EFFECTS OF BIOCHAR APPLICATION AND NITROGEN FERTILIZER REDUCTION ON NUTRIENT UPTAKE AND YIELD OF RICE IN COLD REGIONS

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Abstract. The study aimed to evaluate the effects of biochar application and nitrogen (N) fertilization on rice yield and its components to provide insights into sustainable nutrient management strategies. The experiment assessed three biochar application rates (0 $t \cdot ha^{-1}$, 15 $t \cdot ha^{-1}$, 40 $t \cdot ha^{-1}$) and four nitrogen levels (0 $kg \cdot ha^{-1}$, 95 $kg \cdot ha^{-1}$, 180 $kg \cdot ha^{-1}$, 225 $kg \cdot ha^{-1}$). Data were collected on plant height, spike number, grain number per spike, seed setting rate, thousand-grain weight, and yield. Results showed that biochar significantly improved rice productivity. The highest yield (8464.18 $kg \cdot ha^{-1}$) was achieved under moderate nitrogen application (180 $kg \cdot ha^{-1}$) with 15 $t \cdot ha^{-1}$ biochar. Biochar-treated plots exhibited superior performance in spike number and grain number per spike compared to untreated controls, while excessive nitrogen (225 $kg \cdot ha^{-1}$) provided no significant yield benefits and reduced seed setting rates. Biochar also mitigated nitrogen losses and environmental risks, promoting sustainable production. These findings demonstrate the combined benefits of biochar and moderate nitrogen levels in enhancing rice yield and reducing environmental impacts. The study concludes that biochar is an effective amendment for improving nutrient uptake and achieving sustainable rice production. Future research should explore biochar's long-term effects on soil health and its interactions with other nutrients to further optimize agricultural practices.
Keywords: *biochar application, sustainable agriculture, soil amendment, crop productivity, nutrient management*

Introduction

Rice is a staple food crop in China, and nitrogen (N) plays a crucial role in determining its yield (Wang et al., 2022a). Appropriate nitrogen fertilizer application is essential for promoting crop growth and achieving high yields (Barłóg et al., 2022). However, excessive nitrogen use can increase crop susceptibility to pests and diseases, and adversely affect grain quality and overall yield. Since the 1980s, nitrogen fertilizer application in China has increased dramatically, resulting in resource waste and significant environmental degradation from inefficient practices (Liu et al., 2022). Consequently, developing strategies to reduce nitrogen application rates, minimize nitrogen losses, and maintain stable crop yields has become a critical priority for advancing sustainable agricultural practices.

In recent years, research on the effects of biochar on soil nutrients in China has primarily focused on degraded and nutrient-deficient soils (Yu et al., 2019). Studies have shown that bamboo biochar produced at 600 °C can adsorb ammonium nitrogen through ion exchange, reducing cumulative nitrogen losses by 15.2% within 70 days (Ding et al., 2010). Additionally, biochar has been reported to reduce NO_3^- leaching through adsorption, thereby enhancing nitrogen utilization by crops (Dai et al., 2020). As research progresses, the co-application of biochar with chemical fertilizers has been demonstrated to exert positive synergistic effects (Yuan et al., 2024). Mon and Ueno (2024) found that the co-application of biochar and fertilizer significantly enhances soil NH_4^+ adsorption and retention, thereby increasing nitrogen availability for rice and reducing nitrogen

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losses. Similarly, Chen et al. (2022) reported that the co-application of biochar and nitrogen fertilizer markedly promotes nitrogen uptake in wheat grown on red soil, leading to increased biomass.

Biochar is widely regarded as an effective soil amendment that enhances nutrient availability, promotes crop growth, and improves overall soil health (Agegnehu et al., 2017). Yang et al. (2022) reported that the co-application of biochar and nitrogen fertilizer significantly improved the photosynthetic performance of *Bletilla striata*, demonstrating biochar's positive effects on plant physiological processes. Similarly, applying rice straw biochar at 15 $t{\cdot}ha^{-1}$ combined with a 20–40 % reduction in nitrogen fertilizer not only enhanced the effective uptake of nitrogen in rice production systems but also reduced overall fertilizer input (Zhao et al., 2014). This approach simultaneously enhanced soil microbial activity and boosted crop productivity. Furthermore, Ahmad et al. (2021) found that incorporating biochar (5.0 $t{\cdot}ha^{-1}$) with a 20 % reduction in nitrogen fertilizer significantly increased microbial biomass carbon and nitrogen in the soil, contributing to enhanced rice yield and improved grain quality. These findings underscore the potential of biochar to support sustainable agricultural practices by optimizing nutrient management, promoting soil microbial health, and enhancing crop productivity under reduced nitrogen input conditions. Although the co-application of biochar and reduced nitrogen fertilizer has been extensively validated in improving crop growth, yield, and photosynthetic performance, research remains limited on its effects in the black soil regions of Northeast China. This study aims to address this gap by investigating the synergistic effects of biochar and reduced nitrogen application on soil fertility and rice yield in typical black soil systems, providing insights for sustainable nutrient management in this region.

Materials and methods

Site description and materials

This study was conducted in the field trial area of Zhaoyuan Farm (124°29′E, 45°68′N) in Heilongjiang Province, China, in 2023. The region is characterized by a cold temperate continental monsoon climate with distinct seasonal variations. The frost-free period lasts 135–145 days, and the accumulated temperature (≥10 °C) ranges from 2,900 to 3,200 °C, making the area suitable for rice cultivation. The annual precipitation is approximately 500–600 mm, with rainfall concentrated in the summer months, ensuring sufficient moisture supply during the rice-growing season. The soil in the experimental field is classified as Albic soil (Albi-Udic Cambosols, Chinese Soil Taxonomy), which is typical of the region. The topsoil (0–20 cm) contained 22.3 $g{\cdot}kg^{-1}$ organic matter, 1.32 $g{\cdot}kg^{-1}$ total nitrogen, 42.8 $mg{\cdot}kg^{-1}$ available phosphorus, and 126.7 $mg{\cdot}kg^{-1}$ available potassium, with a pH of 6.3. The tested rice variety was Zhongkefa No. 5 (*Oryza sativa* L.), one of the dominant Japonica rice varieties in the area. This variety has a total growth period of approximately 150.1 days, with an effective panicle number of 273,000 per mu (≈4.1 million per hectare), an average of 118.3 grains per panicle, a seed-setting rate of 79.9%, a 1,000-grain weight of 26.9 g, and a milling rate of 70.1%. It is suitable for cultivation in the upper limits of the first accumulated temperature zone in Heilongjiang Province. The experimental design followed standard agronomic practices. Sowing was conducted on April 15, and transplanting took place on May 20 using a planting density of 30 cm between rows and 13 cm between hills. A shallow, wet, and dry irrigation method was applied to optimize water management, and drainage was

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initiated at the early yellow ripening stage. Throughout the growing period, standard agrotechnical measures, including weed control, pest and disease management, and fertilization, were implemented following local rice cultivation guidelines. Plant protection measures were carried out as needed to prevent pest infestations and ensure crop health. The rice was harvested on September 26. Biochar is a stable, carbon-rich product made from agricultural waste biomass, such as crop straw and peanut shells, via pyrolysis under low temperature and anoxic conditions. The biochar used in this study was commercially supplied by Liao Ning Golden Future Agriculture Technology Co., Ltd. It has a pH of 8.69 and an N:P_2O_5:K_2O ratio of 8:11:15, with total nitrogen, total P_2O_5, and total K_2O contents of 0.8%, 1.1%, and 1.5%, respectively.

Experimental design

This experiment employed a two-factor randomized block design with three biochar application rates: 0 $t\cdot ha^{-1}$ (T0), 15 $t\cdot ha^{-1}$ (T1), and 40 $t\cdot ha^{-1}$ (T3), and four nitrogen fertilizer levels (pure nitrogen): 0 $kg\cdot ha^{-1}$ (N0, with 937.5 $kg\cdot ha^{-2}$ of phosphorus fertilizer and 187.5 $kg\cdot ha^{-1}$ of potassium fertilizer), 95 $kg\cdot ha^{-1}$ (N1), 180 $kg\cdot ha^{-1}$ (N2), and 225 $kg\cdot ha^{-1}$ (N3). Each treatment was replicated three times, with plots measuring 4.0 m × 4.0 m enclosed by iron plates 0.5 m high (0.3 m underground and 0.3 m above ground). Other management practices followed conventional field production methods.

Rice samples were collected during the tillering, heading, filling, and maturity stages by randomly selecting 3 representative plants per plot. At the tillering stage, the sampled plants were separated into leaves and stems, while at the heading, filling, and maturity stages, they were divided into leaves, stems, and panicles. The separated samples were then oven-dried at 105 °C for 30 minutes, further dried at 75 °C until a constant weight was achieved, weighed, ground, and sieved for nutrient content analysis.

Determination of plant nutrient content

The nitrogen (N), phosphorus (P), and potassium (K) contents of various plant parts were determined following the method described by Bao (2005). Plant samples were digested with concentrated sulfuric acid using hydrogen peroxide as a catalyst. Total nitrogen content was measured using a B324 Kjeldahl nitrogen analyzer (manufactured by Beijing Precise Instruments, Beijing, China). Total phosphorus content was determined using the molybdenum-antimony colorimetric method, while total potassium content was analyzed using a Model 410 flame photometer (manufactured by Shanghai Precision Instrument Co., Ltd., Shanghai, China).

After rice maturity, five plants with similar growth status and an average tiller number consistent with the plot average were selected from each plot. These plants were naturally air-dried and analyzed indoors for yield-related traits, including the number of effective panicles, the number of filled grains per panicle, unfilled grains, seed-setting rate, and 1,000-grain weight. The remaining plants were harvested collectively, and the actual yield for each plot was measured.

Statistical analysis

The data were organized, calculated, and visualized using Microsoft Office Excel 365 (Microsoft Corporation, Redmond, WA, USA). To assess the main effects of the experimental factors and their interactions, a two-way analysis of variance (ANOVA) was performed using SPSS 28.0 (IBM SPSS Statistics; IBM Corporation, Armonk, NY, USA), with multiple comparisons conducted using Duncan's method. Statistically significant differences were explicitly reported ($P < 0.05$). Extreme value analysis was carried out using Lingo 19.0 (Lindo Systems, Inc., Vancouver, Canada). Additionally, supplementary analyses, including linear regression and multivariate analysis of variance (MANOVA), were employed to verify the robustness of our findings, with statistical significance consistently specified where applicable.

Results

Effect of nitrogen fertilizer on nitrogen content in rice stems under biochar application

The nitrogen content in rice stems varied significantly across different nitrogen fertilizer levels (N0, N1, N2, N3) and biochar application rates (T0, T1, T2) at various growth stages (tillering, heading, filling, and maturity) in *Figure 1*. During the tillering stage, the nitrogen content generally increased with higher nitrogen fertilizer levels, with the highest content observed under the N3 treatment and the lowest under N0, across all biochar treatments. Significant differences were observed between nitrogen levels, as indicated by the different lowercase letters ($P < 0.05$). At the heading stage, the nitrogen content remained higher with increased nitrogen levels, and the biochar treatments (T1 and T2) showed slightly higher nitrogen content compared to T0 under the same nitrogen levels, with significant differences noted between some treatments. In the filling stage, the nitrogen content declined compared to earlier stages but continued to increase with higher nitrogen levels (N0 < N1 < N2 < N3) in all biochar treatments, with significant differences evident between treatments. By the maturity stage, the nitrogen content reached its lowest values across all growth stages, yet the trend of higher nitrogen content with increased nitrogen levels persisted, and T1 and T2 treatments generally showed higher nitrogen content than T0, with significant differences observed between specific treatments ($P < 0.05$). At the tillering, heading, filling, and maturity stages, under the N2 and N3 treatments, the biochar treatments (T0, T1, and T2) exhibited higher nitrogen content in the rice stems.

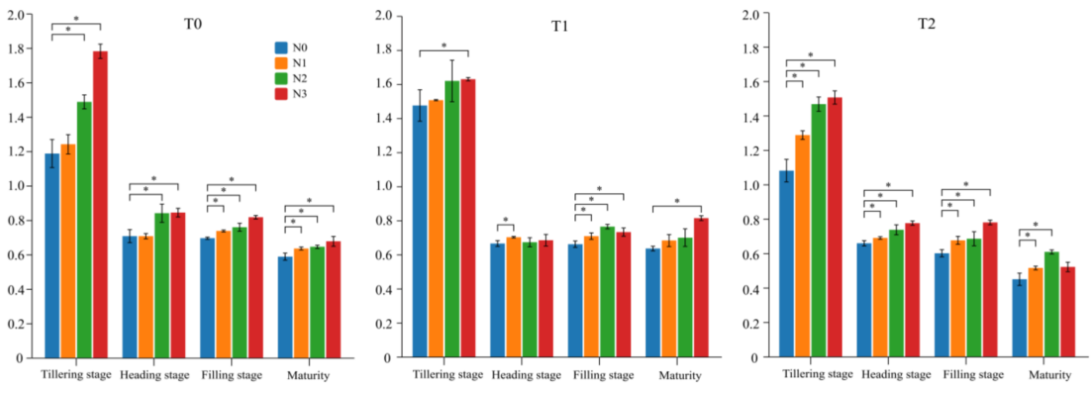

***Figure 1.** Effect of different treatments on nitrogen content in rice stem. Note: "*" indicates a significant interaction at the 0.05 level. N0, N1, N2, and N3 represent nitrogen application rates of 0, 95, 180 and 225 kg·ha^{-1}, respectively. T0, T1, and T2 indicate biochar application rates of 0, 15 and 40 t·ha^{-1}, respectively. The same below*

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Effect of nitrogen fertilizer on nitrogen content in rice leaves under biochar application

The nitrogen content in rice leaves varied significantly across different nitrogen fertilizer levels and biochar application rates at various growth stages as shown in *Figure 2*. During the tillering stage, the nitrogen content increased significantly with higher nitrogen fertilizer levels, with the N3 treatment showing the highest content, followed by N2, N1, and N0. Significant differences were observed between nitrogen levels ($P < 0.05$). At the heading stage, the nitrogen content was higher than in the tillering stage and continued to increase with higher nitrogen fertilizer levels. T1 and T2 treatments generally showed slightly higher nitrogen content than T0 under the same nitrogen levels, with significant differences observed. In the filling stage, the nitrogen content declined compared to the heading stage, but the increasing trend with higher nitrogen levels (N0 < N1 < N2 < N3) remained consistent across all biochar treatments, with significant differences between treatments. By the maturity stage, the nitrogen content decreased further, reaching the lowest levels among all growth stages. However, the trend of higher nitrogen content with increasing nitrogen levels persisted, and T1 and T2 treatments generally maintained slightly higher nitrogen content than T0 under the same nitrogen levels. Significant differences between treatments were observed ($P < 0.05$). These results indicate that nitrogen fertilizer levels and biochar application significantly influenced the nitrogen content in rice leaves, with the effect diminishing as rice approached maturity. At the tillering, heading and filling stages, under the same biochar application level (To, T1 and T2), the nitrogen content in rice leaves showed an increasing trend.

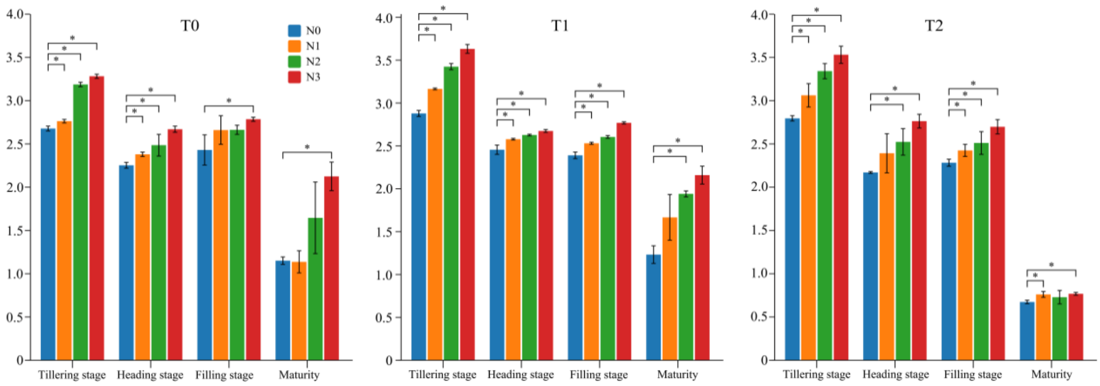

***Figure 2.** Effect of different treatments on nitrogen content in rice leaves*

Effect of nitrogen fertilizer on nitrogen content in rice panicles under biochar application

As shown in *Figure 3*, the nitrogen content in rice panicles was significantly affected by different biochar treatments and nitrogen fertilizer levels at various growth stages. During the heading stage, the nitrogen content in panicles increased with higher nitrogen fertilizer levels, with the highest content observed in the N3 treatment, followed by N2, while N1 and N0 showed lower values. Significant differences were observed among treatments ($P < 0.05$). The nitrogen content under T1 and T2 treatments was generally higher than that under T0. In the filling stage, the nitrogen content in panicles decreased compared to the heading stage; however, the trend of increasing nitrogen content with higher nitrogen levels remained evident, with significant differences among treatments. Similarly, the nitrogen content under T1 and T2 treatments was still higher than that under T0. At the maturity stage, the nitrogen content in panicles further decreased to the lowest levels, but the gradient of variation among nitrogen fertilizer levels persisted. The nitrogen content under T1 and T2 treatments remained slightly higher than that under T0, with significant differences still observed among treatments ($P < 0.05$). At the filling stage, the T3 treatment led to a significant increase in the nitrogen content of rice panicles under the N3 level. These results indicate that nitrogen fertilizer levels and biochar application significantly affected the nitrogen content in rice panicles, but the effect gradually weakened as the rice progressed through its growth stages.

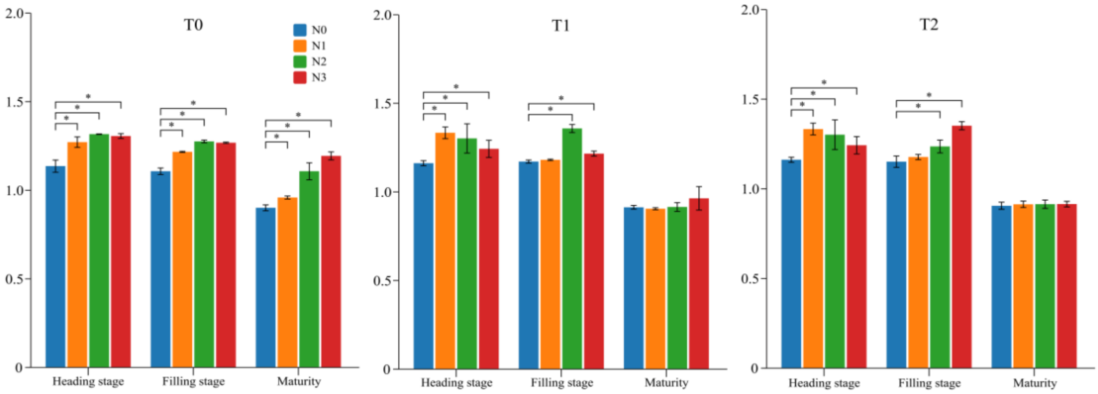

Figure 3. *Effect of different treatments on nitrogen content in rice panicles*

Effect of nitrogen fertilizer on phosphorus content in rice stems under biochar application

As shown in *Figure 4*, the phosphorus content in rice stems increased with higher nitrogen fertilizer levels during the tillering stage, with the N3 treatment yielding the highest content, followed by N2, N1, and N0. Significant differences ($P < 0.05$) were observed among treatments, and the application of biochar (T1 and T2) slightly elevated phosphorus levels compared to T0. A similar pattern emerged at the heading stage, where N3 exhibited the highest phosphorus content and N0 the lowest. The T1 and T2 treatments consistently resulted in higher phosphorus content than T0, with significant differences among treatments. During the filling stage, phosphorus levels declined compared to earlier stages but remained positively associated with nitrogen fertilizer levels (N0 < N1 < N2 < N3). Biochar treatments (T1 and T2) continued to maintain slightly higher phosphorus levels than T0. By the maturity stage, phosphorus content further decreased to the lowest levels, though the trend of higher levels with increasing nitrogen remained evident. Significant differences ($P < 0.05$) were still detected between treatments, with T1 and T2 showing higher phosphorus content than T0. At the tillering stage, the T1 and T2 treatment led to a significant increase in the nitrogen content of rice stems under the N3 level. These findings highlight the significant influence of nitrogen fertilizer levels and biochar application on phosphorus content in rice stems, though the effects diminished as the rice approached maturity.

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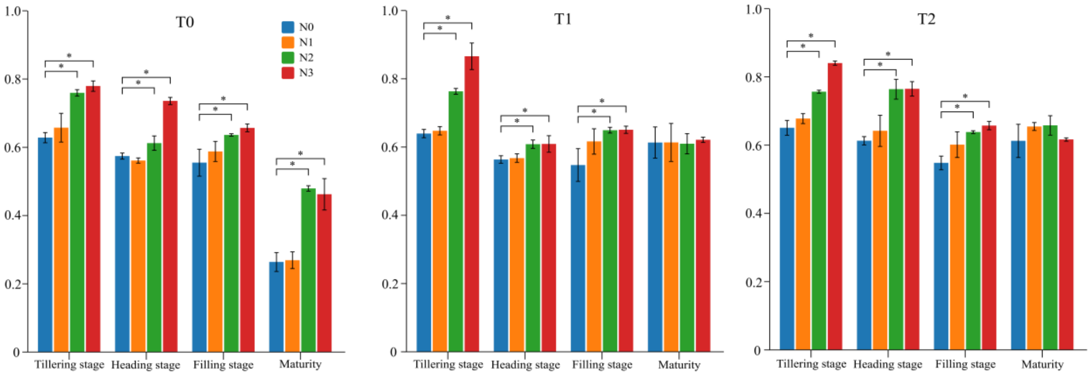

Figure 4. *Effect of different treatments on phosphorus content in rice stems*

Effect of nitrogen fertilizer on phosphorus content in rice leaves under biochar application

Figure 5 shows that the phosphorus content in rice leaves was significantly influenced by different biochar application rates and nitrogen fertilizer levels at various growth stages. During the tillering stage, phosphorus content increased with higher nitrogen fertilizer levels, with N3 showing the highest content, followed by N2, N1, and N0. Significant differences ($P < 0.05$) were observed between nitrogen levels, and biochar treatments (T1 and T2) slightly enhanced phosphorus content compared to T0. At the heading stage, phosphorus content remained positively correlated with nitrogen levels, with N3 maintaining the highest content and N0 the lowest. T1 and T2 treatments consistently showed higher phosphorus levels than T0, with significant differences among treatments. During the filling stage, phosphorus content peaked under N3 and followed the same trend as earlier stages (N0 < N1 < N2 < N3), with T1 and T2 treatments showing higher values than T0. By the maturity stage, phosphorus content declined across all treatments to its lowest levels, but the trend of increasing phosphorus content with higher nitrogen levels persisted. Significant differences ($P < 0.05$) remained, with T1 and T2 showing higher phosphorus content than T0. At the filling stage, the T2 and T2 treatment led to a significant increase in the nitrogen content of rice leaves under the N1, N2 and N3 levels.

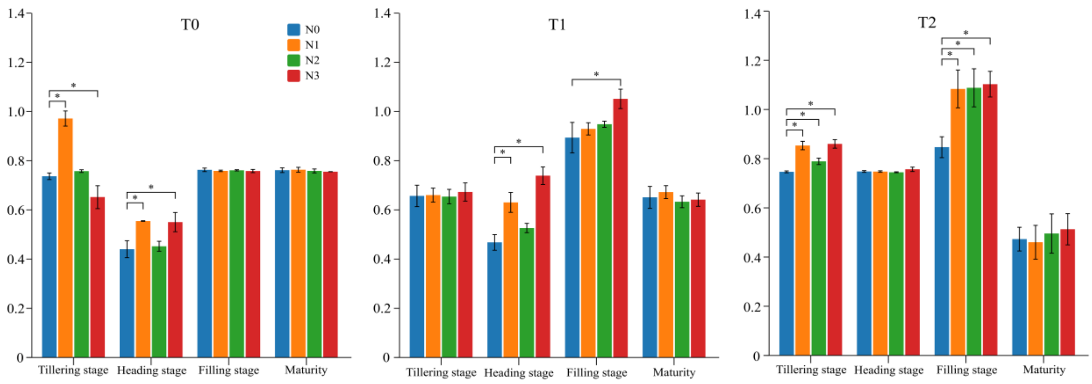

Figure 5. *Effect of different treatments on phosphorus content in rice leaves*

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Effect of nitrogen fertilizer on phosphorus content in rice panicles under biochar application

The phosphorus content in rice panicles was significantly influenced by different biochar application rates and nitrogen fertilizer levels at various growth stages in *Figure 6*. During the heading stage, the phosphorus content increased with higher nitrogen levels, with N3 showing the highest content, followed by N2, N1, and N0. Significant differences ($P < 0.05$) were observed, and T1 and T2 treatments resulted in slightly higher phosphorus content compared to T0. At the filling stage, phosphorus content decreased relative to the heading stage but remained positively correlated with nitrogen levels, with N3 maintaining the highest content and N0 the lowest. Significant differences were still observed among treatments, with T1 and T2 consistently showing higher values than T0. By the maturity stage, phosphorus content declined further to its lowest levels, though the trend of increasing phosphorus content with higher nitrogen levels persisted. T1 and T2 treatments continued to exhibit higher phosphorus content than T0, with significant differences ($P < 0.05$). At the maturity stage, the T2 treatment led to a significant increase in the nitrogen content of rice panicles under the N2 level. These results demonstrate the notable influence of nitrogen fertilizer and biochar application on phosphorus content in rice panicles, with the impact weakening as the rice matured.

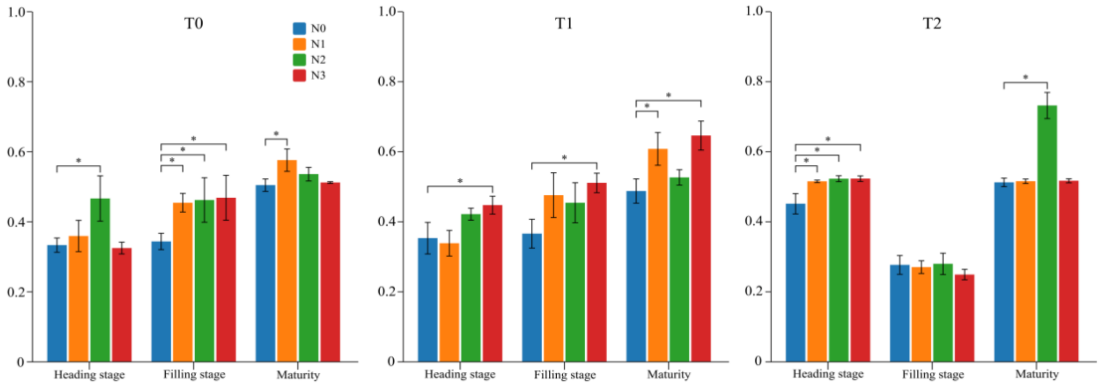

Figure 6. *Effect of different treatments on phosphorus content in rice panicles*

Effect of nitrogen fertilizer on potassium content in rice stems under biochar application

Figure 7 illustrates the variation in potassium content in rice stems under different biochar application rates and nitrogen fertilizer levels across various growth stages. At the tillering stage, potassium content increased with higher nitrogen fertilizer levels, with N3 exhibiting the highest values, followed by N2, N1, and N0. Biochar application (T1 and T2) slightly enhanced potassium levels compared to T0, with significant differences ($P < 0.05$) observed among treatments. During the heading stage, potassium content remained positively correlated with nitrogen levels, with N3 maintaining the highest content and N0 the lowest. Biochar treatments continued to show higher potassium levels than T0, and significant differences were evident. In the filling stage, potassium content declined slightly compared to earlier stages but still increased with higher nitrogen levels, and biochar treatments (T1 and T2) remained superior to T0, with significant differences

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observed (*P* < 0.05). By the maturity stage, potassium content reached its lowest levels across all treatments, though the gradient among nitrogen levels (N0 < N1 < N2 < N3) persisted. Biochar treatments continued to maintain higher potassium levels than T0, with significant differences (*P* < 0.05). At the rice tillering stage, the T0 treatment led to a significant increase in the potassium content of rice stems under the N3 level. These results demonstrate the significant influence of nitrogen fertilizer and biochar application on potassium content in rice stems, with the effects gradually diminishing as the rice matured.

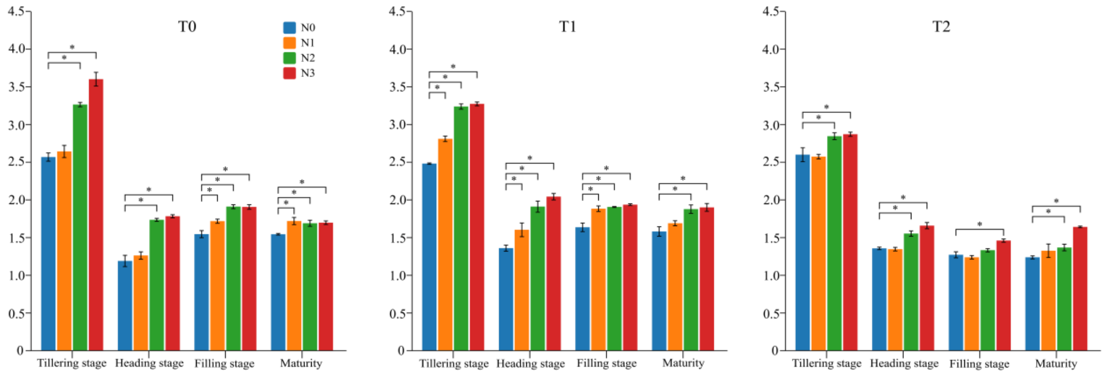

Figure 7. *Effect of different treatments on potassium content in rice stems*

Effect of nitrogen fertilizer on potassium content in rice leaves under biochar application

Figure 8 shows the potassium content in rice leaves under different biochar application rates and nitrogen fertilizer levels across four growth stages. During the tillering stage, potassium content increased with higher nitrogen fertilizer levels, with N3 showing the highest values, followed by N2, N1, and N0. Biochar application (T1 and T2) slightly elevated potassium content compared to T0, and significant differences (*P* < 0.05) were observed among treatments. At the heading stage, potassium levels remained positively correlated with nitrogen fertilizer levels. N3 consistently showed the highest values, while N0 had the lowest. Biochar treatments (T1 and T2) resulted in higher potassium content than T0, with significant differences among treatments. During the filling stage, potassium content declined slightly compared to earlier stages but maintained the trend of increasing with nitrogen levels (N0 < N1 < N2 < N3). Biochar treatments T1 and T2 continued to exhibit slightly higher values than T0, and significant differences (*P* < 0.05) were evident. At the maturity stage, potassium levels further decreased to their lowest across all growth stages. Despite this decline, the positive correlation between nitrogen levels and potassium content persisted, with N3 showing the highest content. Biochar treatments (T1 and T2) still maintained higher potassium levels compared to T0, with significant differences observed (*P* < 0.05). At the rice tillering stage, the T0 treatment led to a significant increase in the nitrogen content of rice leaves under the N2 and N3 levels. These findings indicate that nitrogen fertilizer levels and biochar application significantly influenced potassium content in rice leaves, with the effects weakening as the rice approached maturity.

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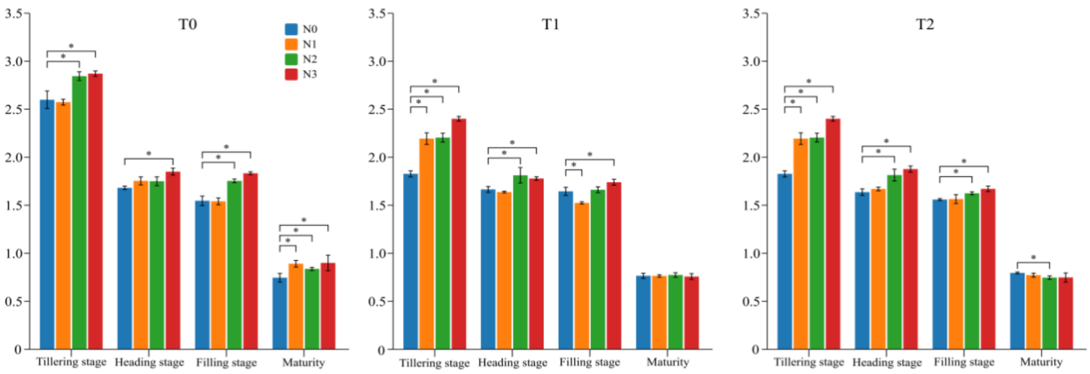

Figure 8. *Effect of different treatments on potassium content in rice leaves*

Effect of nitrogen fertilizer on potassium content in rice panicles under biochar application

Figure 9 shows the potassium content in rice panicles under different biochar rates and nitrogen levels across growth stages. At the heading stage, potassium content increased with higher nitrogen levels, with N3 being the highest and N0 the lowest. Biochar treatments (T1 and T2) slightly enhanced potassium levels compared to T0, showing significant differences ($P < 0.05$). During the filling stage, potassium content peaked, particularly under N3, with T1 and T2 maintaining higher levels than T0. By maturity, potassium content declined across all treatments but remained positively correlated with nitrogen levels. Biochar application continued to boost potassium content, with significant differences observed ($P < 0.05$).

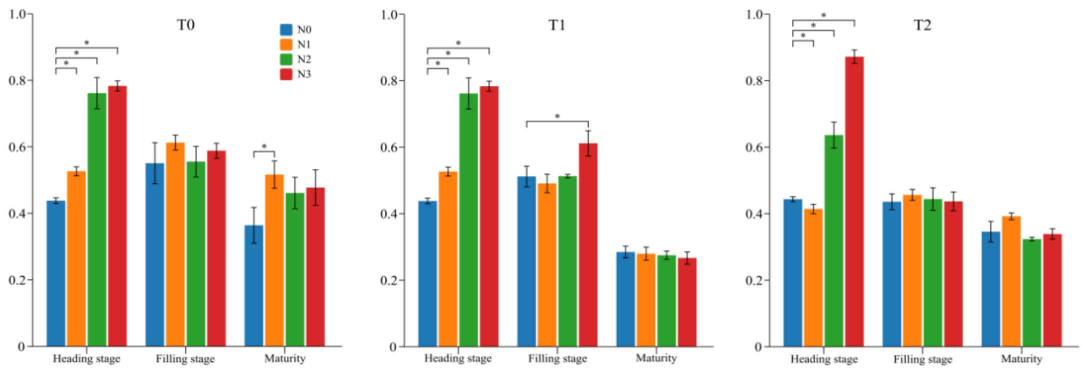

Figure 9. *Effect of different treatments on potassium content in rice panicles*

Effects of nitrogen fertilizer on rice yield and its components under biochar application

Table 1 shows the effects of biochar application and different nitrogen fertilizer levels on rice yield and its components. Plant height increased with higher nitrogen levels, with the tallest plants observed under N2 treatment across all biochar conditions, highlighting the effectiveness of moderate nitrogen application in maximizing plant height. Real grain number was highest under T2, particularly with N3 treatment, indicating that biochar positively influences grain production. Spike length showed no significant differences among treatments, suggesting limited effects of biochar and nitrogen levels on this trait.

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***Table 1.** Effects of biochar and nitrogen fertilizer application on rice yield and components*

Treatments		Plant height (cm)	Real grain number	Spike length (cm)	Number of spikes	Seed setting rate (%)	Thousand weight (g)	Yield ($kg·ha^{-1}$)
T0	N0	80.83±2.26 d	98.10±14.85 a	22.28±2.10 a	7.14±0.53 b	95.21±1.01 a	25.03±0.01 a	3663.42±109.12 d
	N1	87.60±0.40 b	106.78±16.25 asuoshi	20.78±1.63 a	8.39±0.41 b	92.03±2.07 a	24.94±0.86 a	6131.83±231.08 c
	N2	92.07±0.81a	103.62±13.07 a	20.73±0.87 a	10.99±0.23 a	84.02±1.75 b	25.13±0.86 a	8004.76±257.34 a
	N3	85.95±0.18 c	97.13±16.97 a	21.05±0.31 a	11.04±0.45 a	81.06±3.33 b	24.68±1.53 a	7175.25±167.97 b
T1	N0	80.23±2.36 c	92.16±1.62 b	21.35±0.59 a	8.41±0.24 c	92.53±0.27 a	25.14±0.87 a	3796.05±136.64 d
	N1	85.67±3.07 b	114.35±4.06 a	20.31±0.78 a	8.42±0.46 c	95.93±0.66 a	25.03±1.51 a	6697.17±143.56 b
	N2	90.13±0.04 a	116.02±9.25 a	22.21±1.08 a	10.25±0.16 a	92.44±2.07 ab	25.35±0.42 a	8236.57±165.07 a
	N3	88.75±1.32 b	107.83±11.25 a	20.53±0.16 a	9.32±0.25 b	88.76±6.23 b	24.87±0.42 a	7253.35±151.46 ab
T2	N0	81.21±0.38 c	85.15±2.31 c	21.07±0.42 a	7.76±0.82 b	96.25±1.41 ab	25.12±1.66 a	4068.03±103.25 c
	N1	84.40±0.20 b	111.22±4.92 b	21.48±2.10 a	8.33±0.58 b	98.13±0.23 a	25.17±0.59 a	6844.57±168.69 b
	N2	89.12±0.54 a	107.32±2.07 b	20.95±0.14 a	10.64±0.48 a	92.24±2.96 b	24.94±1.16 a	8464.18±215.31 a
	N3	89.93±1.36 a	121.24±13.00 a	21.54±1.40 a	10.07±0.90 a	92.15±0.57 b	24.80±1.23 a	7557.35±213.11 ab

Note: significant differences among treatments are indicated in different lowercase letters ($P < 0.05$)

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The number of spikes increased with higher nitrogen levels, with N2 producing the highest spike count. T1 and T2 treatments resulted in more spikes compared to T0, emphasizing biochar's role in improving spike formation. Seed setting rate decreased with higher nitrogen levels (N2 and N3), especially under T0 and T1, while T2 maintained relatively higher rates. Thousand-grain weight remained stable across all treatments, showing minimal influence from biochar and nitrogen levels. Yield increased significantly with nitrogen level, with the highest yields recorded under T1N2 and T2N2. Biochar treatments (T1 and T2) consistently improved yield compared to T0, demonstrating biochar's significant impact on rice production. In conclusion, the combination of biochar application and moderate nitrogen fertilization (N2) significantly enhanced rice yield and its components, with biochar further amplifying these positive effects.

Discussion

Recent studies have demonstrated that biochar application and nitrogen management significantly influence nitrogen content in rice stems, leaves, and panicles, while promoting sustainable agricultural practices by enhancing nitrogen uptake and reducing fertilizer input (Haque et al., 2022). The results of this study showed that biochar treatment significantly impacted nitrogen content in different rice tissues under various nitrogen levels. In particular, moderate nitrogen application (N2) under biochar conditions resulted in significantly higher nitrogen content in stems, leaves, and panicles compared to untreated T0, highlighting biochar's role in enhancing nitrogen availability and uptake. For stems, biochar enhanced nitrogen retention by improving soil cation exchange capacity and reducing nitrogen leaching losses, thereby ensuring a steady nitrogen supply during critical growth stages and supporting its translocation to panicles. However, excessive nitrogen application (N3) resulted in luxury consumption, leading to increased nitrogen accumulation in stems without corresponding yield benefits. In leaves, biochar significantly increased nitrogen content during early growth stages, such as tillering and heading, improving photosynthetic capacity and chlorophyll synthesis. As leaves act as nitrogen donor organs, nitrogen remobilization to panicles during the grain-filling stage resulted in a decline in leaf nitrogen content at maturity. For panicles, biochar enhanced nitrogen translocation from vegetative organs to reproductive organs, improving grain filling and quality (Riaz et al., 2024). Under moderate nitrogen application (N2), panicle nitrogen content and yield were maximized, while excessive nitrogen (N3) reduced translocation efficiency, causing increased nitrogen accumulation in stems and leaves. This study also confirmed that biochar combined with moderate nitrogen fertilization can significantly reduce nitrogen input while maintaining or improving rice yield, reducing environmental impacts such as nitrous oxide emissions and nitrate leaching. These findings align with Zhang et al. (2023), who reported that biochar application can reduce nitrogen fertilizer use by 20–30%. Overall, biochar enhances nitrogen retention and translocation efficiency, providing a sustainable approach for rice production while supporting nitrogen reduction strategies.

This research demonstrate that biochar application and nitrogen (N) reduction significantly influence phosphorus dynamics in rice stems, leaves, and panicles. Biochar-treated plots consistently exhibited higher P content compared to untreated controls (T0), particularly under moderate nitrogen application (N2), highlighting biochar’s ability to enhance soil phosphorus availability and plant uptake, even with reduced nitrogen input.

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In rice stems, phosphorus content decreased with growth progression, but biochar treatments (T1 and T2) resulted in significantly higher P content, especially under N2 conditions. This aligns with studies which suggest that biochar increases soil pH and reduces phosphorus fixation, enhancing root access to phosphorus. However, excessive nitrogen (N3) may create nutrient imbalances that reduce phosphorus uptake efficiency. In leaves, biochar significantly improved phosphorus content during earlier stages such as tillering and heading by enhancing microbial activity and phosphorus solubilization (Shani et al., 2024). As rice approaches maturity, leaf phosphorus content declines due to remobilization to panicles for grain filling (Sharma et al., 2024). The results indicate that reduced nitrogen levels (N1 and N2) under biochar treatments maintain sufficient phosphorus levels in leaves, ensuring photosynthetic efficiency without nutrient competition. In panicles, biochar enhanced phosphorus translocation from vegetative tissues to reproductive organs, especially under N2 treatment, promoting grain filling and quality. Li et al. (2023) observed similar findings, emphasizing that biochar facilitates efficient nutrient allocation to grains. However, excessive nitrogen (N3) reduced phosphorus translocation efficiency due to nutrient competition. This study confirms that biochar combined with moderate nitrogen application optimizes phosphorus availability and translocation, supporting grain yield and quality. Furthermore, biochar mitigates the negative effects of nitrogen reduction on phosphorus dynamics while reducing environmental losses, such as runoff and leaching (Wang et al., 2022b). These results underscore biochar’s role in sustainable nutrient management strategies and its potential to enhance phosphorus use efficiency under reduced nitrogen inputs (Zhao et al., 2024). Future research should explore biochar’s long-term effects on phosphorus cycling and its interactions with nitrogen and other nutrients in diverse agroecosystems.

This study demonstrates that biochar application and nitrogen reduction significantly influence potassium dynamics in rice stems, leaves, and panicles. Overall, biochar-treated plots (T1, T2) under moderate nitrogen application (N2) showed significantly higher potassium content, especially in leaves and panicles, indicating improved potassium uptake and distribution efficiency. In rice stems, potassium content was higher during early growth stages but declined over time. Biochar treatments significantly increased stem potassium content, particularly under N2 conditions, by enhancing soil cation exchange capacity and reducing potassium leaching losses (Alkharabsheh et al., 2021). However, excessive nitrogen application (N3) resulted in a decline in potassium uptake efficiency, likely due to antagonistic interactions between nitrogen and potassium absorption processes. In leaves, potassium content was highest during early growth stages (tillering and heading) when potassium demand is critical for photosynthesis and stomatal regulation. Biochar treatments significantly increased leaf potassium content, particularly under N2 conditions, as biochar enhanced water retention and potassium solubility (Bilias et al., 2023). As growth progressed to the later stages (grain filling and maturity), potassium content in leaves decreased due to translocation to panicles for grain development. These findings align with Chew et al. (2022), who observed that biochar improves potassium uptake and allocation efficiency. In panicles, biochar treatments significantly enhanced potassium content, especially under N2, by improving potassium translocation from vegetative tissues to reproductive organs. This promotes grain filling and yield, as supported by Chowdhury et al. (2024), who emphasized biochar's role in efficient potassium partitioning. However, under N3, panicle potassium content showed limited improvement, while potassium accumulation in stems and leaves increased, indicating reduced translocation efficiency due to excessive nitrogen. The study

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highlights the synergistic effects of biochar and nitrogen reduction. Moderate nitrogen application (N2) combined with biochar not only increased potassium content in rice tissues but also optimized potassium distribution efficiency among organs (Wan et al., 2024). Biochar's ability to enhance potassium availability and reduce leaching losses supports efficient potassium uptake under reduced nitrogen conditions, while also mitigating environmental risks (Bilias et al., 2023). Biochar application significantly improves potassium uptake and distribution efficiency, particularly under moderate nitrogen levels (N2), contributing to higher rice yield and quality. The synergistic effects of biochar and nitrogen reduction provide a sustainable pathway for efficient potassium utilization and environmental sustainability. Future research should explore the long-term effects of biochar on potassium cycling and its interactions with nitrogen and other nutrients (Egamberdieva et al., 2021).

The combination of biochar application and optimized nitrogen management significantly enhances rice productivity by improving nutrient availability, plant growth, and environmental sustainability (Ali et al., 2020). Biochar’s ability to increase cation exchange capacity, improve soil structure, and enhance water retention directly impacts nitrogen dynamics, making nitrogen more available to plants while reducing losses through leaching or volatilization (Domingues et al., 2020). Excessive nitrogen application (e.g., N3) often leads to nutrient imbalances, reduced nitrogen use efficiency, and environmental risks such as nitrate leaching and nitrous oxide emissions (Hafeez et al., 2022). In contrast, biochar, when combined with moderate nitrogen levels (e.g., N2), creates a balanced nutrient environment that supports efficient nitrogen uptake and utilization, addressing both productivity and sustainability goals (Ullah et al., 2024). Biochar also stabilizes nutrient availability, promoting processes like tillering and spike development that are critical for high productivity. By reducing physiological stress associated with nutrient deficiencies or imbalances, biochar and moderate nitrogen levels enhance tiller formation, spike number, and grain development. Excessive nitrogen, while initially boosting vegetative growth, can cause issues such as lodging, nutrient competition, and reduced seed setting rates, risks that biochar mitigates through improved nutrient partitioning (Oladele et al., 2023). Grain yield, a composite of multiple yield components, is significantly improved by the synergistic effects of biochar and moderate nitrogen levels, which enhance spike number, grain number per spike, and seed setting rates while reducing environmental risks (Khan et al., 2021). Biochar-treated soils provide a consistent nutrient supply, mitigating adverse effects on seed setting and grain filling (Agegnehu et al., 2017). Moreover, biochar reduces greenhouse gas emissions and minimizes nitrate leaching, making it an environmentally friendly amendment for intensive farming systems (Yadav and Ramakrishna, 2023). However, excessive nitrogen application results in inefficient nutrient uptake and increases environmental costs, including soil acidification and eutrophication (Martínez-Dalmau et al., 2021). Biochar addresses these challenges by enabling nitrogen reduction without sacrificing yield (Gwenzi et al., 2015). Future research should focus on the long-term effects of biochar on soil health and its interactions with other essential nutrients, such as phosphorus and potassium (El-Naggar et al., 2019). Understanding biochar’s role in nutrient cycling, microbial activity, and ecosystem services is critical for optimizing its use in diverse agricultural systems (Zhao et al., 2022). In conclusion, the integration of biochar with moderate nitrogen fertilization enhances crop performance by stabilizing nutrient availability, improving nitrogen uptake, and reducing environmental risks, making biochar a cornerstone for sustainable agricultural practices.

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Conclusion

This study demonstrates that the combination of biochar application and optimized nitrogen management significantly enhances rice yield and its components while promoting environmental sustainability. Biochar improves the effective utilization of nitrogen by increasing soil nutrient retention, reducing nitrogen losses, and stabilizing nutrient availability. Under moderate nitrogen application (N2), biochar-treated plots exhibited higher productivity, including increased spike number, grain number per panicle, and seed setting rate, compared to untreated controls. In contrast, excessive nitrogen application (N3) resulted in diminishing returns and environmental risks, such as nutrient imbalances and nitrate leaching. These findings underscore the synergistic effects of biochar and moderate nitrogen levels in achieving sustainable rice production. By enhancing soil health, improving nutrient cycling, and reducing greenhouse gas emissions, biochar serves as a vital tool for sustainable nutrient management. Future studies should focus on long-term field trials to evaluate biochar’s cumulative benefits and explore its interactions with other essential nutrients to further optimize its application in diverse agricultural systems.

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