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ORIGINAL PAPER

Nitrogen Mineralization and Availability at Critical Stages of Rice (*Oryza sativa*) Crop, and Its Relation to Soil Biological Activity and Crop Productivity Under Major Nutrient Management Systems

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Abstract

Adequate nitrogen availability to plants for growth is one of the most important reasons for fertilizer application. Though organic alternatives are recommended, there is uncertainty of their nutrient release characteristics, especially during critical growth stages of a crop. In a 10-year-long experiment on nutrient management for rice-wheat cropping, ion exchange resin (IER) membrane strips were used as plant root simulators to determine daily NH_4^+-N and NO_3^--N availability in soil solution during the rice growing season. The management included inorganic fertilizers at 100% recommended rate (F), compared to reduced rate (55%) of inorganic fertilizers supplemented with organic inputs via green manuring with *Sesbania* (GM), biomass incorporation of an opportunity legume crop-green gram (*Vigna radiata*) (LE), 1/3rd wheat stubble retention and soil incorporation (WS), 1/3rd rice stubble retention and soil incorporation (RS), and farmyard manure application (FYM). The total amount of available N (NH_4^+ + NO_3^-) recorded for the full season was in the order GM (221 μg cm^{-2}) > F (184 μg cm^{-2}) > RS (181 μg cm^{-2}) > FYM (176 μg cm^{-2}) > WS (176 μg cm^{-2}) > LE (175 μg cm^{-2}). Both grain and straw yield related directly and significantly to the N mineralization in soil at 30–60 days after transplanting (DAT), indicating that fertilizer N application before 30 DAT and after 60 DAT could mostly be a loss in transplanted rice crop. Green manured (GM) soils maintained steadily high N mineralization rates throughout the rice growing period. The best alternative to cut down inorganic fertilizer use in rice cropping would be the biomass incorporation from leguminous green manuring crops. Integration of organics afforded almost 50% reduction in recommended inorganic fertilizer use while maintaining better N mineralization status at the critical growth stages of rice.

Keywords Nitrogen · Crop residue · Mineralization · Green manure · Legume · Integrated nutrient management

1 Introduction

Nitrogen (N) fertilization in agriculture is directly related to crop productivity, although excessive doses of N-fertilizers not only add to the cost of cultivation but also pollute the environment. While there has been increased focus on environmental quality worldwide, countries like India have also been struggling hard in meeting the food production targets for rapidly increasing populations and therefore fertilizer use is on the rise (DOF 2010). Several integrated nutrient

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management alternatives, to cut down excessive fertilizer use, are being tested over the years to adequately meet the nutrient requirement of crops. Organic/ecological management improves soil health as well as ecosystem functions (Bhardwaj et al. 2011; Mishra et al. 2015; Bhardwaj et al. 2019). Simplistically, integrated management envisages cutting down the inorganic fertilizer amounts and promoting the use of organic alternatives. These organic alternatives include farmyard manures, green manures, legumes, cover crops, and also cereal crop residues recently (Lal 2005; Ladoni et al. 2015; Blanchet et al. 2016).

The key feature of organic sources of nutrients which differentiate them from inorganic fertilizers is their slow release and unregulated supply of nutrients into soil solution (Fig. 1). The slow nutrient release characteristics also make these sources safer for the environment (Schoenau et al. 2000; Dikgwatlhe et al. 2014). However, it is also possible that slow release may not suffice for the plant nutrition requirements at critical stages, which could have a significant impact on crop yields (Phongpan and Mosier 2003; Said-Pullicino et al. 2014; Xinqiang et al. 2014). This is one of the important reasons, besides labor- and time-intensive operations, that farmers prefer high doses of inorganic fertilizers in comparison to the organic alternatives. Considering these constraints, a number of combinations of organic alternatives and inorganic fertilizers have been recommended for sustainable crop production (Hao et al. 2008; Liu et al. 2009).

Nitrogen is the most important nutrient for crop production. The nitrogen supplying capacity of the soil is influenced by several factors such as moisture, organic matter content, soil characteristics, and management (Zhang et al. 2019; Guo et al. 2019). Soil texture may usually remain constant for a specific location, whereas all other soil properties are affected by management practices (Bhagat et al. 2003). For instance, in transplanted rice (*Oryza sativa* L.) crop, grown under puddled soil conditions, the fields are kept flooded and saturated almost till maturity. This continuous flooding of rice fields results in a substantial loss of N in the form of ammonia emissions and nitrate leaching (Ghosh and Bhatt 1998). Rice crop is the most-grown staple crop in the Asian region. Paddy rice is more responsive to NH_4^+-N than to NO_3^--N. Nitrification, being an aerobic process, is inhibited in highly saturated soils. While NH_4^+-N resists leaching by its absorption onto the cation exchange sites, NO_3^--N is highly susceptible to leaching. This has serious implications for nitrate pollution as well as for the economic use of nitrogenous inorganic fertilizers under such conditions.

However, despite benefits, organic alternatives have not been seriously accepted by a large portion of farmers in the region due to the uncertainty of their nutrient release characteristics and their timely availability to plants, especially at the critical growth stages. Farmers relate the benefits of an agronomic practice to its response in terms of yield gain. In tropical and subtropical conditions, building up soil C to levels where actual soil quality benefits could be gained requires long-term and large amounts of annual additions of organic matter (Snapp et al. 1998). Therefore, adequate nitrogen availability for plant growth, under a particular management, is one such parameter which will be easily accepted by farmers to be a significant benefit to cut down inorganic fertilizer use. Yet there are gaps in our knowledge of net N mineralization

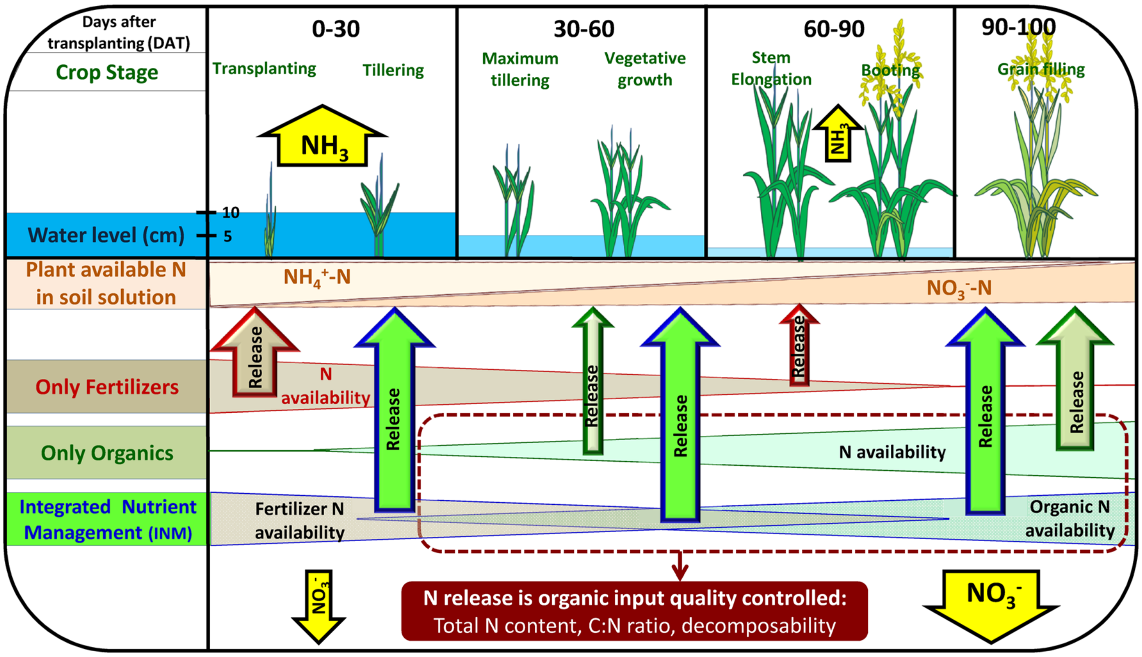

Fig. 1 Nitrogen release from nutrient sources and their plant availability scenarios during different stages of rice (*Oryza sativa*) crop growth

potential as well as temporal release characteristics of the recommended organic alternatives. Also, most N mineralization studies have been under laboratory-scale experiments and regarding gross mineralization potential; field-scale net mineralization reports are rare. The objectives of the present study were (i) to understand daily N mineralization and availability to rice crop under five major integrated nutrient management strategies which are recommended to farmers for rice-wheat cropping and (ii) to relate N release patterns to crop growth stages, microbial/enzymatic activity, and crop yields at field scale.

2 Materials and Methods

2.1 Site Description

A field experiment on integrated nutrient management in the rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system was initiated in 2005 on a soil with sandy loam texture at ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, India, located at 29.43° N and 76.58° E. This soil was one time reclaimed from alkalinity/sodicity using gypsum ($CaSO_4{\cdot}2H_2O$), 10 years before in 1994, and was put under the rice-wheat cropping system immediately after. At that time, immediately after reclamation, the soil (0–15 cm) recorded a pH of 8.7, cation exchange capacity = 9.5, and organic carbon = 3.2 g kg^{-1} (Yaduvanshi et al. 2013). The experimental area lies in a semi-arid, sub-tropical climate zone with very hot summers and cool winters. The mean annual rainfall is 750 mm.

2.2 Experimental Layout and Treatments

The treatments included combinations of different organic and inorganic inputs to provide for nutrient requirements of the rice-wheat cropping sequence. With the treatments imposed for 10 years, the present investigation of N availability in soil solution using ion exchange resin (IER) strips was carried out during the 2013–2014 and 2014–2015 cropping cycles (full procedure covered in later sections). The study involved six treatments in total, including five treatments with reduced inorganic fertilizer doses (55% of recommended) in combination with organic amendments which included green manuring (GM) with *Sesbania aculeata*, a legume opportunity crop (green gram, *Vigna radiata*) between wheat and rice season and its biomass incorporation (LE), farmyard manure (FYM) application, wheat stubble (WS) retention, and rice stubble (RS) retention after harvesting of crops. The amount of nutrients added via organic inputs was determined by multiplying the nutrient concentration in the organic material with the total amount of biomass. The organic inputs were sampled for dry biomass and nutrient content at the time of incorporation (FYM, GM, LE) and harvesting (WS, RS). The concentration of nitrogen in the organic amendments is given in Table 1. These treatments were compared with 100% doses of inorganic fertilizer (F) treatment (N, P, K, Zn @ 180, 26, 42, 7 kg ha^{-1}, respectively). The fertilizer N was applied in the form of urea granules, P as diammonium phosphate, K as muriate of potash, and Zn as zinc sulfate. These are standard and recommended fertilizer forms in the region. The seedlings were transplanted at 20 × 20 cm spacing. The plot size was 5 × 4 m and the treatments were replicated in four completely randomized blocks. The annual cropping system which was followed consisted of rice (*Oryza sativa*) in the summer (July–October) followed by wheat (*Triticum aestivum*) in the fall season (November–April). The transplanting of 30-day-old rice seedlings was done on 6–7 July every year, and the crop was harvested in the third week of October. The management schedule followed for different treatments were as follows:

1. F: Rice followed by wheat was grown with 100% inorganic fertilizer input. No organic inputs were given.
2. LE: A legume crop, *Vigna radiata*, was grown in the summer lean period between wheat and rice as an “opportunity crop”. The *Vigna* seeds were sown in the second week of April, immediately after wheat harvest. In the first week of July (after ~ 75 days of sowing), the pods were harvested and the remaining plant biomass was incorporated into the soil using a power tiller just before rice transplanting. Rice was transplanted in July and wheat was sown in November with reduced (55%) macronutrient (N, P, K) fertilizer inputs. No micronutrient fertilizers were applied.
3. GM: 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 wheat harvest. After 40 days of sowing, the green manure crop was incorporated into the soil using a power tiller, just before rice transplanting. Rice was transplanted in July and wheat was sown in November with reduced (55%) macronutrient (N, P, K) fertilizer inputs. No micronutrient fertilizers were applied.
4. FYM: Farmyard manure (FYM) at the rate of 10 t ha^{-1} was incorporated in the soil just before soil puddling and transplanting of rice. Rice was transplanted in July and wheat was sown in November with reduced (55%) macronutrient (N, P, K) fertilizer inputs. No micronutrient fertilizers were applied.
5. WS: 30 cm standing stubble (~ 1/3 of the total straw) was retained at the time of harvesting of wheat. It was dry plowed into the soil before soil puddling in the first week of July. Rice was transplanted in July and wheat was sown

Table 1 The concentration and the total inputs of nitrogen added via the organic amendments under different management

Organic amendment	Total dry matter added Mg ha^{-1}	Nitrogen concentration %	Total nitrogen input kg ha^{-1}
Opportunity crop-legume (*Vigna radiata*)	5.14	1.71 ± 0.03	87.89
Green manure (*Sesbania aculeata*)	5.35	2.65 ± 0.50	141.78
Farmyard manure	3.67	0.56 ± 0.06	20.55
Wheat stubble	4.06	0.27 ± 0.04	10.96
Rice stubble	3.82	0.46 ± 0.07	17.57

in November with reduced (55%) macronutrient (N, P, K) fertilizer inputs. No micronutrient fertilizers were applied.

6. RS: 30 cm standing stubble (~ 1/3 of the total straw) was retained at the time of harvesting of 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 reduced (55%) macronutrient (N, P, K) fertilizer inputs. No micronutrient fertilizers were applied.

For field preparation for rice, dry plowing was carried out in the last week of June in all of the treatments followed by puddling under flooded conditions. In the first week of July, 30-day-old nursery-raised rice seedlings (*var.* Pusa 44) were transplanted in the plots. N (1/3 dose), P, K, and Zn were applied immediately before transplanting. The N fertilizer application was in three equally split doses for all management. The first 1/3 dose was immediately before transplanting, the second 1/3 dose was at 21 days after transplanting (DAT), and the third 1/3 dose was at 42 DAT. Rice crop was maintained under water-flooded conditions with nearly 10 cm of standing water over soil surface for the first month (with daily irrigation) and under the saturated condition for the next month (with irrigation every penultimate day), and henceforth, it was maintained under near-saturated conditions (with weekly irrigation). Irrigation was stopped 10–15 days before harvesting in mid-October. After the rice crop was harvested, the plots were plowed (field capacity moisture) and wheat seeds were sown in the second week of November. Wheat crop, in all treatments, received only the inorganic fertilizer doses (same amounts as in rice) minus the organic inputs except RS treatment where the stubble retained after rice harvest was tilled into the soil at the time of plowing before wheat sowing.

2.3 Nitrogen Availability in Soil Solution

Nitrogen availability in soils was determined throughout the growing period using the ion exchange resin (IER) membranes. Membrane strips (cation and anion separately) of 2.5 cm by 10 cm size were cut out from large commercially available sheets (General Electricals, Watertown, MA, USA). The strips were charged by dipping and shaking in 0.5 mol/L HCl for 1.2 h, and then in 0.5 mol/L $NaHCO_3$ for 5 h. Finally, they were rinsed with deionized water. The resin strips were placed in vertical slits made in the treated soils using a sharp blade, and the slits were closed firmly so that the strips come into contact with the soil. One cation and one anion strip per plot were placed 5 cm apart in the soil. The strips were kept in the soil for ~ 15-day interval and were replaced with new ones immediately after removing the previous set of strips. This process was continued for the entire cropping cycle for 2 years. After removal from the soil, the strips were rinsed with deionized water to remove any adhering soil. For a treatment, both cation and anion strips were stored and transported together in a vial for extracting NH_4^+-N and NO_3^--N in the laboratory. For extraction, 70 mL of 2 mol L^{-1} KCl was added to the vials containing strips, shaken for 1 h, and decanted into a scintillation vial. The extracts were analyzed using Kjeltec 2200 (Foss, Hillerod, Denmark) for NH_4^+-N and NO_3^--N.

2.4 Amendment Sampling and Analyses

Biomass samples were drawn for all amendments at the time of harvesting. Samples for legume (*Vigna radiata*) and green manure crop (*Sesbania aculeata*) were taken at the end of June, at the time of harvesting and incorporation into the soil. FYM samples were taken at times of its application to soil. Rice stubble was sampled at the rice harvesting, and wheat stubble was sampled at the time of wheat harvest. The nitrogen contents of organic amendments are given in Table 1.

2.5 Soil Sampling and Analyses

Soil samples were drawn after crop harvest during each season. Soil samples were collected for two depths, 0–15 and 15–30 cm, from each of the four replications using an auger. Composite samples were made, air-dried, and ground to pass through a 2.0-mm sieve. The available soil nitrogen was determined using the Kjeldahl distillation method (Subbiah and Asija 1956).

2.6 Enzymatic Activity

The soil samples for enzymatic activity were drawn at 30 and 90 days after the transplanting of the rice crop. The enzyme activities were assayed on < 2-mm field-moist samples in duplicate and one in control, and were expressed on a moisture-free basis. The moisture content of soil samples was determined from loss in weight after drying at 105 °C for 48 h. The enzymes urease (EC 3.5.1.5), dehydrogenase (EC 1.1.1), and β-glucosidase (EC 3.2.1.21) were quantified according to the colorimetric analysis of the reaction products after sample incubation with adequate substrate under standard conditions. Urease activity was performed by the method of Kandeler and Gerber (1988), where urea was used as a substrate. The dehydrogenase activity was estimated according to the method of Casida et al. (1964), and determination was based on reduction of triphenyltetrazolium chloride (TTC). β-Glucosidase activity was determined by the method of Eivazi and Tabatabai (1988), and *ρ*-nitrophenyl-β-D-glucoside was used as a substrate. The absorbance of the products was measured using a spectrophotometer (Specord 200 plus, Analytic Jena, Germany).

2.7 Crop Yield

The rice crop was harvested plot-wise in mid-October and threshed to record grain and straw yields.

2.8 Statistical Analysis

All the data including growth parameters were statistically analyzed using SAS (Cody and Smith 1997). For N availability data at different stages, separation of means was subjected to Tukey's honestly significant difference test using JMP 9.0 (SAS Institute Inc., Cary, NC, USA). The graphing was done using Origin v.8.5 software (Originlab Corporation, Northampton, USA). Correlation analysis was conducted to identify relationships between the measured parameters. All tests were performed at the 0.05 significance level.

3 Results

There were significant differences in ion exchange resin (IER) strip sorbed NH_4^+-N and NO_3^--N, at different stages with tested management (Fig. 2). Up to 60 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 average values of 1.68, 1.73, and 1.16 μg cm^{-2} day^{-1} at 15–30, 30–45, and 45–60 DAT, when the paddy was in anaerobic condition with the water-sediment medium (rhizosphere) flooded by frequent irrigation plus rainfall. Changes in irrigation pattern, i.e., change from flooding to alternate wetting-drying cycle had a significant effect on the availability of NH_4^+-N sorption in soil solution. This practice reduced the amount of NH_4^+-N available in soil solution by 47 and 60% at 60–75 DAT and 75–90 DAT compared to average values for continuous flooding in the preceding period (0–60 DAT). On the other hand, near the irrigation withdrawal during the 90–105 DAT phase, an increase in NH_4^+-N in soil solution was again detected. Crop stage-wise, for 0–15 DAT (transplanting and early tillering), 100% inorganic fertilizer-only management (F) exceeded all integrated nutrient management (INM), except GM, in terms of N availability in soil solution. There were no differences in any management for 15–45 DAT, which coincide with the maximum tillering stage. For 45–60 DAT, management systems F, LE, and GM had significantly more availability than FYM, WS, and RS. While there was a significant decrease in NH_4^+-N availability in F and LE management, there were no marked changes in levels of GM, FYM, and WS. From 75 DAT onwards, there were no significant differences amongst all treatments for NH_4^+-N in soil solution.

The availability of NO_3^--N was the same in all management systems for up to 45 DAT. For the 45–90 DAT period, NO_3^--N availability was maximum in GM. In the case of total N, trends were similar to NH_4^+-N, with no significant difference up to 45 DAT, and GM being the most significant management after 45 DAT. In all, for full rice season, total available N in soil solution was maximum in GM; most of it could be attributed to differences in NO_3^--N from other treatments. Full-season total N in GM was 20% higher compared to F. Averaging all INM management revealed unique patterns, with 100% fertilizers having more available N just after application, while INM treatment matching up to it at 30–60 days after transplanting (DAT), and exceeding F during the rest of the growth period beyond 60 DAT (Fig. 3). The effects were more pronounced for NH_4^+-N than NO_3^--N.

Plant-available nitrogen had a direct and significant ($p \le 0.01$) relation with enzymatic activity in the soils under different management (Fig. 4). On one hand, during early growth period (30 DAT) urease activity, β-glucosidase activity and dehydrogenase activity (as well as N availability) were higher in management with amendments with high N content and ready nutrient availability (lower C:N ratio), like F, GM, and LE, compared to high C:N ratio and low N-amended management like WS and RS. On the other hand, during the late growing season (90 DAT), F and LE had the least enzymatic activity and plant-available N. Management like RS, WS, and FYM had increased activity and consequently release of N in soil solution. Green manuring (GM) maintained high activity and N availability at late stages as well.

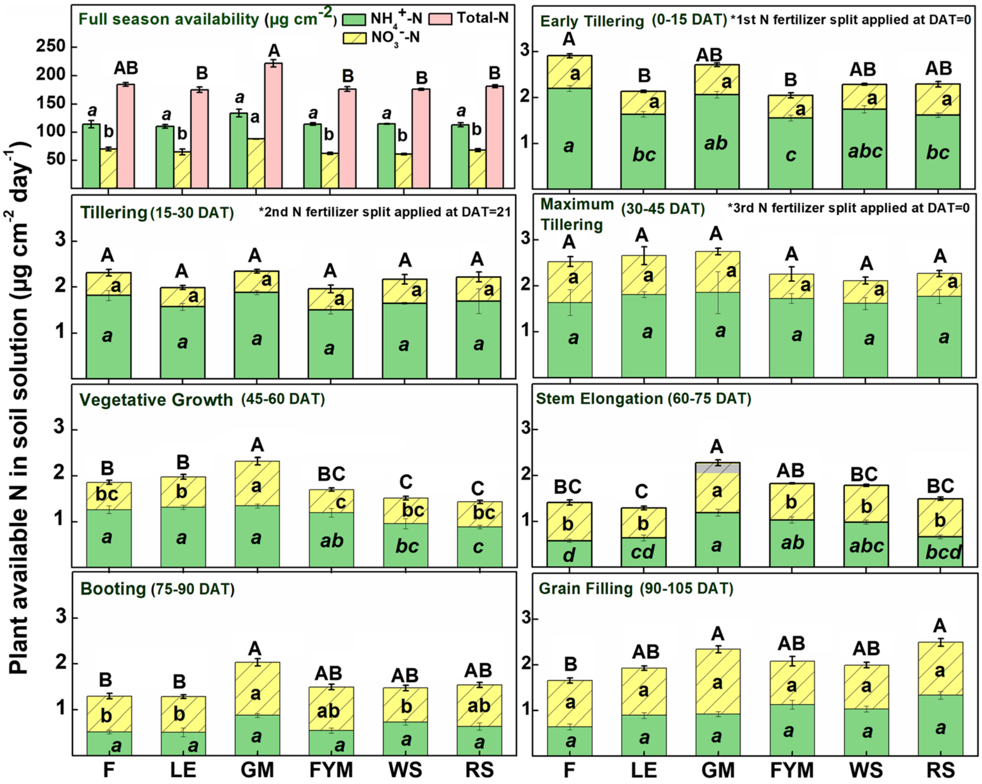

Fig. 2 Full season and stage-wise differences in plant-available NH_4^+-N, NO_3^--N, and total-N in soil solution during the rice-growing season (averaged for two cropping years). Error bars denote ± 1 SE. Treatments with same letters are not different significantly ($P \leq 0.05$). Capital letters denote differences for total-N, small letters for NO_3^--N, and small italic letters for NH_4^+-N. Management: F = 100% inorganic fertilizer, LE = legume (*Vigna radiata*) in rotation and its biomass incorporation + 55% inorganic fertilizers, GM = green manuring with *Sesbania aculeata* + 55% inorganic fertilizers, FYM = farmyard manure incorporation + 55% inorganic fertilizers, WS = 1/3 wheat stubble retention + 55% inorganic fertilizers, RS = 1/3 rice stubble retention +55% inorganic fertilizers. Error bars denote ± 1 SE

The relationship of straw yield with plant available N was direct and highly significant ($p = 0.00$) at 30–45 DAT and slightly significant ($p = 0.15$) at 45–60 DAT (Fig. 5). At other stages, straw yield was significant and negatively related to plant-available nitrogen ($p = 0.03$ at 15–30 DAT, $p = 0.05$ at 60–70 DAT, and $p = 0.08$ at 75–90 DAT). Grain yield had a direct and highly significant ($p = 0.0004$) relation with plant-available N at 30–45 DAT, and a slightly significant ($p = 0.14$) relation at 45–60 DAT (Fig. 6). For other stages, the relationship was mostly negative and non-significant. The plant-available N in soil solution related best to the combined effects of inorganic N applied (100%) in F and 50% in integrated management, plus the organic N added via the organic amendments (Fig. 7).

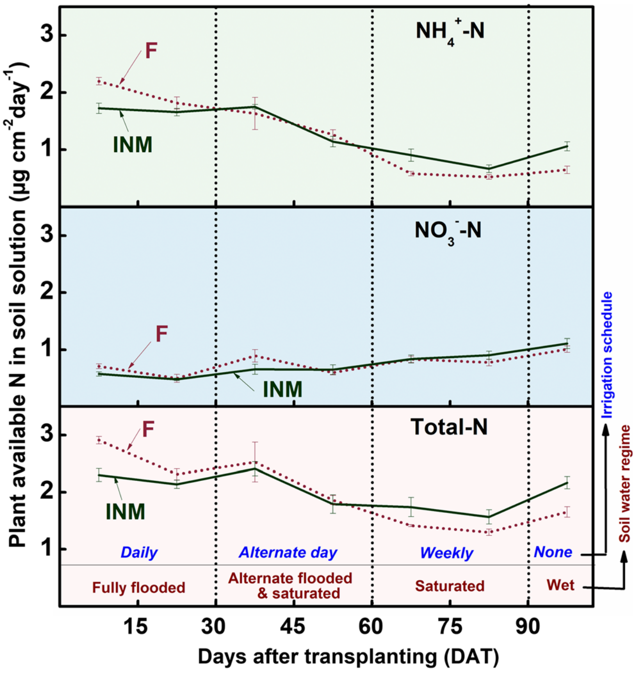

Fig. 3 Trends in plant-available N (NH_4^+-N, NO_3^--N, and total-N) in soil solution with F (100% inorganic fertilizers) and INM (integrated nutrient management, 55% inorganic fertilizers + organic inputs) during rice growth season (averaged for two cropping years). Management: F = 100% inorganic fertilizers only, INM = integrated nutrient management (55% inorganic fertilizer + organic amendment). Error bars denote ± 1 SE

4 Discussion

Compared to 100% inorganic fertilizers (F, 180 kg ha^{-1} nitrogen), organic supplemented treatments had variable amounts of nitrogen (N) added through organic materials along with reduced inorganic fertilizer fraction of 100 kg ha^{-1} (55%). Legume (*Vigna radiata*, LE) biomass and green manure (*Sesbania aculeata*, GM) biomass contributed 88 and 142 kg ha^{-1} N, respectively, getting these treatments into high nitrogen input category. So the total nitrogen inputs in F, LE, and GM were 180, 188, and 242 kg ha^{-1}, respectively. The second category of treatments was constituted by farmyard manure (FYM), wheat

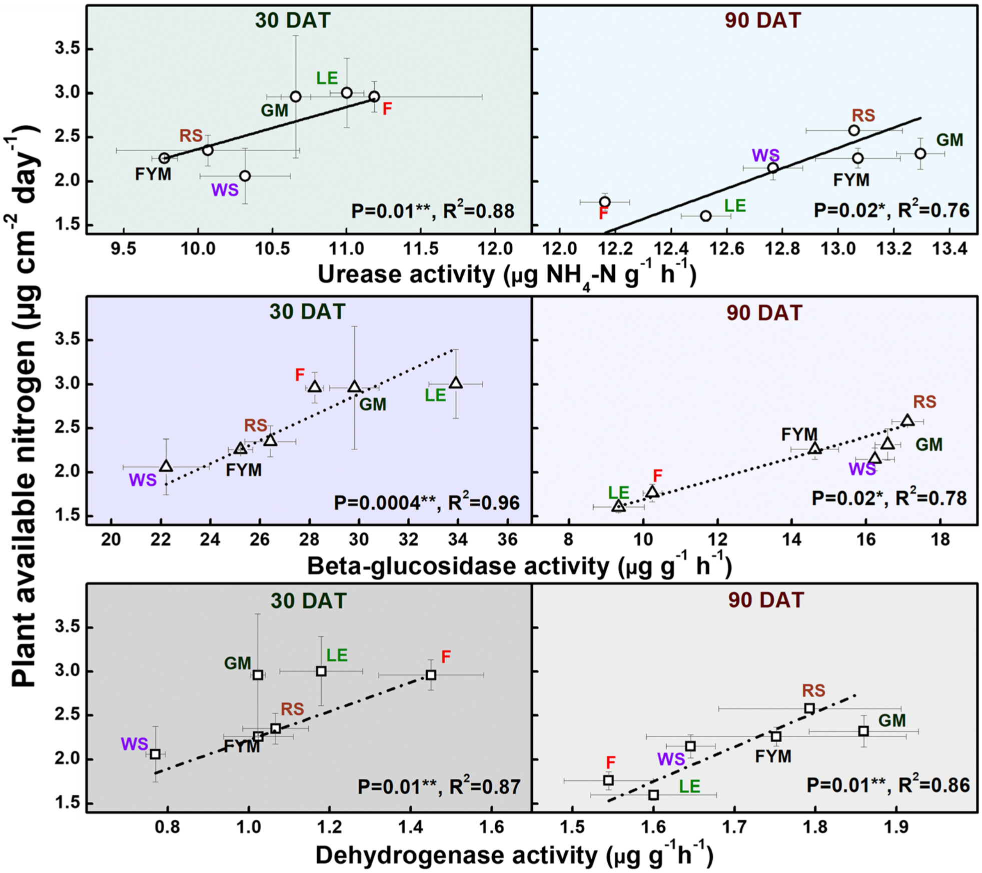

Fig. 4 Relation between enzymatic activity and plant-available nitrogen at 30 and 90 days after transplanting (DAT) (averaged for two cropping years). Management: F = 100% inorganic fertilizer, LE = legume (*Vigna radiata*) in rotation and its biomass incorporation + 55% inorganic fertilizers, GM = green manuring with *Sesbania aculeata* + 55% inorganic fertilizers, FYM = farmyard manure incorporation + 55% inorganic fertilizers, WS = 1/3 wheat stubble retention + 55% inorganic fertilizers, RS = 1/3 rice stubble retention + 55% inorganic fertilizers. Error bars denote ± 1 SD. Treatments with same letters are not different significantly ($p \leq 0.05$)

stubble (WS), and rice stubble (RS) amended management with total nitrogen (N) input of 120 kg (100 kg from inorganic fertilizers + 20 kg from FYM), 111 kg (100 kg from inorganic fertilizers + 11 kg from wheat stubble), and 119 kg (100 kg from inorganic fertilizers + 19 kg from rice stubble), respectively.

Ion exchange resin (IER) membranes placed in direct contact with soil could provide a dynamic assessment of available

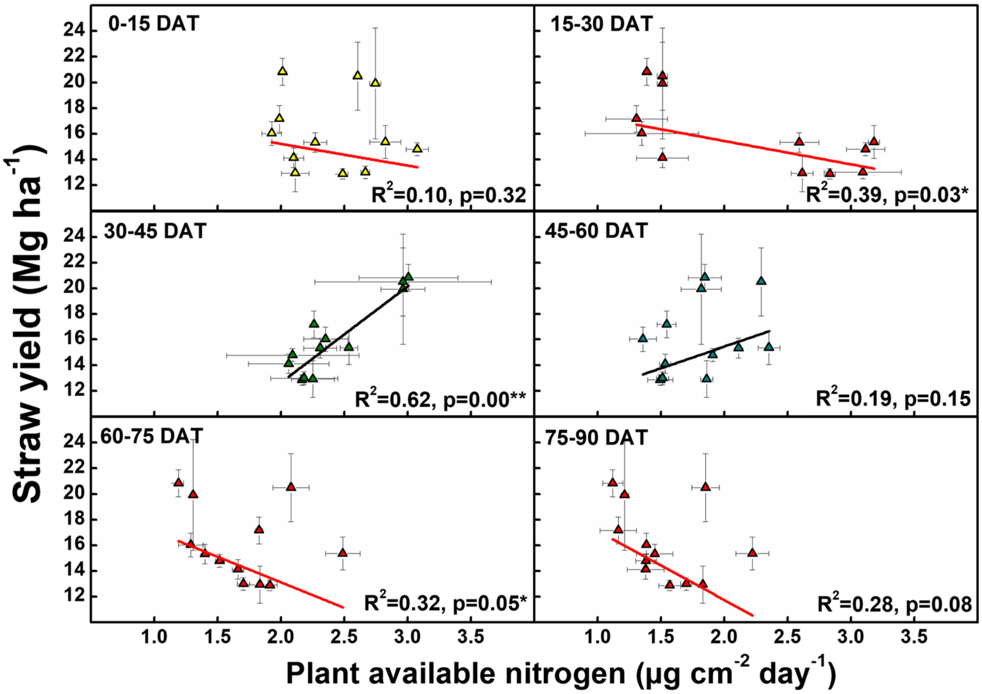

Fig. 5 Relation between plant-available nitrogen at different growth stages and rice (*Oryza sativa*) straw yield. Management: F = 100% inorganic fertilizer, L = legumes (averaged LE and GM; LE = legume (*Vigna radiata*) in rotation and its biomass incorporation + 55% inorganic fertilizers, GM = green manuring with *Sesbania aculeata* + 55% inorganic fertilizers), FYM = farmyard manure incorporation + 55% inorganic fertilizers, R = crop residues (averaged WS and RS; WS = 1/3 wheat stubble retention + 55% inorganic fertilizers, RS = 1/3 rice stubble retention + 55% inorganic fertilizers. Error bars denote ± 1 SD

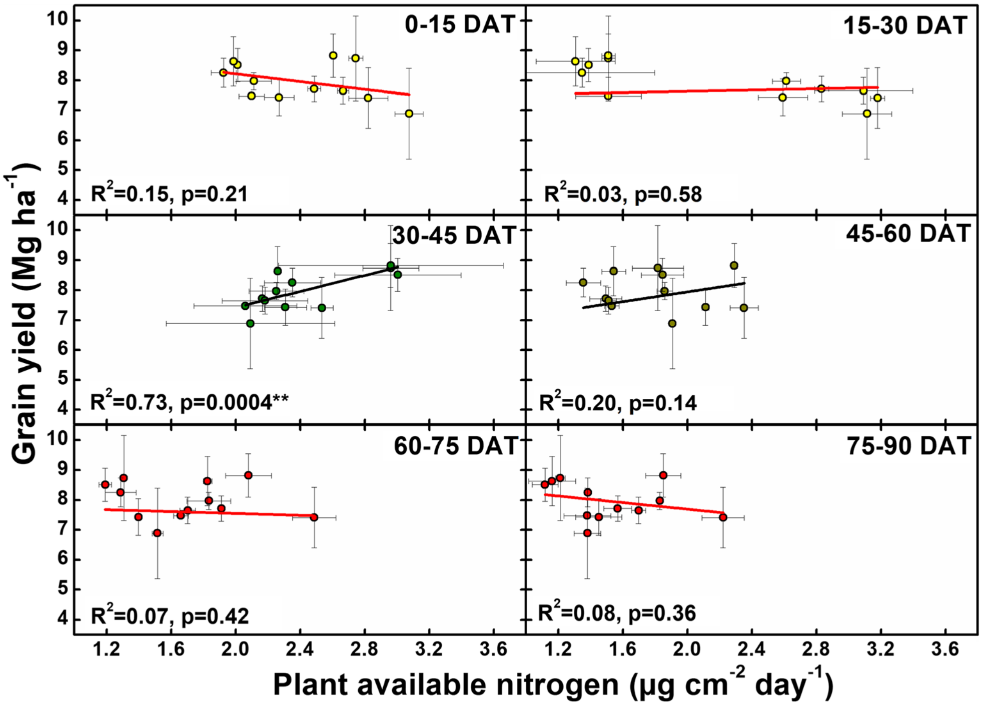

Fig. 6 The relation between plant-available nitrogen at different growth stages and rice (*Oryza sativa*) grain yield. Management: F = 100% inorganic fertilizer, LE = legume (*Vigna radiata*) in rotation and its biomass incorporation + 55% inorganic fertilizers, GM = green manuring with *Sesbania aculeata* + 55% inorganic fertilizers, FYM = farmyard manure incorporation + 55% inorganic fertilizers, WS = 1/3 wheat stubble retention + 55% inorganic fertilizers, RS = 1/3 rice stubble retention + 55% inorganic fertilizers. Error bars denote ± 1 SD. Treatments with same letters are not different significantly at $p \leq 0.05$. Error bars denote ± 1 SE

N fluxes into soil solution (net N mineralization). These assessments make much better relevance than evaluating extractant-based soil nutrient stocks since plants only take nutrients through soil solution in ionic forms. The technique has been found to be a good measure of plant-available N and soil N supply capacity (Qian and Schoenau 2005; Nyiraneza

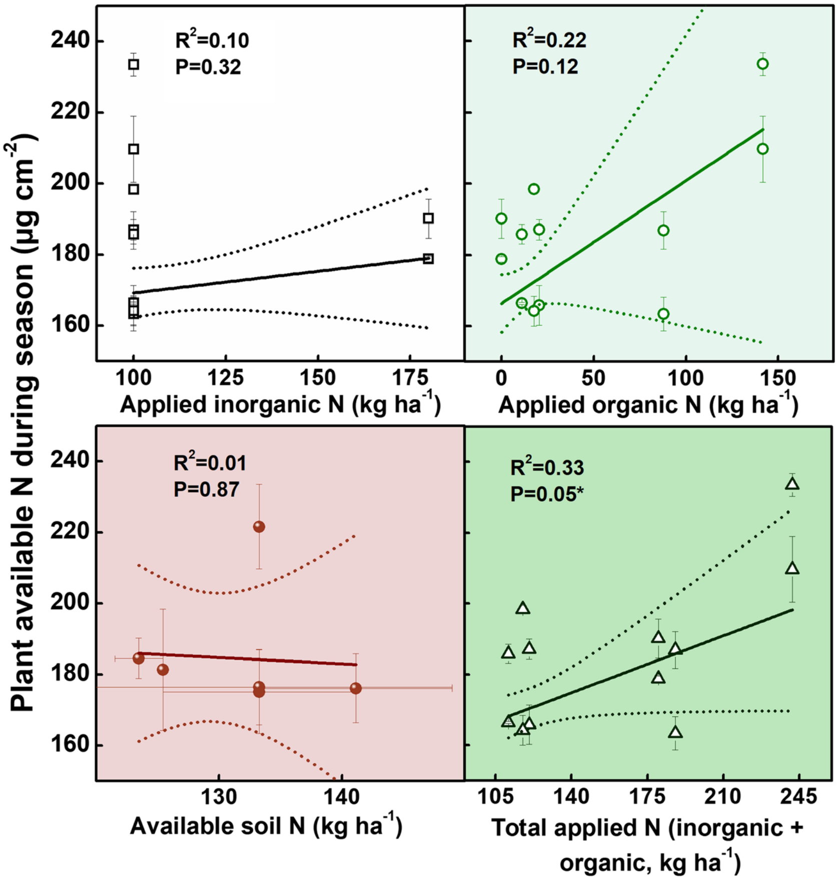

Fig. 7 Relations between nitrogen (N) applied through organic and inorganic sources and N availability in soil solution during rice (*Oryza sativa*) growing season. Error bars denote ± 1 SD. Management: F = 100% inorganic fertilizer, LE = Legume (*Vigna radiata*) in rotation and its biomass incorporation +55% inorganic fertilizers, GM = green manuring with *Sesbania aculeata* + 55% inorganic fertilizers, FYM = farmyard manure incorporation + 55% inorganic fertilizers, WS = 1/3 wheat stubble retention + 55% inorganic fertilizers, RS = 1/3 rice stubble retention + 55% inorganic fertilizers. Error bars denote ± 1 SD. Treatments with same letters are not different significantly ($p \leq 0.05$)

and Snapp 2007; McSwiney et al. 2010). Availability dynamics were unique, for both NH_4^+-N and NO_3^--N forms, for all the management. Higher levels of NH_4^+-N in puddled paddy soil (~ 1.74 μg cm^{-2} day^{-1}, averaged for all management) at 0–45 days after transplanting (DAT) could be due to the conjugated immediate release of N from added fertilizers (split application at 0, 21, and 42 days after transplanting, DAT) and organic sources. Mineralization of organic forms of N to NH_4^+ can supply a pool of NH_4^+-N in soil (De Datta 1981). We observed this shared pool of plant-available NH_4^+-N to be ~ 3.02, 3.48, and 2.49 times higher compared to NO_3^--N at 0–15, 15–30, and 30–45 DAT, respectively. Anaerobic soils, in the absence of O_2, do not favor N mineralization beyond the NH_4^+ production stage, meeting out major N demand in flooded/saturated paddy soils.

The growth stages coinciding with 0–45 DAT are tillering and stem elongation in rice. These are the two most critical stages in crop growth. Supplementing reduced doses of inorganic N fertilizer with organic sources could effectively meet N demand at this stage and save ~ 50% of inorganic fertilizer N. At 0–15 DAT, F and GM had maximum availability of N in soil solution (NH_4^+-N particularly), perhaps due to readily available nitrogen in both these management systems. But these differences became non-significant (compared to other management) at 15–30 and 30–45 DAT, perhaps because (1) most of the readily available nitrogen from fertilizers got lost through leaching or volatilization; (2) decomposition (and release of nutrients) shot up in other organic materials like WS, RS, and FYM; and (3) 2nd (21 DAT) and 3rd (42 DAT) split fertilizer applications provided readily available nitrogen in all management. Residue quality interactions with water regime have a significant influence on N dynamics (Schomberg et al. 1994). Incorporated organic amendments have N immobilization and slower release over time (Corbeels et al. 2003) than fertilizers where N release and leaching can be as early as 5 days of incorporation (Brown et al. 1982).

Beyond 45 DAT, there was a reduction in the available N (particularly a steep decline in NH_4^+-N), for all treatments, in general. This indicated a loss of most of the inorganic forms of fertilizer. However, top dressing of N (at 42 DAT) through urea (and inhibition of *Nitrosomonas* activity through anaerobiosis) maintained average available N levels at 2.40 μg cm^{-2} day^{-1} in F treatment up to 60 DAT. Organic treatments had significantly higher availability from organic forms and, therefore, a sustained release at later stages. Beyond 45 DAT, management F with inorganic fertilizers only indicated a steady decline in N availability while organics-based management picked up, not to a great extent but still better than F. The third split application of synthetic fertilizer in all treatments was at 42 DAT. A decline in N availability in soil solution meant that most of the N through inorganic fertilizers did not sustain longer than 15 days. Of all the management systems, GM sustained high levels of N supply in soil solution throughout the growing period, indicating that high N in organic material played a significant role along with its steady release.

The period of 60–75 DAT coincided with the period of stem elongation and growth. At this stage, the maximum availability was in GM and FYM, but the availability in the form of NO_3^--N steadily increased due to the flooding condition changing to near saturation, since irrigation was managed at weekly intervals. Moreover, alternate wetting and drying cycles facilitated microbial oxidation in soil. Beyond 75 DAT, which is the period of booting, grain filling, and then maturity, NO_3^--N availability in the soil was as significant as that of NH_4^+-N. Organically supplemented management systems maintained significantly higher (37 to 48% more) available N than F, mostly as NO_3^--N. At this stage, availability in WS and RS shot up significantly, indicating delayed decomposition of crop residues leading to maximum release at this stage. Beyond 90 DAT, the N demand for paddy crop at this particular stage is quite low as it is under active pollination and egg fertilization stage.

The IER-based availability scenarios indicated that rice N thirst was largely quenched through the abundance of NH_4^+-N than NO_3-N during most of the cropping period. Overall, nitrogen-rich, low C:N succulents (LE, GM) provided the best advantage, though crop residues (rice/wheat stubble incorporation) seem to mismatch N release at critical stages but it could also be a strategic advantage in the case of long-duration crops/varieties where nutrient release from these materials would coincide with peak nutrient acquisition stages. In the studied management, organic materials seem to release enough nitrogen to compensate for ~ 50% reduction in inorganic fertilizer use. In particular, green manuring (GM) with *Sesbania* had a consistently high supply of N during the complete growing season.

These observations were substantiated by enzymatic activity relations with plant-available N in soil solution. Higher activity related to higher N availability in ready release sources (high total N, low C:N ratio) like F, GM, and LE, during early growth stages, while higher enzymatic activity related to higher N availability in slow-release sources (high C:N ratio, lower total N) during late growth stages. Higher activity and availability of N throughout the growth period in the case of GM were evident as a higher enzymatic activity at both 30 and 90 DAT. In the case of *Sesbania*, leaves with the highest nitrogen percentage and lower C:N ratio (~ 10) decompose rapidly while stems and roots with a higher C:N ratio (~ 100 and 50, respectively) decompose slowly (Palm et al. 1988).

Relations of crop yields (grain and straw) with N availability during the full season did not provide any significant lead, but the yields were highly related to N availability at different stages. The straw yield of rice was directly related to ion exchange resin determined N availability in soil between 30 and 60 DAT with highly significant relations at 30–45 DAT while only slightly significant relations at 45–60 DAT. At all other stages, the relations were negative and significant at 15–30 DAT ($p = 0.03$), 60–75 DAT ($p = 0.05$), and 75–90 DAT ($p = 0.08$). For grain yield too, the relations with available N were direct at 30–45 DAT ($p = 0.0004$) and 45–60 DAT ($p = 0.14$). This perhaps indicated that fertilizer application at transplanting (DAT = 0) is a waste in transplanted rice where flooded conditions favor expedited NH_3 volatilization and denitrification (Zhu et al. 1989). The stage 30–45 DAT was most significantly related to yields, both grain ($p = 0.0004$) and straw ($p = 0.00$). Also, N availability at DAT 45–60 related slightly significantly to grain ($p = 0.14$) and straw ($p = 0.15$) yields. Nitrogen availability at later stages had insignificant negative relations. These results indicate that perhaps 30–60 DAT is the period to be targeted for fertilizer application for maximum gains in yield. Initial period (0–30 DAT) and the period beyond 60 DAT would have most nitrogen lost to the environment. We propose, for consideration of farmers and state extension departments, to encourage inorganic N fertilizer application, whether sole or in integrated mode, between 30 and 60 DAT. But no fertilizer is recommended for application earlier than 15 DAT or after 60 DAT in any case, based on the results of this study. A better N fertilizer splitting strategy could also be 25%, 50%, and 25% instead of equal 1/3rd splits. It is expected that to some extent these relationships may be affected by such factors as crop and soil, and therefore, region-specific recommendations may to be tested and generated.

A strong relationship between added N (inorganic fertilizer N + organic N) and plant-available N, and weak relationship between soil N and plant available N in soil solution indicated that most of the N availability to crop growth should be from the mineralization of freshly applied N. Conversely, most of the N applied through fertilizers and even through organic amendments is mineralized in a cropping cycle and taken up by plants or lost to the environment. In the latter case, it is of utmost importance that the release is slow yet steady to synchronize with plant demand. While 100% inorganic fertilizers straight away lose the case here, crop residues may not keep up with the plant demand at critical stages at the middle of crop growth (e.g,. vegetative growth and stem elongation stages). Perhaps this is an indication that if crop residue incorporation has to be taken up to counter such critical issues like residue burning, then cut down in inorganic fertilizers is not a good option, rather these type of management should be compensated with either recommended levels of fertilizers or even increased fertilizer inputs to expedite decomposition of recalcitrant organic materials like rice straw.

5 Conclusions

The study reported daily net nitrogen (N) mineralization and availability to plants at different crop growth stages for rice crop grown under six major nutrient management systems in the Indo-Gangetic plain: inorganic fertilizers at 100% recommended rate, compared to reduced rate (55%) of inorganic fertilizers supplemented with organic inputs via green manuring with *Sesbania*, biomass incorporation of an opportunity legume crop (green gram, *Vigna radiata*), 1/3rd wheat stubble retention and incorporation, 1/3rd rice stubble retention and incorporation, and farmyard manure application. The integrated nutrient management strategies provided significant advantage in terms of daily N availability to rice plants, especially at peak vegetative growth, booting, and grain filling stages, whereas N availability in 100% inorganic fertilizer-treated soils subsided significantly after the fertilizer application is ceased. Green manuring emerged as the most effective management to cut down fertilizers and for consistently high daily N mineralization (2 $\mu g\ cm^{-2}$) in rice crop, followed by crop residue (rice stubble, wheat stubble, green gram stubble) biomass incorporation, and farmyard manure application (1.6–1.7 $\mu g\ cm^{-2}$). Integration of organics afforded almost 50% reduction in inorganic fertilizer application in rice crop, with better daily N mineralization rates than 100% inorganic fertilizer-only management.

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Data Availability The data supporting the findings in the manuscript are available from the corresponding author on reasonable request.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no competing interests. The funding agency had no role in designing the study, data collection and analysis, and preparation of the manuscript.

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