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ORIGINAL PAPER

Impact of Biochar from Rice Husk on Nutrient Distribution and Rice Growth and Yield: A Soil Column Experiment

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Abstract

Cambodia plans to expand its rice sector and become a prominent rice exporter. A key concern is that soil fertility is a crucial factor affecting rice production, and nutrient leaching into the environment can lead to reduced nutrient uptake and lower rice yield. Carbonized waste biochar has gained recognition not only as a potential soil fertility enhancer but also as a significant nutrient leaching reducer. It is currently being introduced in many regions. The study was to evaluate how a combination of chemical fertilizers and rice husk biochar affects nutrient leaching into the topsoil layer and plow sole of soil columns during direct seeding with continuous flooding, and to assess their combined effects on rice growth and yield. In the leachate from these two soil layers, except for ortho-phosphate (PO_4^{3-}), the combination of CHEM + BIO2 or + BIO4 treatment (chemical fertilizers + biochar at a rate of 2t ha^{-1} or + biochar at a rate of 4t ha^{-1}) significantly decreased ammonium (NH_4^+) and nitrate (NO_3^-) levels more than CHEM alone, particularly in the plow sole, suggesting that their combination and biochar sorption capacity are beneficial for nitrogen use by plants. CHEM + BIO2 had varying effects, whereas CHEM + BIO4 led to a significant increase in rice yield, plant biomass, tiller number, panicle length, grains per panicle, and grain weight per panicle. These findings suggest that incorporating biochar amendments in rice production can reduce N leaching. However, there is no evidence to support its effectiveness in reducing P leaching. Therefore, further studies are needed to determine the usefulness of this approach.

Keywords Soil compaction · Biochar ability · Nutrient losses · Irrigated rice · Rice productivity

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1 Introduction

Rice is a major crop in Cambodia, crucial to the country's economy and food security (Kea et al. 2016; Mishra et al. 2018). Traditional farming methods are used, with smallholder farmers growing rice on small plots of land (i.e., rice fields) using simple tools and techniques (Cramb et al. 2020). Some rice fields are situated under reconstituted or conserved conditions, especially after crop rotation and/or deforestation (Hok et al. 2015; Kong et al. 2021). Under these two conditions, conventional tillage in those rice fields has created a surface layer of soil (called the topsoil layer) and a compacted layer of soil (the plow sole), usually seen in tropical agriculture (Wasaya et al. 2019). Plowing the soil helps to prepare the topsoil surface for new plantations by burying the straws and potential weeds (Azimi-Nejadian et al. 2022; Jin et al. 2020) and allows water infiltration and nutrients to reach the rooting zones (Islam et al. 2021), especially to release an unavailable form of nitrogen (N) (e.g., dinitrogen (N_2), ammonia (NH_3^-), and hydroxyammonia (NH_2OH)) (Singh et al. 2020). Moreover, the implementing tillage (i.e., turning the soil) increases soil moisture in the topsoil layer (Rehm et al. 2021), while the plow sole can limit water infiltration beyond the rooting zones, keeping rice fields under water during rice growth (McDonald et al. 2006) and limiting nutrient leaching (Patel and Singh 1981). Although conventional tillage has been important in rice production since ancient times (Nesbitt 1998), there has been a growing trend towards mechanization and modern farming practices, such as the use of agrochemicals (Chhay et al. 2017; Kimkong et al. 2023).

In this sense, Cambodian farmers often use chemical fertilizers, especially nitrogen (N) (urea), to increase rice yield (Dong et al. 2015). However, more than 55% of N fertilizer applied to irrigated land in tropical agriculture is not taken up by rice itself (Inamura et al. 2009; Zhu et al. 2016), resulting in surface runoff, NH_3^- volatilization, and N leaching (Dong et al. 2015; Li et al. 2017). There is limited awareness of N leaching in Cambodia (Verma et al. 2020; survey data, pers. communication), and long-term use of phosphorus (P) fertilizer or manure can also increase P leaching into groundwater and surface water (Kang et al. 2011). Excess P leaching is, on the other hand, negatively affects water quality (Nelson et al. 2005) and leads to eutrophication (Huang et al. 2018). In previous studies, controlled-release fertilizers such as polymer-coated fertilizer, granular fertilizer, and zeolite have been used to reduce nutrient leaching (N and P) from rice fields (Chen et al. 2018), but their high cost makes them a significant barrier to their widespread use (Lawrencia et al. 2021; Vejan et al. 2021). To address this issue, efficient and comprehensive strategies are needed, such as using other feedstocks like wood biochar, rice straw biochar, converted agricultural residues, bamboo biochar, corn stover, oak wood, spruce, and/or Scots pine (Soinne et al. 2014; Xu et al. 2014; Liu et al. 2016; Munda et al. 2018; Ma et al. 2019; Yin et al. 2021). Interestingly, with its high surface area and ion exchange capacity (e.g., anions or cations depending on the combustion temperature and feedstock used (Lawrinenko and A. Laird 2015; Rizwan et al. 2016; Brassard et al. 2019a), rice husk biochar showed a significant reduction in nutrient leaching through different soil layers during rice growth, thereby increasing yield (Asai et al. 2009; Yoo et al. 2014; Sarong and Orge 2015; Mohammadi et al. 2017; Singh et al. 2018; Brassard et al. 2019b; Wantaneeyakul et al. 2021). A previous study showed significant increases in plant biomass, plant height, tiller number, and panicle number (Selvarajh et al. 2020). Additionally, Koyama et al. (2016) showed better panicle length and root biomass, but Liu et al. (2021) showed a non-significant root length. Chen et al. (2021) and Chen et al. (2023) showed better grains per panicle and grain weight per panicle, respectively.

In recent years, the unaffordable prices of chemical fertilizers have led to a significant underuse of these fertilizers by farmers, with 80% underusing them owing to financial considerations (Chhay et al. 2017; Ye et al. 2022). Overuse of these fertilizers can lead to nutrient leaching into the environment (Tyagi et al. 2014; Huang et al. 2017b; Ke et al. 2018), causing public health issues (Erisman et al. 2013; Gwenzi et al. 2015; Ahmed et al. 2017; Dimkpa et al. 2020). In Cambodia, the use of chemical fertilizers is a major cause of water quality degradation (Ebers et al. 2017; Chhun et al. 2020), threatening the livelihoods of rural Cambodians who rely on groundwater and surface water (Guppy and Shantz 2011; Bun et al. 2021). This study introduces rice husk biochar, a carbonized organic waste from agriculture, as a potential solution (Das et al. 2023). Rice husk is locally abundant and cost-effective, with a production over 2 million tons in 2014. Only 10% of rice husk is used as fuel for household cooking and brick kilns, and the rest is thrown away or burned out (Nguyen et al. 2015). The study aimed to evaluate the impact of chemical fertilizers combined with rice husk biochar on leaching of NH_4^+, NO_3^-, and PO_4^{3-} contents into the topsoil layer and plow sole using a soil column experiment. Additionally, the study assessed the effects of biochar occurrence and quantity on the rice growth and yield. The application of biochar is found to positively affect nutrient leaching and rice growth and yield; however, excessive biochar may result in adverse consequences.

2 Materials and Methods

2.1 Column Experimental Design

The experiment was carried out in a greenhouse at the Cambodian Agricultural Research and Development Institute (CARDI, latitude 11°28′32.33″ N and longitude

104°48′25.37″ E in a tropical climate) from June to the end of September 2021. A soil "Prateah Lang (sand over clay, White et al. 2006)" was selected for this experiment because it is the most common soil group (28%) among the 11 soil groups of Cambodia's irrigated land for rice only (White et al. 1997). Specifically, the FAO/UNESCO soil classification system would classify this soil "Prateah Lang" mainly as Gleyic Acrisols soil (Ballester et al. 2021).

Two sets of soil column samples represent the reconstituted and conserved conditions of rice fields in tropical agriculture (Fig. 1A). Under each condition, all the soil (column) samples were selected at three different sampling profiles (i.e., up to horizon B as defined by the FAO Guidelines for Soil Description (FAO 2006)). And each soil column represents two soil layers (i.e., the topsoil layer and the plow sole; Fig. 1B). For the reconstituted conditions, soil samples were dug from the rice fields. In the laboratory, after removing plastic and stubble, the soil columns were prepared and repacked into the corresponding topsoil layer and plow sole (5.65 kg and 6.82 kg, respectively). The soil columns were then gently compacted with a wooden hammer to reach the field bulk density of each layer (see Table 1). For the conserved conditions, the soil columns were sampled directly from the rice fields to avoid any disturbance of the topsoil layer and plow sole, using a thick-wall 5 mm PVC pipe (50 cm long and 15 cm in diameter) to keep the original structure of each layer.

A rice husk biochar (hereafter, biochar) was burned in a muffle furnace at 400 °C for 4 h (Karam et al. 2022). Before rice sowing, the biochar was added to each soil column, about 10–15 cm in the topsoil layer, as an amendment during the soil preparation. Different treatments were applied in each soil column: chemical fertilizers (CHEM) (including urea, DAP, and KCl) at a ratio rate of 60:30:30 of NPK, respectively; CHEM + BIO2 (i.e., CHEM + biochar at a rate of 2t ha^{-1}); CHEM + BIO4 (CHEM + biochar at a rate of 4t ha^{-1}); and CNTL, control (i.e., no chemical and no biochar). A rice cultivar (locally named Sen Pidao) was selected for the direct seeding irrigation method under continuous flooding (Fig. 1B). During the whole experiment, following the soil group considered, the CHEM treatment was applied two times in each soil column: the first time (NPK: 60 kg ha^{-1}, 50 kg ha^{-1}, 50 kg ha^{-1}; respectively) during the soil preparation at the beginning, and the second time (only N: 100 kg ha^{-1}) during the boosting stage (i.e., 40 days), except for the CNTL treatment. To collect the leachate, the thick-wall 5 mm PVC pipe was drilled with two holes from the two soil layers: one hole at a depth of 30 cm (from the top) for the topsoil layer and another one at 50 cm for the plow sole. The two holes were wrapped in a nylon mesh to prevent an interruption of the sedimentation and were equipped with a faucet.

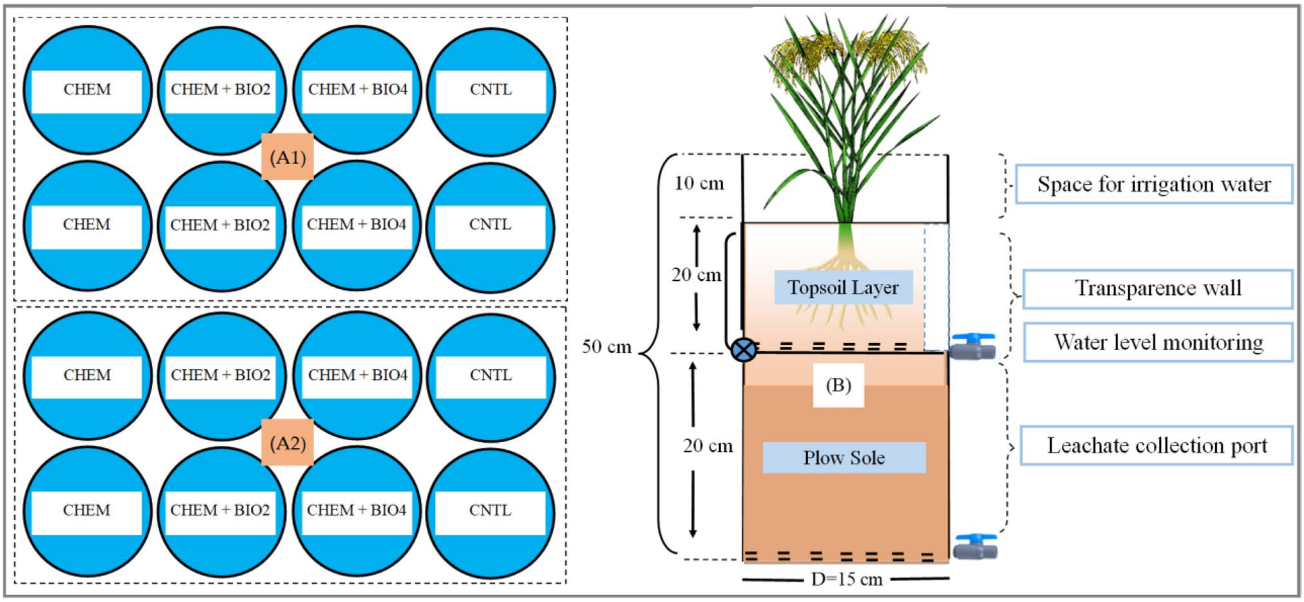


Fig. 1 Two sets of soil column samples were designed to represent rice fields under continuous flooding using a soil group (called Prateah Lang (Gleyic Acrisols soil)) under reconstituted (A1) and conserved (A2) conditions. A soil column (B) represents the topsoil layer and the plow sole, which varies between 15–25 cm depth for rice cultivation (Katoh et al. 2004; Li et al. 2016; Xue et al. 2022) and 15–30 cm depth based on the soil groups and irrigation history (Nosalewicz and Lipiec 2014; Tuzzin de Moraes et al. 2016), respectively. CHEM represents the chemical fertilizers at a ratio rate of 60:30:30 of NPK, respectively; CHEM + BIO2, CHEM + biochar at a rate of 2t ha^{-1}; CHEM + BIO4, CHEM + biochar a rate of 4t ha^{-1}; CNTL, control (no chemical and no biochar)

Table 1 Mean values (±1 SD, standard deviation) for the rice husk biochar (*n* = 3) were randomly estimated from a 3-kg rice husk biochar, and the topsoil layer (*n* = 9) and plow sole (*n* = 9) of the rice fields were estimated from the three soil profiles. SOM stands for soil organic matter; Total N for total nitrogen; Available N for available nitrogen; Exchangeable K for exchangeable potassium; and NH_4^+ for ammonium. The numbers (in bold) were significantly different between the two soil layers (*T*-test, $p < 0.05$)

Description	Bulk density (BD) (g cm^{-3})	pH (1:5 H2O)	SOM (%)	Total N (%)	Available N (mg 100 g^{-1})	Available P (mg 100 g^{-1})	Exchangeable K (cmol kg^{-1})	NH_4^+ (mg 100 g^{-1})
Rice husk biochar	-	7.80 ± 0.162	-	5.60 ± 0.030	29.60 ± 0.009	2.60 ± 0.020	4.03 ± 0.042	-
Topsoil layer (0–20 cm)	1.60 ± 0.052	6.10 ± 0.144	**0.45** ± 0.091	**0.03** ± 0.005	-	**5.97** ± 0.213	**0.17** ± 0.008	5.91 ± 0.172
Plow sole (20–40 cm)	**1.93** ± 0.020	6.52 ± 0.432	0.13 ± 0.009	0.02 ± 0.002	-	4.50 ± 0.327	0.13 ± 0.017	5.94 ± 1.105

2.2 Measuring Biochar and Soil Characteristics

Triplicate samples of the biochar were analyzed for its basic characteristics, including pH (1:5 H_2O), total nitrogen (Total N) (%), available phosphorus (P) (mg 100 g^{-1}), and exchangeable potassium (K) (cmol kg^{-1}) following the methods described for the soil analysis (below), except for available N (mg 100 g^{-1}). The latter was measured with NH_4N-KCl extraction and Kjeldahl methods (Keeney and Nelson 1983; Sáez-Plaza et al. 2013).

Triplicate soil samples from each layer of the three sampling profiles were measured. The soil characteristics (such as bulk density (BD) (g cm^{-3}), pH, soil organic matter (SOM) (%), Total N (%), available N (g 100 g^{-1}), ammonium (NH_4^+) (mg 100 g^{-1}), available phosphorus (P) (mg L^{-1}), and exchangeable potassium (K) (cmol kg^{-1})) were measured immediately after soil sampling. BD was measured using volumetric metal rings (5 cm long, 5 cm in diameter). Soil pH was measured with the pH (1:5 H_2O) soil/water suspension method (Rayment and Higginson 1992). Soil organic matter (SOM) was measured with the Walkley–Black method (Gupta and Chaurasia 2014). Total N and NH_4^+ contents were measured with the Kjeldahl method (Baethgen and Alley 1989; Gupta and Chaurasia 2014; Bremner 2016), whereas available phosphorus (P) was measured with the Olsen method (Olsen 1954; Zhou et al. 2001). Exchangeable potassium (K) was measured with the Flame photometer method (Gupta and Chaurasia 2014).

The basic characteristics of biochar and soil as measured from the topsoil layer and plow sole are shown in Table 1. Total N and exchangeable *K* values for biochar with alkaline pH were high, while available P was low. Soil organic matter (SOM), Total N, and exchangeable *K* values for the topsoil layer were significantly higher than those for the plow sole: t (10) = -7.84, $p < 0.001$; t (10) = -4.24, $p = 0.001$; t (10) = -3.96, $p = 0.002$, respectively. The bulk density (BD) of the plow sole was significantly higher than that of the topsoil layer: t (10) = 13.70, $p < 0.001$. However, neither soil pH nor NH_4^+ values for the two soil layers were significantly different: t (10) = -2.12, $p = 0.059$; t (10) = -0.17, $p = 0.865$, respectively.

2.3 Measuring Soil Column Leachate

Triplicate leachate samples from each faucet of the topsoil layer and plow sole were collected at 7-day intervals using the sampling bottle container (polypropylene material). The leachate samples were measured immediately for ammonium (NH_4^+) (mg L^{-1}) and nitrate (NO_3^-) (mg L^{-1}) with the Vario Tube Test and for ortho-phosphate (PO_4^{3-}) (mg L^{-1}) with the ortho method with a table. All three variables were measured using a photometer (Part Number 214020, MD600, Lovibond, Germany).

2.4 Measuring Rice Growth and Yield

Triplicate rice samples were measured for plant biomass (g $plant^{-1}$), tiller number, grains per panicle, grain weight per panicle (g), panicle length (cm), root biomass (g), and root length (cm), except for total yield (g $plant^{-1}$). The plant height of each soil column was measured at 7-day intervals using a 3-m measuring tape. During the maturity period, plant samples were split into straw and panicle to count the tiller number. Samples of panicle were randomly selected to count the grains per panicle. The soil column was carefully broken to preserve the root structure. The root area was shaped and soaked in water to be cleaned. The root length was then measured, and the dried weight of straw, leaves, and roots were determined after oven-drying at 70 °C to a constant weight for 48 h.

2.5 Data Analysis

All statistical analyses were conducted using R (R Core Team 2021). A one-way analysis of variance (ANOVA) was performed to assess the effects of chemical fertilizers and their combination with biochar on nutrient leaching and the differences among treatments that enhanced all the variables describing rice growth and yield. All effects and differences were statistically significant, followed by post-hoc comparisons using Tukey's HSD (Honestly Significant Difference) test, which differed at the $p < 0.05$ level. The significant differences in variables describing the biochar and the two soil layers computed by the *T*-test for equality of means differed at the $p < 0.05$ level. All data were log-transformed ($y = \log(x + 1)$) to improve the normality and homogeneity of variance. The graphics of nutrient leaching

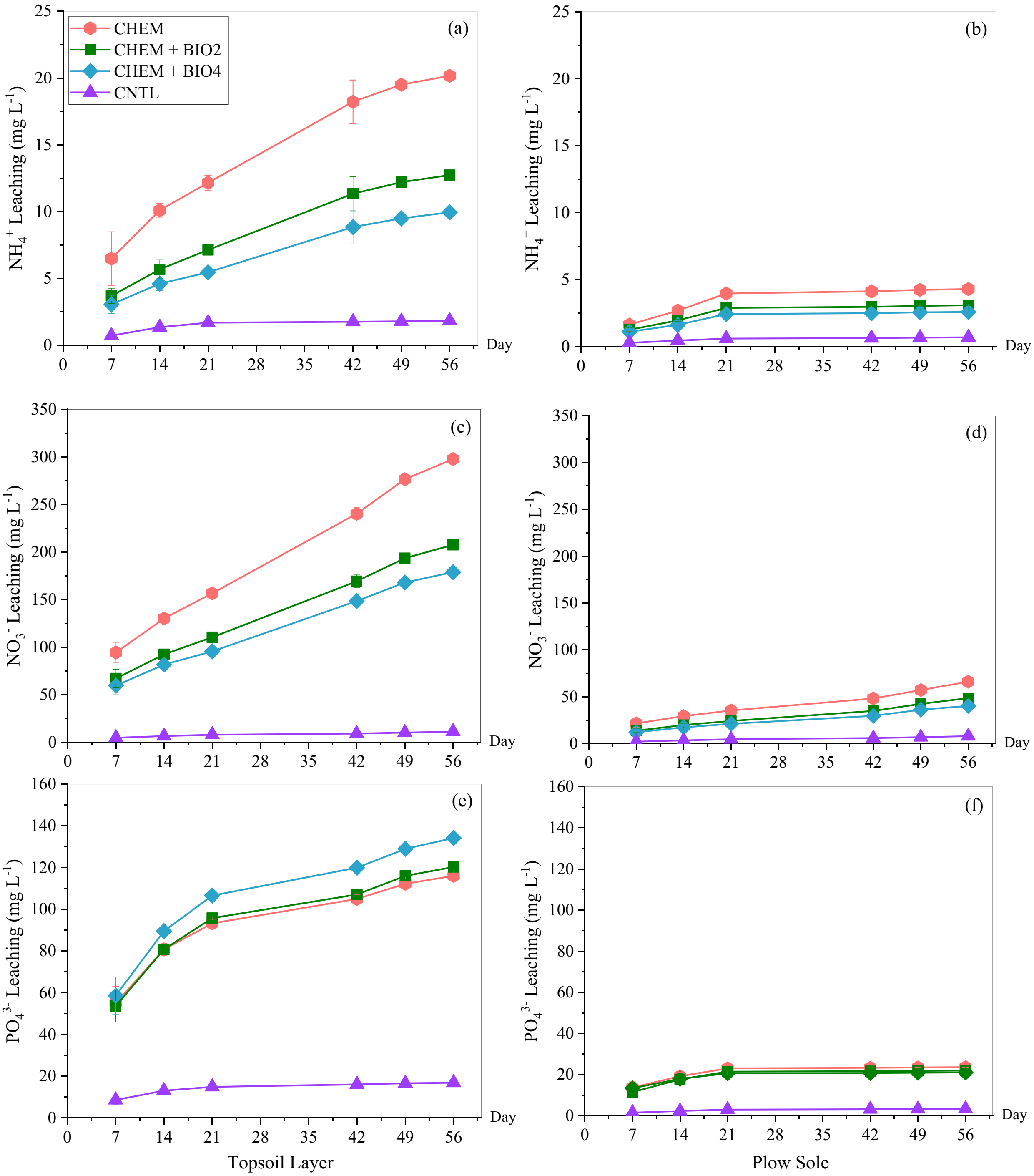


Fig. 2 Mean values (±1 SD, standard deviation) for the nutrient leaching (NH_4^+, NO_3^-, and PO_4^{3-}) ($n = 12$, each) through the topsoil layer and plow sole of soil columns. The graphs show their leachate accumulation at 7-day intervals: (**a**–**b**) ammonium (NH_4^+), (**c**–**d**) nitrate (NO_3^-), and (**e**–**f**) ortho-phosphate (PO_4^{3-}). CHEM represents the chemical fertilizers at a ratio rate of 60:30:30 of NPK, respectively; CHEM + BIO2, CHEM + biochar at a rate of 2t ha^{-1}; CHEM + BIO4, CHEM + biochar at a rate of 4t ha^{-1}; CNTL, control (no chemical and no biochar)

(or leachate) accumulation, rice growth, and yield were plotted using Origin Pro.

3 Results

3.1 Nutrient Leaching in the Topsoil Layer and Plow Sole

There was no significant difference in nutrient leaching between the reconstituted and conserved conditions (Lai et al. 2022). However, rising nutrient leaching (NH_4^+, NO_3^- and PO_4^{3-}) during the experiment (7–56 days) confirmed higher leachate measured in the topsoil layer than that in the plow sole (Fig. 2). Comparing the CHEM treatment with other treatments, including biochar (i.e., CHEM + BIO2 and CHEM + BIO4), the biochar significantly affected the NH_4^+ and NO_3^- contents leaching into the topsoil layer ($p < 0.05$), but not the PO_4^{3-} content (Fig. 3). However, into the plow sole, the biochar did not significantly affect the NH_4^+ content but reduced the NO_3^- content ($p < 0.05$). In any case, the CNTL treatment highlighted the significantly lowest values for these three variables.

3.2 Rice Growth and Yield

The CHEM + BIO4 treatment, followed by CHEM + BIO2, resulted in the highest values for rice yield, plant biomass, and tiller number ($p < 0.05$, Fig. 4a, b and c). On a percentage basis, for the rice yield, the CHEM + BIO4 treatment

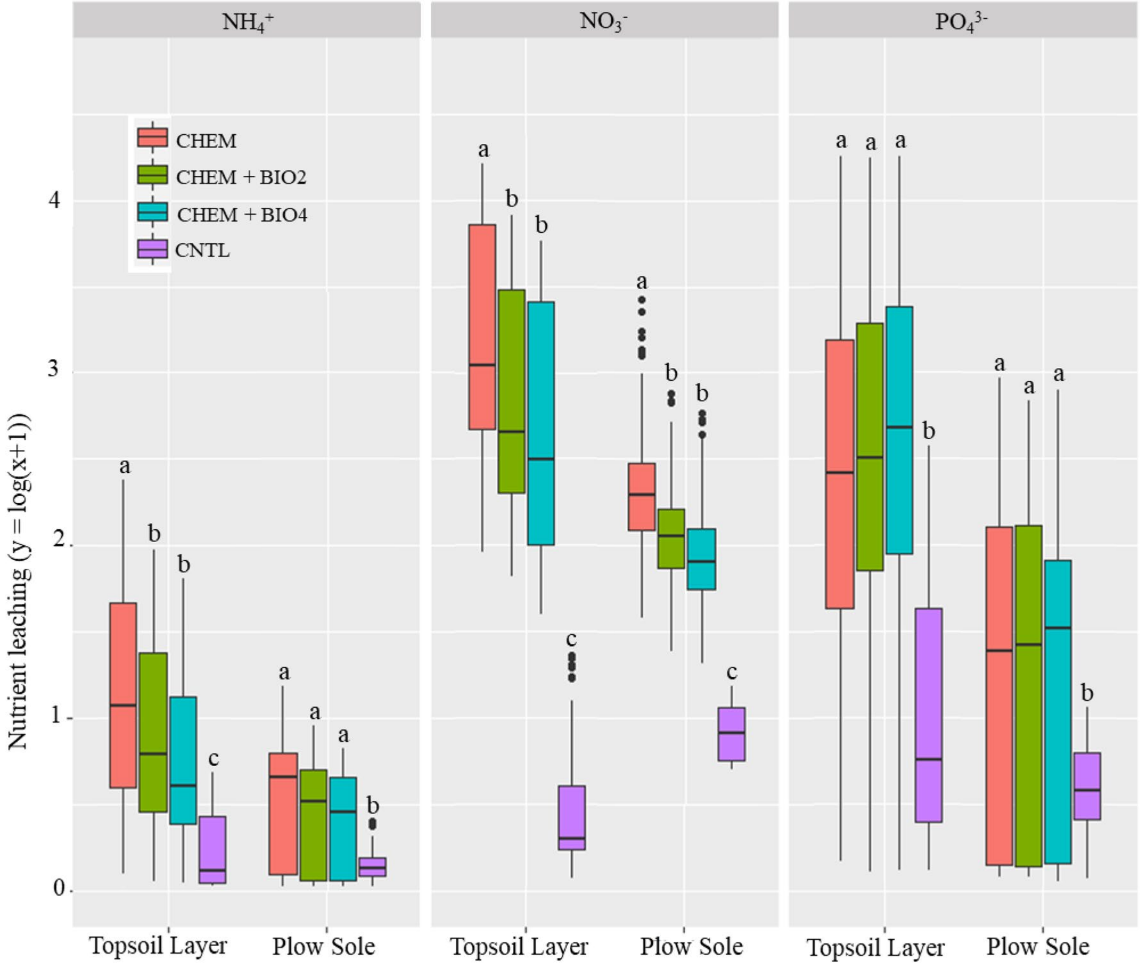


Fig. 3 Boxplots showed the nutrient leaching through the topsoil layer and plow sole of the rice fields under different treatments. Mean values (±1 SD, standard deviation) for NH_4^+, NO_3^-, and PO_4^{3-} ($n = 12$, each) were estimated from the reconstituted and conserved conditions for each soil layer. Nutrient leaching (y) was log-transformed (y = log(x + 1)), x represents each leaching variable (mg L^{-1}). For the topsoil layer and plow sole of soil columns, 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. CHEM represents the chemical fertilizers at a ratio rate of 60:30:30 of NPK, respectively; CHEM + BIO2, CHEM + biochar at a rate of 2t ha^{-1}; CHEM + BIO4, CHEM + biochar at a rate of 4t ha^{-1}; CNTL, control (no chemical and no biochar)

increased it by 16% compared to the CHEM + BIO2 treatment, 31% (CHEM), and 52% (CNTL), while for the plant biomass, by 20% (CHEM + BIO2), 54% (CHEM), and 70% (CNTL). And, for the tiller number, the CHEM + BIO4 treatment increased it by 20% (CHEM + BIO2), 49% (CHEM), and 67% (CNTL). However, the two added biochar treatments enhanced the highest grains per panicle and panicle length ($p < 0.05$, Fig. 4d and e). For the grains per panicle, the CHEM + BIO4 treatment increased it by 15% compared to the CHEM + BIO2 treatment, 26% (CHEM), and 50% (CNTL), while for the panicle length, by 8% (CHEM + BIO2), 20% (CHEM), and 30% (CNTL).

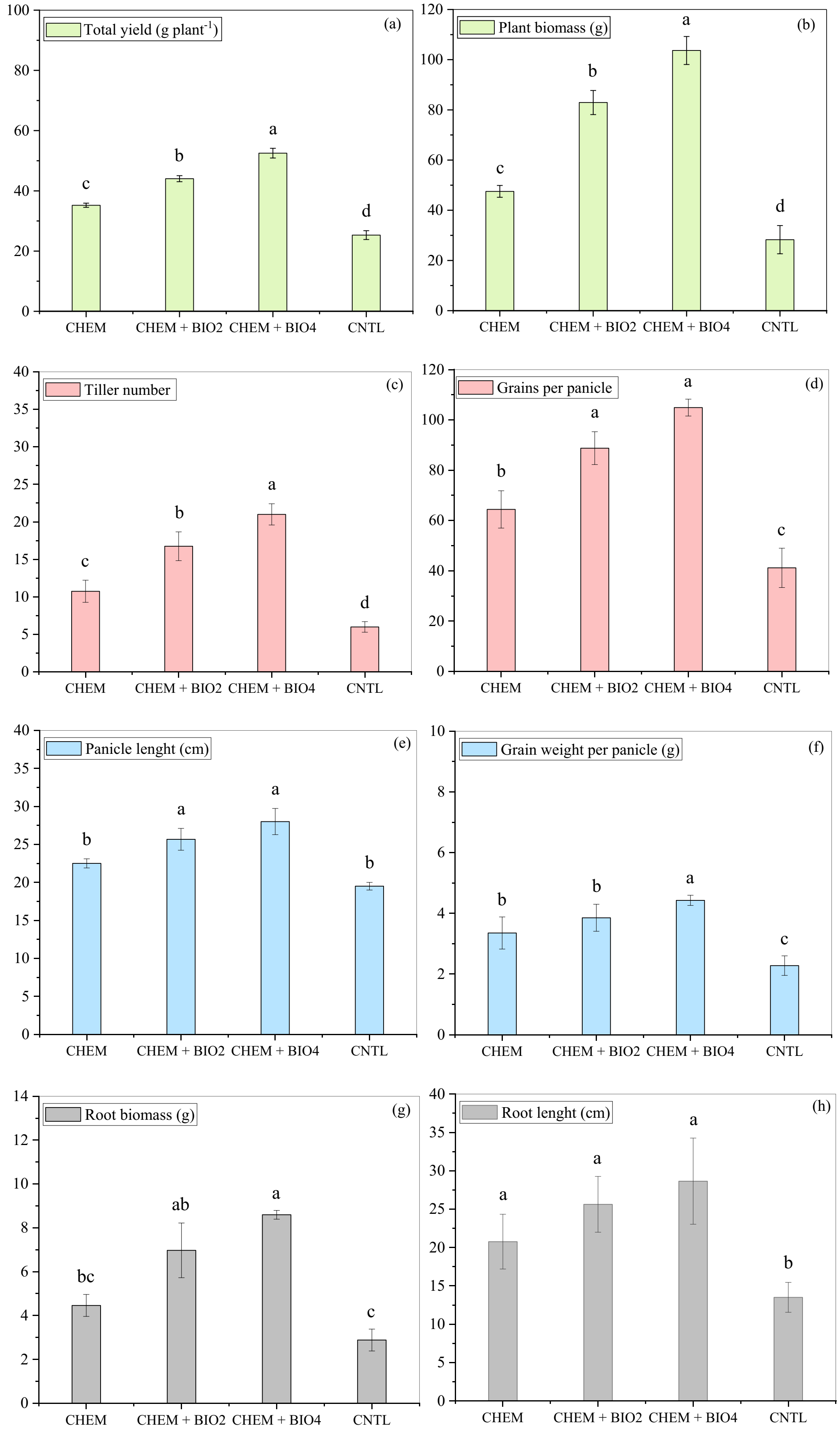
Except for the root length, the CHEM + BIO4 treatment enhanced the highest values for the grain weight per panicle and root biomass ($p < 0.05$, Fig. 4h, f and g). For the grain weight per panicle, the CHEM + BIO4 treatment increased it by 15% compared to the CHEM + BIO2 treatment, 39% (CHEM), and 65% (CNTL), while for the root biomass, by 18% (CHEM + BIO2), 48% (CHEM), and 66% (CNTL).

4 Discussion

Previous studies have suggested that biochar can reduce nitrogen (N) leaching, such as NH_4^+ and NO_3^- (Li et al. 2019; Xu et al. 2014), and increase the use efficiency of chemical fertilizers by rice growth, especially in the surface layer of soil (0–20 cm) like that of this study (Ding et al. 2010; Yang et al. 2015; Oladele et al. 2019; Selvarajh et al. 2021). A meta-analysis by Jeffery et al. (2011) comprising 177 previous studies showed that the positive effects of biochar incorporation into soils outweighed the negative and neutral effects, with the exception of one study showing negative effects (Wang et al. 2016). This study showed that the relationships between chemical fertilizers and biochar applications were responsive to N leaching in the soil layers, but not to P leaching (Fig. 3). Biochar pore surfaces can react with some of the nutrients (i.e., N and P) released from chemical fertilizers (Joseph et al. 2018; Hestrin et al. 2019; Haider et al. 2020). Owing to its larger surface area, negative surface charge, and charge density, biochar plays a role in reducing nutrient leaching, particularly immobilizing N (Lehmann et al. 2003), thereby decreasing N-induced pollution in the environment (Huang et al. 2017a; Sun et al. 2018). For instance, Ding et al. (2010) showed that biochar can absorb ammonium ions (NH_4^+) through cation exchange, resulting in different levels of nutrient leaching in different soil layers. Another study found that average NH_4^+ leaching during whole rice growth (i.e., Oryza sativa L. Nanjing 5055 and Oryza sativa L. Nanjing 9108) decreased in different soil layers (Zheng et al. 2019). This study also revealed that NH_4^+ leaching was higher in the topsoil layer than in the plow sole (Fig. 2a, b*)*. Some mechanisms underlying the decreased NO_3^- leaching were also the ability of biochar to absorb the NO_3^- content from the mixed soil. A study by Chen et al. (2021) showed that rice straw biochar at a rate of 20t ha^{-1} reduced NO_3^- and Total N leaching by 30–39% and 13–14%, respectively. However, more than 30t ha^{-1} of rice straw biochar had negative effects on wheat yield and nutrient uptake (Sun et al. 2019). In contrast to N leaching, Troy et al. (2014) and this study found that wood and rice husk biochar did not reduce PO_4^{3-} leaching, and biochar from different feedstocks (e.g., corn stover, oak wood, spruce, and Scots pine) could not absorb PO_4^{3-} leaching from an aqueous solution (Hollister et al. 2013; Soinne et al. 2014; Xu et al. 2014). Biochar also had the ability to increase PO_4^{3-} leaching because it was a net PO_4^{3-} source (Altland and Locke 2013; Nguyen et al. 2020), adding more PO_4^{3-} content to the soil layers. The added biochar could reduce the ability of the soil to absorb the PO_4^{3-} content (Cui et al. 2011; Soinne et al. 2014). Pratiwi et al. (2016) observed that the ability of biochar to absorb the PO_4^{3-} content was extremely limited, i.e., at a rate of 4% w/w (biochar weight /soil weight) in loamy soil, and even to solubilize some initial PO_4^{3-} contents below 60 mg L^{-1}.

This study found that the topsoil layer and the plow sole have high soil bulk density (BD) values (1.60 g cm^{-3} and 1.92 g cm^{-3}, respectively), indicating Gleyic Acrisols soil. This is higher than rice fields in Cambodia and sandy clay loam soil (1.45 g cm^{-3}) (Olubanjo and Yessoufou 2019). These two authors noted that soil BD is always altered in response to compaction, which may be associated with various field operations, such as the passage of heavy machinery in rice fields (Shaheb et al. 2021). These field operations often cause damage to the soil structure by reducing the pore space between soil particles (soil porosity) (Singh et al. 2015), which favors higher water flux retention in the plow sole with its high soil BD. However, soil organic matter (SOM) in soils was found to have less compaction (Athira et al. 2019) and improved nutrient-holding capacity, reducing N leaching (Malcolm et al. 2019). This study also underlined less N leaching in the topsoil layer and especially in the plow sole when more biochar was added (Fig. 3, CHEM + BIO4). Biochar increases SOM (Han et al. 2016; Luo et al. 2018), a key component in soil interactions (Siedt et al. 2021). Because all soil organisms rely on SOM, biochar can protect soil biodiversity, reduce N leaching, and improve the functioning of soil processes and enzyme activity. Soil enzyme activity can influence soil fertility and crop yield by participating in SOM decomposition and nutrient cycling (Sun et al. 2022). Long-term biochar and N fertilizer applications have been associated with increased rice yield and reduced the Total N leaching (Ullah et al. 2020).

For rice development, soil tillage also releases accessible N content after a process of N fixation and nitrification


Total yield (g plant^{-1})
(a)
c
b
a
d
Plant biomass (g)
(b)
c
b
a
d
Tiller number
(c)
c
b
a
d
Grains per panicle
(d)
b
a
a
c
Panicle lenght (cm)
(e)
b
a
a
b
Grain weight per panicle (g)
(f)
b
b
a
c
Root biomass (g)
(g)
bc
ab
a
c
Root lenght (cm)
(h)
a
a
a
b
CHEM
CHEM + BIO2
CHEM + BIO4
CNTL

◂**Fig. 4** Mean values (±1 SD, standard deviation) for: (**a**) total yield ($n=4$), (**b**) plant biomass ($n=4$), (**c**) tiller number ($n=4$), (**d**) grains per panicle ($n=12$), (**e**) panicle length ($n=12$), (**f**) grain weight per panicle ($n=12$), (**g**) root biomass ($n=4$), and (**h**) root length ($n=12$) 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). CHEM represents the chemical fertilizers at a ratio rate of 60:30:30 of NPK, respectively; CHEM + BIO2, CHEM + biochar at a rate of 2t ha^{-1}; CHEM + BIO4, CHEM + biochar at a rate of 4t ha^{-1}; CNTL, control (no chemical and no biochar)

(Hirsch and Mauchline 2015; Zhang et al. 2021). When chemical fertilizers are combined with biochar, the physical and chemical reactions that occur during biochar granule production slow the rate and extent of N compound dissolution compared to chemical fertilizers alone, resulting in reduced N leaching (Chen et al. 2018; Shi et al. 2020) and increased rice growth and yield. Many studies concluded that higher rice yield was recorded in the presence of any biochar (Dong et al. 2015; Yang et al. 2019; Chen et al. 2021; Xu et al. 2022; Ghorbani et al. 2023) owing to its role in building soil fertility (Xu et al. 2016; Panhwar et al. 2020; Liu et al. 2021). For instance, Yin et al. (2021) found that their biochar treatment (4t ha^{-1}) significantly increased the rice yield. Their results were supported by this study with the same rate under the CHEM + BIO4 treatment (Fig. 4a). The combination of chemical fertilizers (30 kg ha^{-1}) and biochar (3-6t ha^{-1}) significantly affected rice harvest index, yield, and biomass (Oladele et al. 2019). Biochar significantly enhanced tiller number (Kamara et al. 2015; Oladele et al. 2019; Chen et al. 2021) and improved traits such as panicle length, grain weight per panicle, and grains per panicle. However, this study showed that there was no significant difference between chemical fertilizers and biochar in improving root biomass and root length (Fig. 4g, h). Consistently, Pratiwi and Shinogi (2016) showed that biochar only slightly increased root biomass and root length. The effects of biochar on root growth depend on soil nutrient conditions (Liu et al. 2021) and rice growth stages (Biederman and Harpole 2013). In a study of Joseph et al. (2021), rice roots in stage 2 (i.e., tillering starting from 1 month) intercepted and interacted with any biochar.

5 Conclusion

The combination of chemical fertilizers with rice husk biochar (i.e., CHEM + BIO4) effectively decreased ammonium and nitrate leaching in Gleyic Acrisols soil. This effect can be attributed to an increase in soil water-holding capacity, nutrient accessibility, and uptake, leading to improved rice growth and yield. However, the presence of biochar did not reduce ortho-phosphate leaching, suggesting that factors like ion strength, soil texture, pH, and biochar rates should be considered. The study suggests that the combination of chemical fertilizers with rice husk biochar could be a viable solution in Cambodia owing to its low-cost production and ease of use compared to chemical fertilizers alone. As such, developing efficient approaches to control nutrient leaching in rice fields is crucial for improving agricultural production.

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Data Availability The datasets presented and analyzed in this study are available on request from the corresponding author.

Declarations

Conflict of Interest The authors declare no competing interests.

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