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Nitrogen-fortified nanobiochar impacts soil properties, root growth and basmati rice yield

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Abstract

Nanobiochar (NB) has emerged as a promising sustainable soil amendment, enhancing soil fertility due to its high surface area, porous nature, and nutrient retention and slow-release capabilities. Fortified nanobiochar application could be a durable strategy for enhancing soil fertility and crop productivity in nutrient deficient soils. This study investigates the effects of nitrogen-fortified nanobiochar (NBN) on nitrogen-deficient soils, aiming to reduce reliance on mineral fertilizers (MF) without compromising crop yield. An experiment was conducted with twelve treatments including MF at 100%, 75% and 50% of the recommended nitrogen dose alongside NBN applied at rates of 1, 2.5 and 5 kg ha⁻¹, either alone or in combination. Results indicated that the combined application of 75% mineral nitrogen (N₇₅) and 5 kg ha⁻¹ of NBN (N₇₅NBN₅) significantly improved soil moisture content (SM), infiltration rate (IR), aggregate stability (AS) and hydraulic conductivity (H_c) by 1.01 to 1.42 times compared to the N₁₀₀ and N₇₅ treatments. Additionally, soil organic carbon, available N, NH₄ and NO₃ contents increased by 1.22, 1.03, 1.06 and 1.06 times, respectively, under N₇₅NBN₅ over N₁₀₀ leading to enhanced nutrient uptake. Root growth metrics (root weight, length and volume) increased by 24.6%, 15.8% and 18.7%, respectively, while rice yield improved by 26.8% with N₇₅NBN₅ compared to the N₇₅ treatment, with the lowest yield observed in the NBN₁ treatment. The significant and positive correlation between grain yield and soil physical properties and soil nutrient levels, confirmed the beneficial impact of NBN on soil properties that directly influenced crop yield. The study demonstrates that the integration of N₇₅ with NBN₅ not only enhances soil properties and crop growth but also offers ecological benefits by the valorization of agricultural waste into an effective soil amendment, thereby promoting sustainable agricultural practices.

Highlights

- Nitrogen fortified nanobiochar (NBN) triggered beneficial changes in rice rhizosphere, prompting plant health.
- NBN with 75% mineral fertilizer (N₇₅) significantly enhanced grain yield, and improved root attributes and nutrient uptake.
- NBN with N₇₅ significantly increased organic carbon (~ 1.22 times), available N (~ 1.03 times), and ammonium (~ 1.06 times) and nitrate (~ 1.06 times) over RDF.
- NBN with N₇₅ increased soil moisture, MWHC and aggregate stability by 20.6%, 12.3% and 12.2%, respectively, enhancing soil health and drought resilience.

Keywords Nitrogen fortified nanobiochar, Mineral fertilizer, Basmati rice, Soil properties

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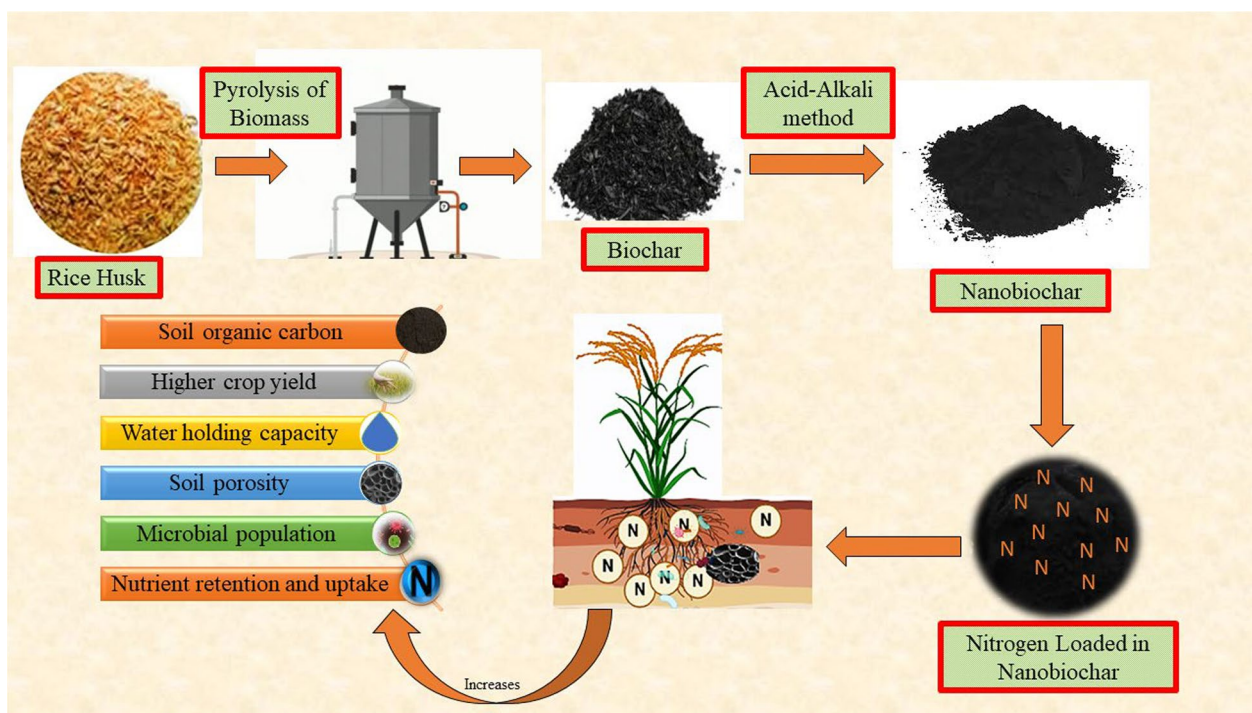
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Graphical Abstract



1 Introduction

Rice (*Oryza sativa* L.) is a staple food source for over two-thirds of the world's population (Zhao et al. 2020). India is the second-largest producer (120 million tons) and leading exporter of rice globally (USDA 2021; APEDA 2020). In addition, the world-famous basmati-370 cultivated in Jammu region of India is popular for its typical characteristics such as aroma, flavor, and long grain (Singh et al. 2021). However, the mismanagement and overuse of synthetic nitrogen (N) fertilizers have caused a potential threat to soil health and water quality (Dissanayake et al. 2019). Furthermore, the soils in basmati-growing areas are often deficient in organic carbon and available nitrogen (Raina Kour et al. 2021). Therefore, integrating organic amendments with mineral fertilizers can be an advantageous strategy to promote sustainable farming practices, maintain soil quality, and mitigate the environmental impact of inorganic fertilizers (Iqbal et al. 2021). It is well known that inorganic fertilizer, in combination with soil amendment, can restore the soil fertility and accelerate crop productivity (Alves et al. 2019; Oladele 2019; Sharma et al. 2021; Abrol et al. 2024a, Sharma et al. 2025). In recent years, biochar and nanobiochar have been widely used to enhance soil aggregation and biological activity that help in improving soil moisture

retention and consequently, crop yield (Sistani et al. 2019; Abrol et al. 2024b; Ali et al. 2020; Brar et al. 2024). Moreover, biochar can significantly reduce greenhouse gas emissions by capturing and storing soil carbon and offer a favourable environment for root growth (Dissanayake et al. 2019; Abrol and Sharma 2019; Ali et al. 2020). India generates 600–800 million tons (MT) of rice straw annually, which is directly burnt to clear fields, a practice that has caused nutrient loss, greenhouse gas emissions and environmental pollution (Pode 2016; Ahmed et al. 2015; Dissanayake et al. 2019; Abrol and Sharma 2019). Potentially, India could valorize 212.04 ± 44.27 MT of biochar from 517.82 MT of crop residues, thereby contributing to improved energy security, supporting livelihoods, enhancing agricultural productivity, and promoting environmental sustainability (Anand et al. 2022; Sharma et al. 2024).

Biochar, a carbon rich, spongy solid material produced through pyrolysis under limited oxygen supply, has been reported to improve soil characteristics, promote crop yield, and influence soil properties due to its high porosity and large surface area (Kumar et al. 2024; Sharma et al. 2025; Liu et al. 2020; Ghani et al. 2024; Meier et al. 2021; Kambo and Dutta 2015; Abrol et al. 2016; Sharma et al. 2025). Additionally, aromatic nature of biochar increases

the carbon sequestration, reduces nitrogen leaching, and supports nutrient and water retention (Sashidhar et al. 2020; Clough et al. 2013). This might be attributed to its large surface area, cation exchange capacity, recalcitrant carbon, and porous structure (Bian et al. 2016; Bolan et al. 2024). Studies have shown that applying biochar to tropical agricultural soils enhances nitrogen uptake by plants (Sistani et al. 2019) and improves nitrogen availability to crops (Li et al. 2017). Nitrogen enriched biochar can function as a slow-release fertilizer, potentially reducing the environmental drawbacks of conventional fertilizers while improving nutrient uptake by crops (Zhang et al. 2017; Shi et al. 2020). In rice farming, biochar has been found to be an effective soil amendment, improving rice yield and soil properties (Abrol et al. 2024b; Ali et al. 2020). Prayogo et al. (2014) found that soil application of biochar enhances microbial activity, which is crucial for soil health and fertility. However, some studies have reported no effects on nutrient retention following the application of biochar (Mukherjee and Lal 2014; Nguyen et al. 2017). Due to its high carbon content, biochar has the potential to improve crop yield while also providing environmental protection (Ali et al. 2020). Biochar is particularly effective in nutrient-poor, coarse-textured sandy soils under adverse water stress conditions (Abrol et al. 2024b). The addition of biochar, especially when combined with manures, has been found to improve soil water-holding capacity and nutrient availability in nutrient-poor, coarse textured sandy soils under adverse water stress conditions (Sharma et al. 2021; Abrol et al. 2024b). Numerous studies have highlighted the beneficial effects of integrating biochar with mineral fertilizers to sustain soil quality and crop yield (Ali et al. 2020; Haque et al. 2022). Abrol et al. (2024b) indicated that the conjunctive use of mineral fertilizer and biochar improved nutrient availability and enzyme activity, resulting in increased crop yield.

Nanobiochar (with particle sizes < 100 nm) possesses a significantly larger specific surface area, smaller hydrodynamic radius, more negative zeta potential, and a greater number of oxygen-containing functional groups as compared to bulk biochar (Naghdi et al. 2018; Rajput et al. 2022). Many studies have shown that incorporating NB significantly improves soil health, increases moisture retention, and enhances nutrient accessibility, thereby creating favourable conditions for optimal plant growth (Brar et al. 2024; Saxena et al. 2014). These benefits can be attributed to the increased catalytic activity, large specific surface area, improved pore structure, and a greater number of surface functional groups and active sites (Naghdi et al. 2018; Tan et al. 2016). NB, even under deficit irrigation, could act as a reservoir of water, regulates nutrients availability and improves plant metabolic

activities, thereby affecting crop growth directly by supplying nutrients and indirectly by modifying soil properties that can improve root development (Raza et al. 2023; Brar et al. 2024; Rasheed et al. 2024). Sammar et al. (2023) also recorded a 20% improvement in wheat yield. Moreover, NB has been suggested as an efficient amendment to reduce nitrogen losses from the soil due to its unique inherent properties (Chen et al. 2020; Rajput et al. 2022). NB exhibit enhanced sorption capabilities, which are influenced by its numerous functional groups, pore characteristics and high reactivity sites (Yue et al. 2019). NB combined with fertilizers has the potential to enhance nutrient availability and microbial activity, which aids in the remediation of harmful pollutants in both soil and water (Rashid et al. 2023; Brar et al. 2024; Zhang et al. 2021).

While previous studies have explored the benefits of biochar and mineral fertilizers, and their combined effects, the present study investigates the sole and combined effect of nitrogen-fortified nanobiochar (NBN) and mineral fertilizers (FM). The novelty of the study lies in the utilization of nanoscale modification of biochar as a smart delivery system, which, when combined with mineral fertilizers, creates a more efficient nutrient synergy than their sole application. Despite these benefits, information on the interactive effect of NBN and MFs especially at differential doses, on crop performance and soil properties is scarce. We hypothesized that NBN would improve nutrient availability, enhance soil properties thereby promote root development and plant growth. Therefore, the present experiment was conducted to explore the effects of NBN and fertilizers on rhizosphere soil properties, root growth and yield of basmati rice.

2 Materials and methods

2.1 Location, climate and soil of the experiment

The study was conducted in a sub-tropical climate with the hot and humid period spanning from July to September and cold winters from November to January. The experimental site was located in the Western Himalayan agro-climatic zone-I (Jammu, J&K) situated in the Shivalik foothills of the North-Western Himalayas at 32°40' N latitude and 74°58' E longitude at an altitude of 332 m above mean sea level. The meteorological data showed that the total rainfall during the crop growth period was 1115 mm, 29.95% higher than the normal rainfall. The highest weekly rainfall occurred in the 29th Standard Meteorological Weeks (SMW) and recorded 174.80 mm rainfall. The rice crop grown during the *kharif* 2023 experienced a maximum mean weekly temperature of 35.60 °C in the 36th SMW and a minimum temperature of 23.50 °C in the 48th SMW in November. The mean weekly morning relative humidity ranged from 80 to 96%,

recorded in the 26th and 49th SMW, while the mean weekly evening relative humidity ranged from 45 to 76%, observed in the same weeks. The detailed weather data were collected from the university weather station and are included in Supplementary Fig. S1. The taxonomical soil unit was an Inceptisol with a sandy clay loam texture, with an initial pH and EC in a 1:2.5 (w:v) soil: distilled water suspension, bulk density, organic carbon, available nitrogen, phosphorus, and potassium of 7.31 ± 0.04 , $0.26 \pm 0.01 \text{ dSm}^{-1}$, $1.45 \pm 0.042 \text{ cm}^{-3}$, $0.44 \pm 0.02 \text{ gkg}^{-1}$, $216 \pm 4.5 \text{ kg ha}^{-1}$, $12.5 \pm 0.67 \text{ kg ha}^{-1}$ and $151.2 \pm 1.89 \text{ kg ha}^{-1}$, respectively.

2.2 Experimental details

Rice (*Oryza sativa*) variety Basmati-370 was grown during the *khari* 2023 (July to November) in pots. Twenty-five-day-old rice seedlings (initially 4 seedlings per pot) were transplanted into pots on 20th July 2023. Each pot having a diameter of 30 cm and a height of 30 cm (with an area of 0.07065 m^2) was filled with 12 kg soil obtained from the university's research farm. To achieve our research objectives, twelve different treatments were applied, namely: T₁–100% N through FM; T₂–75% N through FM; T₃–50% N through FM; T₄–NBN 1 kg ha⁻¹; T₅– NBN 2.5 kg ha⁻¹; T₆– NBN 5 kg ha⁻¹; T₇–75% N through FM+NBN 1 kg ha⁻¹; T₈–75% N through FM+NBN 2.5 kg ha⁻¹; T₉–75% N through FM+NBN 5 kg ha⁻¹; T₁₀–50% N through FM+NBN 1 kg ha⁻¹; T₁₁–50% N through FM+NBN 2.5 kg ha⁻¹; T₁₂–50% N through FM+NBN 5 kg ha⁻¹ were imposed.

Each treatment was replicated three times in a completely randomized design (CRD). Seven days after transplantation, the number of plants per pot was reduced to three, which were then maintained until maturity. The recommended fertilizer dose of P and K @ P₂O₅ 20 and K₂O 10 kg ha⁻¹, respectively, and was applied in all pots using diammonium phosphate and muriate of potash in accordance with the package of practices. The full doses of P and K were applied as the basal dose, while one-third of the N dose was applied at planting, and the remaining N was added in two equal splits doses—one at the mid-tillering stage and the second just after the panicle initiation stage. The crops were irrigated until maturity and irrigation was stopped two weeks before harvest to promote uniform ripening of the crop.

2.3 Preparation of Nitrogen fortified nanobiochar

Biochar was produced from locally available rice husk under limited air supply conditions using a cylindrical drum method (Sharma et al. 2021). The resultant biochar was passed through a 0.5-mm sieve and then was used for the preparation of nanobiochar (NB) chemically using hybrid acid–alkali treatment. Cetyltrimethylammonium

bromide was used as a surfactant to prepare NBN by loading ammonia on to nanobiochar, aiming to utilize it as slow-releasing nanobiochar based fertilizers for soil application. The complete method of preparation is described under patent No. 537907 of the Intellectual Property of India.

2.4 Analytical methods

Fourier transform infrared (FTIR) spectroscopy was used to analyze the functional groups present in the NB (Avtar 370, USA), and measurements were performed at wavelengths ranging from 400 to 4000 cm⁻¹. The surface morphology of the NBs was investigated using scanning electron microscopy (Zeiss EVO-50-EP). The elemental composition was determined using energy-dispersive X-ray spectroscopy (EDX-Oxford system, U.K.). NBN contained carbon (56.33%), nitrogen (1.38%), hydrogen (4.04%), sulphur (0.11%), oxygen (19.54%). Initial soil samples were taken from the surface to a depth of 0–15 cm. The samples were air-dried and crushed to pass through a 2 mm (10 meshes) sieve after the removal of weeds, plant roots, stubbles, and stones. After that, the samples were placed in clean plastic bags for analysis. Soil pH and electrical conductivity (EC) were measured at a 1:2.5 soil-to-water ratio using a pH meter and an EC meter, respectively (Jackson 1973). Available N was determined using alkaline KMNO₄ method (Subbiah and Asija 1956), P was determined from soil by 0.5 M NaHCO₃ Olsen (1954) and available K by flame photometer after extraction with 1N NH₄OAc at pH 7.0 (Jackson 1973), soil organic carbon (SOC) content was estimated using wet digestion method of Walkley and Black (1934). The soil bulk density was measured following the core method. All the reagents used in the experiment were procured from firms of international repute.

2.5 Crop yield, plant growth and root parameters

The effective tillers were measured before harvesting the rice crop using the meter quadrant method. At rice harvest, the grain and straw yield and yield contributing parameters, plant height, effective tiller plant⁻¹, panicle length, number of filled grains panicle⁻¹, number of unfilled grains panicle⁻¹, sterility percentage, grain test weight, grain yield pot⁻¹ were determined by following standard procedure. The crop was harvested at physiological maturity and grain yield was reported at a moisture content of 14%. The crop root samples of each treatment were collected and washed over a 1 mm sieve. Root morphological parameters such as, root length (Tennant 1975), root volume (cm³) and root dry weight (at 65 °C for 24 h) were determined.

2.6 Nutrient uptake

The grain and straw samples after harvesting were chopped, washed and dried at 65 °C until a constant weight was achieved to determine the NPK uptake. The N concentration was determined by digesting samples with concentrated sulfuric acid and then performing distillation and titration using the Microkjeldahl method (Piper 1966). The P and K concentrations were determined using the Vando-Molybdo-Phosphoric acid yellow colour method and a flame photometer (Jackson 1973), respectively. Subsequently, to calculate the nutrient uptake, the concentration of NPK (%) was multiplied by the respective yields of grain and straw.

2.7 Statistical analysis

The soil and plant data collected during the experiment were statistically analyzed using a one-way analysis of variance (ANOVA) based on completely randomized design using online statistical analysis tool OPSTAT (<http://14.139.232.166/opstat>). The significant differences among means of treatments were determined applying Duncan's multiple range test ($p < 0.05$). Linear regression analyses were conducted to examine the relationships between various parameters. Figures were prepared using Origin software 8.0. Principal component analysis (PCA) was employed to determine the contribution of soil attributes to crop yield.

3 Results

3.1 Characterisation of nitrogen-fortified nanobiochar

Scanning Electronic Microscopy (SEM) images of NBN exhibit vertical log-like structure morphology with flakes on the surface, which may represent the fortified nitrogen (Fig. 1a). Energy Dispersive X-ray (EDX) analysis confirmed elevated levels of nitrogen in NBN, revealing a nitrogen content of 11.23% (Fig. 1b). Fourier Transform Infrared (FTIR) analysis identified hydroxyl (-OH) and carboxylic (-COOH) groups, which are commonly found in biochar (Fig. 2). The prominent peaks in the ranges of 3000–3700 cm^{-1} , 2830–2990 cm^{-1} , 2100–2300 cm^{-1} , and 1590–1515 cm^{-1} correspond to hydroxyl (OH), aliphatic (C-H), nitrile (C≡N), and aromatic groups, respectively. Additionally, a peak at 1550–1575 cm^{-1} indicated the presence of NH_2 groups, while a peak at 1371 cm^{-1} suggested the presence of carbon nanotubes (CNTs) in NBN. Furthermore, characteristic peaks at 2347 cm^{-1} and 1557 cm^{-1} confirmed the presence of C≡N and NH_2 groups, respectively, in NBN (Fig. 2).

3.2 Crop growth performance: plant height

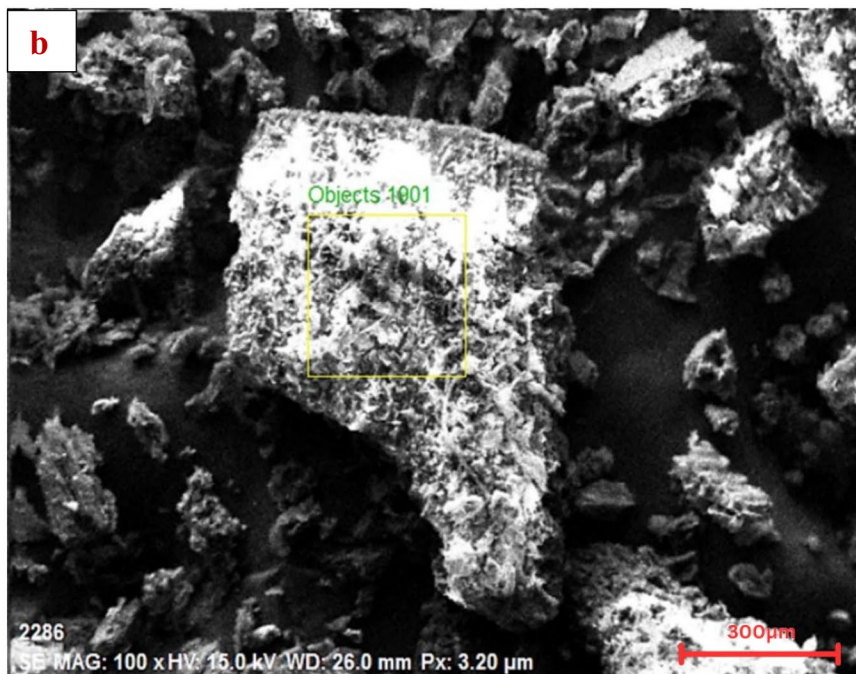
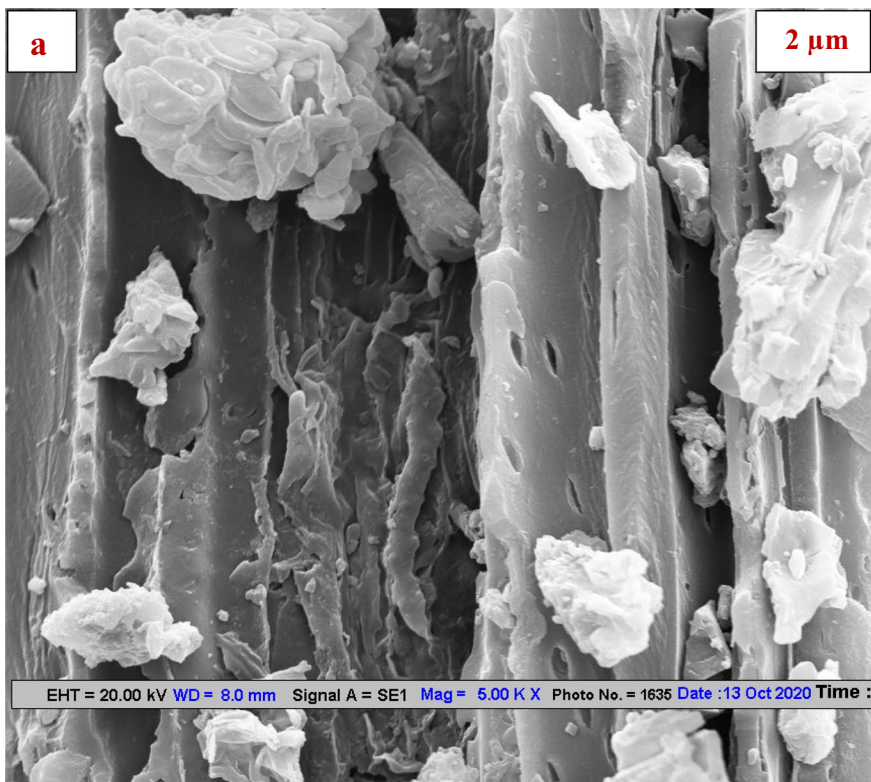
Results indicated that the application of NBN and MF had significant effect ($p < 0.05$) on rice plant height at various growth stages, including 30, 60, 90 days after

transplanting as well as at harvest (Fig. 3). Increasing rate of MF (50–100%) and NBN (1–5 kg ha^{-1}) resulted in enhanced plant height. However, sole application of mineral fertilizer nitrogen (MFN) (50–75%) and NBN (1–5 kg ha^{-1}) led to a decrease in plant height compared to control (T_1 , N_{100}). The combined application of MF and NBN consistently exhibited greater plant height than their sole application across all the growth stages. The highest plant height was recorded in T_9 ($N_{75} + \text{NBN}_5$), which was at par with T_1 and significantly greater than other treatments. Conversely, the lowest plant height was observed in T_4 (NBN_1) at all the growth stages. Compared to treatment receiving 75% mineral N (T_2), treatment T_9 ($N_{75} + \text{NBN}_5$) resulted in increases in plant height of 6.8%, 9.1%, 9.9%, and 10.8% at 30, 60, 90 days after transplanting, and at harvest, respectively.

3.3 Yield attributes and grain yield

The number of effective tillers per plant was significantly ($p < 0.05$) affected by NBN and MF application (Table 1). The results indicated that the mixture of NBN and MF T_9 ($N_{75} + \text{NBN}_5$) produced significantly maximum number of tillers (10.72) which showed statistical parity with T_1 (N_{100}) and represented a 23.7% increased over T_2 (N_{50}). Minimum tillers per plant were found in sole application of NBN (T_4 , NBN_1). The results indicated that combined application of NBN with MFN had positive effects on panicle length, number of filled grains, number of unfilled grains per panicle and sterility percentage (Table 1). The highest panicle length and number of filled grains, (30.23 cm, 89.22, respectively) were recorded in T_9 ($N_{75} + \text{NBN}_5$), which was on par with T_1 treatment (MFN_{100}), while the lowest values (23.72 cm, 71.78, respectively) were recorded in T_4 (NBN_1) (Table 1). Compared to control, reductions in the number of unfilled grains per panicle and sterility percentage were significant and comparable in T_9 and T_1 treatments. The 1000-grain weight did not show significant differences among the treatments. The unfilled grains per panicle and sterility percentage decreased by 23.7% and 29.6%, respectively in T_9 compared to T_2 , highlighting the synergistic effect of reduced MF combined with NBN (Table 1).

The grain yield of rice was significantly affected ($p < 0.05$) by the application of MFN and NBN (Table 1). The sole application of NBN and MFN resulted in decreased rice yield compared with the control (T_1 , MFN_{100}). However, the combined application of MF and NBN led to increased yields with increasing rates of MF (from 50% to 75% nitrogen) and NBN (from 1–5 kg ha^{-1}). The highest yield (31.33 g pot^{-1}) was recorded in treatment T_9 ($N_{75} + \text{NBN}_5$), which was statistically comparable to (T_1 , MFN_{100}) and significantly greater than all other treatments.



Element	Weight (%)	Atomic (%)
C	57.47	67.54
O	20.26	17.87
N	11.23	11.31
Br	6.62	1.17
Ca	1.48	0.52
Mg	1.47	0.85
Si	1.44	0.72
Fe	0.04	0.01

Fig. 1 SEM images at a resolution of 2 μm showing the morphology of nitrogen fortified nanobiochar (NBN) (a) and EDX spectra of NBN (b)

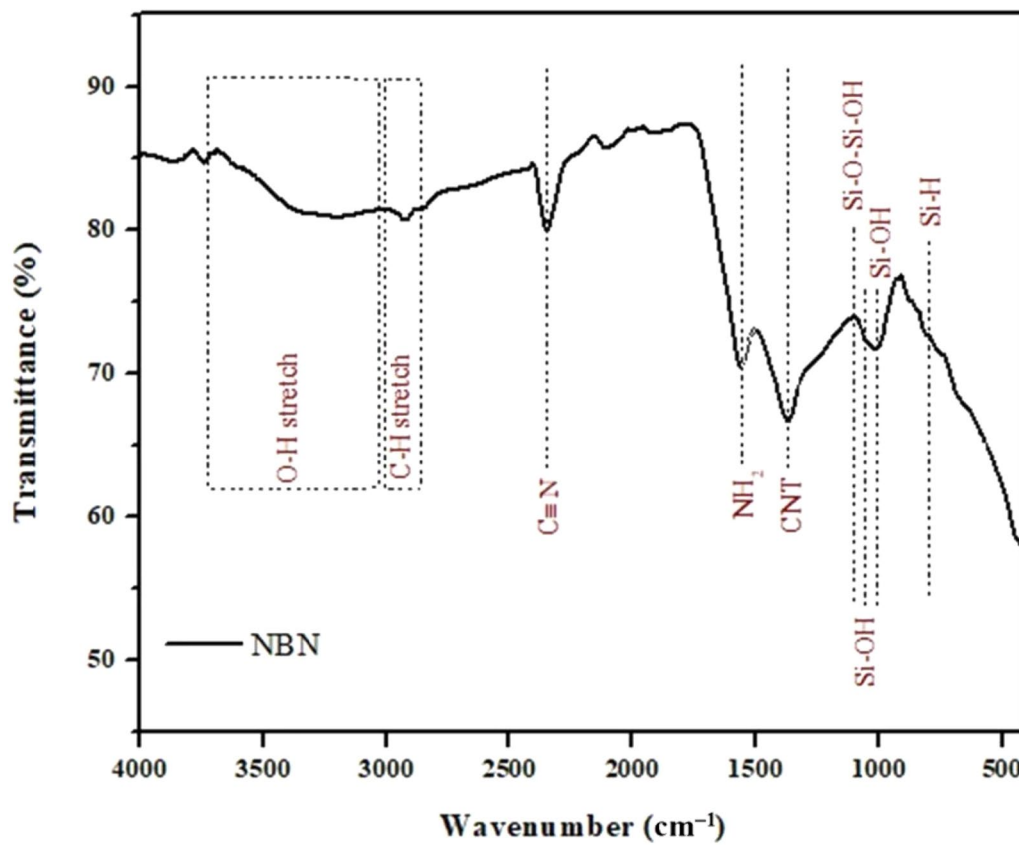


Fig. 2 FTIR spectra of nitrogen fortified nanobiochar (NBN)

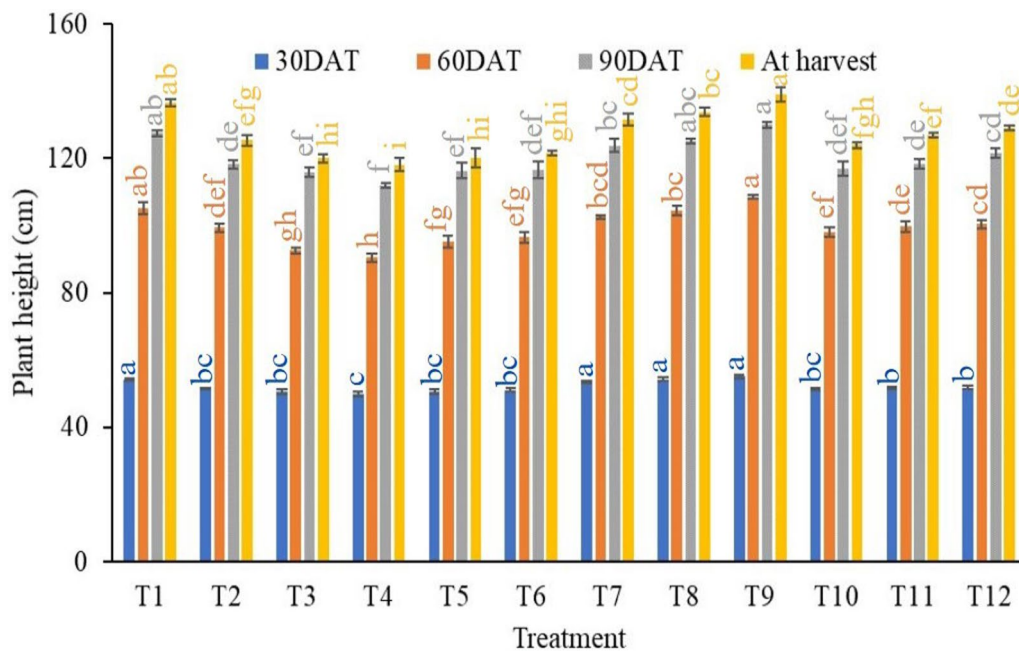


Fig. 3 Effect of mineral fertilizers and nitrogen fortified nanobiochar on plant height at different crop growth stages. Bars indicate standard error from mean

Table 1 Mean (standard error) comparison of effect of nitrogen fortified nanobiochar and mineral fertilizer on yield attributes and grain yield of basmati rice

Treatments	Effective tillers plant ⁻¹	Panicle length(cm)	Grain yield (g pot ⁻¹)	Number of filled grains panicle ⁻	Number of unfilled grains panicle	Sterility (%)	1000 grin weight (g)
T ₁ N ₁₀₀	9.81 ± 0.41ab	28.28 ± 0.80ab	30.03 ± 0.37a	83.22 ± 1.25b	15.78 ± 0.73f	15.94 ± 0.74gh	22.13 ± 0.88a
T ₂ N ₇₅	8.67 ± 0.33bc	25.20 ± 1.29 cd	24.70 ± 0.35c	76.33 ± 1.92defg	20.11 ± 0.95e	20.85 ± 0.98e	21.30 ± 0.78a
T ₃ N ₅₀	7.22 ± 0.57d	23.88 ± 0.70d	20.63 ± 0.38e	72.67 ± 1.45 fg	29.22 ± 0.40b	28.68 ± 0.39b	21.07 ± 0.37a
T ₄ NBN ₁	7.18 ± 0.42d	23.72 ± 0.32d	18.50 ± 0.35f	71.78 ± 1.60 g	32.00 ± 0.58a	30.84 ± 0.56a	21.00 ± 0.20a
T ₅ NBN _{2.5}	7.67 ± 0.38 cd	23.96 ± 0.77d	20.77 ± 0.35e	73.56 ± 1.56 fg	26.56 ± 0.99c	26.53 ± 0.99c	21.17 ± 0.45a
T ₆ NBN ₅	7.77 ± 0.30 cd	24.58 ± 1.23 cd	22.37 ± 0.55d	75.11 ± 0.97efg	23.22 ± 0.48d	23.62 ± 0.49d	21.20 ± 0.83a
T ₇ N ₇₅ + NBN ₁	9.11 ± 0.11b	26.41 ± 0.48bc	27.50 ± 0.25b	80.22 ± 0.97bcd	16.22 ± 0.87f	16.82 ± 0.90fgh	21.67 ± 0.32a
T ₈ N ₇₅ + NBN _{2.5}	9.22 ± 0.48b	28.09 ± 0.25ab	27.90 ± 0.75b	82.22 ± 1.25bc	16.11 ± 0.59f	16.38 ± 0.60fgh	22.10 ± 0.66a
T ₉ N ₇₅ + NBN ₅	10.72 ± 0.51a	30.23 ± 0.28a	31.33 ± 0.58a	89.22 ± 0.62a	15.33 ± 0.51f	14.67 ± 0.49 h	22.20 ± 0.85a
T ₁₀ N ₅₀ + NBN ₁	8.64 ± 0.22bc	24.77 ± 0.20 cd	24.10 ± 0.71c	75.56 ± 2.11efg	22.22 ± 0.62d	22.73 ± 0.63de	21.23 ± 0.22a
T ₁₁ N ₅₀ + NBN _{2.5}	8.77 ± 0.30bc	25.48 ± 0.85 cd	25.10 ± 0.25c	77.22 ± 0.59def	17.44 ± 0.40f	18.43 ± 0.42f	21.43 ± 0.37a
T ₁₂ N ₅₀ + NBN ₅	9.02 ± 0.38b	26.33 ± 0.12bc	25.43 ± 0.61c	78.67 ± 2.00cde	16.78 ± 0.97f	17.58 ± 1.01 fg	21.60 ± 0.67a

Values within the column followed by similar letters are not significantly different at ($p < 0.05$) according to Duncan's Multiple Range test

NBN nitrogen fortified nanobiochar, MF mineral fertilizer, N nitrogen

T₁-100% N through MF; T₂-75% N through MF; T₃-50% N through MF; T₄-NBN 1 kg ha⁻¹; T₅- NBN 2.5 kg ha⁻¹; T₆- NBN 5 kg ha⁻¹; T₇-75% N through MF + NBN 1 kg ha⁻¹; T₈-75% N through MF + NBN 2.5 kg ha⁻¹; T₉-75% N through MF + NBN 5 kg ha⁻¹; T₁₀-50% N through MF + NBN 1 kg ha⁻¹; T₁₁-50% N through MF + NBN 2.5 kg ha⁻¹; T₁₂-50% N through MF + NBN 5 kg ha⁻¹

Conversely, the lowest yield (18.50 g pot⁻¹) was recorded in T₄ (NBN₁). The application of N₇₅ + NBN₅ increased yield by 26.86% compared to T₂ (MFN₇₅). These results indicate that reducing nitrogen fertilizer by 25% while incorporating NBN can achieve higher yields than the conventional 75% nitrogen fertilizer treatment, with yields statistically comparable to those obtained with 100% nitrogen fertilizer.

3.4 Root growth parameters: root weight, root length and root volume

The results indicated that the sole application of MFN (50% to 75% nitrogen) and NBN (1–5 kg ha⁻¹) resulted in decreased root weight, length, and volume compared to the control (T₁, MFN₁₀₀) (Table 2). In contrast, the application of MF combined with NBN (T₉) exhibited significantly greater root parameters than remaining treatments. Root weight, length and volume increased by 24.6%, 15.8% and 18.7%, respectively, compared to T₂. The combined application of MFN and NBN demonstrated enhancements in these parameters with increasing rates of both MFN and NBN. Integration of NBN with reduced amount of nitrogen through MF proved to be more beneficial than applying 100% nitrogen when utilized in the mixture of N₇₅ + NBN₅.

Table 2 Mean (standard error) comparison of effect of nitrogen fortified nanobiochar and mineral fertilizer on yield attributes of basmati rice

Treatments	Root weight (g)	Root length (cm)	Root volume (cm ³)
T ₁ N ₁₀₀	33.67 ± 1.16a	28.23 ± 0.4ab	34.05 ± 0.80ab
T ₂ N ₇₅	28.47 ± 0.46bc	26.10 ± 0.87bc	30.12 ± 0.80 cd
T ₃ N ₅₀	24.60 ± 0.53d	23.73 ± 0.55de	26.78 ± 0.77f
T ₄ NBN ₁	23.53 ± 0.78d	21.63 ± 0.78e	26.39 ± 0.70f
T ₅ NBN _{2.5}	25.07 ± 1.19d	24.73 ± 0.86 cd	27.35 ± 0.64ef
T ₆ NBN ₅	26.17 ± 1.27 cd	24.80 ± 0.52 cd	28.97 ± 0.70de
T ₇ N ₇₅ + NBN ₁	30.80 ± 0.32b	26.73 ± 0.88bc	33.46 ± 0.67b
T ₈ N ₇₅ + NBN _{2.5}	33.47 ± 0.52a	27.53 ± 0.61b	33.64 ± 0.70ab
T ₉ N ₇₅ + NBN ₅	35.47 ± 1.10a	30.23 ± 0.38a	35.76 ± 0.34a
T ₁₀ N ₅₀ + NBN ₁	28.13 ± 1.33bc	25.10 ± 0.91 cd	30.05 ± 0.80 cd
T ₁₁ N ₅₀ + NBN _{2.5}	28.87 ± 0.27bc	26.23 ± 0.73bc	30.85 ± 0.70 cd
T ₁₂ N ₅₀ + NBN ₅	29.47 ± 0.46b	26.27 ± 0.41bc	31.93 ± 0.80bc

Values within the column followed by similar letters are not significantly different at ($p < 0.05$) according to Duncan's Multiple Range test

NBN nitrogen fortified nanobiochar, MF mineral fertilizer, N nitrogen

T₁-100% N through MF; T₂-75% N through MF; T₃-50% N through MF; T₄-NBN 1 kg ha⁻¹; T₅- NBN 2.5 kg ha⁻¹; T₆- NBN 5 kg ha⁻¹; T₇-75% N through MF + NBN 1 kg ha⁻¹; T₈-75% N through MF + NBN 2.5 kg ha⁻¹; T₉-75% N through MF + NBN 5 kg ha⁻¹; T₁₀-50% N through MF + NBN 1 kg ha⁻¹; T₁₁-50% N through MF + NBN 2.5 kg ha⁻¹; T₁₂-50% N through MF + NBN 5 kg ha⁻¹

3.5 Nutrient uptake of nitrogen, phosphorus and potassium

The application of MF and NBN significantly affected nitrogen uptake in rice grain across the different

treatments (Fig. 4a). Results indicated that N uptake was significantly higher (0.392 g pot^{-1}) in T_9 ($N_{75} + \text{NBN}_5$) treatment, which remained significantly superior to T_1 (N_{100}) and T_2 (N_{75}). The minimum N uptake was found in T_4 ($\text{NBN } 1 \text{ kg ha}^{-1}$) at 0.204 g pot^{-1} . Treatment T_9 showed increases in N uptake of 1.06 and 1.50 times compared to T_1 and T_2 , respectively. Similarly, P and K uptake were statistically superior in treatment T_9 compared to the other treatments, with P and K uptake increasing by 1.07 and 1.63 times; and 1.05 and 1.50 times, respectively when compared to T_1 and T_2 (Fig. 4a). The lowest uptake of P and K was also observed in treatment T_4 (NBN_1).

3.6 Effect of nitrogen fortified nanobiochar on soil physicochemical properties

The soil pH and EC were not significantly altered across all the treatments (Table 3). However, the application of NBN with MF significantly increased the soil OC compared to the application of MF alone or NBN alone. The highest soil OC (0.55%) was recorded with the treatment T_9 , which was statistically comparable to T_{12} ($N_{50} + \text{NBN}_5$). Increases of 22.2% and 25% in OC were observed in T_9 compared to treatments T_1 (N_{100}) and T_2 (N_{75}), respectively (Table 3). Available N in soil ranged from 1.4 to 1.66 g pot^{-1} among all the treatments, with the combined application of $N_{75} + \text{NBN}_5$ (T_9) exhibiting the highest available N content (Table 3). Compared to T_1 and T_2 , N content increased by 3.1% and 7.8%, respectively. A significantly lower N content was recorded with sole application of NBN ($1\text{--}5 \text{ kg ha}^{-1}$) compared to sole applied MF and mixture of MF and NBN. Soil available P and K contents ranged from 0.081 to 0.108 g pot^{-1} and 1.038 to 1.122 g pot^{-1} , respectively (Table 3). Compared to MF application, the application of MF and NBN in combination showed significantly higher P and K contents while significantly lower available P and K were observed under treatments with sole application of NBN. Significantly highest available P and K were found in the treatment $N_{75} + \text{NBN}_5$ (T_9) followed by T_1 and T_2 . Compared to the treatments T_1 and T_2 , the conjoint application of $N_{75} + \text{NBN}_5$ enhanced available P and K by 12.5%, 14.9% and 2.1%, 4.3%, respectively. Soil available N, P and K contents were statistically comparable in treatments T_1 , T_8 , T_9 , T_{11} , and T_{12} ; as well as in T_1 , T_7 , T_8 , T_9 , and T_{12} ; and $T_1, T_2, T_3, T_7, T_8, T_9, T_{11}$, and T_{12} , respectively.

The combine use of NBN and MF significantly increased ammonium and nitrate in the soil. The significantly highest value of ammonium (38.16 mg kg^{-1}) and nitrate (11 mg kg^{-1}) was observed in T_9 ($N_{75} + \text{NBN}_5$) while the lowest values of 21.74 mg kg^{-1} and 4.15 mg kg^{-1} were recorded in T_4 (NBN_1) (Fig. 4b). The treatment T_9 demonstrated increases of 1.06 times and

1.04 times in ammonium and nitrate content, respectively, compared to treatment T_1 (Fig. 4c). These findings highlight that the conjunctive use of NBN with a 25% reduction in MF can enhance ammonium and nitrate levels compared to the application of a full dose of chemical fertilizer.

3.7 Effects of nitrogen-fortified nanobiochar and mineral fertilizer on soil physical properties

The effect of NBN and FM on soil bulk density was found non-significant; however, the addition of NBN slightly decreased the bulk density over the recommended dose of fertilizer (Table 4). Treatments T_6 , T_9 and T_{12} showed the highest and similar reductions in bulk density, decreasing by 0.97% compared to the recommended dose of fertilizer (T_1). Similarly, the effect of NBN and MF was non-significant on the total porosity of soil, although it did increase porosity compared to the sole application of chemical fertilizer (T_1) with the greatest increase (1.04 times) recorded in treatments T_6 (NBN_5), T_9 ($N_{75} + \text{NBN}_5$) and T_{12} ($N_{50} + \text{NBN}_5$). The highest soil porosity (45.30%) was found in T_9 , while the lowest (43.37%) was observed in T_3 (N_{50}) and T_2 (N_{75}). The data presented in Table 4 revealed that application of NBN and MF significantly affected soil moisture and maximum water-holding capacity (MWHC), with significantly higher soil moisture level (17.55%) and MWHC (38.40%) recorded in T_9 ($N_{75} + \text{NBN}_5$), followed by T_{12} ($N_{50} + \text{NBN}_5$). Compared to T_1 , increases of 1.21 times and 1.12 times in soil moisture and MWHC were recorded in T_9 , indicating that the addition of NBN, particularly at higher quantities, can enhance the soil moisture retention capacity of soil compared to the recommended dose of fertilizer (T_1). A significantly higher increase in aggregate stability (44.45%) was observed in T_9 ($N_{75} + \text{NBN}_5$), which was statistically comparable to T_6 and T_{12} . Conversely, the lowest soil moisture, MWHC, and aggregate stability were recorded in T_3 (N_{50}), with increases of 20.6%, 12.3%, and 12.2% in soil moisture, MWHC, and aggregate stability, respectively, under treatment T_9 compared to T_1 . Additionally, significantly greater infiltration rate (IR) and hydraulic conductivity (H_c) were found in T_9 ($N_{75} + \text{NBN}_5$), which was statistically comparable to T_6 and T_{12} . The greatest increases in IR (1.27, 1.36, and 1.27 times) and H_c (1.25, 1.35 and 1.30 times) were noted in T_6 ($\text{NBN } 5 \text{ kg ha}^{-1}$), T_9 ($N_{75} + \text{NBN}_5$) and T_{12} ($N_{50} + \text{NBN } 5 \text{ kg ha}^{-1}$) treatments compared to T_1 , while the lowest IR and H_c (0.21 cm hr^{-1} and 0.22 cm hr^{-1}) was recorded in T_3 (N_{50}).

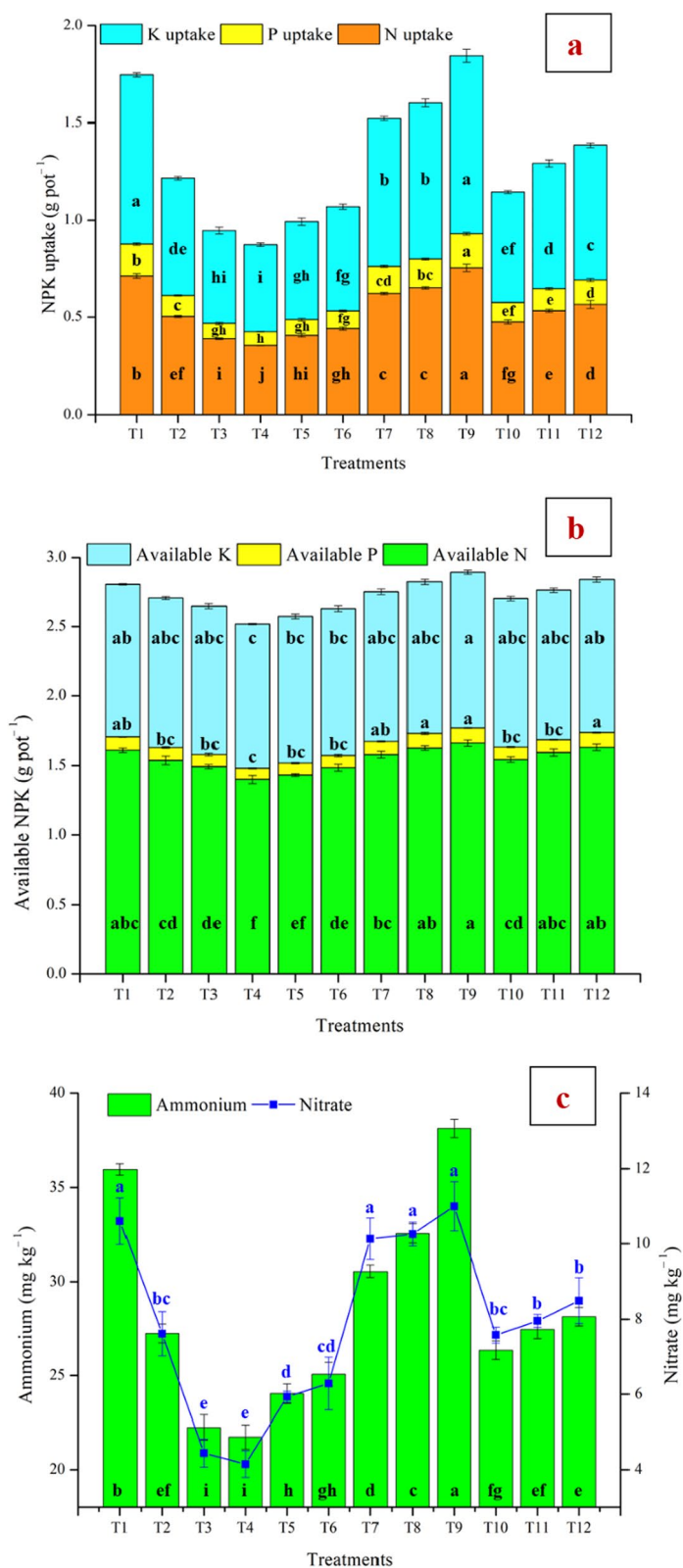


Fig. 4 Effect of mineral fertilizers and nitrogen-fortified nanobiochar on **a** nutrient uptake, **b** available nutrients and **c** ammonium and nitrate. Bars indicate standard error from mean

Table 3 Mean (standard error) comparison of effect of nitrogen fortified nanobiochar and mineral fertilizer on physicochemical properties of soil

Treatments		pH	EC (dS m ⁻¹)	OC (%)
T ₁	N ₁₀₀	7.42 ± 0.05ab	1.46 ± 0.009a	0.46 ± 0.01def
T ₂	N ₇₅	7.39 ± 0.02abccd	1.47 ± 0.018ab	0.45 ± 0.02ef
T ₃	N ₅₀	7.34 ± 0.02abccd	1.47 ± 0.015ab	0.43 ± 0.01f
T ₄	NBN ₁	7.30 ± 0.05d	1.46 ± 0.012b	0.46 ± 0.01def
T ₅	NBN _{2.5}	7.31 ± 0.02 cd	1.45 ± 0.015b	0.48 ± 0.01cde
T ₆	NBN ₅	7.33 ± 0.01bcd	1.42 ± 0.003ab	0.51 ± 0.01abc
T ₇	N ₇₅ + NBN ₁	7.40 ± 0.03abc	1.44 ± 0.019a	0.47 ± 0.01cdef
T ₈	N ₇₅ + NBN _{2.5}	7.41 ± 0.03ab	1.43 ± 0.009a	0.50 ± 0.01bcd
T ₉	N ₇₅ + NBN ₅	7.43 ± 0.04a	1.42 ± 0.015a	0.55 ± 0.01a
T ₁₀	N ₅₀ + NBN ₁	7.35 ± 0.0abccd	1.45 ± 0.012ab	0.46 ± 0.02def
T ₁₁	N ₅₀ + NBN _{2.5}	7.37 ± 0.01abccd	1.43 ± 0.015ab	0.49 ± 0.02bcde
T ₁₂	N ₅₀ + NBN ₅	7.38 ± 0.02abccd	1.42 ± 0.012ab	0.53 ± 0.01ab

Values within the column followed by similar letters are not significantly different at ($p < 0.05$) according to Duncan's Multiple Range test

NBN nitrogen fortified nanobiochar, MF mineral fertilizer, N nitrogen, EC electrical conductivity, OC organic carbon

T₁ – 100% N through MF; T₂–75% N through MF; T₃–50% N through MF; T₄–NBN 1 kg ha⁻¹; T₅– NBN 2.5 kg ha⁻¹; T₆– NBN 5 kg ha⁻¹; T₇–75% N through MF + NBN 1 kg ha⁻¹; T₈–75% N through MF + NBN 2.5 kg ha⁻¹; T₉–75% N through MF + NBN 5 kg ha⁻¹; T₁₀–50% N through MF + NBN 1 kg ha⁻¹; T₁₁–50% N through MF + NBN 2.5 kg ha⁻¹; T₁₂–50% N through MF + NBN 5 kg ha⁻¹

4 Discussion

4.1 Characterization of nitrogen fortified biochar

Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) analyses confirmed the successful nitrogen loading in NBN, revealing a vertical log-like

structure with dense, rigid flakes on the surface. The prominent peaks observed in the analysis indicated the presence of hydroxyl, aliphatic, nitrile, and aromatic groups (Figueredo et al. 2017; Naghdi et al. 2019). According to Tomczyk et al. (2020), hydroxyl and aliphatic groups enhance the cation exchange capacity of the soil, aiding in nutrient and water retention. Nitrile group contributes to reducing nutrient leaching losses by serving as a slow-release nitrogen source, while the aromatic structure of NBN promotes microbial abundance and carbon sequestration (Jiang et al. 2023). Additionally, the presence of NH₂ groups and carbon nanotubes (CNTs) in NBN stimulates microbial activity and enhances structural stability (Naghdi et al. 2019) and the inclusion of Si-H group in rice husk biochar enhances the surface reactivity (Hossain et al. 2020). Moreover, the stretching of aliphatic C-H groups in NBN induces structure stability and hydrophobicity (Tomczyk et al. 2020). The nitrogen content observed in EDX spectra of NBN validates the successful synthesis and characterization of this innovative material.

4.2 Soil chemical properties

In characterization of NBN by SEM, EDX and FTIR analysis, we found the presence of elevated nitrogen, uniformly distributed pores, aromaticity and a crystalline structure. The existence of oxygen, carboxyl, sulfonyl, and nitrile groups confirmed the positive effect of NBN on soil properties. Chen et al. (2020) and Zhao et al. (2021) also reported that large surface area and

Table 4 Mean (standard error) comparison of effect of nitrogen fortified nanobiochar and mineral fertilizer on physical properties of soil

Treatments		Bulk density (g cm ⁻³)	Porosity (%)	Soil moisture (%)	MWHC (%)	Aggregate stability (%)	IR (cmhr ⁻¹)	H _c (cmhr ⁻¹)
T ₁	N ₁₀₀	1.46 ± 0.01ab	43.50 ± 0.34bc	14.55 ± 0.76c	34.20 ± 0.67c	39.59 ± 0.51ef	0.22 ± 0.006ef	0.25 ± 0.026def
T ₂	N ₇₅	1.47 ± 0.02a	43.37 ± 0.64c	14.53 ± 0.39c	34.02 ± 0.75c	39.57 ± 0.59ef	0.21 ± 0.006f	0.24 ± 0.013ef
T ₃	N ₅₀	1.47 ± 0.01a	43.37 ± 0.56c	14.43 ± 0.64c	33.71 ± 0.67c	37.88 ± 0.80f	0.21 ± 0.003f	0.22 ± 0.010f
T ₄	NBN ₁	1.46 ± 0.01ab	43.63 ± 0.45abc	14.67 ± 0.57bc	34.48 ± 0.41c	40.50 ± 0.38de	0.24 ± 0.003de	0.26 ± 0.008def
T ₅	NBN _{2.5}	1.45 ± 0.02ab	44.02 ± 0.59abc	15.08 ± 0.98bc	35.62 ± 0.54bc	41.12 ± 0.95cde	0.26 ± 0.012bcd	0.28 ± 0.005cde
T ₆	NBN ₅	1.42 ± 0.00b	45.05 ± 0.13abc	16.36 ± 0.76abc	35.90 ± 0.90abc	43.01 ± 0.66abc	0.28 ± 0.012ab	0.31 ± 0.006abc
T ₇	N ₇₅ + NBN ₁	1.44 ± 0.02ab	44.53 ± 0.72abc	14.81 ± 0.37bc	35.50 ± 0.61bc	41.07 ± 0.52de	0.25 ± 0.006 cd	0.28 ± 0.005cde
T ₈	N ₇₅ + NBN _{2.5}	1.43 ± 0.01ab	44.66 ± 0.34abc	15.66 ± 0.45abc	35.71 ± 0.44bc	41.96 ± 0.63bcd	0.27 ± 0.008bc	0.29 ± 0.016bcd
T ₉	N ₇₅ + NBN ₅	1.42 ± 0.01b	45.30 ± 0.56a	17.55 ± 0.34a	38.40 ± 1.27a	44.45 ± 0.38a	0.30 ± 0.015a	0.34 ± 0.017a
T ₁₀	N ₅₀ + NBN ₁	1.45 ± 0.01ab	44.02 ± 0.45abc	14.71 ± 0.81bc	35.04 ± 0.83bc	40.60 ± 0.37de	0.24 ± 0.007de	0.27 ± 0.013cde
T ₁₁	N ₅₀ + NBN _{2.5}	1.43 ± 0.01ab	44.92 ± 0.56abc	15.33 ± 0.45bc	35.69 ± 1.30bc	41.74 ± 0.37bcd	0.26 ± 0.007bcd	0.29 ± 0.015bcd
T ₁₂	N ₅₀ + NBN ₅	1.42 ± 0.01b	45.17 ± 0.45ab	16.68 ± 0.70ab	37.34 ± 0.96ab	43.62 ± 0.72ab	0.28 ± 0.009ab	0.33 ± 0.010ab

Values within the column followed by similar letters are not significantly different at ($p < 0.05$) according to Duncan's Multiple Range test

NBN nitrogen fortified nanobiochar, MF mineral fertilizer, N nitrogen, MWHC maximum water holding capacity, IR infiltration rate, H_c hydraulic conductivity

T₁ – 100% N through MF; T₂–75% N through MF; T₃–50% N through MF; T₄–NBN 1 kg ha⁻¹; T₅– NBN 2.5 kg ha⁻¹; T₆– NBN 5 kg ha⁻¹; T₇–75% N through MF + NBN 1 kg ha⁻¹; T₈–75% N through MF + NBN 2.5 kg ha⁻¹; T₉–75% N through MF + NBN 5 kg ha⁻¹; T₁₀–50% N through MF + NBN 1 kg ha⁻¹; T₁₁–50% N through MF + NBN 2.5 kg ha⁻¹; T₁₂–50% N through MF + NBN 5 kg ha⁻¹

charged surface of NB facilitate adsorption and availability of nutrients after fertilization. Sellergren et al. (2022) suggested that oxygen-containing functional groups increased the adsorption and availability of NH_4^+ and NH_3 on NB. This is consistent with the findings of (Zhang et al. 2021). Zhang et al. (2021) also found that NB reduces nutrients loss and catalyzes their retention in soil. This adsorption capability of NB decreases nutrient leaching, improves volatilization and encourages N availability for plants (Rashid et al. 2023). Similar results were reported by Clough et al. (2013). Conjunctive application of NBN and MF had significant effect on ammonium and nitrate of soil as NB can adsorb and retain ammonium ions. This adsorption can initially reduce the availability of ammonium for plant uptake after some time counterbalanced by the gradual release of N from the NB itself (Rashid et al. 2023). The porous structure of NB can capture and hold nitrate ions, preventing them from being washed away by irrigation or rainfall (Yang et al. 2020). We found elevated soil pH and EC with the application of NBN alone and in combination with MF. Incorporation of rice husk biochar in coarse textured soil under water stress condition act as a liming material in increasing the soil pH (Ghorbani and Amirahmadi 2018). The combined application of MF and NBN exhibited higher soil EC than the sole application could be attributed to release of soluble salts (Deepshikaa et al. 2024). NBN had a significant role in increasing soil OC content. The addition of $\text{N}_{75} + \text{NBN}_5$ (T_9) induced a rise in OC by 19.5% and 22.2% compared to 100% chemical fertilizer and 75% chemical fertilizer application due to high carbon content (56.3%) in NBN. Our study demonstrated that the rice husk NBN significantly increased the content of OC in the soil, which also verified the results of the Dong et al., (2019) and Koyama et al. (2016a, b).

4.3 Soil physical properties

The application of NB has been demonstrated as an effective approach for improving soil physical properties, improving soil aggregation and facilitating water movement through soil matrix (Li et al. 2019a; Yang et al. 2020). Additionally, modified microbial communities resulting from biochar application contributes to improved porosity and infiltration (Abrol et al. 2024b, 2016). In this investigation, MF and NBN significantly influenced soil physical properties (Table 4). Moreover, increasing rate of NBN application gradually increased soil moisture, maximum water holding capacity (MWHC), infiltration rate (IR), aggregate stability (AS) and hydraulic conductivity (H_c). These findings align with those of Yang et al. (2020) and Rajput et al. (2022), who reported that NB provides an array of benefits and helps increase soil water retention. These results are

consistent with those of Gupta et al. (2024) who observed a reduction in bulk density and an increase in porosity as reported in our studies with the combined application of $\text{N}_{75} + \text{NBN}_5$ (T_9) demonstrating better water retention and infiltration associated with the high surface area and porosity of NB. Furthermore, Chen et al. (2022) noted improved hydraulic characteristics with the application of NB. Relative to the recommended MF application, the treatment receiving $\text{N}_{75} + \text{NBN}_5$ showed increases in soil moisture, MWHC, IR, AS and H_c by 20.6%, 12.3%, 36.3%, 12.2% and 36%, respectively. This enhancement may be owing to increased soil available N and improved microbial dynamics (Li et al. 2019b; Chen et al. 2020), which promote the production of microbial exudates that act as binding agents, thereby enhancing soil aggregate stability (Liu et al. 2020).

4.4 Nutrient's availability in soil

The balanced nutrition is crucial for improving root and crop growth. In this study, the application of NBN with MF (T_9) had a positive impact on enhancing availability of N, P and K, followed by treatments $\text{N}_{75} + \text{NBN}_{2.5}$ and $\text{N}_{50} + \text{NBN}_5$. The increment in nutrients availability could be linked to the synergistic effect of NBN and MF on microbial diversity and abundance (Li et al. 2019a, b; Liu et al. 2020). In addition to serving as a N source, NBN can absorb nutrients and reduce leaching losses (Chen et al. 2020). Increases in soil moisture, MWHC, IR AS and H_c along with reduction in bulk density (BD) in NBN-amended treatments, likely enhanced rice root development compared to the control. The NBN treatment positively impacted rice plant height, supporting the findings by Ibrahim et al. (2023), who reported a 6.9 per cent increase in plant height by applying 0.75% NB. Furthermore, a significant correlation was observed between the 1000-grain weight, yield parameters and varying NB contents (Yang et al. 2020). Khaliq et al. (2023) noted that both basal and foliar forms of NB carbon substantially improved the carrot growth, while Saxena et al. (2014) reported a linear increase in wheat shoot length with increasing water-soluble carbon nanoparticles. Additionally, NB acts as a slow nutrient-releasing fertilizer (Ramanayaka et al. 2020), contributing to improved soil fertility and crop productivity (Sharma et al. 2024). The observed increase in growth parameters in rice with NB application was mainly attributed to synergistic effect of NB and MF (Chaudhary et al. 2024). Comparative studies have also demonstrated that the combined use of NB and MF yield substantial improvements in growth parameters, including increased plant height and tiller number, highlighting their effectiveness as nutrient sources for rice cultivation (Yue et al. 2019; Rashid et al., (2023).

4.5 Crop growth and nutrient uptake

Our results showed that the combined application of NBN and MF was more effective in maximizing rice growth and yield attributes. This could be explained by the findings of Brar et al. (2024) that integrated approach enhanced the N use efficiency and resulted in higher dry matter accumulation compared to the application of either amendment alone. Similar results were found by Yang et al. (2024), who suggested that biochar significantly enhances rice yields. The application of NB has been found to improve soil nutrient dynamics by increasing microbial activity and enhancing soil moisture retention, which together facilitate improved nutrient retention and availability for rice crops (Yue et al. 2019). Furthermore, the co-application of biochar with MF not only improves yield attributes but also enhances N use efficiency, which is essential for sustainable rice production (Haque et al. 2022). The highest N uptake (0.75 g pot⁻¹) was observed in treatment T₉, which involved the application of 75% N from MF combined with 5 kg ha⁻¹ NB. This enhancement in N uptake can be attributed to the ability of NB to improve soil N processes, such as mineralization and nitrification, thereby increasing

N availability and their rapid supply for plant uptake and ultimately leading to improved plant productivity (Brar et al. 2024; Zhang et al. 2021). Additionally, NB improves soil properties and microbial diversity, which further boosts nutrient availability (Helalet al. 2019). Our study demonstrated a significant and positive correlation between grain yield and available N (R²=0.82), P (R²=0.65), K (R²=0.79), NH₄ (R²=0.95) and NO₃ content (R²=0.95) as depicted in Fig. 5a. These results highlight the favourable impact of NBN application on N retention in soil, corroborating findings from previous studies (Shah et al 2024, Kumar et al. 2024).

The significant and positive correlation between soil organic carbon and AS (R²=0.95), H_c (R²=0.95), IR (R²=0.92), soil moisture (R²=0.92), MWHC (R²=0.91) and porosity (R²=0.92) as depicted in Fig. 5b confirms that NBN, being rich in carbon content, has the potential to enhance soil properties, thereby improving root growth, nutrient and water availability, and the yield of rice (Tourajzadeh et al. 2024). The conjoint use of NBN and MF improved the soil properties as evident from positive correlations among various soil properties (Table 5), which ultimately led to enhanced crop

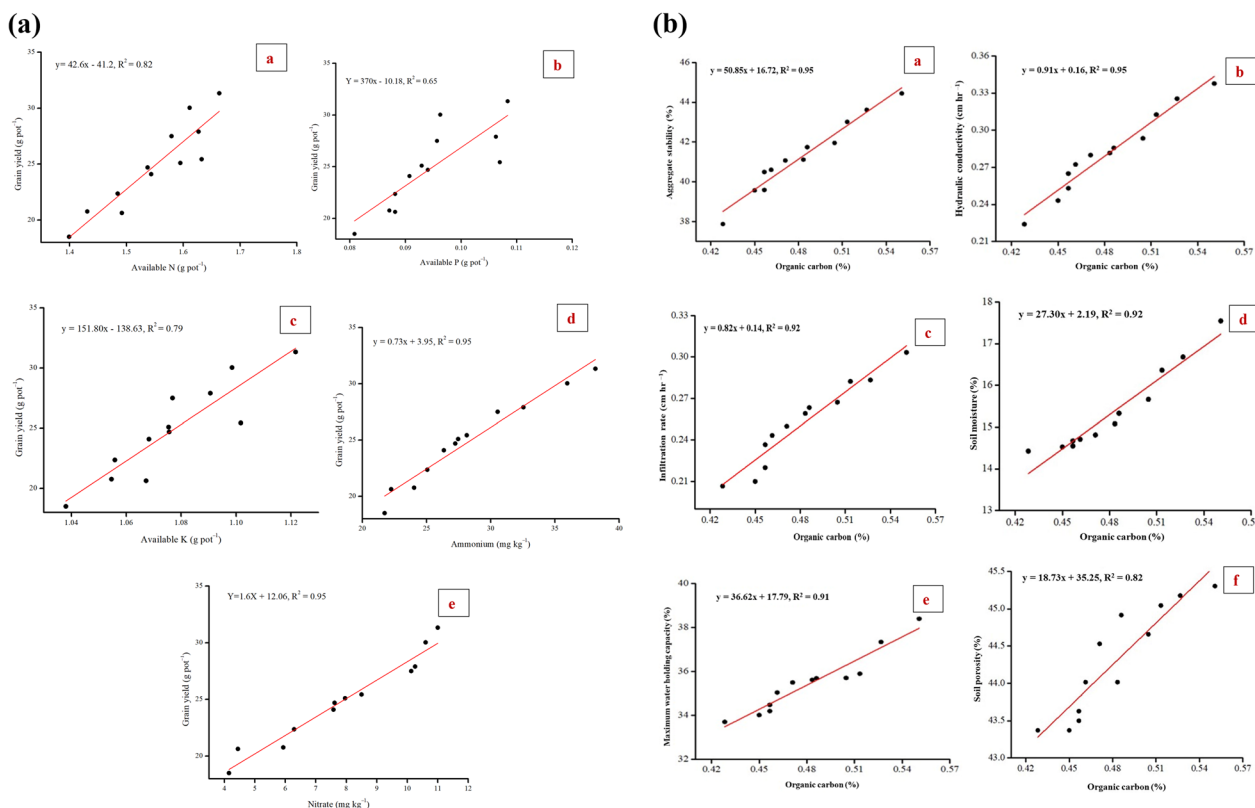


Fig. 5 a The linear relationship between rice grain yield and soil nutrients a available nitrogen, b available phosphorus, c available potassium, d ammonium, e nitrate. b The linear relationship between organic carbon and different soil physical properties a aggregate stability, b hydraulic conductivity c infiltration rate, d soil moisture, e maximum water holding capacity, f soil porosity

productivity (Rashid et al. 2023). The application of NB in the soil can adsorb mineral N, reducing its leaching and runoff losses, thereby increasing N retention (Chen et al. 2020). Additionally, the application of NBN and MF significantly affected P uptake, with the highest P uptake (0.18 g pot⁻¹) observed in treatment T₉, which involved 75% N from MF combined with 5 kg ha⁻¹ of NBN. This enhancement can be attributed to the application of nutrient-rich organo-mineral fertilizers to the soil, which boosted microbial activity, decomposition, and nutrient mineralization of the organic compounds, ultimately enhancing nutrient availability for crop uptake (Altaf et al. 2021; Ramanayaka et al. 2020). Furthermore, the application of NBN and MF also significantly influenced K uptake, likely due to the structure of NB allowing for a slow release of nutrients, which reduces leaching and runoff, thereby improving nutrient uptake efficiency by plants (Sarma et al. 2024). Moreover, NB serves as a rich source of silicon, enhancing nutrient availability and root development (Maillard et al. 2018; Schaller et al. 2020).

The enhanced soil microbial biomass resulting from the improved living conditions provided by NB likely contributed to increased crop yield (Liu et al. 2020; Rashid et al. 2023). In our analysis, approximately 76% of the variance in the first principal component (PC-1) was explained by OC (0.955), MWHC (0.942), Amm (0.937), HC (0.928), AS (0.919), SM (0.918), IR (0.874), AvP (0.837), AvK (0.751), AvN (0.743) and Nit (0.728) while second principal component (PC-2) accounted AvP (0.478), AvK (0.607), AvN (0.640), Nit (0.588), OC (-0.271), MWHC (-0.257), AS (-0.375), SM (-0.287) and IR (-0.447)s (Fig. 6). These results

further substantiate that increase in rice yield is attributable to the beneficial effects of conjoint use of MF and NBN on soil physicochemical and biological properties (Abrol et al. 2024a, b). The cumulative contributions of PC-1 and PC-2 explained 94.50% of the total variance in soil parameters, validating our findings that improvements in soil properties catalyzed increased crop yield (Supplementary Table 1).

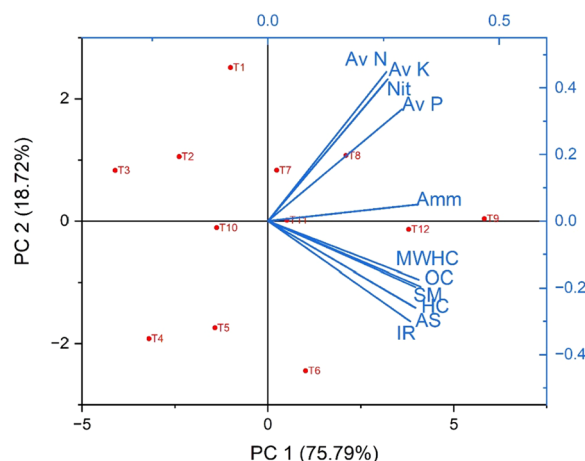


Fig. 6 Biplot analysis of different variables. OC organic carbon, MWHC maximum water holding capacity, Amm Ammonium, HC hydraulic conductivity, AS aggregate stability, SM soil moisture, IR infiltration rate, AvP available phosphorus, AvK available potassium, AvN available nitrogen, Nit nitrate

Table 5 Correlation coefficient between different components

Correlations											
	OC	Av N	Amm	Nit	Av P	Av K	SM	IR	H _c	MWHC	AS
OC	1	.530*	.857**	.532*	.673**	.567*	.970**	.951**	.977**	.963**	.979**
Av N	.530*	1	.754**	.893**	.920**	.935**	.491	.360	.473	.531*	.448
Amm	.857**	.754**	1	.746**	.798**	.683**	.810**	.783**	.847**	.816**	.856**
Nit	.532*	.893**	.746**	1	.835**	.859**	.447	.417	.478	.519*	.454
Av P	.673**	.920**	.798**	.835**	1	.927**	.643*	.512*	.600*	.673**	.584*
Av K	.567*	.935**	.683**	.859**	.927**	1	.567*	.361	.473	.582*	.447
SM	.970**	.491	.810**	.447	.643*	.567*	1	.908**	.928**	.940**	.931**
IR	.951**	.360	.783**	.417	.512*	.361	.908**	1	.969**	.937**	.965**
HC	.977**	.473	.847**	.478	.600*	.473	.928**	.969**	1	.967**	.993**
MWH _c	.963**	.531*	.816**	.519*	.673**	.582*	.940**	.937**	.967**	1	.950**
AS	.979**	.448	.856**	.454	.584*	.447	.931**	.965**	.993**	.950**	1

OC organic carbon, MWHC maximum water holding capacity, Amm ammonium, HC hydraulic conductivity, AS aggregate stability, SM soil moisture, IR infiltration rate, AvP available phosphorus, AvK available potassium, AvN available Nitrogen, Nit nitrate

* Correlation is significant at the 0.05 level (1-tailed)

** Correlation is significant at the 0.01 level (1-tailed)

5 Conclusions

The findings highlighted that NBN could be a potential soil amendment for improving soil health and rice productivity. The study demonstrated that the combined application of 75% N through FM+NBN 5 kg ha⁻¹ not only provides an eco-friendly management of surplus crop residue but also significantly improves soil physical (AS, SM, water retention, H_c, IR), chemical properties (including OC, NH₄, NO₃ and NPK), nutrient uptake, root growth, and yield of basmati rice compared to the individual applications of NBN or MF. The study highlights that NBN, integrated with MFs, holds great potential for sustainable agriculture as a smart fertilizer, synchronizing nutrient release with crop growth to enhance nutrient efficiency and reduce waste. In future, we will expand its application to wide array of crops, transforming agricultural practices by enhancing crop productivity and creating more resilient agriculture.

Supplementary Information

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Additional file 1.

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Author contributions

VA and PS conceived, designed and wrote original draft, AS conducted trial and analysis work, CSR, ASP, ML, AK, MK, AH, KFA, EFA_A reviewed and edited the manuscript, AH and EFA_A acquired funding. All the authors have carefully examined and approved the final submission of this manuscript.

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Data availability

The authors declare that all relevant data supporting the findings of this study are included in this article and its supplementary information file.

Declarations

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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