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The effect of silica-enriched rice husk biochar and NPK fertilizer on soil total Nitrogen, Nitrogen uptake, and yield of lowland rice

Abstract. Rice production in Indonesia increasingly relies on agricultural intensification, which can accelerate soil degradation and reduce fertilizer-use efficiency. Therefore, sustainable soil management is needed to maintain soil fertility. Silica-enriched rice husk biochar (biochar-silica) is a promising soil amendment because it improves soil properties and nutrient retention. This study evaluated the effects of biochar-silica and NPK fertilization on soil total nitrogen, nitrogen uptake, and yield of lowland rice (*Oryza sativa* L.). The experiment was conducted from September 2025 to January 2026 using a two-factor randomized block design with nine treatment combinations and three replications. The treatment consisted of three levels of amendment (0 t biochar ha^{-1}; 1.25 t biochar ha^{-1} + 160 kg SiO2 ha^{-1}; 2.5 t biochar ha^{-1} + 320 kg SiO2 ha^{-1}) and three levels of NPK fertilizer application (0 kg urea ha^{-1} + 50 kg SP-36 ha^{-1} + 37.5 kg KCl ha^{-1}; 100 kg urea ha^{-1} + 50 kg SP-36 ha^{-1} + 37.5 kg KCl ha^{-1}; 200 kg urea ha^{-1} + 100 kg SP-36 ha^{-1} + 75 kg KCl ha^{-1}). Significant interaction effects were observed on soil total nitrogen, harvested dry grain yield, and milled dry grain yield, whereas nitrogen uptake was significantly affected only by NPK fertilizer application. Under the experimental conditions, the interaction between biochar-silica and NPK fertilizer application resulted in soil total nitrogen to 0.42% and milled dry grain yield to 6.63 t ha^{-1}. These findings demonstrate that integrating biochar-silica with NPK fertilizer application can improve soil nitrogen status and support lowland rice production.
Keywords: Fertilizer efficiency, Inceptisols, Nutrient Retention, Sustainable intensification

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Introduction

Lowland rice (*Oryza sativa* L.) is a major staple food crop consumed by more than half of the global population, particularly in Asia, which contributes approximately 90% of global rice production (Becker et al., 2023; Shah & Wu, 2019). In Indonesia, national rice production increased by 13.29% or 7.06 million tons of milled dry grain in 2025 compared with 2024, reflecting the increasing demand for rice as a strategic food commodity (Badan Pusat Statistik, 2026). However, this increase in production has occurred under decreasing agricultural land availability. During 2019–2025, Indonesia experienced a reduction of 554.62 thousand ha of protected paddy fields due to land conversion, creating greater production pressure on existing paddy ecosystems (Prasetyo, 2025).

These conditions indicate that national rice production increasingly depends on agricultural intensification. Although intensification contributes to short-term productivity improvement, long-term dependence on intensive cultivation practices, particularly excessive inorganic fertilizer application with limited organic matter inputs, may negatively affect soil quality and threaten sustainable rice production. Continuous intensification can accelerate soil degradation, increase erosion risk, reduce soil biological activity, and decrease nutrient use efficiency (Somansudaram et al., 2020; Shah & Wu, 2019). Therefore, improving soil fertility has become essential for maintaining long-term rice productivity in paddy ecosystems.

The productivity of rice cultivation is highly dependent on the availability of primary macronutrients, particularly nitrogen (N), phosphorus (P), and potassium (K). Nitrogen plays an essential role in chlorophyll synthesis, protein formation, enzymatic metabolism, and vegetative growth; phosphorus supports energy transfer, root development, and grain formation; whereas potassium contributes to osmotic regulation, assimilate translocation, and plant resistance to environmental stress (Liu et al., 2024; Du et al., 2021; Ajaykumar & Sivakumar, 2020). However, the efficiency of NPK fertilizer application in paddy soils remains relatively low due to nutrient losses, nutrient fixation, and limited nutrient retention in soil (Becker et al., 2023; Midya et al., 2021).

Among these macronutrients, nitrogen is considered the most dynamic nutrient in flooded rice ecosystems because it is highly susceptible to leaching, volatilization, and other transformation processes in soil (Shen et al., 2024; Ullah et al., 2023). Low nitrogen retention reduces nitrogen availability for plant uptake and may ultimately limit rice productivity. Therefore, improving nitrogen retention and utilization efficiency is an important strategy to sustain rice production under intensive cultivation systems.

To improve nutrient use efficiency, the integration of mineral fertilizers with soil amendments has become increasingly important. Biochar has been recognized as a promising soil amendment due to its high carbon stability, porous structure, and strong nutrient retention capacity (Khan et al., 2021). Rice husk biochar is particularly relevant in rice-based agricultural systems because of its abundant availability and potential to improve soil fertility while recycling agricultural residues (Iqbal et al., 2019). In addition, silicon (Si) is considered a beneficial element for rice because it enhances plant structural integrity, improves resistance to biotic and abiotic stresses, and supports nutrient utilization efficiency (Rao & Susmitha, 2017; Jinger et al., 2021; Su et al., 2024). The combined application of biochar and silica may provide synergistic effects by improving nutrient retention in soil and enhancing plant nutrient absorption.

Previous studies have shown that biochar-silica application combined with NPK fertilization improved soil fertility and rice productivity in paddy ecosystems (Sofyan et al., 2025). However, information regarding its effects on soil total nitrogen, nitrogen uptake, and yield of lowland rice remains limited. Therefore, this study aimed to evaluate the effects of biochar-silica and NPK fertilizer application on soil total nitrogen, nitrogen uptake, and yield of lowland rice.

Materials and Methods

Research area. The experiment was conducted for five months, from September 2025 to January 2026, under field and laboratory conditions. The field experiment was carried out at the experimental field of the Soil Chemistry and Plant Nutrition Laboratory, Faculty of Agriculture, Universitas Padjadjaran, Jatinangor, Sumedang, West Java, Indonesia (6°55′23.1″ S, 107°46′24.4″ E) at an altitude of 768 m above sea

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level. The study site is located in a tropical monsoon climate with a wet tropical agroclimatic zone, characterized by distinct wet and dry seasons. During the experimental period (October 2025–January 2026), monthly rainfall ranged from 85 to 235.5 mm, maximum air temperature from 27.8 to 29.8°C, minimum air temperature from 14.2 to 15.2°C, and relative humidity from 85 to 92%. Sunshine duration during the study ranged from approximately 4–7 hours day^{-1}, reflecting seasonal cloud cover during the rainy season. The experimental field was supported by an irrigation system to maintain adequate water availability for rice cultivation throughout the growing period. Laboratory analyses were conducted at the Soil Chemistry and Plant Nutrition Laboratory, Department of Soil Science and Land Resources, Faculty of Agriculture, Universitas Padjadjaran.

Materials and Tools. The materials used in this study consisted of lowland rice seeds (*Oryza sativa* L.) cv. Mapan P-05, rice husk biochar enriched with silica powder derived from zeolite containing 65% SiO_2, and single inorganic fertilizers consisting of urea (46% N), SP-36 (36% P_2O_5), and KCl (60% K_2O). Soil and plant samples were analyzed for selected chemical properties, including soil total nitrogen and plant nitrogen uptake. Field tools for land preparation, crop maintenance, and sampling were used during the experiment. Laboratory instruments and chemical reagents required for soil and plant analyses were provided by the laboratory.

Experimental Design and Treatments. The experiment was arranged in a factorial Randomized Block Design (RBD) consisting of two factors with three replications, resulting in 27 experimental plots. Each plot measured 4 m × 4 m with a planting distance of 25 cm × 25 cm, containing 256 plants per plot.

The first factor was silica-enriched biochar, consisting of:

a_0 = 0% recommended dose (without application);
a_1 = 50% recommended dose (1.25 t ha^{-1} rice husk biochar + 160 kg ha^{-1} silica powder);
a_2 = 100% recommended dose (2.5 t ha^{-1} rice husk biochar + 320 kg ha^{-1} silica powder).

The second factor was NPK fertilizer dose, consisting of:

b_0 = 0% recommended dose (without application);
b_1 = 50% recommended dose (100 kg ha^{-1} urea, 50 kg ha^{-1} SP-36, and 37.5 kg ha^{-1} KCl);
b_2 = 100% recommended dose (200 kg ha^{-1} urea, 100 kg ha^{-1} SP-36, and 75 kg ha^{-1} KCl).

Experimental Procedures. Soil samples were collected from paddy fields using a composite sampling method from five points at a depth of 0–30 cm. The field was prepared through plowing and harrowing, followed by plot arrangement and irrigation channel establishment. Biochar-silica amendment was applied according to the treatments, evenly incorporated into the soil, and incubated under moist soil conditions for 14 days before transplanting.

Rice seeds were pre-germinated and raised in seedling trays. Seedlings aged 16–21 days after sowing were transplanted into the experimental plots with one seedling per planting hole. NPK fertilizers were applied according to treatment levels. Urea fertilizer was applied in three split applications: 30% at transplanting, 30% at 30 days after transplanting (DAT), and 40% at 45 DAT. KCl fertilizer was applied twice, at transplanting and 15 DAT, while SP-36 was applied once at transplanting. Irrigation was managed using an intermittent wetting and drying system throughout the growing season. Standard crop management, including replanting, weed control, pest management, and harvesting at physiological maturity (about 90–95% of the grains had turned golden yellow) approximately 117 DAT, was carried out according to the recommended rice cultivation practices (Abdulrachman et al., 2011).

Sampling and Measurements. Soil samples were collected before treatment application and at the late vegetative stage for soil total nitrogen analysis. Plant samples were collected at the late vegetative stage from 20 representative hills per plot for nitrogen uptake analysis. Fully expanded leaves from the upper canopy were sampled, oven-dried at 60–65°C for seven days, ground, and prepared for laboratory analysis.

Rice growth parameters were observed every two weeks from 14 to 56 DAT using 20 sample plants per plot. Yield observations were conducted at harvest (117 DAT) when approximately 90% of panicles had reached physiological maturity. Grain yield components included harvested dry grain, milled dry grain, and 1000-grain weight. Grain yield was then converted to a hectare basis after applying a 15% correction factor to account for field bunds and non-planted areas.

Laboratory Analysis. Fresh soil samples collected from the field were immediately analyzed for total nitrogen using the standard Kjeldahl method (Eviati et al., 2023). Plant samples were oven-dried to constant weight, ground into a fine powder, and analyzed for nitrogen concentration using the Kjeldahl method. Plant nitrogen uptake was determined based on nitrogen concentration in plant tissue multiplied by dry biomass (Eviati et al., 2023)

Data Analysis. Data were analyzed using IBM SPSS Statistics version 27. Normality and homogeneity of variance were tested using the Shapiro–Wilk and Levene's tests, respectively. Treatment effects were evaluated using analysis of variance (ANOVA) at the 5% significance level. When significant differences were detected, mean comparisons were performed using Duncan's Multiple Range Test (DMRT) at the 5% level.

Results and Discussion

Pre-treatment Analysis. The experiment was conducted using Inceptisols collected from Jatinangor, West Java. The soil at 0–30 cm depth was characterized by a silty clay loam texture, consisting of 3% sand, 65% silt, and 32% clay (Table 1). Initial soil analysis showed that the soil had pH (H_2O) of 6.60, organic C of 3.01%, total N of 0.30%, available P (Olsen) of 95.00 ppm, CEC of 31.80 cmol kg^{-1}, K_2O of 17.35 mg 100 g^{-1}, and SiO_2 of 32.42%. Compared with the optimum nutrient requirement for rice cultivation, the soil total N content was relatively low, indicating potential nitrogen limitation. The relatively low SiO_2 content may also be associated with the low sand fraction (3%), indicating limited quartz-derived silica release in the soil (Ahmed et al., 2025; Bimasri et al., 2018; Pati et al., 2016).

Biochar-silica Properties. The soil amendment used in this study consisted of rice husk biochar enriched with silica powder derived from zeolite. Chemical analysis showed that the biochar contained 30.30% organic C, 0.49% total N, 0.09% P, 0.63% K, 43.11% SiO_2, pH 9.56, C/N ratio of 61.9, cation exchange capacity of 19.40 cmol kg^{-1}, and ash content of 47.20%. Based on the technical standards for biochar as soil amendment established by the Indonesian Ministry of Agriculture, the biochar used in this study met the quality requirements, particularly in organic carbon content (grade B) and pH range (Kepmentan No. 261/2019). The relatively high carbon content, alkaline pH, and silica concentration indicate its potential to improve soil chemical properties, enhance nutrient retention, and support nitrogen availability in paddy soils (Ullah et al., 2023; Ippolito et al., 2020).

Soil Total Nitrogen. The interaction between biochar-silica and NPK fertilizer significantly affected soil total nitrogen (STN). The highest STN (0.42%) was observed under the combination of 100% recommended biochar-silica and 50% recommended NPK fertilizer, and this treatment was significantly different from all other treatments. In contrast, the application of 100% biochar-silica combined with 100% NPK fertilizer resulted in a lower STN value (0.30%) and was not significantly different from the unfertilized control (0%).

Table 1. Interaction effects of silica-enriched biochar and NPK fertilizer on soil total Nitrogen (%)

Silica-enriched Biochar (a)	NPK Fertilizer (b)		
	b_0 (0%)	b_1 (50%)	b_2 (100%)
a_0 (0%)	0.35 a A	0.35 a A	0.31 a A
a_1 (50%)	0.33 b A	0.32 a A	0.32 a A
a_2 (100%)	0.35 a A	0.42 b B	0.30 a A

Notes: Means followed by the same letters are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level; lowercase letters indicate comparisons within rows, whereas uppercase letters indicate comparisons within columns; coefficient of variation (CV): 9.29%.

This pattern indicates that the response of STN is not solely determined by the amount of fertilizer applied, but rather by the balance between nitrogen input and the soil's capacity to retain nitrogen. Biochar-silica improves soil structure and provides porous surfaces that enhance microbial activity while increasing nutrient retention through its high cation exchange capacity (Tang et al., 2024; Danapriatna & Ismarani, 2023). In addition, silicate amendments may improve nitrogen use efficiency by plants, thereby reducing unnecessary depletion of soil nitrogen.

However, the decrease in STN under the highest N fertilization rate suggests that excessive

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nitrogen input may exceed the nitrogen retention capacity of the biochar-silica amendment. Although biochar enhances cation exchange capacity and provides negatively charged functional groups capable of adsorbing NH_4^+, its adsorption capacity is finite. Once the available adsorption sites become saturated, excess NH_4^+ remains in the soil solution and becomes more susceptible to volatilization, denitrification, and leaching under flooded paddy conditions (Hagemann et al., 2017; Li et al., 2019; Delin & Stenberg, 2014). Furthermore, excessive N application may stimulate microbial and enzymatic processes involved in nitrogen mineralization and nitrification (Ouyang et al., 2018; Liu et al., 2018). Consistent with Zhang et al. (2021), biochar application increased nitrogen mineralization by 15.3% and nitrification by 48.5%, promoting the formation of highly mobile NO_3^-, which is more prone to loss under flooded conditions when fertilizer is applied in excess.

Our findings indicate that biochar-silica does not act as a primary nitrogen source because of its relatively low nitrogen content (Fiorentino et al., 2019). Instead, it functions as a soil amendment that improves nitrogen retention and synchronizes nutrient availability with plant demand (Peng et al., 2021). Therefore, the combination of 100% biochar-silica with 50% N, P, K fertilizer likely provided sufficient nitrogen without exceeding the adsorption capacity of biochar, resulting in greater soil nitrogen retention and the highest STN. In contrast, increasing the fertilizer rate to 100% reduced nitrogen retention efficiency despite the same biochar-silica application, leading to lower STN.

Nitrogen Uptake. Statistical analysis showed that NPK fertilizer application significantly affected nitrogen uptake of lowland rice, whereas biochar–silica application and the interaction between both factors showed no significant effects (Table 2). Nitrogen uptake increased consistently with increasing NPK fertilizer rates. The highest nitrogen uptake was observed at 100% of the recommended NPK dose (0.19 g/plant), followed by 50% of the recommended dose (0.15 g/plant), while the lowest value was recorded in the unfertilized treatment (0.13 g/plant).

The significant effect of NPK fertilizer application on nitrogen uptake was mainly associated with increased nutrient availability in the rhizosphere. Nitrogen supplied from urea is rapidly hydrolyzed and transformed into plant-available forms, particularly ammonium under flooded soil conditions, thereby supporting active nitrogen absorption by rice roots. In addition to nitrogen supply, phosphorus availability may stimulate root growth and root branching, while potassium supports osmotic regulation and assimilate translocation, which collectively improve nutrient uptake efficiency. Previous studies reported that adequate NPK fertilization significantly improved root development, biomass accumulation, and nutrient absorption in rice cultivation systems (Iqbal et al., 2019; Moe et al., 2019). Therefore, higher NPK application rates likely promoted more efficient nitrogen acquisition through improved root activity and nutrient accessibility.

Table 2. Main effects of silica-enriched biochar and NPK fertilizer on Nitrogen uptake (g/plant)

Treatments	Nitrogen Uptake (g/plant)
Silica-enriched Biochar (a)	
a_0 (0%)	0.15
a_1 (50%)	0.16
a_2 (100%)	0.16
NPK Fertilizer (b)	
b_0 (0%)	0.13 a
b_1 (50%)	0.15 b
b_2 (100%)	0.19 c

Notes: Means followed by the same letters are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level; coefficient of variation (CV): 19.75%.

In contrast, biochar–silica amendment did not significantly affect nitrogen uptake during the observation period. This suggests that under the present experimental conditions, the role of biochar–silica was more closely related to improving soil chemical properties and regulating nutrient dynamics rather than directly increasing nitrogen absorption by plants. The absence of a significant response may be associated with the slow-release characteristics of biochar. Biochar possesses a porous surface and reactive functional groups capable of adsorbing ammonium and nitrate ions, thereby reducing nitrogen losses through leaching and volatilization (Selvarajh & Chng, 2021; Lai et al., 2023)). In addition, silica-rich biochar may contribute to more controlled nutrient release by stabilizing nutrient retention in the soil matrix (Nguyen, 2021).

As a consequence, nitrogen retained within the biochar matrix may not be immediately available for plant uptake during the relatively short observation period. Instead, the retained nitrogen may be gradually released into the soil solution over time, contributing more to long-term nutrient availability than immediate physiological uptake. These findings indicate that inorganic NPK fertilization played a dominant role in improving short-term nitrogen uptake of lowland rice, whereas the benefits of biochar–silica amendment may become more evident under longer-term soil management.

Yield of Lowland Rice. There is a significant interaction between biochar–silica amendment and NPK fertilizer application on harvested dry grain yield (Table 3). Overall, increasing the application rates of biochar–silica and NPK fertilizer increased harvested dry grain yield. The highest yield was obtained from the combination of 50% of the recommended biochar–silica dose with 100% of the recommended NPK dose, reaching 7.68 t ha⁻¹. This treatment was statistically similar to the combination of 100% biochar–silica with 50% NPK fertilization, which produced 7.61 t ha⁻¹. In contrast, the lowest yield was recorded in the control treatment without biochar–silica and NPK application, with only 2.20 t ha⁻¹.

Table 3. Interaction effects of silica-enriched biochar and NPK fertilizer on harvested dry grain (t ha^{-1})

Silica-enriched Biochar (a)	NPK Fertilizer (b)		
	b_0 (0%)	b_1 (50%)	b_2 (100%)
a_0 (0%)	2.20 a A	2.77 b A	3.65 c A
a_1 (50%)	4.34 a B	6.07 b B	7.68 c C
a_2 (100%)	3.92 a B	7.61 c C	6.35 b B

Notes: Means followed by the same letters are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level; lowercase letters indicate comparisons within rows, whereas uppercase letters indicate comparisons within columns; coefficient of variation (CV): 7.80%.

The significant interaction indicates that biochar–silica amendment and NPK fertilization worked synergistically in improving grain production. Biochar improved soil nutrient retention and reduced nutrient losses, while silica strengthened plant tissues and improved tolerance to environmental stress, thereby supporting photosynthetic efficiency and assimilate accumulation during grain filling (Wu et al., 2020; Gou et al., 2023; Malhotra et al, 2016). At the same time, NPK fertilization supplied essential macronutrients required for tiller formation, photosynthesis, and reproductive development, resulting in greater grain production.

A similar response was observed for milled dry grain yield, where a significant interaction between biochar–silica amendment and NPK fertilization was also detected (Table 4). Overall, increasing both treatment levels increased milled dry grain yield. The highest yield was observed under the combination of 50% biochar–silica with 100% NPK fertilization, producing 6.70 t ha⁻¹, which was statistically similar to the combination of 100% biochar–silica and 100% NPK fertilization, with a yield of 6.63 t ha⁻¹. The lowest milled dry grain yield was recorded in the control treatment, with 1.92 t ha⁻¹.

Table 4. Interaction effects of biochar–silica and N, P, K fertilizer on milled dry grain (t ha^{-1})

Silica-enriched Biochar (a)	NPK Fertilizer (b)		
	b_0 (0%)	b_1 (50%)	b_2 (100%)
a_0 (0%)	1.92 a A	2.41 b A	3.18 c A
a_1 (50%)	3.79 a B	5.29 b B	6.70 c C
a_2 (100%)	3.42 a B	6.63 c C	5.54 b B

Notes: Means followed by the same letters are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level; lowercase letters indicate comparisons within rows, whereas uppercase letters indicate comparisons within columns; coefficient of variation (CV): 7.81%.

The increase in milled dry grain yield suggests that the combined application of biochar–silica and NPK fertilizer improved nutrient availability and nutrient use efficiency during the grain filling stage. Phosphorus and potassium are known to support assimilate translocation and endosperm development, while nitrogen supports chlorophyll synthesis and photosynthetic activity (Shah & Wu, 2019; Paramesh et al., 2023). When combined with biochar–silica, these nutrients may remain more available in the rhizosphere, resulting in better grain filling and higher final grain yield. These findings are consistent with Sofyan et al. (2025), who reported that biochar–silica combined with

NPK fertilization produced higher rice yields than single applications.

Although grain yield increased significantly, the obtained yield remained below the genetic yield potential of the cultivar (13 t ha^{-1}). This may be associated with microclimatic fluctuations during reproductive growth and the gradual residual effect of biochar, which generally requires multiple cropping cycles to fully improve soil buffering capacity and long-term productivity (Liu et al., 2025; Xu et al., 2022).

Table 5. Main effects of silica-enriched biochar and NPK fertilizer on 1000 grain weight (g)

Treatment	1000 Grain Weight (g)
Silica-enriched Biochar (a)	
a_0 (0%)	34.63 a
a_1 (50%)	36.43 ab
a_2 (100%)	40.46 b
NPK Fertilizer (b)	
b_0 (0%)	36.13
b_1 (50%)	37.43
b_2 (100%)	37.97

Notes: Means followed by the same letters are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level; coefficient of variation (CV): 11.47%.

Unlike harvested and milled grain yield, our study showed no significant interaction between biochar–silica amendment and NPK fertilization on 1000 grain weight. However, biochar–silica amendment alone significantly affected this parameter (Table 5). Increasing biochar–silica application rates increased 1000-grain weight. The highest value was obtained under 100% of the recommended biochar–silica dose, reaching 40.46 g, followed by 50% of the recommended dose (36.43 g), while the lowest value was recorded in the treatment without biochar–silica application (34.63 g).

The increase in 1000-grain weight indicates that biochar–silica application improved grain development and grain filling. Grain weight is generally influenced by genetic characteristics and environmental adaptability (Sravan et al., 2022). The observed values exceeded the genetic potential of the Mapan P-05 variety (35.70 g), suggesting that biochar–silica created more favorable soil and plant growth conditions. Improved root development, nutrient availability, and stress tolerance may have contributed to better assimilate accumulation in grains (Jin et al., 2024; Abbas et al., 2024). Although NPK fertilizer application did not significantly affect this parameter, the average grain weight remained above the varietal potential, indicating that adequate nutrient supply still supported grain filling.

Conclusion

The interaction between biochar-silica amendment and NPK fertilizer application plays a key role in regulating soil nitrogen dynamics and grain production of lowland rice cultivated on Inceptisols. Significant interaction effects on soil total nitrogen and grain yield indicate that the effectiveness of inorganic fertilization is governed not only by the amount of nutrients applied but also by the soil's capacity to retain and regulate nitrogen availability. In this regard, biochar-silica primarily functions as a soil amendment rather than a direct nutrient source by enhancing nitrogen retention within the soil system and creating more favorable conditions for sustaining nutrient availability during crop growth. The absence of an interaction effect on nitrogen uptake further suggests that improvements in soil nitrogen status do not necessarily translate into proportional increases in plant nitrogen accumulation, highlighting the complexity of nitrogen transformation and utilization under flooded paddy conditions. Collectively, these findings emphasize that optimizing nutrient management in paddy soils should focus on achieving a balance between nutrient supply and nutrient retention rather than relying solely on increasing fertilizer inputs. Therefore, integrating biochar-silica with NPK fertilizer application represents a promising strategy for improving soil quality and sustaining rice production on Inceptisols, while providing a scientific basis for developing more efficient and environmentally sustainable fertilizer application practices.

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