



Combined Effects of Biochar and Chemical Fertilizers on Rice Yield, Quality, and Nutrient Loss in Cambodian Soils Under Various Irrigation Methods

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Abstract

Rice production in Cambodia faces challenges due to water scarcity and improper fertilizer use, which raise environmental concerns. Integrating biochar and water-saving irrigation methods offers a promising solution for farmers. This study evaluated how biochar and chemical fertilizers affect rice yield, quality, and nutrient loss under different soil types and irrigation methods. A column experiment was conducted using clay (S1) and sandy loam (S2) soils, with two irrigation methods: alternate wetting and drying (AWD) and continuous flooding (CF). The treatments included a control (T0), chemical fertilizer only (T1), chemical fertilizer supplemented with 4 tons per hectare ($t\ ha^{-1}$) of biochar (T2), and chemical fertilizer supplemented with $6\ t\ ha^{-1}$ of biochar (T3). Across both soil types and irrigation methods, T3 resulted in the highest dry grain yield and protein content compared to T1. This biochar at $6\ t\ ha^{-1}$ was effective in both clay and sandy loam soils, though its efficiency varied slightly; for instance, under AWD irrigation, rice yield increased by approximately 35% in sandy loam and 40% in clay soil. Biochar application at $6\ t\ ha^{-1}$ significantly reduced the leaching of NO_3^- , NH_4^+ , and PO_4^{3-} compared to other treatments. Although there were no significant differences in amylose content among the treatments, biochar application positively influenced plant biomass and chlorophyll content. These results show that increasing the biochar rate from 4 to $6\ t\ ha^{-1}$ further enhances rice yield and protein content without affecting amylose content, while both rates reduce nutrient leaching and contribute to more sustainable farming practices.

Keywords Soil type · Irrigation method · Nutrient loss by leaching · Rice productivity

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1 Introduction

Rice is considered the backbone of Cambodian cuisine. Recently, the Royal Government of Cambodia has been promoting the sustainable production of high-quality rice through environmentally friendly agricultural methods (Khema et al. 2022). With the improvement in people's living standards, the demand for high-quality rice has grown significantly, focusing on both quantity and quality (Cheng et al. 2019; Su et al. 2019). According to the Cambodia Agriculture Survey 2023, the average rice yield was 3.14 t ha⁻¹ for non-aromatic varieties and 2.62 t ha⁻¹ for aromatic varieties, reflecting differences by rice type and agro-ecological zone (NIS 2023). The yield limitation stems from challenges such as poor irrigation systems, soil degradation, drought, and high costs of production and fertilizers (Touch et al. 2024). However, infrastructure for irrigation development remains limited, leading to persistent water shortages during the dry season (Sithirith 2021). In 2023–2024, dry-season rice occupied around 19% of total paddy land, with some farmers continuing to cultivate despite concerns over water scarcity (Touch et al. 2024). While awareness of water-saving methods is growing, many smallholder farmers still face challenges in accessing water and efficient management knowledge (Hoogesteger et al. 2023; McPhee et al. 2022).

Another significant challenge is fertilization, including the overuse or underuse of chemical fertilizers (Kong et al. 2020). Cambodia's use of synthetic fertilizers remains widespread, with 63.9% of agricultural holdings applying them, particularly in rice cultivation (NIS 2023). Average application rates for rice are estimated at 180 kg ha⁻¹, varying by rice cultivar and agro-ecological zone; non-aromatic varieties typically receive higher inputs, and irrigated systems generally achieve greater productivity than rainfed lowlands (NIS 2023). Prolonged use of chemical fertilizers harms soil quality by decreasing organic matter and increasing pollution (Chen et al. 2024). Additionally, excess phosphorus (P) can leach into groundwater, increasing the risk of eutrophication in nearby water bodies, especially in sandy soils or areas with tile drainage (Wurtsbaugh et al. 2019). Among the nutrient anions, nitrate (NO₃⁻) is the most easily leached because of its negligible reaction with the soil matrix and, therefore, is very mobile in various soil types (Dou et al. 2016; Zhao et al. 2021). Notably, sandy soil, known for its high permeability and susceptibility to nutrient leaching, is the most abundant soil group for rice cultivation in Cambodia, as classified under the Cambodian Agronomic Soil Classification (CASC) (White et al. 2006). The Prateah Lang and Bakan soils, although infertile, present fewer constraints to rice production and are widespread, occurring on about 45% of the rice-growing area. Hence, quantifying N

and P loss through surface runoff and leaching is essential to optimize fertilization practices (Hua and Zhu 2020).

Due to these pressing issues, there is an urgent need to improve sustainable practices and enhance water productivity in rice production, ensuring higher yields while optimizing water use efficiency. Introducing water-saving irrigation methods, such as alternative wetting and drying (AWD), along with incorporating soil amendments, can enhance water productivity and reduce fertilizer loss. While AWD may occasionally cause minor yield losses, combining it with soil amendments can maintain the yield by improving water retention, nutrient release, and uptake (Haque et al. 2022). Applying soil amendments like rice husk biochar has been introduced recently for soil improvement (He et al. 2022). Rice husk biochar (RHB) is a cheap and renewable material that is rich in carbon and has many tiny holes, making it useful for cleaning up water and soil (Na et al. 2025; Ullah et al. 2024). In Cambodia, rice husk is primarily used for energy production, with a portion remaining unused (Nam et al. 2024a). Additional residues such as cassava stems, corn stover, and mango seeds are widely available and often considered waste. Medium-scale kilns yield 7–15 kg per run, and larger systems up to 400 kg, making biochar application practical for local farmers,¹ except when sourcing certified carbon-grade products, which are typically more expensive.

Biochar can retain nutrients (N and P), improve soil properties, and enhance phosphorus utilization rates (Bian et al. 2016; Glaser and Lehr 2019; Liu et al. 2016; Shi et al. 2020; Yang et al. 2021). Under different irrigation methods, such as AWD, biochar helps maintain soil moisture and nutrient availability, mitigating the negative effects of water stress on rice growth. Research indicates that biochar application under AWD irrigation can increase rice yield by up to 12.5%, improving nutrient uptake and water-use efficiency (Chen et al. 2021). Biochar not only improves soil nutrient retention but also plays a crucial role in enhancing rice yield (Agarwal et al. 2022) and grain quality, including protein content (Ali et al. 2020), but its effectiveness varies with biochar rate, soil type, climate, and experimental conditions (Chen et al. 2023; Ma et al. 2019; Munda et al. 2018). Lai et al. (2024) investigated biochar application rates of 2 t ha⁻¹ and 4 t ha⁻¹. While 4 t ha⁻¹ showed promising results in reducing nitrogen leaching, it did not significantly reduce phosphorus loss. However, in Cambodia, scientific studies on the effects of biochar on rice yield and nutrient loss under different irrigation methods are limited. Specifically, there is a lack of studies on water management practices such as alternative wetting and drying (AWD) and continuous

¹ Chan Saruth. *Biochar Production Technology in Cambodia*. Presentation at the UN-CSAM Regional Workshop on Sustainable Agricultural Mechanization, 2020. Available at [PowerPoint 演示文稿](#).

flooding (CF) when combined with biochar incorporation in rice cultivation and quality (Ballester et al. 2021; Becker et al. 2023). Thus, the objectives of this study were to evaluate the effect of biochar and application rate incorporated with chemical fertilizer on rice productivity, quality, and nutrient loss via leaching for clay soil and sandy loam under irrigation methods (i.e., CF and AWD) using the soil column experiment. Rice husk biochar is hypothesized to improve rice productivity and quality while reducing nutrient loss via leaching. These effects may vary with biochar application rate, soil type, and irrigation methods, with biochar potentially offsetting AWD-induced yield reductions by improving nutrient availability and soil conditions.

2 Materials and Methods

2.1 Soil and Biochar Characteristics

Biochar used in this study was a local product derived from rice husk using the protocol described in Lai et al. (2024). The biochar characteristics were analyzed before experimenting, including electrical conductivity (EC) ($\mu\text{S cm}^{-1}$) and pH (1:5 H_2O) soil/water suspension method (Rayment and Higginson 1992). Total carbon was determined using an elemental analyzer (Flash 2000, Thermo Fisher, USA). The organic matter (OM) (%) was measured with the Walkley–Black method (Gupta 2014). Total N (g kg^{-1}), NO_3^- (mg L^{-1}), and NH_4^+ (mg L^{-1}) contents were measured with Kjeldahl method (Baethgen and Alley 1989; Bremner 2016; Gupta 2014), whereas available P (mg kg^{-1}) was measured with Olsen method (Olsen 1954; Zhou et al. 2001). Exchangeable potassium (K) (cmol kg^{-1}) was measured with the Flame photometer method (Gupta 2014). The cation exchange capacity (CEC) ($\text{cmol}^+ \text{kg}^{-1}$) biochar was measured with the ammonium-acetate compulsory displacement method (Sumner and Miller, 1996). Specific surface area (SSA) ($\text{m}^2 \text{g}^{-1}$) of biochar was analyzed using the ethylene glycol monoethyl ether (EGME) method.

The two soils selected for this study are the most abundant among the 11 soil groups for rice cultivation in Cambodia, with 10–15% (Bakan) and 25–30% (i.e., Prateah Lang), respectively (White et al. 1997). Specifically, the soil "Bakan (S1) was classified by the FAO/UNESCO as Luvisols (White et al. 2006), while the soil "Prateah Lang (S2)" as Gleyic Acrisols (Ballester et al. 2021). The S1 and S2 soil samples were selected in triplicate at three different sampling locations (i.e., up to horizon B as defined by the FAO Guidelines for Soil Description (FAO 2006).

Before the experiment, the initial samples of both soil types were analyzed to determine different physicochemical properties, including pH, EC (uS cm^{-1}), soil organic

carbon (%), soil organic matter (SOM) (%), bulk density (BD) (g cm^{-3}), Total N (%), NO_3^- ($\text{mg } 100 \text{ g}^{-1}$), NH_4^+ ($\text{mg } 100 \text{ g}^{-1}$), available P (mg L^{-1}), exchangeable K (cmol kg^{-1}), CEC and soil texture. Soil pH, EC, BD, organic matter, Total N, NO_3^- , NH_4^+ , available P, exchangeable K, and CEC were analyzed following the same methods used for the biochar properties. In addition, soil organic carbon was analyzed using the Walkley–Black method, while the soil texture was determined by the hydrometer test (USDA) (Gee and Or 2002).

The basic characteristics of biochar and soil as measured from the two soil types (i.e., clay and sandy loam) are summarized in Supplementary Table S1. The EC of biochar was $57.27 \pm 1.17 \mu\text{S cm}^{-1}$ with an alkaline pH of 8.43 ± 0.09 . The total carbon, organic matter, and SSA were considered high, with values of $54.07 \pm 3.41\%$, $64.88 \pm 4.09\%$, and $102.20 \pm 3.80 \text{ m}^2 \text{ g}$, respectively. The clay soil had significantly higher values of soil EC, organic carbon, organic matter, total N, available P, exchangeable K, and CEC compared to the sandy loam. The pH of the clay was also significantly higher than that of the sandy loam. However, neither NO_3^- nor NH_4^+ values for the two soil types were significantly different.

2.2 Soil column design

Soil columns of clay (S1) and sandy loam (S2) were collected directly from the field under undisturbed conditions to preserve the original soil structure. A thick-walled PVC pipe (5 mm wall thickness, 65 cm length, and 15 cm diameter) was used for sampling (Supplementary Fig. S1a). Then, the columns were installed in a greenhouse. To collect the leachate, a hole was drilled at 30 cm depth (from the top, because we keep 10 cm empty for irrigation), one at 45 cm depth, and the last at 65 cm depth (bottom) for the percolation. To prevent sedimentation disruption, the two holes were covered with a nylon mesh and fitted with faucets. The percolation was collected at the bottom of the column by removing a tiny piece of soil and inserting sand and gravel above a third faucet. About 20 cm long and 5 cm wide, a transparent wall was built to monitor the water level and root growth. Three sets of soil column samples represent the soils for rice paddy in Cambodia (i.e., S1 and S2) (Supplementary Fig. S1b) and under two irrigation methods: alternative wetting and drying (AWD) and continuous flooding (CF).

2.3 Soil Preparation and Treatments

The experiment consisted of four treatment groups: T0 served as the control, with no chemical fertilizer or biochar; T1 included chemical fertilizers which is urea (46%

N), diammonium phosphate (DAP; 18% N, 46% P₂O₅), and potassium chloride (KCl; 50% K); T2 combined T1 with biochar at a rate of 4 t ha⁻¹; and T3 combined T1 with biochar at 6 t ha⁻¹. Fertilizer application was split into two stages: the first during soil preparation (urea, DAP, and KCl), and the second at the booting stage (urea and DAP only), with a total input of 133 kg N ha⁻¹, 46 kg P₂O₅ ha⁻¹, and 30 kg K₂O ha⁻¹. This chemical fertilizer was applied to approximately 3.7 kg of topsoil of the column, resulting in total nutrient inputs equivalent to 63.5 mg N kg⁻¹, 35.5 mg P kg⁻¹, and 11.86 mg K kg⁻¹ of soil. In addition, before rice sowing, biochar was added to the corresponding soil column and mixed into the top 10–15 cm soil layer as an amendment with 0.706 g for T2 and 1.06 g for T3.

The four treatments were applied to the two soil types (i.e., the clay (S1) and sandy loam (S2)). An alternative wetting and drying (AWD) method was applied to the two soil types (S1 and S2). In contrast, the continuous flooding (CF) method was only applied to S2 (Supplementary Fig. S1b) due to resource limitations. Three replications of each soil column were prepared, along with additional columns set aside for variable measurements at the tillering, flowering, and harvesting stages. A rice cultivar (locally named OM 5451) was selected for the direct seeding method.

2.4 Irrigation Management

For the continuous flooding (i.e., CF) irrigation, a continuous ponded layer of water, approximately 10 cm deep, was maintained over the soil surface throughout the entire rice-growing period. For alternative wetting and drying (i.e., AWD), after the column was initially flooded, it was allowed to dry until the ponded water level reached approximately -15 cm below the soil surface. This drying period was followed by another flooding event, repeating the cycle. The total water requirements for each irrigation were recorded for the whole period. For AWD, the total water irrigated was about 15,000 mL for S1 and 18,000 mL for S2, while it was 24,000 mL for CF.

2.5 Rice Yield and Quality

Dry grain yield (g plant⁻¹) was measured at the harvesting stage. For the grain quality assessment, after harvesting, the grains were carefully threshed, cleaned, air-dried to a constant weight, and stored at ambient temperature before grain quality analysis. Total protein (μg L⁻¹) was estimated by modifying Lowry's method given by Hartree (1972). The contents were mixed well, and a spectrophotometer measured the absorbance at 650 nm after 15 min. The amylose content (%) of milled rice was determined using the colorimetric iodine assay index method. The values for absorbance were plotted at 620 nm against the concentration of

anhydrous amylose (mg), and the conversion factor was determined.

2.6 Rice Growth and Plant Nutrient Content

Triplicate rice samples were measured for plant biomass (g plant⁻¹), root biomass (g), and chlorophyll at each tillering stage, flowering, and harvesting stage from the spared column. The soil column was carefully broken to keep the root structure. The dried weight of straw, leave, and root was determined after oven-drying at 70 °C to a constant weight for 48 h.

The leaves of rice plants were analyzed for NO₃⁻, NH₄⁺, and PO₄³⁻ contents at the tillering, flowering, and harvesting stages. Dried leaves were ground into a powder, weighed, and used for extraction. NO₃⁻, NH₄⁺, and PO₄³⁻ contents were determined using colorimetric assays: NO₃⁻ by the salicylic acid method (Zhao and Wang 2017), NH₄⁺ by the Bertholet reaction (Bräutigam et al. 2007), and PO₄³⁻ by the molybdenum blue assay (Pinit et al. 2020). Concentrations were calculated from absorbance values relative to a standard curve and expressed as micrograms per gram dry weight (μg g⁻¹).

2.7 Measuring Soil Nutrient Leaching

Each week, 50 mL of leachate was sampled from each port 1 and port 2 using sampling bottles (polypropylene material) to track the nutrient content in each layer. Percolation water (i.e., port 3) was allowed to drain freely to observe the nutrient loss through the vertical condition (Zheng et al. 2019) and the volume was recorded at 7-day intervals. The leachate samples were measured immediately for nitrate (NO₃⁻) (mg L⁻¹) and ammonium (NH₄⁺) (mg L⁻¹) with the Vario Tube Test, and ortho-phosphate (PO₄³⁻) (mg L⁻¹) with the ortho method with tablets. All three variables were measured using a photometer (Part Number 214020, MD600, Lovibond, Germany). The leachate sample was also analyzed for pH value using a pH meter (Thermo Scientific™, 9617BNWP, Lenexa, US).

2.8 Data Analysis

All statistical analyses were conducted using R (R Core Team 2021). A one-way analysis of variance (ANOVA) (Tukey's HSD test, $p < 0.05$) was used to see how chemical fertilizers and their mix with biochar affected nutrient loss through leaching in two types of soil, and to find out how different treatments improved all the factors related to rice growth, yield, nutrition, and quality. The important differences in the factors related to biochar and the two soil types, calculated using the T-test for comparing averages, were significant at the $p < 0.05$ level. Principal Component Analysis (PCA) was

conducted to examine the relationships between different treatments and their impact on rice growth, yield, and nutrition using the *ade4* and *FactoMineR* packages in R. Biplots were generated with confidence ellipses at a 95% confidence level and color coding to distinguish between treatments.

3 Results

3.1 Effect of Biochar on Rice Yield and Quality

The yield and quality of the rice showed a marked enhancement following the biochar application, as illustrated in

Fig. 1. The dry grain yield and total protein in rice were significantly the highest for chemical fertilizer+biochar 6 t ha⁻¹ (T3), followed by chemical fertilizer+biochar 4 t ha⁻¹ (T2), chemical fertilizer (T1), and control (T0), for both soil types (i.e., the clay (S1) and sandy loam (S2)) and irrigation methods (i.e., AWD and CF) ($p < 0.05$) (Fig. 1a, b). For the quantity basis of dry grain yield, T3 increased by 40% compared to T1 in S1_AWD, 35% (S2_AWD), and 37% (S2_CF), respectively. In addition, for total protein, T3 increased by 20% compared to T1 in S1_AWD, 18% (S2_AWD), and 19% (S2_CF). However, there was no significant difference in amylose content among all the treatments for both soil types and irrigation methods (Fig. 1c).

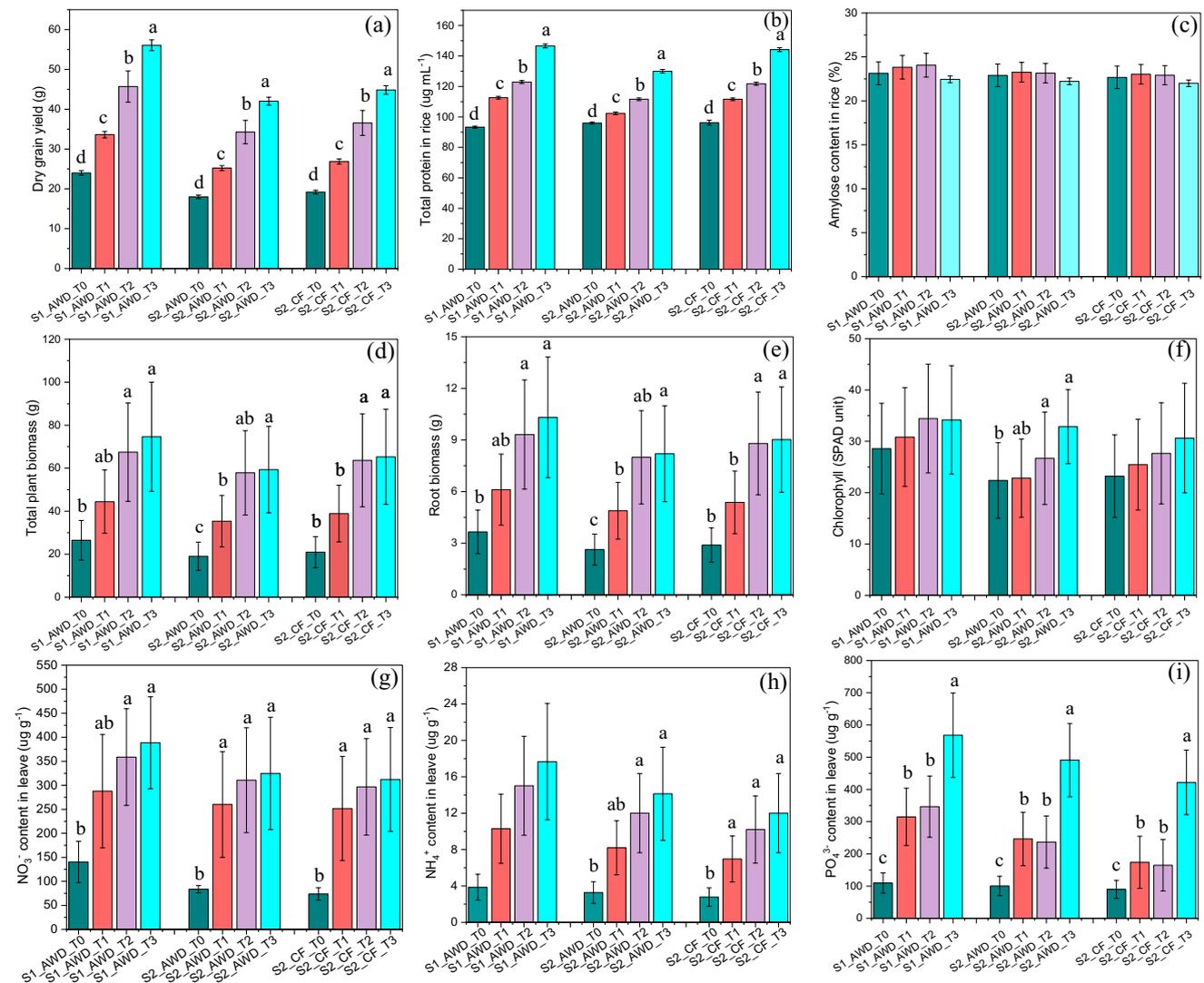


Fig. 1 Mean values (±1 SD, standard deviation) for: **a** dry grain yield ($n=3$), **b** total protein ($n=3$), **c** amylose content ($n=3$), **d** total plant biomass ($n=9$), **e** root biomass ($n=9$), **f** chlorophyll ($n=9$), **g** NO₃⁻ content in leave ($n=9$), **h** NH₄⁺ content in leave ($n=9$), **i** PO₄³⁻ content in leave ($n=9$) were estimated from each treatment. The significant differences among treatments were analyzed using a one-way analysis of variance (ANOVA) (Tukey's HSD test, $p < 0.05$)

and were indicated by lower letters (**a**, **b**, **c**). T0 served as the control, with no chemical fertilizer or biochar; T1 consisted of chemical fertilizers including urea, diammonium phosphate (DAP), and potassium chloride (KCl); T2 combined T1 with biochar at a rate of 4 t ha⁻¹; and T3 combined T1 with biochar at 6 t ha⁻¹. S1 represents the clay soil; S2, sandy loam; AWD, alternative wetting and drying; and CF, continuous flooding

3.2 Effect of Biochar on Rice Growth and Plant Nutrients

Figure 1 shows the impact of various treatments on rice growth, including total plant biomass, root biomass, and chlorophyll, across two soil types and irrigation methods: clay (S1) and sandy loam (S2), as well as AWD and CF. For total plant biomass and root biomass, there was no statistically significant difference between biochar rates of 4 t ha⁻¹ (T2) and 6 t ha⁻¹ (T3) in either soil type or irrigation method (Fig. 1d, e). This suggests that increasing biochar beyond 4 t ha⁻¹ may not yield additional biomass benefits under the tested conditions. In addition, the S2_AWD for chlorophyll (Fig. 1f) showed notable differences only between treatments, T3 and T0.

For NO₃⁻ and NH₄⁺ content in leaves, T0 was the lowest, while there was no significant difference between T1, T2, and T3 for both soil types and irrigation methods (Fig. 1g, h). However, for PO₄³⁻ content in leaves, T3 was significantly the highest, followed by T2, T1, and T0 for both soil types and irrigation methods ($p < 0.05$). Furthermore, there was no significant difference between T1 and T2 for this variable (Fig. 1i).

3.3 Principal Component Analysis

Principal Component Analysis (PCA) was used to look at how plant nutrient content, rice growth, yield, and quality are related under different treatments for both soil types and irrigations (Fig. 2). The first two components (Dim1 (79.1%) and Dim2 (12.5%)) explain 91.6% of the total variance. The dry grain yield, total protein, NH₄⁺ content in leaves, and PO₄³⁻ content in leaves were positively correlated with each

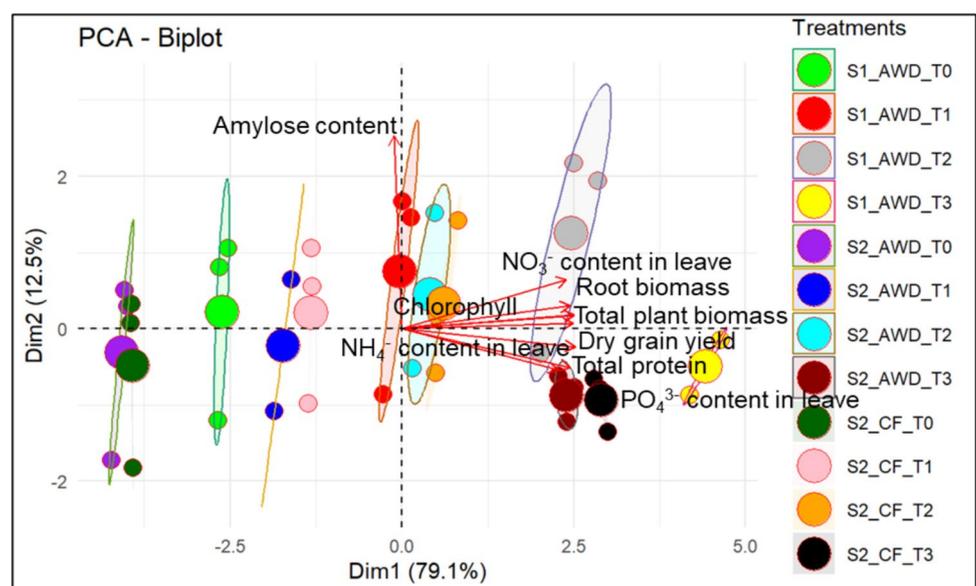
other, and this reflects increased variability in the presence of biochar at a rate of 6 t ha⁻¹ (T3) in both soil types and irrigation methods. In contrast, control treatments, including S1_AWD_T0, S2_AWD_T0, and S2_CF_T0, were observed to be farther from these variables. Conversely, amylose content showed a negative correlation with higher biochar; thus, it is higher in the treatment without biochar (i.e., S1_AWD_T1).

3.4 Effect of Biochar on N and P Loss

A mean comparison of the time effect on the NO₃⁻ loss accumulation from the vertical percolation port was presented in Fig. 3. During the experiment, NO₃⁻ loss accumulation increased significantly and almost continuously, reaching a steady rate in the last two weeks. The total NO₃⁻ loss accumulation was higher in chemical fertilizer treatment (T1) for both soil types and irrigation method (i.e., 78.1 mg, 94.8 mg, 115.8 mg) in S1_AWD, S2_AWD, and S2_CF, respectively (Fig. 3a, b, c). In the same order for NH₄⁺ loss accumulation, the higher T1 values were 16.9 mg, 20.7 mg, and 25.6 mg (Fig. 3d, e, f). In addition, for PO₄³⁻ loss accumulation, T1 were 10 mg, 9.1 mg, and 10.9 mg, and it decreased to 6.81 mg, 5.91 mg, and 7.62 mg for T3 in S1_AWD, S2_AWD, and S2_CF, respectively.

The statistical significance ($p < 0.05$) of nutrient leaching across treatments is illustrated in Fig. 4 with the original concentration data provided in Supplementary Table S2. The control (T0), which received no chemical fertilizer or biochar, consistently showed the lowest leaching values across all nutrients. Among the biochar treatments, only T3 significantly reduced NO₃⁻, NH₄⁺, and PO₄³⁻ leaching compared to T1 across both soil types and irrigation methods.

Fig. 2 PCA biplot depicting the relationship between the estimated variables and treatments. PC1 on the x-axis accounted for 79.1% of the total variables, while PC2 explained 12.5% of total variability and is shown on the Y-axis. The different colors represent the treatments. T0 served as the control, with no chemical fertilizer or biochar; T1 consisted of chemical fertilizers including urea, diammonium phosphate (DAP), and potassium chloride (KCl); T2 combined T1 with biochar at a rate of 4 t ha⁻¹; and T3 combined T1 with biochar at 6 t ha⁻¹. S1 represents the clay soil; S2, sandy loam; AWD, alternative wetting and drying; and CF, continuous flooding



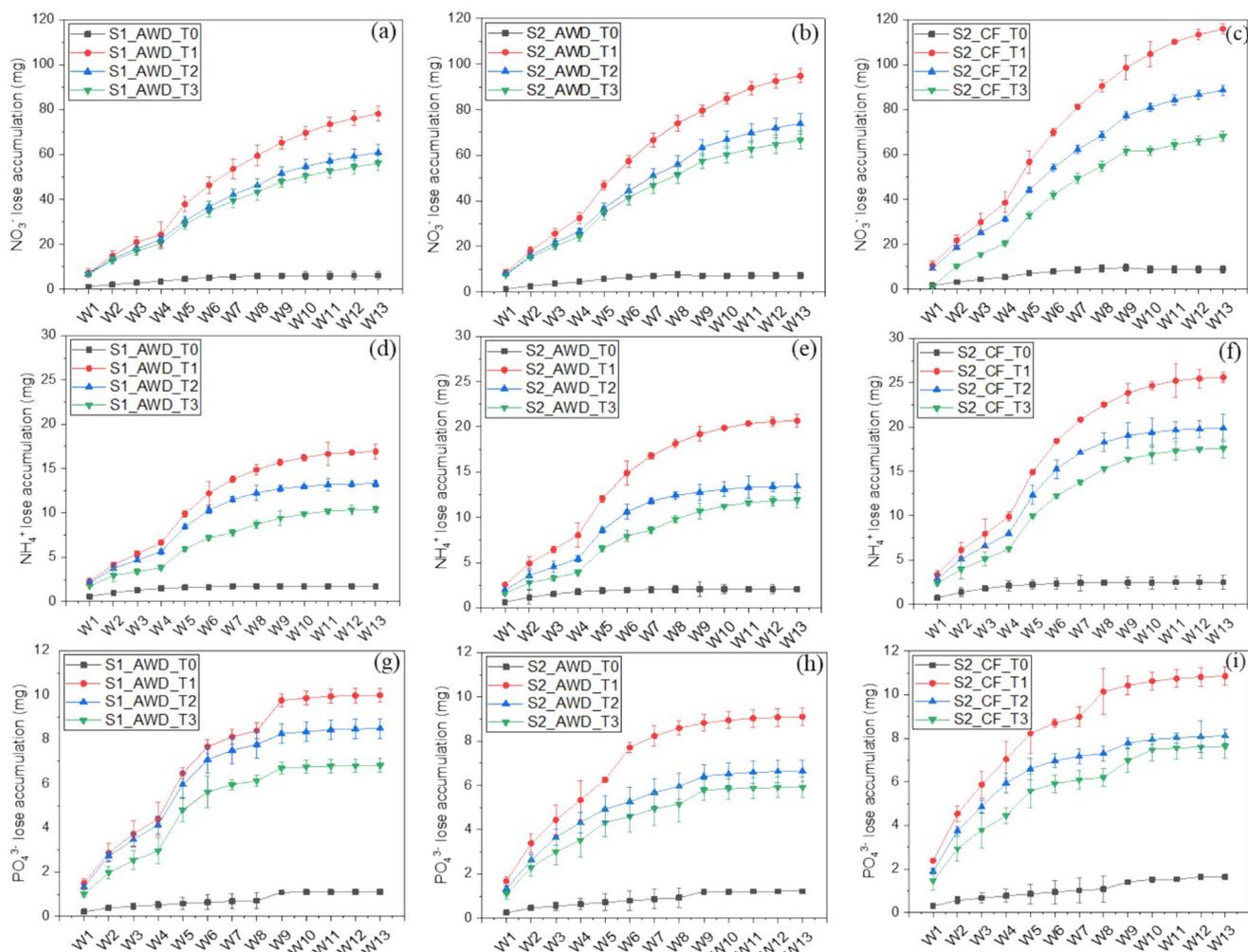


Fig. 3 Mean values (± 1 SD, standard deviation) for weekly loss accumulation for: **a, b, c** NO_3^- , **d, e, f** NH_4^+ , and **g, h, i** PO_4^{3-} ($n = 3$, each). T0 served as the control, with no chemical fertilizer or biochar; T1 consisted of chemical fertilizers including urea, diammonium phos-

phate (DAP), and potassium chloride (KCl); T2 combined T1 with biochar at a rate of 4 t ha⁻¹; and T3 combined T1 with biochar at 6 t ha⁻¹. S1 represents the clay soil; S2, sandy loam; AWD, alternative wetting and drying; and CF, continuous flooding

T2 did not differ significantly from T3 for NO_3^- and NH_4^+ , and showed no significant differences from either T1 or T3 for PO_4^{3-} .

4 Discussion

The present study found that biochar application at the highest rate of 6 t ha⁻¹ (i.e., T3) significantly enhanced rice yield and rice growth (i.e., total plant biomass, NH_4^+ , NO_3^- , and PO_4^{3-} content in leaves) in both clay (S1) and sandy loam soil (S2) (Figs. 1 and 2). However, the effectiveness of biochar is influenced by soil texture, irrigation method, and application rate, leading to variations in yield improvement ranging from 10 to 30% (Abbas et al. 2024; Asadi et al. 2021; Nam et al. 2024b). In clay soils, biochar's alkaline pH and high cation exchange capacity (CEC) promote nutrient retention,

particularly ammonium ions, while its fine particle structure improves soil aggregation and aeration (Demirkaya et al. 2025). In sandy loam, biochar's porosity and water-holding capacity help reduce rapid nutrient leaching and improve moisture availability, compensating for low native fertility (Li et al. 2021). Specifically, these results showed that clay soil (S1_AWD_T3) provided a higher dry grain yield compared to other treatments, highlighting the influence of soil texture on biochar effectiveness. While the AWD irrigation method combined with biochar showed water savings and maintained high yields, the CF method also provided substantial benefits. These differences were mainly caused by the type of soil, the irrigation method used, and how much biochar was applied, all of which affected how well nutrients were kept in the soil and how efficiently water was used, leading to better rice production (Chen et al. 2021). Under AWD, biochar's porous matrix retains nutrients during dry

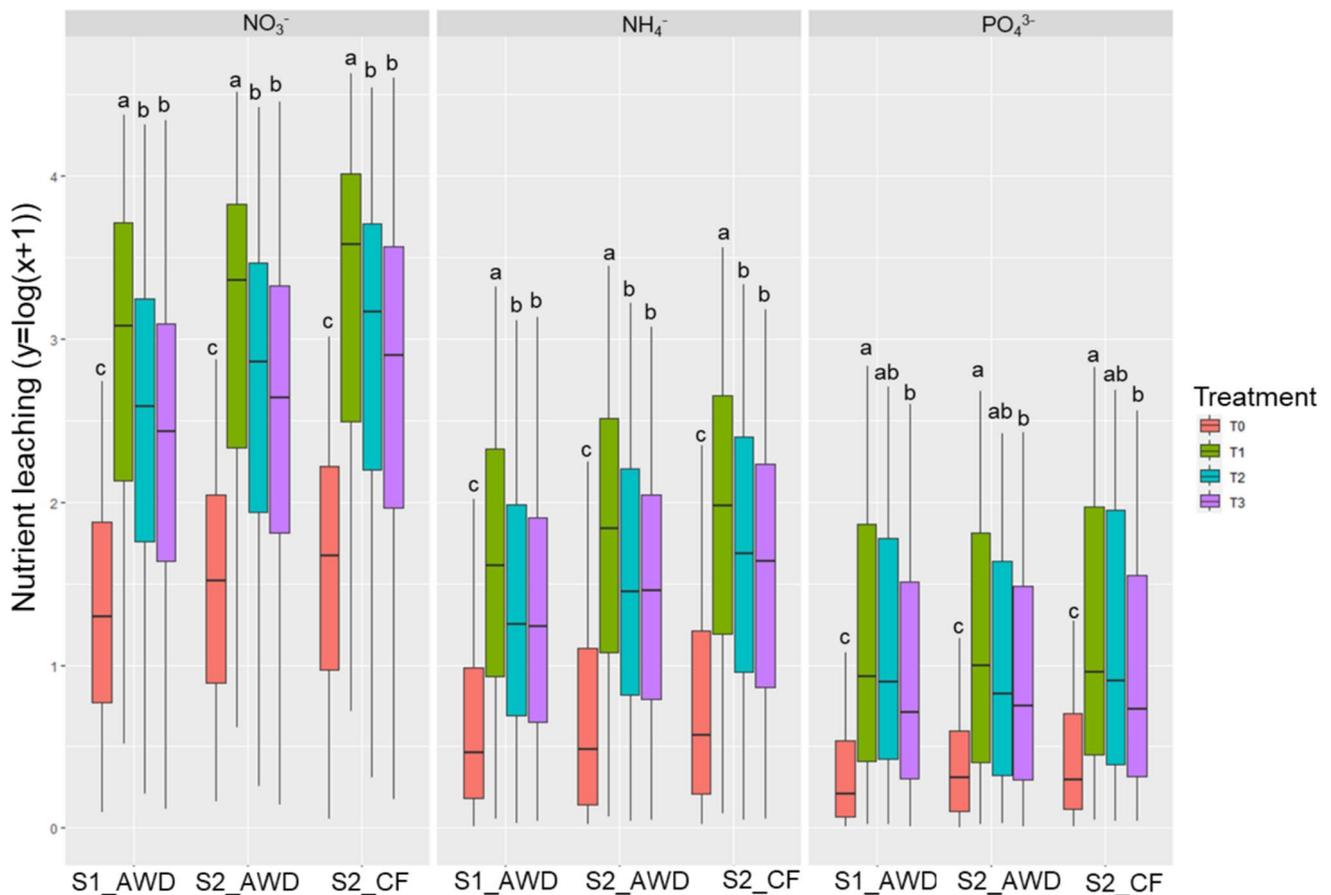


Fig. 4 Boxplots showed the nutrient leaching under different treatments. Mean values (± 1 SD, standard deviation) for NO_3^- , NH_4^+ , and PO_4^{3-} ($n=117$ each) were estimated from 3 ports of the 13 weeks. Nutrient leaching (y) was log-transformed ($y=\log(x+1)$), and x represents each nutrient leaching variable (mg L^{-1}). For each condition, the significant differences among treatments were analyzed using a one-way analysis of variance (ANOVA) (Tukey's HSD test, $p<0.05$) and

were indicated by lower letters (**a**, **b**, **c**) in the soil columns. T0 served as the control, with no chemical fertilizer or biochar; T1 consisted of chemical fertilizers including urea, diammonium phosphate (DAP), and potassium chloride (KCl); T2 combined T1 with biochar at a rate of 4 t ha^{-1} ; and T3 combined T1 with biochar at 6 t ha^{-1} . S1 represents the clay soil; S2, sandy loam; AWD, alternative wetting and drying; and CF, continuous flooding

intervals, reducing leaching and improving nutrient use efficiency (Haque et al. 2022). In CF, continuous saturation may reduce biochar's adsorption efficiency, especially in sandy soils where drainage is rapid.

The amylose and protein content are crucial for nutritional and cooking quality (Ahmed et al. 2020; Iqbal et al. 2019; Yuan et al. 2014). In this study, while slight variations in amylose content were observed across treatments, no statistically significant differences were detected among them ($p>0.05$), as shown in Fig. 2. This suggests that biochar application, even at higher rates combined with chemical fertilizers, did not markedly influence amylose synthesis. Nonetheless, the trend aligns with findings from Chen et al. (2023), who reported minor reductions in amylose under similar conditions. This may be due to biochar's influence on soil pH and nutrient availability, which can affect starch biosynthesis pathways. Although biochar is known to improve soil structure and water retention, its potential influence on nutrient

uptake related to amylose biosynthesis remains inconclusive and warrants further investigation (Ullah et al. 2024). On the other hand, T3 in both clay and sandy loam led to the highest total protein levels (Figs. 1b and 2). AWD and CF methods had similar effects on rice protein, and both irrigation methods showed significant benefits when combined with biochar. The results of this study were similar to those of Fahad et al. (2016) and Novak et al. (2019), who observed that biochar improved yield and quality through higher amino acid and N availability. Additionally, biochar-enhanced nitrogen metabolism, including nitrate reductase, glutamine synthetase, and glutamine 2-oxoglutarate aminotransferase activities, further contributed to efficient nitrogen utilization and improved grain protein content (Ali et al. 2020).

The combined application of biochar and chemical fertilizer enhanced nutrient availability and uptake, resulting in higher P content in leaves (Figs. 1i and 2). These findings align with the results of Ali et al. (2020), which also

highlighted biochar's role in improving soil fertility and nutrient retention. The higher nutrient content under AWD may be due to reduced nutrient leaching compared to CF, as supported by Song et al. (2021). Shen et al. (2016) revealed that P uptake by plants notably improved by 76% after applying biochar to the soil. Biochar improves P utilization efficiency and reduces P loss, enhancing root growth and crop production (Fei et al. 2019; Olmo et al. 2016). Additionally, biochar stimulates chlorophyll synthesis, increasing photochemical efficiency, quantum yield, and electron transport rate, leading to improved photosynthesis and higher rice productivity (Ali et al. 2020). However, this study indicated short-term benefits for rice yield and nutrient retention, while past research shows that ongoing biochar use improves nitrogen uptake, yield, water-use efficiency, and grain size over time (Fahad et al. 2016; Huang et al. 2018). Therefore, further long-term field studies are needed to fully understand the sustained impact of biochar on soil health and crop productivity.

In this study, chemical fertilizer combined with biochar 6 t ha⁻¹ (i.e., T3) significantly reduced NO₃⁻ and NH₄⁺ loss in both soil types and irrigation methods. The starting levels of NO₃⁻ and NH₄⁺ were about the same in S1 and S2 (Supplementary Table S1), but more of them were lost through leaching in S2 (Fig. 3), showing that nitrogen breaks down more quickly in sandy soil. According to Liu et al. (2017), using biochar likely helps soil hold onto nitrogen better because it improves the soil's ability to hold water and increases the cation exchange capacity, along with helping microbes keep nitrogen in the soil (Jiménez et al. 2023). This explains why clay soils (59.62% clay) show less NO₃⁻ and NH₄⁺ loss than sandy loam (8.68% clay). Biochar's SSA and CEC help retain nitrogen in clay soils by adsorbing ammonium and reducing mobility. In sandy loam, its porous structure slows water movement and nutrient loss, improving retention (Torchia et al. 2025). In terms of irrigation practices, CF irrigation resulted in higher nutrient loss compared to AWD. In CF, the soil stays saturated, increasing N leaching into groundwater. In AWD, soil alternates between wet and dry periods, better retaining nutrients and reducing N loss. Clay soil showed superior nutrient retention compared to sandy loam, and AWD was more effective in retaining nutrients and reducing N loss than CF (Phwe and Chidthaisong 2019).

Interestingly, chemical fertilizer combined with biochar 6 t ha⁻¹ (i.e., T3) exhibited the lowest PO₄³⁻ loss in both soil types and irrigation methods. Specifically, adding biochar 6 t ha⁻¹ worked particularly well in S2 under AWD, significantly reducing leaching compared to biochar 4 t ha⁻¹ and chemical fertilizer alone. This higher rate of biochar application enhances the soil's ability to retain P, preventing it from leaching into the groundwater (Yang et al. 2022).

Therefore, a higher biochar application rate, T3, proved to be more effective in reducing PO₄³⁻ loss compared to other treatments. Biochar is an efficient PO₄³⁻ adsorbent in soil (Eduah et al. 2019; Fei et al. 2019; Zhang et al. 2016) and can reduce PO₄³⁻ loss via P adsorption (Dari et al. 2016). Its ability to exchange anions also helps reduce P loss by capturing insoluble PO₄³⁻ (Chintala et al. 2014). However, Pratiwi et al. (2016) found that biochar's ability to take in PO₄³⁻ content was sometimes not very effective, such as at a rate of 4% w w⁻¹ in loamy soil, and it struggled to dissolve some initial PO₄³⁻ contents below 60 mg L⁻¹.

While these findings underscore the effectiveness of biochar, particularly at 6 t ha⁻¹ in reducing nutrient loss and enhancing rice yield, they need to be considered within the context of the study's design. This study was conducted at the column scale under controlled conditions, which allowed for precise monitoring of soil and water dynamics. However, this setup may not fully capture the complexity of field-scale interactions. Therefore, future field-scale research is essential to validate these findings under real-world conditions and assess their practical relevance for Cambodian rice production systems.

5 Conclusions

Incorporating biochar with chemical fertilizer could significantly enhance nutrient uptake and improve rice yield and quality while reducing nitrogen and phosphorus loss via leaching. Specifically, chemical fertilizer combined with biochar 6 t ha⁻¹ (T3) increased rice yield by 40% compared to chemical fertilizer only (T1) for clay soil under Alternate Wetting and Drying (AWD), and by 35% and 37% for sandy loam under AWD and Continuous Flooding (CF), respectively. Increasing the biochar rate from 4 to 6 t ha⁻¹ further enhances these benefits, demonstrating the importance of optimizing biochar application rates. Notably, biochar not only improves yield but also enhances the protein content in rice, accordingly contributing to better rice quality and health benefits. When combined with the AWD irrigation method, biochar proves advantageous for both clay soil and sandy loam. This combination helps retain essential nutrients and minimizes nutrient leaching into groundwater, contributing to more efficient and sustainable agricultural practices. Although the benefits of biochar in reducing nutrient loss and enhancing soil fertility are evident, it is important to limit its use to a specific amount. Further research should focus on long-term field experiments to validate these findings. Additionally, studies should consider the agricultural cost and economic benefits to assess the economic viability of biochar use under Cambodian farming conditions.

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Declarations

Conflicts of interest The authors declare no conflict of interest.

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