrogen
GHG	Greenhouse gas emissions
P	Phosphorus
K	Potassium
DAP	Diammonium phosphate
MOP	Muriate of potash
IER	Ion exchange resin
RS	Rice straw
WS	Wheat straw
RSC	Rice straw compost
FYM	Farmyard manure
GM	Green manure
NUE	Nitrogen use efficiency
NUEdiff	NUE with nitrogen difference approach
NUEbal	NUE with nitrogen balance approach
SNMI	Sustainable nitrogen management index
DAT	Days after transplanting
RDF	Recommended dose of fertilizer

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Author contributions
Conceptualization of the experiments was done by AKB, NB, SKC, and DKS. Data analysis, preparing visualizations, and writing the original draft were done by AKB, KM, MR, and UKM. AS and RKY helped with sample and statistical analyses. All authors contributed to the writing of the manuscript and reviewed the draft. All authors approved the final manuscript. The authors acknowledge the contributions of support staff in collecting agronomic data and helping in analyzing test samples of soil and plants.

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Availability of data and materials
All relevant data used and/or analyzed during the current study are either included in the main text of the paper from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare no competing interests that might have been perceived as having influenced the work presented in this publication, either financially or otherwise.

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