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Synergistic Effects of Integrated Nutrient Management through Green Manuring on Soil Fertility under Direct Seeded Rice Cultivation

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

An experiment was conducted during the *kharif* season of 2024 at the College of Agriculture (Kaul) CCS Haryana Agricultural University, Hisar to ascertain the viablity of integrated nutrient management through green manuring on soil fertility under direct seeded rice (DSR). The experiment was laid out in a randomized block design with nine treatments comprising different combinations of green manuring crops (dhaincha and mungbean) and recommended dose of nitrogen (RDN). The treatments included T_1 (control), T_2 (Dhaincha), T_3 (Mungbean), T_4 (50% RDN + Dhaincha), T_5 (50% RDN+ Mungbean), T_6 (75% RDN), T_7 (75% RDN + Dhaincha), T_8 (75% RDN + Mungbean) and T_9 (100% RDN), each replicated thrice. The treatments were evaluated for their

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effects on soil physico-chemical properties and availability of macro and micronutrients. Incorporation of dhaincha and mungbean significantly enhanced the availability of both macro (N, P, K) and micronutrients (Fe, Mn, Zn, Cu) while soil bulk density, pH, organic carbon, and electrical conductivity did not differ significantly among the treatments. A slight reduction in pH and bulk density, along with minute appraisal in organic carbon, was observed in green manured plots. The highest available nitrogen (139.3 kg ha^{-1}), phosphorus (27.2 kg ha^{-1}), and potassium (343.8 kg ha^{-1}) contents were recorded in the T_7 treatment, which was statistically comparable with T_8 and T_9. Similarly, T_7 also recorded the highest concentrations of DTPA-extractable zinc (2.05 mg kg^{-1}), iron (14.62 mg kg^{-1}), manganese (3.03 mg kg^{-1}), and copper (1.54 mg kg^{-1}). The results indicate that partial substitution of inorganic nitrogen with green manure crops can effectively enhance soil nutrient availability and improve soil fertility in direct seeded rice systems. Therefore, integration of green manuring with reduced fertilizer application can be considered a sustainable nutrient management strategy for maintaining soil fertility and productivity.

Keywords: Organic carbon; green manuring; direct seeded rice; integrated nutrient management.

1. Introduction

Rice (*Oryza sativa* L.), the world's most important food crop has been grown for more than 6000 years in South Asia. Furthermore, it stands out from other common cereal grains by its unique qualities, having the highest digestible energy levels and net protein utilization (Xie *et al*., 2022). The Asia-Pacific region produces and consumes more than 90% of the world's rice. India ranks as the world's second-largest producer and consumer of rice (Mishra *et al*., 2017). In India, it is grown on an area of 47.7 million hectares with a production of 136.4 million ton (Anonymous, 2024). Productivity of the crop in India and Haryana is 2859 kg ha^{-1} and 3749 kg ha^{-1} respectively (Anonymous, 2024b, Mangaraj et al., 2023).

Introduction of high yielding varieties of rice during green revolution enhanced production and enabled the country to become a food surplus nation. However, the high nutrient input demand of these varieties necessitated the application of nutrients particularly Nitrogen, Phosphorus and Potassium externally through synthetic fertilizers to sustain the yield. Excessive and imbalanced use of fertilizers along with faulty nutrient management has led to significant reduction in soil organic matter which has caused severe soil health degradation. The productive potential of soil has declined to such a level that farmers are forced to apply ever increasing amount of chemical fertilizers to maintain the same yield levels. This has caused a sustainability trap forming a chemical treadmill where higher inputs are required just to keep productivity from declining. The breaking of this cycle requires a sustainable approach that not only improves soil health but also maintains the yield in an environment friendly manner.

Excessive reliance on chemical fertilizers for sustaining crop productivity has led to deterioration of soil health, decline in soil organic matter and imbalance in nutrient availability. Continuous application of high fertilizer doses without adequate organic inputs has resulted in reduced soil fertility and environmental concerns. Therefore, sustainable nutrient management strategies are required to maintain soil productivity while minimizing adverse environmental impacts. Integrated nutrient management (INM), which combines inorganic fertilizers with organic sources such as green manure crops, has been recognized as an effective approach for improving soil fertility, enhancing nutrient cycling and maintaining long-term soil productivity.

Green manuring refers to the agricultural practice of incorporating fresh, undecomposed green plant biomass into the soil to enhance its fertility and improve its physical, chemical, and biological properties. This practice involves ploughing or turning under succulent plant tissues before they undergo decomposition, thereby enriching the soil with organic matter and nutrients. Green manure (GM) crops generally produce substantial quantities of biomass, both above and below ground, which contributes to improved soil structure and microbial activity.

Green manuring can be broadly categorised into two types: *in situ* and *ex situ*. In *in situ* green manuring, the green manure crop is cultivated and subsequently incorporated directly into the same field where it is grown. In contrast, *ex situ* green manuring involves the collection of green plant materials from external sources and their subsequent incorporation into the soil (Mahey et al., 2024). Both approaches aim to enhance soil organic matter content and promote nutrient cycling.

The use of nitrogen-fixing leguminous crops as green manure plays a particularly significant role in nutrient management in rice-based cropping systems. These legumes establish symbiotic associations with nitrogen-fixing microorganisms, thereby contributing a substantial proportion of the nitrogen (N) required by rice crops. Moreover, the incorporation of green manure biomass enriches the soil with organic matter, which helps maintain soil fertility, improves soil structure, and enhances microbial activity. Consequently, green manuring is considered an important component of sustainable agricultural practices, particularly in maintaining long-term soil productivity and ecological balance (Latt et al., 2009).

GM crops can absorb low availability nutrients by developing a deep root system, which allows nutrient uptake from deeper soil in addition to providing nutrients to the soil. This can reduce the requirement for fertilizers, especially nitrogen fertilizers, and improve the concentration of plant nutrients in the surface soil (Van Nordwijk *et al*., 2015). In cereal-based intensive cropping systems, incorporation of green manure biomass to the soil aids in the buildup of organic matter, nutrient addition and recycling and the enhancement of the hydro-physical characteristics of the soil. They encourage a quicker mineralization of nitrogen since their C:N ratio is lower than that of cereals (Li *et al*., 2021). Soil health degradation, environmental pollution, and food security have emerged as some of the most pressing challenges confronting modern agriculture. With the rapid growth of the global population, the demand for staple crops such as rice continues to rise substantially. To meet this increasing demand, agricultural systems have undergone significant intensification, often relying heavily on chemical inputs, particularly synthetic fertilisers. Although these inputs have contributed to increased crop productivity in the short term, their excessive and prolonged use has resulted in considerable deterioration of soil physicochemical properties. Such practices have adversely affected soil structure, nutrient balance, and microbial activity, ultimately compromising long-term soil fertility and sustainability (Singh et al., 2014). Moreover, chemical fertilizer-dependent rice production technology resulted in severe losses of soil organic matter, affecting nutrient flows and consequently limiting yield. Restoring soil health is crucial for ensuring sustainable crop production, especially in the context of feeding an exponentially growing global population. Although soil fertility can be improved through the application of chemical fertilizers and other soil amendments, the indiscriminate and excessive use of chemical fertilizers has led to the degradation of soil quality. A more sustainable and cost-effective approach involves the integrated application of chemical fertilizers in combination with green manuring, which can help mitigate soil fertility issues while maintaining productivity (Naz *et al*., 2023). Studies involving INM in direct seeded rice through green manuring are scarce and the present investigation was carried out explore the feasibility of partial substitution of inorganic nitrogen with green manure crops with an objective to attain comparable yield obtained from inorganic fertilizers.

2. Material and Methods

The experiment was conducted in a Randomized Block Design (RBD) comprising nine treatments with three replications. The treatments included different combinations of green manuring and recommended dose of nitrogen (RDN), namely T_1: Control (no fertilizer and no green manure), T_2: Dhaincha as green manure, T_3: Mungbean as green manure, T_4: 50% RDN + Dhaincha, T_5: 50% RDN + Mungbean, T_6: 75% RDN, T_7: 75% RDN + Dhaincha, T_8: 75% RDN + Mungbean, and T_9: 100% RDN. The experiment was initiated with the sowing of green manuring crops Dhaincha (25 kg ha^{-1}) and Moong (30 kg ha^{-1}) in the 1st week of May, 2024 by broadcasting 45 days prior to the preparation of the main field and their subsequent incorporation in the month of June followed by the sowing of direct seeded rice crop 15 days after the incorporation. Rice seeds were sown with seed drill maintaining the row spacing of 20 cm @ 20 kg seeds per hectare area on June 20th, 2024. The physico-chemical characteristics of the surface soil (0–15 cm) were analyzed prior to the initiation of the experiment and are presented in Table 1.

Fertilizers application: For the cultivation of direct seeded rice (DSR), recommended dose of fertilizers was applied as per the package of practice of CCSHAU, Hisar. The recommended dose of fertilizers $N_{75}P_{30}K_{30}$ kg ha^{-1} was supplied using 137 kg ha^{-1} of urea, 65 kg ha^{-1} of diammonium phosphate (DAP), and 50 kg ha^{-1} of muriate of potash (MOP).

2.1 Soil Sampling and Soil Analysis

To determine the bulk density (BD) of soil, the Core sampler method established by Blake and Hartge in 1986 was utilized. The bulk density was then calculated using the appropriate formula

$$\text{Bulk Density (g/cc)} = \frac{\text{Oven dry weight of soil}}{\text{Volume of soil}} \times 100$$

Table 1. Initial properties of the experimental soil

Soil texture	Clay loam
Bulk density (Mg m^{-3})	1.34
pH	8.23
Electrical conductivity (dS m^{-1})	0.19
Organic Carbon (%)	0.651
Available N (kg ha^{-1})	117
Available P (kg ha^{-1})	23.2
Available K (kg ha^{-1})	318
DTPA extractable Zn (mg kg^{-1})	1.87
DTPA extractable Fe (mg kg^{-1})	13.46
DTPA extractable Cu (mg kg^{-1})	1.38
DTPA extractable Mn (mg kg^{-1})	2.79

The pH of the soil was assessed using a 1:2 soil-water suspension. The mixture was stirred intermittently and the pH readings were taken by a glass electrode pH meter after calibrating it with three buffer solutions of pH 4.0, 7.0 and 9.5 respectively. Electrical conductivity was determined by Solu bridge method as described by Richards (1954) preparing 1:2 soil: water suspension. Soil organic carbon was estimated by the wet digestion method (Walkley and Black, 1934). The available nitrogen in the soil sample is determined by the alkaline permanganate method,following the procedure described by Subbiah and Asija (1956). The sodium bicarbonate ($NaHCO_3$) extraction and colorimetry method described by Olsen *et al*. (1954) was used to determine the available P content in soil samples. Available K content in soil samples was determined by using the method of Jackson (1973). Diammonium penta acetic acid (DTPA)-extractable micronutrients were determined by following the method described by Lindsay and Norvell (1978).

2.2 Statistical Analysis

The data were statistically analyzed using the OPSTAT statistical software package developed by the Department of Statistics, CCS HAU (Sheoran *et al*., 1998) to perform an ANOVA test at a significance level of p = 0.05. The significance of the treatment means was determined by applying Duncan's Multiple Range Test (DMRT) at the 5% level of significance.

3. Results

3.1 Soil pH and EC

The findings indicated that there was no significant change in soil pH across the treatments when compared to the control. Soil pH ranged between 8.17 dS m^{-1} to 8.21 dS m^{-1} (Table 2). The lowest pH (8.17) was observed in T_7 (75% RDN + Dhaincha) and T_8 (75% RDN + Mungbean) treatments while the highest (8.21) was observed in T_1 (control). There was no significant change in soil pH across the treatments. Soil EC ranged between 0.18 and 0.19 dS m^{-1} across treatments (Table 2). The control (T_1), T_6 (75% RDN), and T_9 (100% RDN) recorded the highest EC values (0.19 dS m^{-1}), while the lowest EC (0.18 dS m^{-1}) was noted in treatments involving green manuressuch as T_2 (Dhaincha), T_3 (Mungbean), T_4 (50% RDN + Dhaincha), T_5 (50% RDN+ Mungbean)and T_8 (75% RDN + Mungbean).

Soil organic carbon: Statistically there was no significant difference in organic carbon across the treatments (Table 2). The soil organic carbon varied from 0.65 to 0.69%. The highest soil organic carbon (0.69%) was recorded in T_7 (75% RDN + Dhaincha) treatment while the lowest (0.65%) was recorded in T_1 (control).

Available N, P, K: The data presented in Table 3 indicated a significant improvement in the available nitrogen, phosphorus and potassium content of soil under green manured treatments over the control. The available N, P and K contents after harvest ranged from 112.7 to 139.3 kg ha^{-1}, 22.4 to 27.2 kg ha^{-1}, , and 313.0 to 343.8 kg ha^{-1}, respectively. Compared with the initial soil status (117, 23.2 and 318 kg ha^{-1} of N, P and K, respectively), most of the integrated treatments recorded a build-up in nutrient availability, whereas the control showed a slight decline.

The highest available nitrogen (139.3 kg ha^{-1}), phosphorus (27.2 kg ha^{-1}) and potassium content (343.8 kg ha^{-1}) were recorded under T_7 (75% RDN + Dhaincha)followed closely by T_9 (100% RDN) and T_6(75% RDN), which represented an increase of about 23.6% in N, 21.8% in P and 9.8% in K over the control. The control treatment (T_1) registered the lowest nutrient availability for all three macronutrients.

Table 2. Effects of Integrated Nutrient Management through green manuring on physico-chemical properties of soil

Treatments	Bulk Density (Mg m^{-3})	pH (1:2)	EC (dS m^{-1}) (1:2)	Organic Carbon (%)
T_1 – Control	1.341±0.011^{a}	8.21±0.208^{a}	0.19±0.006^{a}	0.65±0.012^{a}
T_2 – Dhaincha	1.324±0.002^{a}	8.18±0.199^{a}	0.18±0.006^{a}	0.66±0.006^{a}
T_3 – Mungbean	1.327±0.010^{a}	8.19±0.193^{a}	0.18±0.000^{a}	0.66±0.012^{a}
T_4 - 50% RDN + Dhaincha	1.323±0.019^{a}	8.17±0.078^{a}	0.18±0.006^{a}	0.67±0.015^{a}
T_5 - 50% RDN+ Mungbean	1.325±0.005^{a}	8.18±0.203^{a}	0.18±0.000^{a}	0.67±0.012^{a}
T_6 -75% RDN	1.339±0.025^{a}	8.19±0.161^{a}	0.19±0.000^{a}	0.66±0.000^{a}
T_7 -75% RDN+ Dhaincha	1.322±0.024^{a}	8.17±0.116^{a}	0.18±0.000^{a}	0.69±0.009^{a}
T_8 - 75% RDN + Mungbean	1.324±0.025^{a}	8.17±0.167^{a}	0.18±0.003^{a}	0.68±0.015^{a}
T_9 - 100% RDN	1.338±0.008^{a}	8.19±0.047^{a}	0.19±0.006^{a}	0.66±0.015^{a}
CD ($p \le 0.05$)	N/S	N/S	N/S	N/S
SE(m)	0.019	0.10	0.00	0.01

*The means with different Letters as superscripts are significant ($P < 0.05$); (*RDN- recommended dose of nitrogen)*

Table 3. Effects of integrated nutrient management through green manuring on available N, P and K in soil

Treatments	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
T_1 - Control	112.7± 1.19^{f}	22.4± 0.42^{d}	313.0± 0.15^{c}
T_2 - Dhaincha	126.2± 0.71^{de}	25.4± 0.50^{bc}	332.3± 1.72^{ab}
T_3 - Mungbean	122.4± 1.93^{e}	24.7± 0.27^{c}	326.1± 3.54^{b}
T_4 - 50% RDN + Dhaincha	133.1± 2.91^{bc}	26.8± 0.09^{ab}	339.6± 5.68^{a}
T_5 - 50% RDN+ Mungbean	129.2± 1.40^{cd}	26.3± 0.47^{ab}	333.4± 2.97^{ab}
T_6 -75% RDN	132.7± 0.21^{bc}	25.9± 0.27^{abc}	340.7± 2.65^{a}
T_7 -75% RDN+ Dhaincha	139.3± 2.71^{a}	27.2± 0.21^{a}	343.8± 2.35^{a}
T_8 - 75% RDN + Mungbean	135.6± 0.78^{ab}	26.1± 0.57^{abc}	338.1 ± 6.16^{a}
T_9 - 100% RDN	138.8± 1.67^{a}	26.6± 0.62^{ab}	342.9± 1.96^{a}
CD ($p \le 0.05$)	4.9	1.3	10.8
SE(m)	1.7	0.4	4.2

*The means with different Letters as superscripts are significant ($P < 0.05$); (*RDN- recommended dose of nitrogen)*

Table 4. Effects of Integrated Nutrient Management through green manuring on DTPA-extractable Zn, Fe, Mn and Cu in soil

Treatments	Zn (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})
T_1 - Control	1.84± 0.030^{e}	13.34±0.089^{b}	2.66±0.021^{d}	1.36±0.015^{e}
T_2 - Dhaincha	1.98± 0.006^{abcd}	14.51±0.295^{a}	2.88±0.009^{bc}	1.47±0.009^{bc}
T_3 - Mungbean	1.95±0.042^{cd}	14.38±0.158^{a}	2.83±0.054^{c}	1.44±0.036^{cd}
T_4 - 50% RDN + Dhaincha	2.03±0.000^{ab}	14.57±0.006^{a}	2.97±0.050^{abc}	1.52±0.000^{ab}
T_5 - 50% RDN+ Mungbean	1.99±0.030^{abcd}	14.42±0.006^{a}	2.94±0.015^{abc}	1.50±0.000^{ab}
T_6 - 75% RDN	1.93±0.003^{d}	14.39±0.158^{a}	2.85±0.050^{bc}	1.41±0.009^{de}
T_7 - 75% RDN+ Dhaincha	2.05±0.009^{a}	14.62±0.359^{a}	3.03±0.026^{a}	1.54±0.018^{a}
T_8 - 75% RDN + Mungbean	2.02±0.012^{abc}	14.49±0.172^{a}	2.98±0.068^{ab}	1.52±0.003^{ab}
T_9 - 100% RDN	1.96±0.026^{bcd}	14.40±0.235^{a}	2.87±0.047^{bc}	1.42±0.033^{cd}
CD ($p \le 0.05$)	0.07	0.52	0.13	0.05
SE(m)	0.03	0.15	0.04	0.02

*The means with different Letters as superscripts are significant ($P < 0.05$); (*RDN- recommended dose of nitrogen)*

DTPA-Extractable Micronutrients: The data presented in Table 4 indicated a significant influence of different nutrient management treatments on the availability of DTPA-extractable zinc (Zn), iron (Fe), manganese (Mn) and copper (Cu) in soil after harvest. The concentration of micronutrients varied from 1.84 to 2.05 mg kg^{-1} for Zn**,** 13.34 to 14.62 mg kg^{-1} for

Fe, 2.66 to 3.03 mg kg^{-1} for Mn, and1.36 to 1.54 mg mg kg^{-1} for Cu across the treatments. The control treatment (T_1) recorded the lowest values of all micronutrients, indicating comparatively poor micronutrient status in the absence of nutrient inputs.

The highest availability of Zn (2.05 mg kg^{-1}), Fe (14.62 mg kg^{-1}), Mn (3.03 mg kg^{-1}) and Cu (1.54 mg kg^{-1}) was observed under T_7 (75% RDN + Dhaincha), followed closely by treatments involving combined application of green manure with inorganic nitrogen such as T_4 and T_8.

4. Discussion

Bulk density: A slight non-significant decrease in its value was observed in the treatments where green manures were incorporated along with RDN as compared to the control. The increase in soil organic carbon, which is a binding agent for soil particles aids in increasing soil aggregation, may be the cause of the decrease in bulk density (Kumar *et al*., 2012). This might also be due to the addition of organic matter from the incorporated dhaincha and mungbean which is decomposed by microorganisms. Green manure may improve the soil microbial activities for organic matter decomposition which leads to enhancement of soil porosity and a decrease in soil bulk density (Naz *et al*., 2023, Islam *et al*., 2019, Carter *et al*., 2014 and Sultani *et al*., 2007).

Soil pH: The perusal of data indicated a non-significant difference in soil pH by incorporation of green manures. Although, incorporation of dhaincha and mungbean had slightly lowered soil pH compared with the control treatment. The decrease in soil pH may be due to the production of CO_2 and organic acids during decomposition of incorporated green manure which can supply protons to the soil inducing a decrease in pH (Islam *et al*., 2019). Kumar *et al*. (2012) also reported a decrease in soil pH due to production of organic acids during the decomposition of organic materials. Similar results were reported by Kumar *et al.* (2023) Adekiya*et al*. (2019), Meena *et al*. (2018), Alagappan and Venkitaswamy (2016) and Pathak *et al*. (2015).

Soil EC: It was observed that the application of green manures in combination with RDN had a non-significant influence on the EC value of soil. However, there was a slight decrease in soil EC in treatments with GM incorporation as compared to the control. These results were confirmed by the findings of Pathak *et al*. (2015) and Kumar *et al*. (2012).

Soil organic carbon: The data indicated a non-significant increase in soil organic carbon due to incorporation of green manure along with RDN (T_7 -75% RDN+ Dhaincha, T_8 - 75% RDN + Mungbean , T_4 - 50% RDN + Dhaincha and T_5 - 50% RDN+ Mungbean) as compared to the control. The increase in soil organic carbon might be due to the incorporation of green manure into the soil which upon decomposition increased the soil organic carbon.This might also be due to residual effect of added organic matter and enhanced microbial biomass carbon (Rautaray *et al*., 2020). The increase in soil organic carbon content with green manures has also been reported previously by Ansari *et al*. (2022), Kumar *et al*. (2022), Li *et al*. (2020), Swarup *et al*. (2019) and Meena *et al*. (2018).

Available Nitrogen: The increase in soil available N might be due to the direct addition of inorganic N and through decomposition of green manures promoting greater multiplication of soil microbes, which could convert organically bound N to inorganic form (Sandhya Rani *et al*., 2022). Also, green manuring with *dhaincha*fixes the atmospheric N via root nodulation that results in enhanced N availability in soil (Das *et al*., 2024). Dhaincha and mungbean are legumes that perform biological nitrogen fixation through symbiotic association with *Rhizobium* bacteria in their root nodules that convert atmospheric N into ammonia. The favourable soil conditions resulting from green manuring might have helped the mineralization of soil N leading to its enhanced availability (Gabhane *et al*., 2023). These results are in line with findings of Ansari *et al*. (2022), Meena *et al*. (2018), Yang *et al*. (2018), Kumar & Singh (2010) and Mandal *et al*. (2003).

Available Phosphorus: The increased available P might be because organic anions compete with phosphate ions for binding sites on soil particles hence reducing the P fixation in soil (Kumar *et al*., 2018). The organic matter present in soil forms a protective cover on sesquioxides and this facilitates a reduction in the phosphate fixing capacity of soil (Kumar and Singh, 2010). This might also be due to the enhancement of biological phosphorus cycling due to inclusion of green manuring crops that improves the dissolution and bioavailability of sparingly soluble phosphates (Sandhya Rani *et al*., 2022). The increase in available P content with increase in N levels might be due to increased crop growth, which might have led to more root exudates and ultimately solubilized more soil P hence, resulting increased available P. Similar results were observed by Ansari *et al*. (2022), Narayan *et al*. (2006) and Randhawa *et al*. (2005).

Available Potassium: The availability of K might be due to addition of K to the available pool of the soil, reducing K fixation and release of K due to interaction of decomposed green manure biomass with clay (Sandhya Rani *et al*., 2022). Gabhane *et al*. (2023) also reported the reduction in potassium fixation and its release from non-exchangeable sites due to the interaction of organic matter with clay surface. Increase in available K with nitrogen application might be due to the increase in the concentration of NH^{4+} ion in the soil solution which would have replaced K from the clay complexes (Phillips *et al*.,1998). This finding corroborated with Sharma *et al*. (2023), Yadav *et al*. (2019), Singh *et al*. (2002), Singh *et al*. (2001) and Kumar & Singh (2010).

DTPA-extractable Zn, Fe, Mn and Cu in soil: DTPA-extractable Zn, Fe, Mn and Cu in soil were found significantly higher in treatments with incorporation of dhaincha or mungbean with application of inorganic fertilizers as compared to control. This might be due to better physico-chemical soil properties and higher nutrient availability in the green manured treatments (Yadav *et al*., 2020). Nayyar and Chhibba (2000) also reported the increase in the availability of DTPA extractable Fe and Zn due to the incorporation of green manures into soil. Singh and Shivay (2016) also noted that dhaincha produced the highest dry matter (5.46–5.77 t ha^{-1}), creating a larger pool of organic residues rich in micronutrients and its incorporation released significant Zn, Cu, and Fe back into the soil, elevating micronutrient availability. Moreover, green manures on decomposition release a wide range of organic acids which form soluble organometallic complexes, hindering adsorption, precipitation, and fixation by soil constituents, thereby enhancing the solubility and availability of micronutrients from the non-labile pools (Gruter *et al*., 2017). These results are in line with findings of Sanwal *et al*. (2023), Mandi *et al*. (2022), Duhan and Singh (2002) and Singh *et al*. (1992).

5. Conclusion

The present study demonstrated that integration of green manuring with inorganic fertilizers significantly improved soil nutrient availability under direct seeded rice cultivation. Incorporation of dhaincha or mungbean along with 75% recommended dose of nitrogen enhanced the availability of both macro- and micronutrients compared with sole fertilizer application and control treatments. Among the treatments, 75% RDN combined with dhaincha proved to be the most effective in improving soil fertility status. These findings suggest that partial substitution of chemical nitrogen fertilizers with leguminous green manure crops can serve as a sustainable nutrient management strategy for maintaining soil health, improving nutrient availability and ensuring long-term productivity of direct seeded rice systems.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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