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Enhancing Soil Nitrogen Availability and Rice Growth by Using Urea Fertilizer Amended with Rice Straw Biochar

Gunavathy Selvarajh [1] and Huck Ywih Ch'ng [1,2,*]

[1] Faculty of Agro-Based Industry, Universiti Malaysia Kelantan, Jeli Campus, Jeli 17600, Malaysia; gunavathy92@gmail.com
[2] Agro Techno Park, Universiti Malaysia Kelantan, Jeli Campus, Jeli 17600, Malaysia
* Correspondence: huckywih@umk.edu.my; Tel.: +60-17-8537510

Abstract: Urea fertilizer as a nitrogen source is used widely and globally. However, N loss through ammonia volatilization from applied urea has become a major drawback to agriculture. A pot experiment was conducted to determine the effect of rice straw biochar on (1) total N, soil exchangeable NH_4^+, and available NO_3^- (2) uptake of N, P, and K in rice plants. The treatments evaluated were: (S: Soil only, U: soil + 175 kg ha^{-1} urea, B1: soil + 175 kg ha^{-1} urea + 5 t ha^{-1} rice straw biochar, B2: soil + 175 kg ha^{-1} urea + 10 t ha^{-1} rice straw biochar, CB1: 50% soil + 50% commercial biochar potting media and CB2: 100% commercial biochar potting media). The addition of rice straw biochar at 5–10 t ha^{-1} in the pot experiment significantly increased the soil total N availability by 33.33–46.67%. Treatments B1 and B2 also had significantly increased exchangeable NH_4^+, NO_3^-, P, and K in the soil over U. The soil availability nutrients increment in soil was attributed to the higher adsorption capacity of the rice straw biochar. Increment in soil nutrient availability such as N, P, and K increased the plant height, tiller number, greenness, and panicle number because of effective rice plant absorption. This resulted in dry matter production increment in line with plant nutrient uptake and use efficiency. Rice straw biochar at 5–10 t ha^{-1} can improve the productivity of rice plants by increasing N retention in soil.

Keywords: ammonia volatilization; biochar; urea; nitrogen loss; ammonium; nitrate

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1. Introduction

Irrigated lowland rice system is the most common rice planting method adopted by rice growers in Malaysia by using rice cultivar MR219, MR297, and MR232. This system of rice planting is more advantageous and economical, but there are many arising problems leading to poor rice plant growth. One of the major problems is N loss in the irrigated lowland rice field. The broadcasted urea in the rice field is prone to volatilization in the form of NH_3. The loss of N in the form of NH_3 is higher and contributes to the economic loss. Nkebiwe et al. [1] stated that soil surface broadcasted urea is commonly adopted by rice growers because of the ease of application and cost-saving. However, the N loss is higher whereby approximately 60% of urea volatilized in the form of NH_3 is lost to the environment [2]. The loss of urea N through volatilization reduces its efficiency and incorporating it deep in the soil will be costly and not practical in large-scale agricultural fields [3]. Therefore, the volatilization of NH_3 from applied urea needs to be minimized so that the nutrient will be available for plant uptake. These will directly increase the growth performance and yield production of rice plants. Simultaneously, the excessive application of fertilizers to overcome nutrient deficiency and environmental quality degradation can be reduced [4].

The NH_3 loss from urea fertilizer can be minimized using biochar produced from agricultural waste such as rice residues. Abundant rice residues were unutilized and just being burnt to avoid excessive accumulation. Rice straw is an unwanted waste that is easily obtainable for free in Malaysia or elsewhere because a substantial amount of rice straw is produced (>7,518,073 tonnes) as a byproduct from rice cultivation annually [5]. Pandey et al. [6] stated that farmers prefer not to recycle the rice straw in situ because of slow degradation of rice straw. The unprocessed raw rice straw is highly prone to diseases and pathogens for the cultivated plants, and accumulation of the rice straw wastes in the field also causes hindrance to the agricultural field management works. Alternative use of the rice straw is to turn it into biochar which benefits agronomically. Biochar remains in the soil for a more extended period of time because of its stability and resiliency; hence it is suitable for use as a soil ameliorant. It was further supported that biochar is resistant to microbial degradation; thus, it stays in the soil for a more extended period of time and provides long-term benefits to soil fertility [7]. Biochars have been categorized as highly porous, possess strong aromatic structure, usually alkaline, and exhibit large surface area. Due to these inherent chemical and physical properties, biochar readily influences soil pH, water holding capacity, and bulk density [8]. Furthermore, a large surface area of biochar helps in binding anions and cations, which directly increase cation exchange capacity (CEC) [9]. To further specify, rice husk biochar application as a soil amendment had increased the soil available N, Mg, P, silica, C, and K [10]. The retention of N, NH_4^+, and NO_3^- is higher in the soil amended with biochars made from wheat straw, corn straw, and peanut shell [11]. Singh et al. [8] stated that rice hull and chipped stemwood had profoundly chelate NH_4^+ and NO_3^- in the soil. Past research clearly showed that biochar increases the NH_4^+ and NO_3^- in the soil by reducing NH_3 loss to the environment. Additionally, the retention of ions increased due to dual adsorption capacity, where it binds both charged ions onto its surface exchange sites [12]. Studies have shown that biochar, with a pool of negative charges, adsorbs more cations which increase the potential for biochar to be a nutrient-retaining material [13]. Besides, biochar has also been used to modify the acid soil as an alternative approach to liming. Biederman and Harpole [14] acclaimed that biochars with high pH can improve soil nutrient availability and reduce soil acidity. The increase in pH indicates the ability of soil to adsorb cations [15].

Hence, biochar can retain more nutrients in the soil for efficient plant uptake. However, there is a dearth of information on the use of biochar with a large surface area and high negative charges to minimize the NH_3 loss from urea in acid soils. Our hypothesis is this process would fundamentally enable long-term chelation of the positively charged NH_4^+ by biochar. This is possible because functional groups such as carboxyls and phenols in humic substances such as humic acids, fulvic acids, and humin in the biochar are known to be negatively charged in alkaline conditions to chelate and retain N in the form of NH_4^+. This is so because the functional groups have a high affinity for NH_4^+. Retention of N in the form of exchangeable NH_4^+ will retard rapid volatilization of N in the form of NH_3 and NH_4^+ will be retained in soil for crop uptake. N will then be released gradually from the urea due to it being temporarily fixed in the form of exchangeable NH_4^+, which enables synchronization of N supply with crop requirement. Hence, N supply from urea will become readily available for efficient plant use. The great surface area of these substances is an added advantage. Hence, this study was carried out to determine the effect of urea fertilizer amended with rice straw biochar application in improving soil N availability and nutrient uptake of cultivated rice plants in tropical acid soil.

2. Materials and Methods

2.1. Soil Sampling and Characterization

The soil used in this study was sampled from a depth of 0–30 cm on an uncultivated land in Agro Techno Park of Universiti Malaysia Kelantan Jeli Campus, Malaysia (5.6955 latitude and 101.8389 longitudes), which had not been cultivated since 2007. The soils were collected randomly at the sampling area of 60 m × 60 m. The collected soil samples were air-dried, crushed, and sieved to pass through a 2 mm sieve for initial soil characterization. Soil pH was measured in a ratio of 1:2.5 (soil:water) by using a digital pH meter [16]. Soil organic matter, ash content, and soil organic carbon (TOC) were determined by using the loss-on ignition method [17]. The total N was determined by using the Kjeldahl method [18].

Double acid method described by Mehlich [19] was used to extract soil available P and exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), after which the cations were determined by using an Atomic Absorption Spectrophotometer (AAS) (Analyst 800, Perkin Elmer, Norwalk, CT, USA) while soil available P was determined by using molybdenum blue method [20]. The developed blue color was analyzed by a UV-VIS Spectrophotometer (Thermo Scientific Genesys 20, Waltham, MA, USA) at 882 nm wavelengths. Soil CEC was determined by the ammonium acetate leaching method [21]. The exchangeable acidity and exchangeable Al^{3+} were determined by the acid–base titration method described by Rowell [22]. The method described by Keeney and Nelson [23] was used to extract exchangeable $NH_4{}^+$ and available $NO_3{}^-$, after which the ions were determined via steam distillation [17].

The selected physicochemical properties of the soil used in this study were shown in Table 1. The texture of the soil was sandy clay loam with a pH of 5.5. Generally, the soil is acidic due to the high concentrations of Al^{3+} (1.14 $cmol_c$ kg^{-1}) and Fe^{2+} (0.091 $cmol_c$ kg^{-1}). The soil P availability (0.385 mg kg^{-1}) is low due to its immobilization as oxides of Al^{3+} and Fe^{2+}. Due to the acidity of the soil, the content of N (0.07%), $NH_4{}^+$ (89 mg kg^{-1}), and $NO_3{}^-$ (30 mg kg^{-1}) in the soil was found to be low because it slows down the mineralization process. Exchangeable K^+, Ca^{2+}, Mg^{2+}, and Na^+ were low in the soil as well.

Table 1. Selected soil chemical properties.

Property	Value Obtained
pH (H_2O using soil:water ratio of 1:2.5)	5.5
EC (dS m^{-1})	0.022
Soil organic matter (%)	6.24
Carbon (%)	3.62
Ash content (%)	6.4
Cation Exchange Capacity (CEC) ($cmol_c$ kg^{-1})	5.4
$NH_4{}^+$ (mg kg^{-1})	89
$NO_3{}^-$ (mg kg^{-1})	30
N (%)	0.07
P (mg kg^{-1})	0.385
K^+ ($cmol_c$ kg^{-1})	0.084
Ca^{2+} ($cmol_c$ kg^{-1})	0.10
Mg^{2+} ($cmol_c$ kg^{-1})	0.082
Na^+ ($cmol_c$ kg^{-1})	0.024
Fe^{2+} ($cmol_c$ kg^{-1})	0.091
Exchangeable acidity ($cmol_c$ kg^{-1})	0.7
Al^{3+} ($cmol_c$ kg^{-1})	1.14

2.2. Characterization of Rice Straw

Rice straw collected from Kemubu granary area, Kota Bharu, was analyzed for pH [16] and total N [18]. Single dry ashing method [17] was used to extract nutrients from rice straw for analysis of Ca, Mg, Na, P, and K. The content of Ca, Mg, Na, and K were determined by using an AAS (Analyst 800, Perkin Elmer, Norwalk, CT, USA). Meanwhile, total P content was determined by using molybdenum blue method after which the blue color developed was analyzed by using a UV-VIS Spectrophotometer (Thermo Scientific Genesys 20, Waltham, MA, USA) [20]. The CEC was determined by using the aforementioned methods in the soil characterization section.

2.3. Rice Straw Biochar Production and Activation

Two cylindrical kilns, 200 L with removable chimney caps and air-tight 110 L drum were constructed for biochar production. Rice straw was bulked inside the 110 L and closed before placed in the middle of the 200 L drum, where the fire was kindled starting from the bottom of the drum. The residence time was 4 h with temperature ranging from 300–400 °C and left for cooling for 2 h. Later, the pile of biochar sample was spread out for cooling. After that, activation was carried out by soaking biochar in a 5% chicken slurry solution, known as chicken litter waste, for 7 days. Then biochar was dried and stored in a big container for further use. The activation of biochar with chicken slurry was essential to increase the pore size further, alter the surface area, and increases the nutrient content [24,25]. The analysis conducted for biochar characterization is similar to those of the aforementioned characterizations of soil and rice straw. Additionally, microanalysis through scanning electron microscopy attached with energy dispersive X-ray spectroscopy analysis (SEM-EDX JEOL JSM-6400) was carried out to analyze the surface morphology of rice straw biochar.

The rice straw biochar has a larger surface area and porosity (Figure 1). The rice straw biochar also more alkaline properties (pH > 9), and it has a significantly higher CEC value than rice straw which suggests that the capacity to hold nutrients is high. Rice straw biochar also had shown a relatively high concentration of total N, total P, and total cations with less concentration of K and Mg than rice straw (Table 2). The total Na in the rice straw biochar was significantly higher than rice straw. Besides, there is no significant difference between rice straw and rice straw biochar NH^{4+} and NO_3^- content.

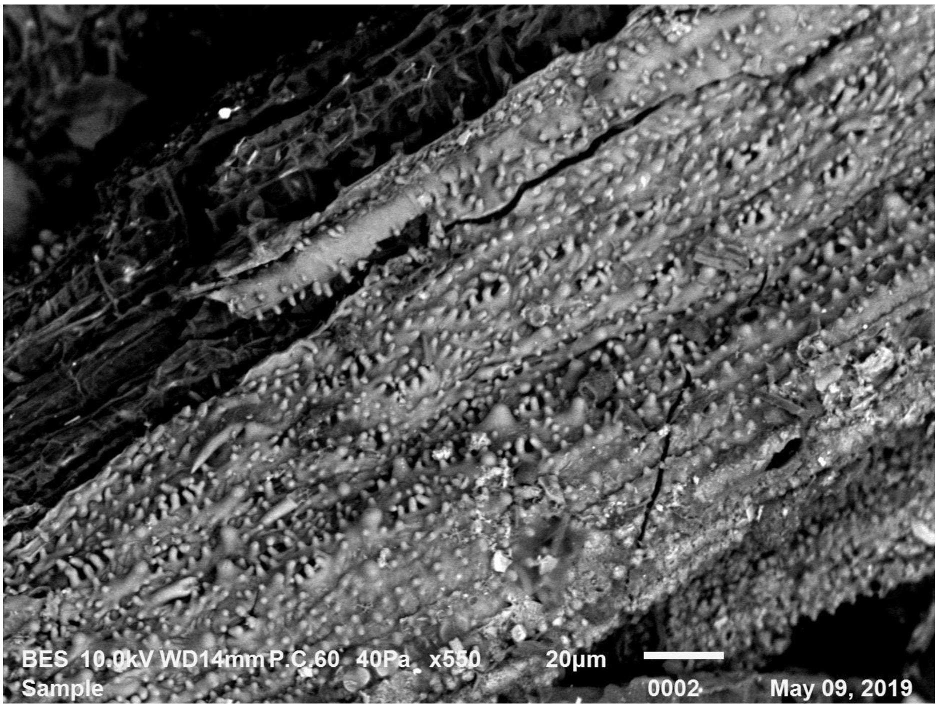

Figure 1. Activated rice straw biochar physiological morphology at ×550 under SEM.

Table 2. Selected physico-chemical properties of rice straw and rice straw biochar.

Property	Rice Straw	Rice Straw Biochar
pH (water)	7.0 ± 0.07 [a]	9.2 ± 0.12 [b]
Cation exchange capacity (CEC) ($cmol_c$ kg^{-1})	38.0 ± 2.39 [a]	75.6 ± 0.16 [b]
Nitrogen (%)	0.38 ± 0.01 [a]	0.45 ± 0.02 [b]
NH_4^+ (mg kg^{-1})	187.11 ± 0.05 [a]	179.05 ± 0.12 [a]
NO_3^- (mg kg^{-1})	38.0 ± 0.03 [a]	36.0 ± 0.02 [a]
P (mg kg^{-1})	10.7 ± 0.12 [a]	14.3 ± 0.17 [b]
Ca^{2+} (mg kg^{-1})	3205 ± 0.14 [a]	3599 ± 0.9 [b]
Mg^{2+} (mg kg^{-1})	1288 ± 0.06 [b]	809 ± 0.01 [a]
K^+ (mg kg^{-1})	25,450 ± 0.03 [a]	12,030 ± 0.04 [b]
Na^+ (mg kg^{-1})	52.1 ± 0.001 [a]	246.3 ± 0.002 [b]

Means within row with different letter(s) indicate significant difference between treatments by Independent T-test at $p \leq 0.05$.

2.4. Ammonia Volatilization Laboratory Incubation Study

The NH_3 loss volatilization study was conducted by using a close-dynamic airflow system [26–28]. The system includes a 250 mL conical flask exchange chamber containing soil mixture and a trap 250 mL conical flask chamber containing 75 mL of boric acid, which were stoppered and fit with inlet/outlet pipes. The inlet of the chamber containing the water was connected with an aquarium air pump, and the outlet was connected with pipe tubing to the trap containing boric acid solution. Air was passed through the chambers at a rate of 2.75 L^{-1} min^{-1} $chamber^{-1}$. This setup was done to create soil aeration and trap NH_3 loss via the volatilization process.

Soil and different rates of rice straw biochar (5, 10, 15, and 20 t ha^{-1}) were mixed well before it was deposited into a 250 mL conical flask. Next, water was added into the conical flask to create waterlogged condition, whereby water was added to surpass the soil's 100% field capacity so as to create a waterlogged condition. The water level was marked in the conical flask and maintained 3 cm above the soil throughout the incubation study period. After that, urea was added. The produced rice straw biochar were compared with a commercial biochar potting media (CB1: mixture of 50% soil and 50% commercial biochar potting media, and CB2: 100% commercial biochar potting media) on the efficiency in reducing NH_3 loss. The boric acid solution was replaced every 24 h and back-titrated with 0.01 M HCl to estimate the NH_3 loss from the applied urea. The measurement was continued until the NH_3 decreased to 1% of the added N to the system [29]. After the NH_3 volatilization was evaluated, the soil samples were used for pH, exchangeable NH_4^+, and available NO_3^- determinations. Treatments were arranged in a completely randomized design (CRD) with three replications, and the treatments evaluated were listed in Table 3.

Table 3. Treatments evaluated in ammonia volatilization study.

Treatment	Description
S	100 g soil only (Negative control)
U	100 g soil + 175 kg urea ha^{-1} (0.7 g per pot) (Positive control)
B1	100 g soil + 175 kg urea ha^{-1} (0.7 g per pot) + 5 t rice straw biochar ha^{-1} (2.8 g per pot)
B2	100 g soil + 175 kg urea ha^{-1} (0.7 g per pot) + 10 t rice straw biochar ha^{-1} (5.5 g per pot)
B3	100 g soil + 175 kg urea ha^{-1} (0.7 g per pot) + 15 t rice straw biochar ha^{-1} (8.3 g per pot)
B4	100 g soil + 175 kg urea ha^{-1} (0.7 g per pot) + 20 t rice straw biochar ha^{-1} (11.1 g per pot)
CB1	50 g soil + 50 g commercial biochar potting media 175 kg urea ha^{-1} (0.7 g per pot)
CB2	100 g of commercial biochar potting media + 175 kg urea ha^{-1} (0.7 g per pot)

Notes: S (soil), U (urea), B (rice straw biochar), and CB (commercial biochar).

2.5. Pot Experiment

After completing the laboratory NH_3 volatilization study, a pot experiment was conducted in a netted house located at the Universiti Malaysia Kelantan Jeli Campus, Malaysia. Only five treatments were selected and carried forward to the pot experiment from the NH_3 volatilization study. Treatments with 15 t ha^{-1} and 20 t ha^{-1} rice straw biochar were excluded. Application of 15 t ha^{-1} and 20 t ha^{-1} did not minimize NH_3 loss significantly compared to 5 t ha^{-1} and 10 t ha^{-1} rice straw biochar. Hence, low rates of rice straw biochar application (5 t ha^{-1} and 10 t ha^{-1}) were chosen since it is more economical. Treatments with soil only, soil + urea, 50%, and 100% commercial potting media was carried forward to pot experiment to serve as a comparison to rice straw biochar effectiveness in minimizing NH_3 loss, nutrient retention in soil, and improving plant nutrient uptake.

Rice plant MR297 cultivar was used as a test crop in the pot experiment, and the seedlings were planted in pots (23 cm height, 23 cm wide, and 23 cm diameter) which were filled with 5 kg of 5 mm sieved soil. Before planting, MR297 rice seeds were germinated in a plastic tray filled with germination medium and transferred on the 7th day into the pot.

The biochar rates of 5 t ha^{-1} and 10 t ha^{-1} were mixed thoroughly with the soil 24 h before transplantation of 7th day rice seedlings into the pot. Three rice seedlings were planted in each pot, equivalent to three seedlings per hill [30]. The water level in each pot was maintained at 3 cm from the soil surface. After seven days of transplantation, N, P, and K fertilizer in the form of urea (46% N), Christmas Island Rock Phosphate (CIRP) (32% P_2O_5), and Muriate of Potash (MOP) (60% K_2O) was applied at the rate of 175 kg ha^{-1}, 97.8 kg ha^{-1}, and 130 kg ha^{-1}, respectively. These rates were scaled down based on the recommendation of Muda Agricultural Development Authority, Malaysia [31], with some modifications where urea was increased to 175 kg ha^{-1} for 5 kg soil per pot. The fertilizers were applied in three equal split at 7, 30, and 55 days after transplantation (DAT) by surface application. The lists of treatments evaluated in the pot experiment are listed in Table 4.

Table 4. Treatments evaluated in pot study.

Treatment	Description
S	5 kg soil (Negative control)
U	5 kg soil + 175 kg urea ha^{-1} (3.96 kg per pot), 97.8 kg CIRP ha^{-1} (2.21 kg per pot), and 130 kg MOP ha^{-1} (2.94 kg per pot) (Positive control)
B1	5 kg soil + 175 kg urea ha^{-1} (3.96 kg per pot), 97.8 kg CIRP ha^{-1} (2.21 kg per pot), and 130 kg MOP ha^{-1} (2.94 kg per pot) + 5 t rice straw biochar ha^{-1} (0.11 kg per pot)
B2	5 kg soil + 175 kg urea ha^{-1} (3.96 kg per pot), 97.8 kg CIRP ha^{-1} (2.21 kg per pot), and 130 kg MOP ha^{-1} (2.94 kg per pot) + 10 t rice straw biochar ha^{-1} (0.23 kg per pot)
CB1	2.5 kg soil + 2.5 kg commercial biochar potting media + 175 kg urea ha^{-1} (3.96 kg per pot), 97.8 kg CIRP ha^{-1} (2.21 kg per pot), and 130 kg MOP ha^{-1} (2.94 kg per pot) (50% soil + 50% commercial biochar potting media)
CB2	5 kg commercial biochar potting media+ 175 kg urea ha^{-1} (3.96 kg per pot), 97.8 kg CIRP ha^{-1} (2.21 kg per pot), and 130 kg MOP ha^{-1} (2.94 kg per pot) (100% commercial biochar potting media)

Notes: S (soil), U (urea), B (rice straw biochar), CB (commercial biochar), Christmas Island Rock Phosphate (CIRP) and Muriate of Potash (MOP).

The pot experiment was carried out in a completely randomized design with three replications in a net house. Plants were checked regularly and monitored up to the heading stage (70 days). The plants were harvested at 70 DAT. This is because the amount of soil used in the pot was not sufficient to support rice plants up to the flowering and ripening stage; thus it is not economically practical to estimate the yield of rice based on the pot experiments. This was in agreement with Palanivell et al. [32].

At the heading stage (70 DAT), the plant height was measured by using a measuring tape. Plant greenness was measured by using SPAD Meter 502-nm. The number of tillers and the number of panicles were counted and recorded. The aboveground parts of the plants were harvested and dried in an oven at 60 °C until a constant weight was attained [33]. The oven-dried plant samples were then grounded by using a grinding machine, after which they were analyzed for total N, P, and K. Total N was determined by using the Kjeldahl method. Meanwhile, a single dry ashing method was used to extract the total P and K in the plant tissues. The filtrates were analyzed by using AAS to determine the total K and P was determined by using the molybdenum blue colorimetric method. The concentrations of N, P, and K in the leaf were multiplied by the dry weight of leaves to obtain the amount of N, P, and K uptake by the rice plants. Rice plant nutrient use efficiency was calculated using the method of Dobermann [34].

$$\text{Nutrient uptake (mg plant}^{-1}\text{)} = \text{Nutrient concentration (\%)} \times \text{plant dry weight (g)} \quad (1)$$

$$\text{Nutrient use efficiency } (\%) = \frac{A - B}{R} \times 100 \quad (2)$$

where, A = plant nutrient uptake from fertilized soil, B = plant nutrient uptake from unfertilized soil, and R = rate of fertilizer nutrients applied.

The soil samples from pots were collected immediately upon plant harvesting. The soil was air-dried, crushed, and sieved to pass through a 2 mm sieve. Afterwards, the soil samples were analyzed for pH, EC, total N, available P, total organic matter, total C, exchangeable acidity and Al, exchangeable cations (K, Ca, Mg, Zn, and Fe) by using the aforementioned procedures in section (Soil sampling and characterization).

2.6. Statistical Analysis

Statistical analysis for all the data was performed by using SPSS software version 24.0 (SPSS Inc., Chicago, IL, USA). An unpaired t-test was conducted to compare the significant difference among rice straw and rice straw biochar. The effect of different rates of rice straw biochar addition was subjected to one-way analysis of variance (ANOVA). Significant differences among treatments were separated by Tukey's test and considered significant at $p \leq 0.05$.

3. Results and Discussion

3.1. Effect of Rice Straw Biochar on Ammonia Volatilization in Laboratory Incubation Study

The addition of rice straw biochar had effectively minimized NH_3 volatilization from the added urea fertilizer. There was no activity of NH_3 volatilization for S (soil only). The volatilization started on day 2 for U (soil + urea) (Figure 2A). Treatments with commercial biochar potting media CB1 and CB2 had recorded NH_3 volatilization on day 3. Among the treatments with rice straw biochar, NH_3 loss in B1, B3, and B4 started on day 4; meanwhile B2 started on day 5 (Figure 2A). Rice straw biochar effectively delayed and slowed down the NH_3 loss by about 4–5 days consecutively before it reaches the peak of volatilization. The peak of volatilization under treatments amended with rice straw biochar is after 10 days onwards and showed a slow declination afterwards. Omar et al. [35] had stated that added organic amendments delayed the NH_3 loss by 3–6 days during incubation study, and it reaches the peak of volatilization slowly. The rice straw biochar minimizes NH_3 loss by increasing the formation of inorganic NH_4^+. The delayed process of NH_3 loss upon addition of rice straw biochar showed that there is ample time for conversion to inorganic NH_4^+ ions in soil for efficient utilization by plants. This will reduce the excessive addition of urea fertilizer which tends to volatilize easily. Overall, all the rice straw biochar added treatments showed a positive effect in reducing NH_3 loss compared to U, CB1, and CB2.

Application of rice straw biochar as additives to soil (B1, B2, B3, and B4) had significantly minimized NH_3 loss compared to urea without additives (U) and commercial biochar potting media (CB1 and CB2) (Figure 2B). Averaged across rice straw biochar application rate, B1 (5 t ha^{-1}) and B2 (10 t ha^{-1}) have shown significant effect in minimizing NH_3 loss over U. Biochar application at the rate of 5–10 t ha^{-1} is highly recommended to avoid plant phytotoxicity, to retain nutrients, and water retention in soil [36,37]. The addition of rice straw biochar successfully minimized NH_3 loss irrespective of the application rate. This finding was in agreement with Xu et al. [38]. Besides, Chen et al. [39] stated that porous biochar structure and large surface area reduces the NH_3 volatilization by increasing the formation and adsorption of NH_4^+ and NO_3^-.

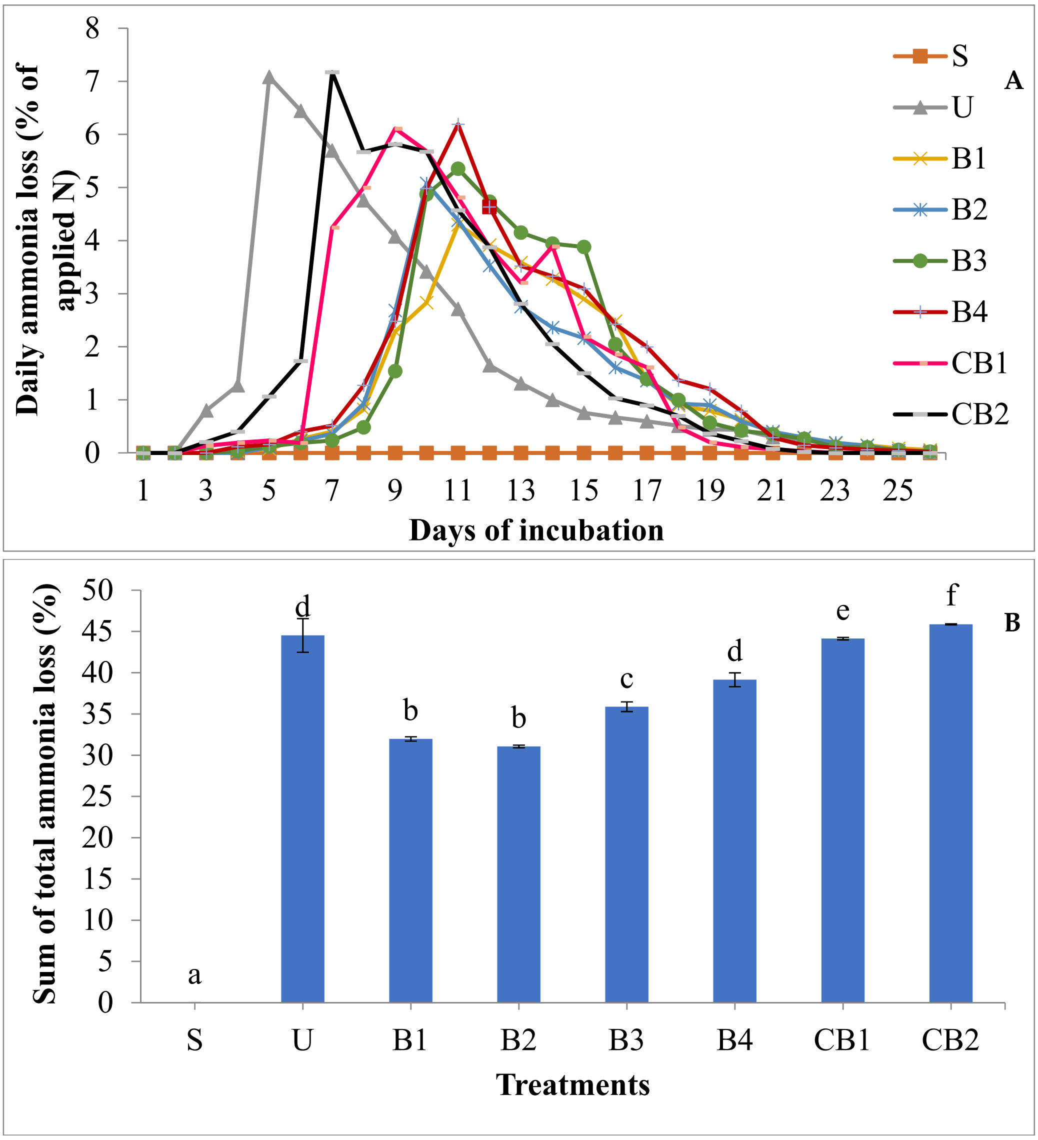

Figure 2. (**A**) Daily ammonia loss during 26 days of incubation study, and (**B**) sum of total ammonia loss in incubation study under waterlogged conditions. Mean values with different letter(s) indicate significant difference between treatments by Tukey's test at $p \leq 0.05$. Bars represent the mean values ± SE. The treatments evaluated were: S: Soil only, U: Soil + 175 kg ha^{-1} urea, B1: Soil + 175 kg ha^{-1} urea + 5 t ha^{-1} rice straw biochar, B2: Soil + 175 kg ha^{-1} urea + 10 t ha^{-1} rice straw biochar, B3: Soil + 175 kg ha^{-1} urea + 15 t ha^{-1} rice straw biochar, B4: Soil + 175 kg ha^{-1} urea + 20 t ha^{-1} rice straw biochar, CB1: Soil + 50% commercial biochar, and CB2: 100% commercial biochar.

3.2. Effect of Rice Straw Biochar on Selected Soil Chemical Properties in Pot Study

The addition of rice straw biochar had significantly improved soil nutrients by minimizing NH_3 volatilization. At 70 DAT, the soil NH_4^+ and NO_3^- were significantly higher in treatments amended with rice straw biochar (B1 and B2) in comparison to soil (S), soil + urea (U), and commercial biochar potting media (CB1 and CB2) (Table 5). B2 had significantly retained more NH_4^+ and NO_3^- compared to the rest of the treatments. Rice straw biochar has a higher affinity to bind and retain more NH_4^+ and NO_3^- in soil. This is due to the nature of rice straw biochar which is highly porous and has a large surface area [40]. Large surface area is an essential property for rice straw biochar to be a sorbent material. The result in Figure 2A further signifies that the addition of rice straw biochar had minimized NH_3 loss. The rice straw biochar had successfully adsorbed the NH_3 from being lost to the environment. The adsorbed NH_3 onto the surface of rice straw biochar will undergo a series of protonation reactions. This implies that the protonation of NH_3 will give rise to the formation of NH_4^+. Besides, the inherent NH_4^+ and NO_3^- in the rice straw biochar might increase the presence of the ions in the soil. This observation is also consistent with the study of Sun et al. [41], who concluded that treatments with organic amendments had a stronger affinity for NH_4^+ and NO_3^-. Additionally, the higher CEC of rice straw biochar (75.6 $cmol_c\ kg^{-1}$) contributes to the adhering capacity of the ions (Table 3). Gai et al. [11] stated that CEC is a dominating factor influencing the adsorption ability of biochars. Besides, biochar has dual adsorption capacity properties, where ions adhere to negative and positive charged sites on its surface [42]. It has been said that biochar has a significant role in enhancing the adsorption capacity of ions while minimizing NH_3 volatilization [41]. The high adsorption capacity of biochar resulted in additional NH_4^+ and NO_3^- found in soil, where it is crucial for rice plants uptake [43].

Table 5. Effects of rice straw biochar on soil N, NH_4^+, and NO_3^- of pot experiment.

Treatments	N (%)	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})
S	0.07 ± 0.02 ^{a}	23.35 ± 2.34 ^{a}	25.69 ± 6.18 ^{a}
U	0.15 ± 0.01 ^{b}	31.35 ± 5.24 ^{a}	38.52 ± 2.02 ^{ab}
B1	0.20± 0.01 ^{c}	73.53 ± 2.01 ^{b}	66.55 ± 2.02 ^{c}
B2	0.22 ± 0.02 ^{c}	94.57 ± 2.02 ^{c}	89.06 ± 2.01 ^{d}
CB1	0.07 ± 0.01 ^{a}	35.03 ± 4.04 ^{a}	46.70 ± 2.34 ^{b}
CB2	0.05 ± 0.02 ^{a}	31.52 ± 2.02 ^{a}	42.03 ± 4.04 ^{ab}

Mean values within column with different letter(s) indicate significant difference between treatments by Tukey's test at $p \leq 0.05$. Columns represent the mean values ± SE. The treatments evaluated were: S: Soil only, U: Soil + 175 kg ha^{-1} urea, B1: Soil + 175 kg ha^{-1} urea + 5 t ha^{-1} rice straw biochar, B2: Soil + 175 kg ha^{-1} urea + 10 t ha^{-1} rice straw biochar, CB1: Soil + 50% commercial biochar, and CB2: 100% commercial biochar.

The total N in the soil was significantly increased with treatments amended with rice straw biochar (Table 5). Total N content in B1 and B2 is significantly higher than U by 33.3% and 46.7%, respectively. The improvement in soil total N retention might be contributed by the presence of organic matter (20.5%) in the rice straw biochar. Due to the presence of organic matter, organic N might have mineralized slowly to release NH_4^+ and NO_3^- [44]. Therefore, the increase in soil total N following biochar is also related to the soil's buildup of organic matter over time. Ros et al. [45] also stated that the increase in soil total N is due to the increased organic matter in soil over time. Besides, total N was higher due to the mineralization of biochar [46], and it was capable of retaining more NH_4^+ and NO_3^- from being volatilized or leached. However, commercial biochar potting media treatments (CB1 and CB2) and soil only (S) have the least total N in the soil.

Rice straw biochar amended treatments (B1 and B2) had significantly increased soil available P compared to S, U, CB1, and CB2 (Table 6). Treatment with the highest rate of rice straw biochar 10 t ha^{-1} (B2) showed the highest available P in the soil. Biochar is alkaline in nature and can alter the soil environment to avoid P fixation by Al^{3+} and Fe^{2+} [47]. P fixation is a major limiting factor for the unavailability of P in the soil for plant uptake. Biochar which is alkaline, can be used as a liming agent. Since biochar is alkaline, it increased the soil pH level. A study conducted by Ch'ng et al. [48] reported that the biochar application increases the soil pH due to the proton exchange in between biochar and soil. The soil pH of U is alkaline (6.17) without the addition of biochar might be due to the inherent Ca^{2+} and Mg^{2+} contents of the soil, which might be released during the period of pot study. Besides, the addition of CIRP might increase the pH of the soil in U because of the Ca^{2+} dissolution from the applied fertilizer. The soil pH of the treatments applied with rice straw biochar (B1 and B2) was significantly higher compared to the treatments without rice straw biochar (S and U) (Table 7). This is due to the initial higher pH of rice straw biochar (Table 3). In addition, biochar also contains basic cations contents (K^+, Ca^{2+}, Mg^{2+}, and Na^+). The release of these cations from rice straw biochar contributed to the increased soil pH because there is an exchange of protons between rice straw biochar and soil. Similarly, commercial biochar potting media (CB1 and CB2) did not show any significant difference in soil pH compared to B1 and B2.

Table 6. Effects of rice straw biochar on selected soil chemical properties of pot experiment.

Treatments	CEC ($cmol_c$ kg^{-1})	Exchangeable Acidity ($cmol_c$ kg^{-1})	Exchangeable Al^{3+} ($cmol_c$ kg^{-1})	P (mg kg^{-1})
S	2.95 ± 0.26 ^{a}	0.33 ± 0.04 ^{b}	0.26 ± 0.02 ^{a}	2.57 ± 0.68 ^{a}
U	4.17 ± 0.27 ^{b}	0.32 ± 0.03 ^{b}	0.18± 0.03 ^{a}	29.38 ± 3.99 ^{b}
B1	5.83 ± 0.18 ^{c}	0.26 ± 0.03 ^{b}	0.17 ± 0.02 ^{a}	93.60 ± 2.54 ^{d}
B2	7.60 ± 0.17 ^{d}	0.16 ± 0.01 ^{a}	0.16 ± 0.01 ^{a}	122.00 ± 4.59 ^{e}
CB1	4.47 ± 0.26 ^{b}	0.32 ± 0.01 ^{b}	0.35± 0.02 ^{a}	51.37 ± 0.97 ^{c}
CB2	3.80 ± 0.21 ^{ab}	0.52 ± 0.04 ^{c}	0.58± 0.09 ^{b}	37.50 ± 3.18 ^{bc}

Mean values within column with different letter(s) indicate significant difference between treatments by Tukey's test at $p \leq 0.05$. Columns represent the mean values ± SE. The treatments evaluated were: S: Soil only, U: Soil + 175 kg ha^{-1} urea, B1: Soil + 175 kg ha^{-1} urea + 5 t ha^{-1} rice straw biochar, B2: Soil + 175 kg ha^{-1} urea + 10 t ha^{-1} rice straw biochar, CB1: Soil + 50% commercial biochar, and CB2: 100% commercial biochar.

Table 7. Effects of rice straw biochar on selected soil chemical properties of pot experiment.

Treatments	pH (Water)	EC (ds m^{-1})	Total Organic Matter (%)	Total C (%)
S	5.81 ± 0.13 ^{a}	0.006 ± 0.01 ^{a}	0.70 ± 0.06 ^{a}	0.41 ± 0.03 ^{a}
U	6.17 ± 0.03 ^{a}	0.007 ± 0.01 ^{a}	1.02 ± 0.19 ^{a}	0.59 ± 0.11 ^{a}
B1	6.96 ± 0.09 ^{b}	0.02 ± 0.01 ^{b}	3.63 ± 0.21 ^{b}	2.10 ± 0.12 ^{b}
B2	6.88 ± 0.14 ^{b}	0.02 ± 0.02 ^{b}	5.80 ± 0.32 ^{c}	3.36 ± 0.19 ^{c}
CB1	6.83 ± 0.06 ^{b}	0.02 ± 0.01 ^{b}	2.91 ± 0.59 ^{b}	1.69 ± 0.34 ^{b}
CB2	6.67 ± 0.07 ^{b}	0.01 ± 0.01 ^{bc}	3.35 ± 0.27 ^{b}	1.94 ± 0.16 ^{b}

Mean values within column with different letter(s) indicate significant difference between treatments by Tukey's test at $p \leq 0.05$. Columns represent the mean values ± SE. The treatments evaluated were: S: Soil only, U: Soil + 175 kg ha^{-1} urea, B1: Soil + 175 kg ha^{-1} urea + 5 t ha^{-1} rice straw biochar, B2: Soil + 175 kg ha^{-1} urea + 10 t ha^{-1} rice straw biochar, CB1: Soil + 50% commercial biochar, and CB2: 100% commercial biochar.

The addition of rice straw biochar at 10 t ha^{-1} (B2) showed a significant reduction of exchangeable acidity compared to S, U, B1, CB1, and CB2 (Table 6). Van Zwieten et al. [49] also stated that the addition of biochar reduces the exchangeable acidity of acidic soil. However, there was no significant difference in the reduction of exchangeable soil Al^{3+} and Fe^{2+} among S, U, B1, and B2 (Table 7). It has been said that incorporation of biochar releases their base cations into acidic soil, which can participate in exchange reactions and replace the exchangeable Al^{3+} and H^{+} on the soil surface and decreases the soil exchangeable acidity [50,51]. However, the findings in this study contrast with the previous authors' findings. Rice straw biochar does not significantly reduce the Al^{3+} and Fe^{2+} in soil but reduces soil exchangeable acidity significantly. The reason is that different charring methods, feedstock material, and temperature of biochar production offer the different capabilities of biochar in terms of soil amendments, nutrient retention, and fixation. This was in agreement with Lehmann and Joseph [40].

The total organic matter is significantly higher in B2 compared to other treatments (Table 7). The highest rate of rice straw biochar (10 t ha^{-1}) resulted in an increment of soil organic matter. The least amount of soil organic matter was found in S, followed by U because there were no additions of any organic materials into the soil. Increases in soil organic matter influenced the total C to be increased simultaneously (Table 7). It is proven that organic amendments such as compost or biochar will eventually increase the soil organic matter and soil organic C of the soil [52]. The soil EC value did not significantly increase between rice straw biochar and commercial biochar treatments. However, biochar added treatments showed significantly higher soil EC content than S and U. The increase in soil EC with biochar addition could be due to the presence of salts in the biochar [53].

Further, Spokas et al. [54] and Brewer et al. [55] stated that the salt content of biochars differs according to the type of feedstock used to be charred.

The highest rate of biochar at 10 t ha^{-1} (B2) had significantly increased Ca^{2+} and Zn^{2+} levels in soil and did not show any significant increase in Mg^{2+} (Table 8). The B2 also showed a significant positive increase in K^{+} in soil over S, U, CB1, and CB2. This is due to the high affinity of biochar for cations. Biochar, as excellent sorbent materials [56], bind the cations to its surface, and this explains the reason for higher exchangeable concentrations of cations in the soil. The CEC of rice straw biochar is another factor that leads to higher exchangeable cations in soil. Besides, the treatments amended with rice straw biochar had positively increased the soil CEC (Table 6). This could be due to the inherent characteristics of biochar that have a higher surface area and porous nature. Glaser et al. [57,58] also stated that the increase soil CEC might be due to the slow oxidation of biochar material which slowly boosts the development of organo-mineral complexes.

Table 8. Effects of rice straw biochar on selected soil cations of pot experiment.

Treatments	K^{+} (cmol kg^{-1})	Ca^{2+} (cmol kg^{-1})	Mg^{2+} (cmol kg^{-1})	Zn^{2+} (cmol kg^{-1})	Fe^{2+} (cmol kg^{-1})
S	0.0009 ± 0.0001 a	0.0022 ± 0.0001 a	0.0007 ± 0.00002 a	$6(10^{-6}) \pm 0.000006$ a	0.0004 ± 0.0002 ab
U	0.0016 ± 0.0004 a	0.0038 ± 0.0011 a	0.0006 ± 0.00001 a	$7(10^{-6}) \pm 0.00003$ ab	0.0003 ± 0.0001 a
B1	0.0023 ± 0.0001 ab	0.0092 ± 0.0003 b	0.0004 ± 0.00003 a	$2(10^{-5}) \pm 0.00007$ c	0.0002 ± 0.0001 a
B2	0.0023 ± 0.0001 b	0.0166 ± 0.0003 c	0.0005 ± 0.00002 a	$4(10^{-5}) \pm 0.000009$ d	0.0001 ± 0.0001 a
CB1	0.0006 ± 0.00002 a	0.0005 ± 0.0001 a	0.0003 ± 0.00001 a	$2(10^{-5}) \pm 0.000001$ c	0.0007 ± 0.0003 b
CB2	0.0007 ± 0.00001 a	0.0031 ± 0.0006 a	0.0004 ± 0.00001 a	$2(10^{-6}) \pm 0.00003$ bc	0.0013 ± 0.0013 c

Mean values within column with different letter(s) indicate significant difference between treatments by Tukey's test at $p \leq 0.05$. Columns represent the mean values ± SE. The treatments evaluated were: S: Soil only, U: Soil + 175 kg ha^{-1} urea, B1: Soil + 175 kg ha^{-1} urea + 5 t ha^{-1} rice straw biochar, B2: Soil + 175 kg ha^{-1} urea + 10 t ha^{-1} rice straw biochar, CB1: Soil + 50% commercial biochar, and CB2: 100% commercial biochar.

3.3. Effect of Rice Straw Biochar on Rice Plant Dry Matter Production and Nutrient Uptake

The increment in soil available inorganic NH_4^{+} directly increases rice plant growth and nutrient uptake, strengthening the study's objectives. The effect of rice straw biochar treatment on the growth performance of rice plants is shown in Table 9. The plant height, panicle number, and plant greenness were significantly increased upon application of rice straw biochar rate 10 t ha^{-1} (B2) compared to other treatments. Plant greenness increment with the addition of rice straw biochar suggests that the plant's ability to photo synthesize efficiently, thus contributing to the increased plant height. Treatments B1 and B2 showed a significantly higher tiller number percentage compared to other treatments. Increased tiller number directly increases panicle number, but only rice straw biochar rate 10 t ha^{-1} (B2) had significantly increased productive panicle number. This gives a clear idea that the increased application rate of biochar aids in more significant growth of rice plants. Uzoma et al. [59] reported that the addition of biochar increases the growth performance of plants because biochar able to release slowly the inherent nutrient that readily available in and the one adsorbed from the external source. The slow-release is advantageous and consistent with the growth of rice plants where the nutrient can be utilized effectively by the rice plants. Besides, the rice straw biochar used in this study was activated with chicken slurry. It might contribute to the plant growth since chicken slurry acts as organic fertilizer in the agricultural field.

Table 9. Effects of rice straw biochar on plant growth performance of rice plant MR297 cultivar.

Treatments	Dry Weight (g)	Height (cm)	Tiller Number	Panicle Number	Greenness (%)
S	7.64 ± 0.84 [a]	41.94 ± 0.19 [a]	2.00 ± 0.33 [a]	1.00 ± 0.02 [a]	100.00 ± 0.97 [a]
U	22.97 ± 2.99 [cd]	76.18 ± 2.92 [bc]	3.00 ± 0.34 [a]	2.00 ± 0.33 [a]	106.31 ± 3.47 [a]
B1	28.30 ± 1.99 [d]	81.47 ± 0.72 [c]	7.00 ± 0.35 [b]	5.00 ± 0.57 [b]	113.06 ± 2.63 [ab]
B2	37.43 ± 0.87 [e]	97.13 ± 1.16 [d]	7.00 ± 0.58 [b]	9.00 ± 0.58 [c]	146.28 ± 2.56 [c]
CB1	17.54 ± 1.14 [bc]	73.20 ± 3.07 [bc]	3.00 ± 0.37 [a]	3.00 ± 0.33 [a]	125.23 ± 2.84 [b]
CB2	14.62 ± 1.37 [ab]	67.67 ± 0.98 [b]	2.00 ± 0.37 [a]	1.00 ± 0.34 [a]	123.31 ± 3.58 [b]

Mean values within column with different letter(s) indicate significant difference between treatments by Tukey's test at $p \leq 0.05$. Columns represent the mean values ± SE. The treatments evaluated were: S: Soil only, U: Soil + 175 kg ha^{-1} urea, B1: Soil + 175 kg ha^{-1} urea + 5 t ha^{-1} rice straw biochar, B2: Soil + 175 kg ha^{-1} urea + 10 t ha^{-1} rice straw biochar, CB1: Soil + 50% commercial biochar, and CB2: 100% commercial biochar.

Moreover, biochar application at the rate of 10 t ha^{-1} (B2) had increased the dry weight of rice plants significantly over other treatments. The dry weight of the rice plant affected by the application of rice straw biochar was presented in Table 9. According to the observation in the pot study, the increase in dry matter production of rice plants was due to an increase in the number of tillers and number of leaves. Besides, the concentrations of primary nutrients (N and P) had been increased significantly in rice plants amended with rice straw biochar at 10 t ha^{-1} plants (Table 10). There is no significant increase of K in treatments B1 and B2 over U, but showed significantly higher K over S, CB1, and CB2. Increased primary nutrient concentrations contribute directly to the increase of plant nutrient uptake and plant nutrient use efficiency (Table 10). The N uptake and N use efficiency of the rice plant increased significantly in treatments applied with 10 t ha^{-1} rice straw biochar (Figure 3A and Table 11). This is because the adsorption rate of rice straw biochar is increased along with the application amount. The increased rice straw biochar application rate directly increases the volume of biochar present in the soil which aids in more nutrient retention and adsorption. Hence, a higher rate of biochar application directly increases the availability of NH_4^+ and NO_3^- in the soil for rice plant uptake. Besides, the rice straw biochar significantly reduces NH_3 loss and retains more N in the NH_3 volatilization study. Similarly, this might have increased the N uptake in the rice plants in the pot study. This was in agreement with a study by Palanivell et al. [32]. It also has been stated that increased N uptake by the plant directly increases the rice's overall growth performance [60,61]. The total P and total K uptake by the rice plants had given a significantly positive increment in B1 and B2 compared to other treatments (Figure 3B,C). There is no significant difference between B1 and B2, but plants in B2 treatment had shown most significant P and K uptake. Similarly, the P and K use efficiency was the highest in B1 and B2 (Table 11). The plant N, P, and K uptake and use efficiency of the rice plants are contributed by the concentration of primary nutrients. The availability of these nutrients is due to the efficient mineralization process triggered by the rice straw biochar, where it acts as a slow-release agent. It captures nutrient from being lost to the environment and release it slowly for plant uptake. Hence, rice straw biochar has tremendous potential to increase soil nutrient concentration and plant nutrient uptake.

Table 10. Effects of rice straw biochar on plant nutrients concentrations of rice plant MR297 cultivar.

Treatments	N (%)	P (mg kg^{-1})	K (mg kg^{-1})
S	0.31 ± 0.02 [a]	3.87 ± 0.35 [a]	0.35 ± 6.47 [a]
U	0.89 ± 0.07 [b]	6.77 ± 0.49 [bc]	2.30 ± 1.26 [cd]
B1	1.09 ± 0.04 [a]	33.33 ± 2.70 [d]	2.84 ± 5.75 [d]
B2	1.48 ± 0.01 [c]	33.6 ± 2.86 [d]	2.49 ± 1.49 [d]
CB1	0.90 ± 0.03 [b]	18.43 ± 0.55 [c]	1.90 ± 1.26 [bc]
CB2	0.80 ± 0.15 [b]	12.53 ± 0.72 [bc]	1.63 ± 1.38 [b]

Mean values within column with different letter(s) indicate significant difference between treatments by Tukey's test at $p \leq 0.05$. Columns represent the mean values ± SE. The treatments evaluated were: S: Soil only, U: Soil + 175 kg ha^{-1} urea, B1: Soil + 175 kg ha^{-1} urea + 5 t ha^{-1} rice straw biochar, B2: Soil + 175 kg ha^{-1} urea + 10 t ha^{-1} rice straw biochar, CB1: Soil + 50% commercial biochar, and CB2: 100% commercial biochar.

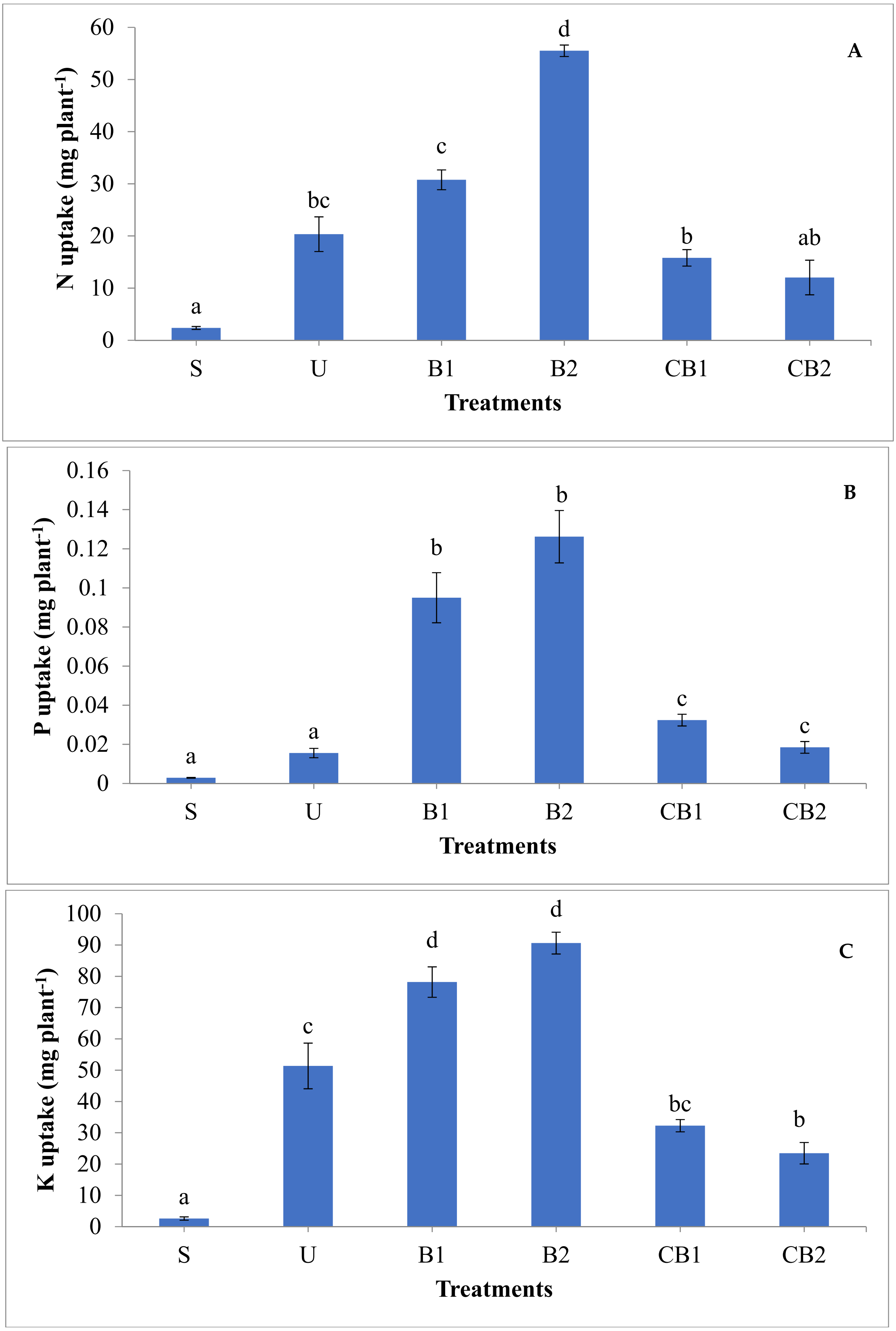

Figure 3. Effect of amending rice straw biochar on (**A**) N, (**B**) P, and (**C**) K uptake of rice plants. Mean values with different letter(s) indicate significant difference between treatments by Tukey's test at $p \leq 0.05$. Bars represent the mean values ± SE. The treatments evaluated were: S: Soil only, U: Soil + 175 kg ha^{-1} urea, B1: Soil + 175 kg ha^{-1} urea + 5 t ha^{-1} rice straw biochar, B2: Soil + 175 kg ha^{-1} urea + 10 t ha^{-1} rice straw biochar, CB1: Soil + 50% commercial biochar, and CB2: 100% commercial biochar.

Table 11. Effects of rice straw biochar on N, P, and K use efficiency of rice plant MR297 cultivar.

Treatments	N Use Efficiency (%)	P Use Efficiency (%)	K Use Efficiency (%)
U	18.99 ± 3.40 [ab]	0.013 ± 0.002 [a]	49.36 ± 6.89 [b]
B1	29.42 ± 1.80 [b]	0.09 ± 0.013 [b]	76.15 ± 4.43 [c]
B2	54.16 ± 1.25 [c]	0.12 ± 0.014 [b]	88.62 ± 3.53 [c]
CB1	14.45 ± 1.65 [a]	0.03 ± 0.003 [a]	30.27 ± 1.61 [ab]
CB2	10.68 ± 3.18 [a]	0.02 ± 0.004 [a]	21.48 ± 3.59 [a]

Mean values within column with different letter(s) indicate significant difference between treatments by Tukey's test at $p \leq 0.05$. Columns represent the mean values ± SE. The treatments evaluated were: U: Soil + 175 kg ha^{-1} urea, B1: Soil + 175 kg ha^{-1} urea + 5 t ha^{-1} rice straw biochar, B2: Soil + 175 kg ha^{-1} urea + 10 t ha^{-1} rice straw biochar, CB1: Soil + 50% commercial biochar, and CB2: 100% commercial biochar.

4. Conclusions

The addition of rice straw biochar effectively minimized NH_3 loss from being volatilized to the environment. It increased NH_4^+ and NO_3^- ions in the soil for efficient rice plant uptake. It also improved the soil available P and exchangeable K. Rice straw biochar also enhanced nutrient uptake, nutrient use efficiency, and dry matter production of rice plants. Hence, rice straw biochar at the rate of 5–10 t ha^{-1} (B1 and B2) can be used to minimize N loss and retain more ions for efficient plant uptake and nutrient use efficiency. The rice straw biochar benefits the environment and agriculture in multiples ways. It is a valuable end product that leads to sustainable rice straw waste management, paves a way to reduce excessive urea fertilizer consumption in the agricultural field, increases soil nutrient especially N, and improves rice plant growth.

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