



Enhancing rice-wheat productivity and nitrogen use efficiency through integrated nutrient and crop residue management

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ABSTRACT

The rice-wheat system is the predominant cropping sequence in the Indo-Gangetic Plain (IGP), where crop residue burning and rising fertilizer costs are major concerns. Integrated nutrient management (INM) can help address both issues by recycling residues and reducing dependence on chemical fertilizers. A field experiment was conducted to evaluate integrated nutrient management (INM) and in situ crop residue retention in the rice-wheat cropping system. An INM experiment was initiated in 2015 at the Central Soil Salinity Research Institute (CSSRI), Karnal, to evaluate the effectiveness of different integrated nutrient management (INM) treatments. The treatments comprised *in situ* retention and incorporation of 1/3rd rice stubble with 100% (RS-F100) or 150% (RS-F150) recommended fertilizers, and 1/3rd wheat stubble with 100% (WS-F100) or 150% (WS-F150) recommended fertilizers; paddy straw compost @ 5 t ha⁻¹ with 50% recommended fertilizer (PSC-F50); PSC @ 5 t ha⁻¹ + FYM @ 5 t ha⁻¹ with 50% recommended fertilizer (PSC+FYM-F50); green manuring with *Sesbania aculeata* + FYM @ 5 t ha⁻¹ with 50% recommended fertilizer (GM+FYM-F50); and green manuring with *Sesbania aculeata* + PSC @ 5 t ha⁻¹ with 50% recommended fertilizer (GM+PSC-F50). These were compared with 100% recommended fertilizer (F100) and an absolute control without fertilizer (O). Green manuring-based modules supplemented with farmyard manure (FYM) or pressmud compost (PSC) with 50% recommended fertilizer (F50) recorded the highest grain and straw yields in both crops. GM+PSC-F50 increased rice grain, rice straw, wheat grain and wheat straw yields by 23.3, 36.7, 9.5 and 15.8%, respectively, over F100. Green manuring-based treatments recorded superior fertilizer-N use efficiency (F-NUE), while PSC-based modules showed higher total-N use efficiency (T-NUE). Organic-input-based treatments also enhanced total net mineralized N, particularly in wheat, compared with F100. Temporal patterns of mineral N availability indicated greater NH₄⁺-N and total-N availability under integrated organic and inorganic nutrient management during critical crop-growth stages. Overall, green manuring combined with FYM or PSC and reduced fertilizer application improved crop productivity, NUE and soil N availability, offering a sustainable nutrient management strategy for the rice-wheat system.

Keywords: Integrated nutrient management, Nitrogen use efficiency, Nitrogen mineralization, Green manure, Paddy straw compost

INTRODUCTION

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) constitute one of the most important cereal-based cropping systems in South Asia and play a major role in food and nutritional security.

The rice-wheat system covers nearly 13.5 million hectares in South Asia, including about 10.3 million hectares in India, with a major concentration in the Indo-Gangetic Plain (IGP) (Brar *et al.*, 2013). Assured irrigation, high-yielding varieties, fertilizer inputs and favourable minimum support prices have

made rice-wheat one of the most productive and economically important cropping sequences. However, prolonged intensification has resulted in declining factor productivity, deterioration of soil fertility, depletion of soil organic carbon (SOC), groundwater scarcity and increasing production costs (Kumar and Sharma, 2020). These constraints highlight the need for nutrient management strategies that can sustain productivity while improving resource-use efficiency.

Continuous cultivation of rice and wheat is highly nutrient demanding and can progressively deplete soil nutrient reserves and disturb nutrient balance. Long-term reliance on chemical fertilizers without adequate nutrient recycling may adversely affect soil quality and contribute to secondary and micronutrient deficiencies (Nayak *et al.*, 2012; Alam *et al.*, 2013). In addition, intensive tillage and removal or burning of crop residues reduce opportunities for nutrient recycling and contribute to environmental degradation (Chaki *et al.*, 2021). Hence, maintaining crop productivity through improved nutrient cycling and efficient fertilizer utilization is essential for the long-term sustainability of the rice-wheat system.

Nitrogen (N) is a key nutrient determining crop growth and yield, but its inefficient management is a major constraint to sustainable cereal production. Excessive or poorly synchronized N application can result in substantial nutrient losses, increased production costs and environmental problems. Nitrogen-use efficiency (NUE) is therefore an important indicator of sustainable crop production because it reflects the effectiveness with which applied N is utilized for crop production while minimizing losses (Ding *et al.*, 2018). Fertilizer management, soil properties, crop demand and nutrient transformation processes collectively influence NUE (Dwivedi *et al.*, 2016). The contrasting soil environments of rice and wheat further complicate N management. Flooded rice cultivation promotes anaerobic conditions, whereas wheat is grown under aerobic conditions, resulting in substantial changes in soil N transformations. Ammonia volatilization can be an important N-loss pathway under flooded conditions, while nitrate leaching becomes more relevant under aerobic conditions (Duan *et al.*, 2007). Therefore, understanding soil N dynamics, particularly N mineralization, is important for explaining N availability and NUE in rice-wheat systems.

Integrated nutrient management (INM), based on the combined use of inorganic fertilizers and organic nutrient sources, offers a promising approach for improving nutrient cycling and sustaining crop productivity. The basic principle of INM is the efficient and judicious combination of mineral fertilizers with organic manures, crop residues, green manures and other nutrient sources to maintain soil fertility and crop productivity (Vashisht *et al.*, 2021). Mineral fertilizers provide readily available nutrients to meet immediate crop requirements, whereas organic materials release nutrients gradually and contribute organic matter to the soil (Bhardwaj *et al.*, 2020). Their integration can improve nutrient availability and synchronization with crop demand while reducing dependence on chemical fertilizers.

Rice-wheat cultivation also generates substantial quantities of crop residues that can serve as valuable sources of nutrients and carbon when appropriately recycled. Residue retention and FYM application can improve soil aggregation and enhance carbon and nitrogen sequestration (Brar *et al.*, 2013). Green manures and legumes additionally contribute biologically fixed N and improve nutrient availability and soil quality (Bhardwaj *et al.*, 2019). Continuous application of organic materials can modify soil N dynamics by influencing decomposition, microbial activity and N mineralization (Singh *et al.*, 2014). Thus, enhanced N mineralization under INM may improve mineral N availability and contribute to higher crop productivity and NUE. However, organic sources alone may not supply nutrients rapidly enough to meet crop requirements during periods of high demand because of their relatively slow nutrient release (Xinqiang *et al.*, 2014). Therefore, combining organic and inorganic nutrient sources is considered a more effective strategy for balancing immediate crop nutrient requirements with long-term soil fertility improvement (Liu *et al.*, 2009).

Despite considerable research on fertilizer management in rice-wheat systems, information on the long-term effects of INM on the interrelationship between crop yield, NUE and soil N mineralization remains limited. Most available studies on NUE are based on short-term experiments, whereas the effects of repeated organic inputs on soil N dynamics and crop nutrient-use efficiency may become more apparent over longer periods (Li *et al.*, 2012). Long-term evaluation is therefore necessary to identify nutrient management strategies capable of

Table 1. Experimental details of integrated nutrient management (INM) modules in rice wheat cropping system

S. No.	Treatment	Details
1	O	Absolute Control
2	F	100 % recommended fertilizer
3	RS 100	in situ 1/3rd rice stubble retention and incorporation + 100 % recommended fertilizers
4	RS 150	in situ 1/3rd rice stubble retention and incorporation + 150 % recommended fertilizers
5	WS 100	in situ 1/3rd wheat stubble retention and incorporation + 100 % recommended fertilizers
6	WS 150	in situ 1/3rd wheat stubble retention and incorporation + 150 % recommended fertilizers
7	PSC 50	Paddy straw compost @ 5 t ha ⁻¹ + only 50 % of recommended fertilizers
8	PSC+FYM 50	Paddy straw compost @ 5 t ha ⁻¹ + Farm-yard manure @ 5 t ha ⁻¹ + only 50 % of recommended fertilizers
9	GM-FYM 50	Green manuring with <i>Sesbania Aculeata</i> + Farm-yard manure @ 5 t ha ⁻¹ + only 50% of recommended fertilizers
10	GM-PSC 50	Green manuring with <i>Sesbania Aculeata</i> + paddy straw compost @ 5 t ha ⁻¹ + only 50% of recommended fertilizers

maintaining productivity while improving N cycling and fertilizer-use efficiency. Therefore, the present study was undertaken to evaluate five INM systems under a long-term rice-wheat cropping system, with particular emphasis on crop yield, NUE and soil N mineralization. The study aimed to assess whether integrated application of organic and inorganic nutrient sources could sustain crop productivity while enhancing N availability and improving NUE.

MATERIALS AND METHODS

Experimental site

A research experiment was initiated in 2015 on integrated nutrient management (INM) in the rice-wheat cropping system at ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, India, located at 29.43° N latitude and 76.58° E longitude. The soil of the experimental field was sandy loam in texture. At the initiation of the experiment, the soil (0-15 cm) recorded a pH of 8.7, bulk density of 1.43 Mg m⁻³, cation exchange capacity of 9.5 cmol_(p+) kg⁻¹, and organic carbon of 3.2 g kg⁻¹. A semi-arid sub-tropical climate prevailed at the experimental location, with very hot summers, cool winters, and an average annual rainfall of 750 mm.

Experimental layout and treatments details

The treatments comprised of a combinations of different organic and inorganic inputs to provide for nutrient requirements of rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) cropping system. The treatments were implemented in 9 m × 3.5 m plots area with three replications in completely

randomized plots. The experiment consisted of eight integrated nutrient management (INM) modules *viz*; RS-F100 = *in situ* rice stubble retention + 100% recommended fertilizers, RS-F150 = *in situ* rice stubble retention + 150% recommended fertilizers, WS-F100 = *in situ* wheat stubble retention + 100% recommended fertilizers, WS-F150 = *in situ* wheat stubble retention + 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, compared to F = 100% recommended fertilizer, and O = absolute control. The management schedule followed for different treatments (Table 1) were as follows:

- I. **O:** Rice followed by wheat was grown without any inorganic fertilizers or organic inputs
- II. **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.
- III. **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.
- IV. **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.
 - V. **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.
 - VI. **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.
 - VII. **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.
 - VIII. **PSC+FYM-F50:** Paddy straw compost (PSC@ 5 t ha⁻¹) and farmyard manure (FYM) at the rate of 5 t ha⁻¹ was 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.
 - IX. **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.
 - X. **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 in 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 sequence comprised rice (*Oryza sativa* L.) during July-October, followed by wheat (*Triticum aestivum* L.) during November-April. Rice (cv. Pusa 44) was transplanted in the first week of July at 20 cm row spacing after dry ploughing and puddling, with irrigation maintained according to crop requirements. Wheat (cv. HD 2967) was dry-tilled and sown in the second week of November, receiving 3-4 irrigations. The recommended fertilizer dose for both crops was 150, 26 and 42 kg ha⁻¹ N, P and K, respectively. Nitrogen was applied through urea in three equal splits, while P and K were applied basally through DAP and MOP. Rice and wheat were harvested in late October and early April, respectively.

Mineralized Nitrogen

Ion exchange resin (IER) membranes were used to measure nitrogen availability (net mineralization) in soils during the growing season. Membrane strips of 2.5cm by 10cm were cut out of big commercially available sheets (cation and anion separately) (General Electricals, Watertown, MA, USA). The strips were charged by dipping and stirring for 1.2

hours in 0.5 molL⁻¹HCl and then for 5 hours in 0.5 molL⁻¹NaHCO₃. Finally, deionized water was used to rinse them. The resin strips were inserted into vertical slots cut into the treated soils and securely closed, ensuring that the strips made contact with the soil. Both cation and anion strips were planted 5 cm apart, left in the soil for 15 days, and then replaced with new strips immediately after removing the old ones. This procedure was followed throughout the cropping season. The strips were rinsed with deionized water after being removed from the soil to eliminate any remaining soil. Both cation and anion strips were preserved and carried in a vial for extraction of NH₄⁺-N and NO₃⁻-N in the laboratory. For extraction, 70 mL of KCl (2 mol L⁻¹) was added to the vial with strips, which were agitated for 1 hour before being decanted into a scintillation vial. The extracts were tested for NH₄⁺-N and NO₃⁻-N using the Kjeltac 2200 (Foss, Hillerod, Denmark).

Nitrogen Use Efficiency (NUE)

The nitrogen use efficiency (NUE) was calculated as:

$$\text{NUE} = (Y - Y_0)/A \quad (i)$$

Where Y is the yield in the treatment plots, Y₀ is the yield in the control (no fertilizer application), and A is the amount of nitrogen applied, all in kg ha⁻¹. Nitrogen use efficiency was calculated based on the total N applied as inorganic fertilizers in each management and through inorganic fertilizers plus organic inputs.

Crop yield

The rice and wheat crop were plot-wise harvested and threshed to record grain and straw yields on a hectare basis.

Statistical analysis

Data were analyzed using ANOVA under a completely randomized design in JMP 9.0 (SAS Inc., Cary, USA), excluding the first year as a stabilization period. Treatment means were compared using Tukey's test at $P \leq 0.05$. Correlation analysis was performed to assess relationships among measured parameters. Graphs were prepared using Origin v.8.5 (OriginLab Corporation, Northampton, USA).

RESULTS

Green manuring-based INM modules supplemented with FYM or pressmud compost and reduced chemical fertilizer application (GM+FYM-F50 and GM+PSC-F50) recorded the highest grain and straw yields in both rice and wheat. GM+PSC-F50 increased rice grain, rice straw, wheat grain and wheat straw yields by 23.3, 36.7, 9.5 and 15.8%, respectively, over F100, while GM+FYM-F50 resulted in increases of 17.1, 26.0, 6.1 and 8.7%, respectively. The *in situ* residue retention treatments RS-F150 and WS-F100 performed statistically at par with F100 for both grain and straw yield. RS-F100 recorded a slight reduction in rice grain yield compared with F100, while maintaining comparable wheat yield (Table 2).

For both rice and wheat, fertilizer nitrogen use efficiency (F-NUE) differed significantly among nutrient management treatments (Table 3). In rice, the highest F-NUE was recorded with GM+PSC-F50, which was statistically at par with GM+FYM-F50, while both were significantly higher than F100. The F-NUE under PSC-F50 was also significantly

Table 2. Five years (2016-2021) average grain and straw yields (t ha⁻¹) of rice and wheat crop under different nutrient management modules. Refer to table 1 for a description of treatments. Treatments with same letters are not different significantly ($P \leq 0.05$)

Management	Rice		Wheat	
	Grain yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)	Grain yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)
O	3.49 ± 0.47f	5.82 ± 0.61e	1.48 ± 0.23e	4.56 ± 0.77f
F100	5.37 ± 0.41de	8.66 ± 0.30d	5.77 ± 0.48abc	12.48 ± 1.01c
RS-F100	5.17 ± 0.30e	9.13 ± 0.58cd	5.29 ± 0.59bcd	11.21 ± 1.00d
RS-F150	5.47 ± 0.25de	9.39 ± 0.65bcd	5.74 ± 0.52abc	12.82 ± 0.88bc
WS-F100	5.31 ± 0.27de	8.69 ± 0.60cd	5.69 ± 0.71abc	12.49 ± 0.94bc
WS-F150	5.68 ± 0.22cd	9.47 ± 0.42bcd	5.88 ± 0.44ab	12.82 ± 0.93bc
PSC-F50	5.77 ± 0.33cd	9.96 ± 0.65bcd	4.64 ± 0.35d	10.08 ± 0.74e
PSC+FYM-F50	6.00 ± 0.36bc	10.31 ± 0.66abc	5.06 ± 0.48cd	11.16 ± 0.48d
GM+FYM-F50	6.29 ± 0.25ab	10.91 ± 0.62ab	6.12 ± 0.53a	13.56 ± 1.21ab
GM+PSC-F50	6.62 ± 0.34a	11.84 ± 0.52a	6.32 ± 0.71a	14.45 ± 1.27a

Table 3. Five years (2016-2021) average nutrient use efficiency (NUE) of rice and wheat crop under different nutrient management modules. Refer to table 1 for a description of treatments. Treatments with same letters are not different significantly ($P \leq 0.05$)

Management	Rice		Wheat	
	F-NUE (kg kg ⁻¹)	T-NUE (kg kg ⁻¹)	F-NUE (kg kg ⁻¹)	T-NUE (kg kg ⁻¹)
F100	12.6 ± 4.6d	12.6 ± 4.6bc	28.6 ± 3.7c	28.6 ± 3.7bc
RS-F100	11.2 ± 2.3d	9.4 ± 1.9cd	25.4 ± 2.3cd	21.3 ± 2.0def
RS-F150	8.8 ± 1.8d	7.7 ± 1.6d	18.9 ± 1.8d	16.6 ± 1.5f
WS-F100	12.2 ± 3.6d	11.8 ± 3.4bcd	28.1 ± 4.5c	27.1 ± 4.2bcd
WS-F150	9.8 ± 2.2d	9.5 ± 2.1cd	19.5 ± 1.5d	19.1 ± 1.4ef
PSC-F50	33.5 ± 8.8bc	25.1 ± 6.6a	47.7 ± 4.1b	35.7 ± 3.1a
PSC+FYM-F50	30.5 ± 7.8c	21.9 ± 5.6a	42.1 ± 5.7b	30.1 ± 4.1ab
GM+FYM-F50	37.4 ± 7.0ab	14.3 ± 3.0b	54.7 ± 7.3a	24.3 ± 3.1bcde
GM+PSC-F50	41.9 ± 9.2a	14.6 ± 2.9b	57.2 ± 10.4a	22.5 ± 4.4cdef

higher than F100. In wheat, GM+PSC-F50 and GM+FYM-F50 recorded the highest F-NUE and were statistically at par with each other, but significantly higher than F100. Conversely, RS-F150 and WS-F150 recorded significantly lower F-NUE than F100 in both crops. In rice, the maximum T-NUE was recorded with PSC-F50, which was statistically at par with PSC+FYM-F50 and significantly higher than F100. In wheat, PSC-F50 recorded the highest T-NUE and was statistically at par with PSC+FYM-F50, both being significantly higher than F100. The T-NUE under GM+FYM-F50 and GM+PSC-F50 was statistically comparable with F100 in wheat, whereas RS-F150 and WS-F150 resulted in significantly lower T-NUE than F100.

Nutrient management significantly influenced total net mineralized N in both rice and wheat (Table

4). In rice, total net mineralized N ranged from 160.2 to 270.4 $\mu\text{g cm}^{-2}$, with the lowest value recorded under the unfertilized control (O). Among the fertilized treatments, PSC+FYM-F50 recorded the highest net mineralized N, followed by GM+PSC-F50 and PSC-F50; however, these treatments were statistically at par with F100. Compared to F100, PSC+FYM-F50 and GM+PSC-F50 increased net mineralized N by 16.3 and 14.5%, respectively. The residue-retention treatments (RS-F100, RS-F150, WS-F100 and WS-F150) also remained statistically at par with F100. In wheat, net mineralized N was substantially higher than in rice, ranging from 235.8 to 696.3 $\mu\text{g cm}^{-2}$. GM+FYM-F50 and GM+PSC-F50 recorded the maximum net mineralized N and were statistically at par with each other. These treatments resulted in 45.4 and 41.9% higher mineralized N, respectively, than F100. The residue-based treatments showed intermediate values, with WS-F150 and WS-F100 being statistically at par with the green-manuring treatments as well as F100.

Table 4. Effect of nutrient management on IER-sorbed N ($\mu\text{g cm}^{-2}$) in soil during full season of rice and wheat crop under different nutrient management modules. Refer to table 1 for a description of treatments. Treatments with same letters are not different significantly ($P \leq 0.05$)

Management	Total Net mineralized N ($\mu\text{g cm}^{-2}$)	
	Rice	Wheat
O	160.2 ± 1.0b	235.8 ± 14.7c
F100	232.5 ± 4.6a	478.8 ± 27.9b
RS-F100	240.7 ± 2.8a	496.0 ± 24.8b
RS-F150	253.6 ± 28.3a	513.4 ± 1.4b
WS-F100	246.2 ± 10.6a	536.9 ± 60.4ab
WS-F150	240.8 ± 18.5a	565.0 ± 36.5ab
PSC-F50	258.2 ± 6.3a	476.8 ± 0.6b
PSC+FYM-F50	270.4 ± 12.6a	537.2 ± 5.9ab
GM+FYM-F50	251.1 ± 4.3a	696.3 ± 61.5a
GM+PSC-F50	266.2 ± 13.1a	679.4 ± 127.4a

Nutrient management markedly influenced the temporal dynamics of IER-sorbed mineral N in the soil during the rice growing season (Fig. 1). NH_4^+ -N was highest during the initial 0-15 DAT period, followed by a progressive decline up to 60-75 DAT, irrespective of nutrient management treatment. The highest NH_4^+ -N concentration at 0-15 DAT was observed under PSC + FYM-F50, followed by GM + FYM-F50 and RS-F100, whereas F100 recorded comparatively lower values. Thereafter, treatment differences narrowed considerably, although a slight increase in NH_4^+ -N was evident at 90-105 DAT in most treatments. The concentration of NO_3^- -N remained relatively low and stable throughout the

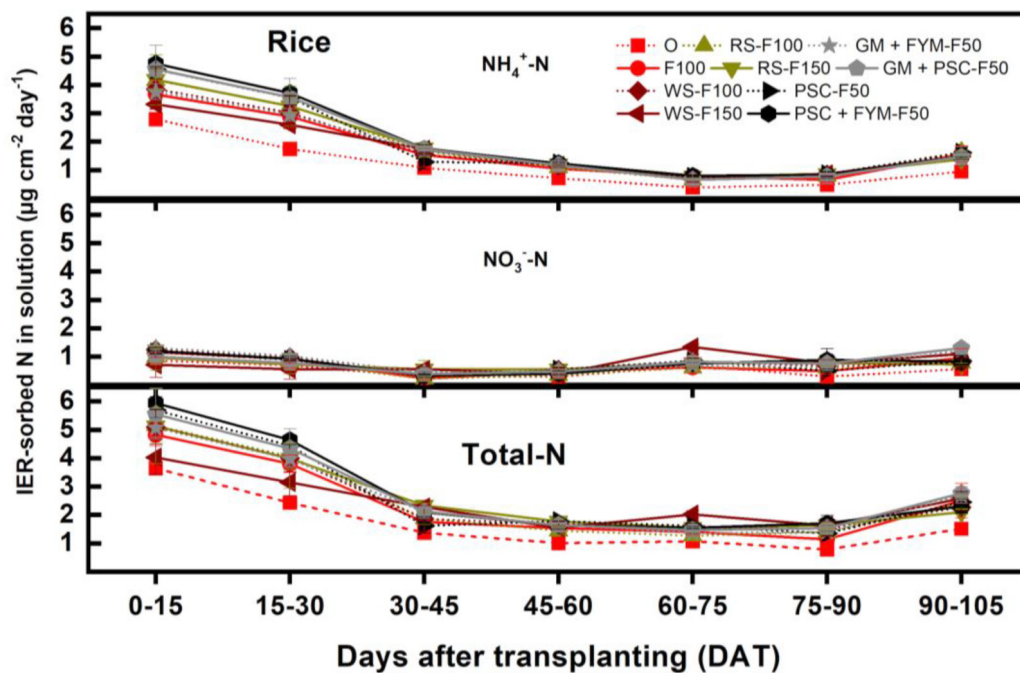


Fig. 1. Effect of nutrient management on IER-sorbed N ($\mu\text{g cm}^{-2} \text{ day}^{-1}$) in soil rice season under different nutrient management modules. Refer to Table 1 for a description of treatments. Treatments with same letters are not different significantly ($P \leq 0.05$)

crop period, generally ranging around $0.5\text{--}1.2 \mu\text{g cm}^{-2} \text{ day}^{-1}$. Values tended to decline from 0-15 to 30-45 DAT, followed by a modest increase towards crop maturity. The GM + FYM-F50, GM + PSC-F50 and PSC + FYM-F50 treatments generally maintained comparatively higher NO_3^- -N availability during the later crop stages, while F100 remained among the lower treatments at several sampling periods. A similar temporal pattern was observed for total-N, with substantially higher values during the early crop stage followed by a sharp decline up to 30-45 DAT. At 0-15 DAT, PSC + FYM-F50 and GM + FYM-F50 recorded the highest total-N, whereas F100 had a comparatively lower concentration. From 45-60 DAT onwards, differences among treatments were relatively small, although organic-input-based INM treatments generally maintained higher total-N availability than F100. A slight recovery in total-N was observed at 90-105 DAT across most treatments.

Integrated nutrient management markedly influenced the temporal dynamics of IER-sorbed mineral N in the soil during the wheat growing season (Fig. 2). NH_4^+ -N showed relatively low values during the initial 0-15 DAS, followed by a gradual increase up to 60-75 DAS. The highest NH_4^+ -N values were generally observed around 105-150 DAS,

particularly under the treatments involving integrated organic and inorganic nutrient sources. Among the treatments, GM + FYM-F50, GM + PSC-F50 and PSC + FYM-F50 generally maintained higher NH_4^+ -N availability. After 75 DAS, NH_4^+ -N gradually declined and remained relatively low during the later stages (90-150 DAS). The NO_3^- -N dynamics were more pronounced than those of NH_4^+ -N. During the early growth period, NO_3^- -N increased up to 30-45 DAS, with particularly high values under RS-F100 and GM + FYM-F50. Thereafter, NO_3^- -N declined sharply at 45-60 DAS. A secondary increase was observed around 75-90 DAS, especially under some integrated nutrient management modules, followed by a marked decline after 90 DAS. During 105-150 DAS, NO_3^- -N levels remained relatively low and differences among treatments were comparatively small. A similar pattern was observed for total-N. Total-N increased during the early crop-growth period and attained its highest values around 30-45 DAS, particularly under RS-F100 and GM + FYM-F50. Total-N subsequently declined around 45-60 DAS, followed by a moderate increase around 60-90 DAS in several treatments. Thereafter, total-N progressively decreased towards crop maturity, reaching the lowest levels during 105-150 DAS.

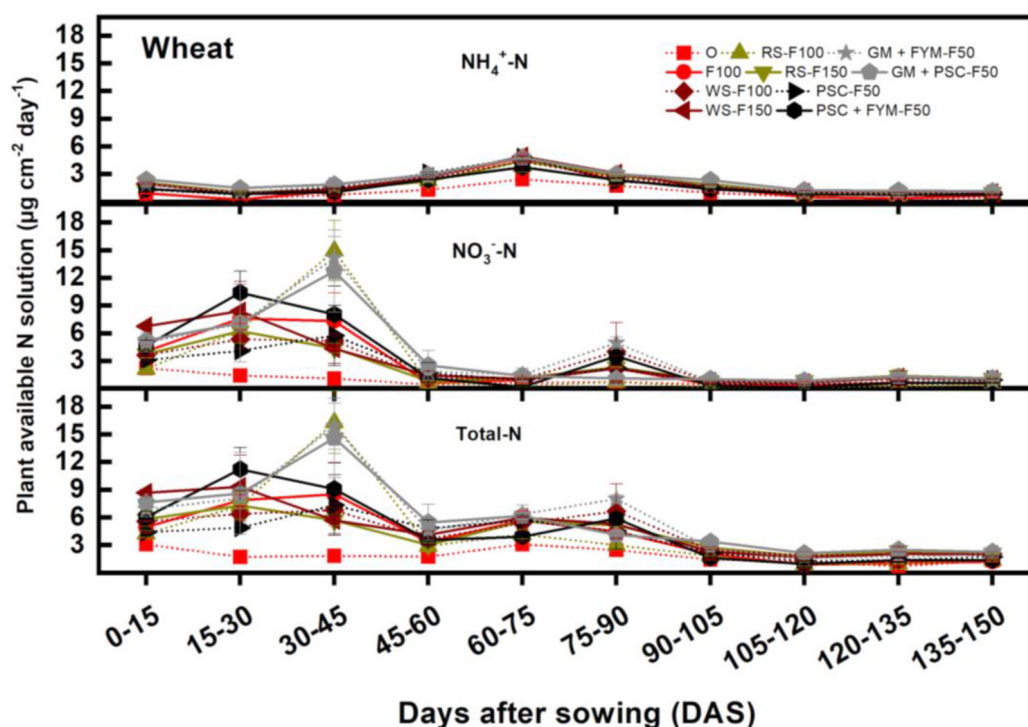


Fig. 2. Effect of nutrient management on IER-sorbed N ($\mu\text{g cm}^{-2} \text{ day}^{-1}$) in soil wheat season under different nutrient management modules. Refer to Table 1 for a description of treatments. Treatments with same letters are not different significantly ($P \leq 0.05$)

DISCUSSION

The rice-wheat system is characterized by seasonal shifts between aerobic and anaerobic soil conditions, coupled with intensive use of labour, energy, and external inputs. Imbalanced nutrient management and declining resource-use efficiency have contributed to stagnating productivity, while residue burning has emerged as a major environmental concern in the Western Indo-Gangetic Plains. Despite the development of several resource-conserving technologies, their adoption remains constrained by various biophysical, socioeconomic, and operational factors. Therefore, integrating crop residues and other organic nutrient sources into nutrient management strategies could improve nutrient cycling, resource-use efficiency, and soil health while reducing the environmental problems associated with residue burning.

Green manure-based integrated nutrient management (INM) treatments supplemented with FYM or pressmud compost and receiving 50% reduced fertilizer application (GM+FYM-F50 and GM+PSC-F50) recorded the highest grain and straw yields in both rice and wheat. Among these treatments, GM+PSC-F50 provided the greatest yield advantage over F100, followed by GM+FYM-

F50. The residue retention treatments RS-F150 and WS-F100 generally produced yields comparable to F100, whereas RS-F100 resulted in a slight reduction in rice grain yield but maintained a comparable wheat yield (Table 2). The higher productivity under organic-based INM treatments may be attributed to improved nutrient availability and a more continuous supply of nutrients throughout crop growth. Organic nutrient sources, either applied alone or in combination with inorganic fertilizers, have been reported to enhance crop productivity by improving soil nutrient availability and providing a more sustained supply of N during crop growth (Ali *et al.*, 2020). Similarly, residue retention can improve soil aggregation, increase soil organic carbon (SOC) sequestration, and enhance soil physical properties, thereby supporting crop productivity in rice-wheat systems (Chaudhary *et al.*, 2014). The retention of both rice and wheat residues can further increase SOC, improve soil quality, and contribute to greater system productivity (Zhu *et al.*, 2015). Thus, the superior yield performance of the integrated treatments may reflect the combined effects of improved nutrient availability, enhanced nutrient cycling, and gradual nutrient release from organic inputs.

Fertilizer N use efficiency (F-NUE) varied significantly among nutrient management treatments in both rice and wheat (Table 3). GM+PSC-F50 and GM+FYM-F50 recorded the highest F-NUE and were significantly superior to F100 in both crops, whereas the residue retention treatments generally showed comparatively lower F-NUE. Total N use efficiency (T-NUE) was highest under PSC-F50 and PSC+FYM-F50, which significantly exceeded F100. Overall, the results indicate that green manure-based modules were particularly effective in improving the efficiency of fertilizer-derived N, whereas pressmud compost-based treatments were more effective in enhancing overall N use efficiency, particularly when combined with reduced fertilizer application. The higher NUE under these treatments may be associated with improved synchronization between N release and crop demand, thereby reducing the proportion of applied N susceptible to loss. Nitrogen is a major nutrient limiting crop growth and yield in intensive rice-wheat systems; however, substantial losses through volatilization, leaching, runoff, and denitrification can markedly reduce N recovery by crops (Bhardwaj *et al.*, 2020). Improving NUE therefore requires synchronization of N supply from different sources with crop demand throughout the growing season (Bhardwaj *et al.*, 2021a). Integrated nutrient management can facilitate such synchronization by combining readily available inorganic N with slowly mineralizable organic sources, thereby improving N recovery and sustaining crop productivity (Dwivedi *et al.*, 2016).

Nutrient management significantly affected total net mineralized N in both rice and wheat (Table 4), indicating differences in the capacity of the treatments to supply plant-available N through mineralization. In rice, net mineralized N ranged from 160.2 to 270.4 $\mu\text{g cm}^{-2}$, with the lowest value recorded under the unfertilized control. PSC+FYM-F50 recorded the highest mineralized N, followed by GM+PSC-F50 and PSC-F50. The PSC+FYM-F50 and GM+PSC-F50 treatments recorded 16.3 and 14.5% higher mineralized N than F100, respectively. In wheat, net mineralized N ranged from 235.8 to 696.3 $\mu\text{g cm}^{-2}$, with GM+FYM-F50 and GM+PSC-F50 recording the highest values and 45.4 and 41.9% greater mineralized N than F100, respectively. The greater mineralization under organic-based INM treatments suggests that the addition of readily decomposable organic materials stimulated microbial activity and enhanced the

transformation of organically bound N into mineral forms. The comparatively greater mineralized N observed in wheat may also reflect the cumulative effect of organic inputs and residue-derived N carried over from the preceding rice crop ((Bhardwaj *et al.*, 2020).

The dynamics of IER-sorbed N also varied with crop growth stage and nutrient management (Figures 1 and 2), demonstrating the temporal changes in mineral N availability during crop development. In rice, $\text{NH}_4^+\text{-N}$ and total-N concentrations were highest during the early growth period and subsequently declined, whereas $\text{NO}_3^-\text{-N}$ remained comparatively low, with a slight increase towards maturity. The predominance of $\text{NH}_4^+\text{-N}$ during the early growth stages is consistent with the anaerobic soil conditions prevailing under flooded rice, which favour ammonium accumulation over nitrate. Organic-based INM treatments generally maintained greater N availability than F100, suggesting a gradual release of N from organic inputs during crop growth. In wheat, $\text{NH}_4^+\text{-N}$ increased up to 60-75 DAS, while $\text{NO}_3^-\text{-N}$ and total-N generally reached their maximum during the early to mid-growth stages and subsequently declined towards maturity. The decline in N availability towards maturity may be associated with increasing crop N uptake and depletion of the available N pool as crop demand intensifies.

Overall, the greater mineral N availability under organic-based INM treatments indicates that integrating organic and inorganic nutrient sources can improve the temporal synchronization of N supply with crop demand at critical growth stages (Bhardwaj *et al.*, 2021a). Inorganic fertilizers provide a readily available source of nutrients during the initial stages of crop growth, whereas organic inputs such as green manure, FYM, compost, and retained rice and wheat residues undergo gradual decomposition and mineralization, thereby extending N availability into later growth stages. This complementary nutrient-release pattern can improve N availability, reduce the risk of N losses, and enhance fertilizer recovery by crops. Therefore, strategies that enhance N mineralization and synchronize nutrient release with crop demand, while minimizing N losses, are essential for improving NUE and sustaining productivity in rice-wheat systems (Bhardwaj *et al.*, 2021b). The higher yield, NUE, and net N mineralization observed under the organic-based INM treatments collectively

suggest that partial substitution of inorganic fertilizer with organic nutrient sources can maintain or enhance crop productivity while improving the efficiency of N use.

CONCLUSION

Integrated nutrient management improved productivity, nitrogen-use efficiency, and soil N availability in the rice-wheat system. Green manuring with *Sesbania aculeata* + PSC @ 5 t ha⁻¹ with 50% recommended fertilizer (GM+PSC-F50) and green manuring with *Sesbania aculeata* + FYM @ 10 t ha⁻¹ with 50% recommended fertilizer (GM+FYM-F50) recorded the highest rice and wheat yields and superior F-NUE, while PSC-based modules showed better T-NUE. These treatments also enhanced net N mineralization and maintained greater mineral N availability during crop growth. *In situ* residue-retention treatments remained statistically at par with 100% fertilizer only for most yield parameters, although higher fertilizer application under residue retention reduced nitrogen use efficiency. Overall, green manuring with FYM or pressmud compost and 50% fertilizer emerged as the most efficient nutrient management strategy, while *in situ* residue retention provided a viable alternative for sustaining productivity and soil N availability.

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