https://doi.org/10.1590/1678-4499.20230104

Enriched rice straw biochar improves soil nitrogen availability and rice plant growth under waterlogged environment

Gunavathy Selvarajh[1,2], Huck Ywih Ch'ng[2,*], Norhafizah Binti Md Zain[1], Osumanu Haruna Ahmed[3], Mohamadu Boyie Jalloh[4], Issariyaporn Damrongrak[5], Jeng Young Liew[1], Siti Nuurul Huda Mohammad Azmin[1], Laila Naher[1]

1. University Malaysia Kelantan – Faculty of Agro Based Industry –Jeli, Kelantan, Malaysia.
2. Lincoln University College – Department of Agriculture – Petaling Jaya, Selangor, Malaysia.
3. Sultan Sharif Ali Islamic University – Faculty of Agriculture – Tutong, Brunei Darussalam.
4. University Malaysia Sabah – Faculty of Sustainable Agriculture – Sandakan, Sabah, Malaysia.
5. Yala Rajabhat University – Faculty of Science Technology and Agriculture – Yala Province, Thailand.

Received: May 3, 2023 | **Accepted:** Aug. 7, 2023

Section Editor: Aline Renée Coscione

***Corresponding author:** huckywih@umk.edu.my

How to cite: Selvarajh, G., Chng, H. Y., Zain, N. B. M., Ahmed, O. H., Jalloh, M. B., Damrongrak, I., Liew, J. Y., Azmin, S. N. H. M. and Naher L. 2023. Enriched rice straw biochar improves soil nitrogen availability and rice plant growth under waterlogged environment, Bragantia, 82, e20230104. https://doi.org/10.1590/1678-4499.20230104

ABSTRACT: Ammonia volatilisation causes major nitrogen losses from the soil and applied urea which results in low urea-N usage efficiency. Incubation experiment and pot experiment were conducted to assess the effect of enriched rice straw biochar on ammonia volatilisation, soil pH, exchangeable ammonium, available nitrate, and rice plant growth in comparison to the urea without additives under waterlogged conditions. During the incubation study, urea was amended with different rates of enriched rice straw biochar (5, 10, 15, and 20 t·ha^{-1}). Urea amended with biochar at 5 to 10 t·ha^{-1} had successfully minimized ammonia loss compared to urea without biochar. Besides, application rate of 5 to 10 t·ha^{-1} of biochar also preserved more ammonium ions (65.37% and 66.54%, respectively), while at the same time, the retention of nitrate ions was 50.9% and 45.3% over urea without biochar. Similarly, 5 to 10 t·ha^{-1} of enriched rice straw biochar increased soil N level and improved rice plant growth significantly in pot experiment. Precisely, incorporation of enriched rice straw biochar at rate of 5 and 10 t·ha^{-1} offers wide variety benefits to soil amendments and rice plant nutrient uptake. Hence, the findings suggest that urea amended with enriched rice straw biochar altered the nutrients level in soil by improving rice plant growth.

Key words: agricultural wastes, ammonia loss, nitrogen, enriched rice straw biochar, urea.

INTRODUCTION

Ammonia (NH_3) volatilisation is one the major processes that leads to poor urea-N use efficiency by crops. The applied urea is easily hydrolysed and volatilised to the environment. A serious volatilisation occurs if the urea is applied on top of the soil instead of soil incorporation or deep placement. Mariano et al. (2019) and Jadon et al. (2018) stated that N loss from urea in the form of NH_3 is higher due to the adoption of surface application method which speeds up volatilisation process. Rapid volatilisation occurs due to the nature of urea which hydrolyses easily upon contact with water where it causes higher formation of NH_3. The NH_3 gas dissipates easily through volatilisation process because it is lighter and does not settle in low-lying areas. It also agreed that a main pathway of applied-N loss in cropping systems is through NH_3 volatilisation (Zheng et al. 2018). A study by Xu et al. (2019) also revealed that the volatilisation rate is higher due to the urea application. Hence, an organic amendment is vital to herald the NH3 volatilisation from applied urea fertilizer.

Organic amendments by using agricultural residues would benefits both the environment and agricultural sector. Currently, one of the global challenges faced is the sustainable management of the rice wastes after grain harvesting. The annual production of wastes is always increasing and never ceases globally. Similarly, in Malaysia, the production of paddy residue is higher, more than 7.5 million tonnes of rice straw are being produced annually (Mansor et al. 2018). Excess rice straw was being accumulated and allowed to dry which eventually burnt by the farmers before commencement of the next cycle of rice planting (Rosmiza et al. 2014; Singh and Patel, 2022). Burning of wastes directly increases the pollution rate and creates hazardous environment for both atmosphere and living things. Rather than wasting the unused plant residues, it can be utilized to valuable end-product since it is cost effective, renewable, and abundant (Sarkar et al. 2012).

Recently, there is much renewed interest in the use of organic amendments such as biochar as an alternative source to retain nutrients in soil and contributes to soil fertility. Biochar can be produced from abundant and unutilized agricultural wastes such as rice straw. Charring of rice straw to create biochar appears to be promising approach to address concerns regarding improvements of soil fertility, increase carbon storage and reduce nitrogen losses. Biochar is a carbon-rich product obtained when biomass such as wood, manure, leaves, red oak, paper, grass, wheat straw and sewage sludge burned or heated in a closed container or no available air (Basso et al. 2013; Lehmann et al. 2009; Lehmann and Joseph 2015;). A study by Yeboah et al. (2009) and Kapoor et al. (2022) stated that biochar enhances soil nutrient retention which in overall reduces the total fertilizer requirements in agricultural soil. The retention of charged ions such as ammonium (NH_4^+) and nitrate (NO_3^-) in soil is also aided by the cation exchange capacity (CEC). Biochar has higher CEC and it is able to retain more nutrients in the soil due to its huge adsorption capacity. The large surface area of biochar aided its potent to be adsorptive agent. However, the surface area, CEC, pore volume, and adsorption capacity of biochar vary depending on the biomass and the pyrolysis conditions (Narzari et al. 2015). It has been stated that rice residues biochar with large surface area can be used to recycle nutrients, sequester C, and improve soil fertility (Gamage et al. 2021; Haefele et al. 2011). Sun et al. (2018) observed that canola straw biochar application reduces NH_3 volatilisation successfully and retain more nutrients in soil for plant uptake. Biochar is crucially necessary for soil nutrients ameliorant to retain more N in soil.

The volatilisation of N applied in rice fields need to be addressed because the losses of N are due to the poor soil nutrient holding capacity. Biochar can be used to retain, for instance (NH_4^+) from the urea fertilizer because of their high affinity for these ions. Application of biochar was found to enhance the NH_4^+ adsorption due to its high negative charges, larger surface area, and porosity (Lehmann and Joseph 2015). The biochar functional group had its dominancy in adsorbing NH_3 released to its oxygen group bonding of hydroxyl and carboxyl. Thus, the adsorption of N in the form of NH_4^+ has a huge potent to retard the rapid volatilisation of NH_3, where NH_4^+ retained in the soil will be beneficial for plant uptake. The production of agricultural wastes from the farms can be used by the farmers to produce a sufficient amount of biochar by using simple biochar kilns. The unit of biochar kiln is least expensive and feasible to farmers to pay (approximately US$ 30-50), mobile and it is easy for the small farmers to move the biochar kiln to desired place (Venkatesh et al. 2015). It can help the small farmers to save time in carrying a larger amount of feedstock available periodically for combustion purposes. The general concept of pyrolysis technology is similar and applies in the design of biochar kiln. The optimum size of the biochar kiln is designed which can produce sufficient amount of biochar for small farmers. Normally, after the crops have been harvested, most of the waste is thrown away without consideration for other uses. The waste can be processed into biochar through pyrolysis for soil enrichment by using biochar kiln (Kew and Kong 2020). Farmers could also use the biochar in combination with urea to replenish N deficiencies and ensure proper supply of N for plant uptake. Hence, the implications of the co-application of enriched rice straw biochar and urea-N fertilizer could be an attempt to delay urea hydrolysis, minimize formation of NH3 and enhance adsorption of NH_4^+ for proper rice plant growth. Therefore, this study was carried out to determine the effect of mixing urea with enriched rice straw biochar on NH_3 volatilisation, soil exchangeable NH_4^+, available nitrate (NO_3^-) and rice plant growth compared with applied urea without additives under waterlogged condition.

METHODS

Soil sampling, preparation, and characterization

The soil used in this study was sampled at 0-30 cm in an undisturbed area of University Malaysia Kelantan Jeli Campus, Malaysia. The soil type (Rengam series, *Typic Paleudult*) was selected because it is commonly cultivated with crops in Malaysia.

The collected soil was air-dried, crushed and sieved to pass through 2-mm sieve for initial characterization. The soil texture was determined by using hydrometer method (Bouyoucos 1962). Soil pH was measured in ratio (1:10 soil:water) using a digital pH meter (Peech 1965); organic matter content (OM), ash content and total carbon by using Loss-on ignition method (Tan 2005); total N using Kjeldahl method (Bremner 1965). Double acid method described by Mehlich (1953) was used to extract soil available P and exchangeable cations (Ca, Mg, K, Na), where later the cations were determined by using Atomic Absorption Spectrophotometer (AAS) and soil available P was determined by using molybdenum blue method (Murphy and Riley 1962). Soil Cation Exchange Capacity (CEC) was determined by using ammonium acetate leaching method (Cottenie 1980). The exchangeable acidity and exchangeable Al^{3+} were determined by using acid-base titration method described by Rowell (1994). The method described by Keeney and Nelson (1982) was used to extract the exchangeable NH_4^+ and available NO_3^- after which the ions were determined using steam distillation (Tan 2005).

Biochar production and enrichment

Rice straws were collected from Pasir Puteh, Kelantan granary area. The rice straw was charred in cylindrical kilns for 4 hours in temperature ranging from 300 - 400 0C to produce rice straw biochar. After cooling, the biochar was soaked with 5% chicken slurry for 7 days to further enhance the biochar nutrients, which later were dried and stored in a big container for further use. It has been stated that enrichment of biochar by using chicken slurry will further enhance the biochar surface area, porosity, and nutrient content (Selvarajh et al. 2020a, 2021).

Characterization of enriched and non-enriched rice straw biochar

Enriched and non-enriched rice straw biochar was subjected for analysis of pH (Peech 1965) and Total N (Bremner 1965). Single dry ashing method (Tan 2005) used to extract nutrients from enriched rice straw biochar for analysis of Ca, Mg, Na, P and K. The content of Ca, Mg, Na and K were determined using Atomic Absorption Spectrophotometer (AAS) (Analyst 800, Perkin Elmer, Norwalk, USA), meanwhile total P content was determined by using UV-VIS Spectrophotometer (Thermo Scientific Genesys 20, USA) (Murphy and Riley 1962). Organic matter and ash content was determined by using the loss on ignition method (Tan 2005). Exchangeable NH_4^+ and available NO_3^- were extracted by using the method described by Keeney and Nelson (1982), after which the ions were determined using steam distillation (Tan 2005). The CEC was determined by using ammonium acetate method (Tan 2005). Additionally, microanalysis through Scanning Electron Microscopy-attached with Energy Dispersive X-ray Spectroscopy analysis (SEM-EDX JEOL JSM- 6400) was carried out to analyses surface morphology of enriched rice straw biochar.

Ammonia volatilisation incubation study

For laboratory scale NH_3 volatilisation incubation study, the treatments evaluated were listed in Table 1 based on 175 $kg \cdot ha^{-1}$ urea and enriched rice straw biochar rate of 5 $t \cdot ha^{-1}$, 10 $t \cdot ha^{-1}$, 15 $t \cdot ha^{-1}$ and 20 $t \cdot ha^{-1}$. Soil, urea, and biochar were mixed well before it was deposited into 250 mL conical flask after which water was added to create a waterlogged condition. The water level was maintained 3 cm above the soil throughout the study. The system was set to be closed dynamic air flow system and the NH_3 loss from urea was measured daily (Ahmed et al. 2006a, 2006b; Siva et al. 1999). 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 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 $L^{-1} \cdot min^{-1} \cdot chamber^{-1}$. This setup was done to create soil aeration and trap NH_3 loss via volatilization process. The released NH_3 was captured in the trapping solution containing 75 mL of boric acid with colour indicator. The incubation chambers Boric acid-indicator traps were replaced every 24 h and back titrated with 0.01 M HCl, to estimate the NH_3 released. Measurement was continued until the loss declined to 1% of the N added with urea (Selvarajh et al. 2022). After the NH_3 volatilisation was evaluated, the soil samples were used for pH, exchangeable NH_4^+ and available NO_3^- determinations.

Table 1. Treatments evaluated for ammonia volatilisation incubation study.

Treatments	Descriptions
T0	100 g soil only
T1	100 g soil + 0.7 g urea
T2	100 g soil + 0.7 g urea + 2.8 g enriched rice straw biochar
T3	100 g soil + 0.7 urea + 5.5 g enriched rice straw biochar
T4	100 g soil + 0.7 g urea + 8.3 g enriched rice straw biochar
T5	100 g soil + 0.7 g urea + 11.1 g enriched rice straw biochar

Source: Elaborated by the authors.

Pot experiment

After the completion of laboratory NH_3 volatilisation study, a pot experiment was conducted in a netted house located at the Universiti Malaysia Kelantan Jeli Campus, Malaysia. Only 4 treatments were selected and carried forward to the pot experiment from the NH_3 volatilisation study. Treatments with 15 t·ha^{-1} and 20 t·ha^{-1} enriched 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} enriched rice straw biochars. Hence, low rates of enriched rice straw biochar application (5 t·ha^{-1}1 and 10 t·ha^{-1}) were chosen since it is more economical. Treatments with soil only and soil + urea, was carried forward to pot experiment to serve as a comparison to enriched rice straw biochar effectiveness in minimizing NH_3 loss, nutrient retention in soil and improving plant nutrient uptake.

Rice plant cultivar MR297 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 plastic tray filled with germination medium and transferred on 7th days into the pot. The biochar rates of 5 t·ha^{-1} and 10 t·ha^{-1} were mixed thoroughly with the soil 24 hours before transplantation of 7th day rice seedlings into the pot. Three rice seedlings were planted in each pot, equivalent to three seedlings per hill(Selvarajh et al. 2022). 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 (32% P_2O_5), and Muriate of Potash (60% K_2O) was applied at 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 (Rosmiza et al. 2014) 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 splits 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 2.

Table 2. Treatments evaluated in pot study.

Treatments	Descriptions
T0	5 kg soil (Negative control)
T1	5 kg soil + 3.96 kg urea + 2.21 kg·ha^{-1} CIRP + 2.94 kg·ha^{-1} MOP (Positive control)
T2	5 kg soil + 3.96 kg urea + 2.21 kg·ha^{-1} CIRP + 2.94 kg·ha^{-1} MOP + 0.11 kg enriched rice straw biochar
T3	5 kg soil + 3.96 kg urea + 2.21 kg·ha^{-1} CIRP + 2.94 kg·ha^{-1} MOP + 0.23 kg enriched rice straw biochar

Source: Elaborated by the authors.

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 heading stage (70 days). The plants were harvested at 70 DAT. This is because the amount of soil used in pot was not sufficient to support rice plants up to flowering and ripening stage, thus it is not economically practical to estimate the yield of rice based on pot experiments. This was in agreement with Palanivell et al. (2016).

At heading stage (70 DAT), the plant height was measured by using a measuring tape. Number of tillers and number of panicles were counted and recorded. The aboveground parts of the plants were harvested and dried in oven at 60 °C until constant weight was attained (Lija et al. 2014). The oven-dried plant samples were then grounded by using a grinding machine after which they were analysed for total N by using Kjeldahl method. The concentrations of N in leaf were multiplied by the dry weight of leaves to obtain the amount of N uptake by the rice plants (eq. 1).

$$Nutrient\ uptake = Nutrient\ concentration\ (\%)\ \ x\ plant\ dry\ weight\ (g) \quad (1)$$

Statistical analysis

The experiments were arranged in completely randomized design with three replicates. An independent t-test was conducted by using SPSS software version 24.0 (SPSS Inc, US) to compare the significant difference between rice straw biochar and enriched rice straw biochar. The effect of different rates of enriched rice straw biochar addition on all the treatments was subjected to one-way analysis of variance (ANOVA). Statistical analysis for all the data was performed using SPSS software version 24.0 (SPSS Inc, US). Significant differences among treatments were separated by Tukey's HSD test and considered significant at $p \leq 0.05$.

RESULTS AND DISCUSSION

Selected characteristics of soil and enriched rice straw biochar

The selected soil physico-chemical properties are summarized in Table 3. The soil used in this study was acidic (pH 5.5) and characterized as sandy clay loam. Acidic soil slows down the process of mineralization and this is the causal factor for low content of N (0.07 %), NH_4^+ (89 ppm) and NO_3^- (30 ppm) in the soil. Due to the high exchangeable Al (1.14 $cmol_c \cdot kg^{-1}$), exchangeable Fe (0.091 $cmol_c \cdot kg^{-1}$) and acidity (0.7 $cmol_c \cdot kg^{-1}$) in the soil, the P content was low (0.385 ppm). Generally, the P content is low in soil due to the fixation by Al and Fe. This form of P is not free moving ions and not available for uptake. Besides, exchangeable K, Ca, Mg and Na were also low in the soil (Table 3). This might be due to the low CEC of the soil (5.4 $cmol_c \cdot kg^{-1}$), where it unable to retain and hold nutrients effectively. The incapability to hold nutrients also directly related to the soil texture which was sandy clay loam. The soil with low nutrients status needs amendments to improve the quality of the soil by retaining more nutrients.

Table 3. Selected soil chemical properties

Property	Value obtained
Texture	Sandy clam loam
pH	5.5
EC ($dS \cdot m^{-1}$)	0.022
Soil organic matter (%)	6.24
Total Carbon (%)	3.62
Ash content (%)	6.4
Cation Exchange Capacity (CEC) ($cmol_c \cdot kg^{-1}$)	5.4
Ammonium(ppm)	89
Nitrate (ppm)	30
Total N (%)	0.07
Available P (ppm)	0.385
Exchangeable K ($cmol_c \cdot kg^{-1}$)	0.084
Exchangeable Ca ($cmol_c \cdot kg^{-1}$)	0.10
Exchangeable Mg ($cmol_c \cdot kg^{-1}$)	0.082
Exchangeable Na ($cmol_c \cdot kg^{-1}$)	0.024
Exchangeable Fe ($cmol_c \cdot kg^{-1}$)	0.091
Exchangeable acidity ($cmol_c \cdot kg^{-1}$)	0.7
Exchangeable Al ($cmol_c \cdot kg^{-1}$)	1.14

Source: Elaborated by the authors.

Additionally, rice straw biochar composes numerous pores and comes with large surface area (Fig. 1a). The porous structure of enriched rice straw biochar is highly favourable for capturing nutrients and releases it slowly. It is observable under Scanning Electron Microscopy image where the biochar is compacted with nutrients after activation (Fig. 1b). Yet, there are still free pores that can bind nutrients from the soil. Enriched rice straw biochar has higher CEC (75.6 $cmol_c \cdot kg^{-1}$). The content of P, K, Ca, and Na of enriched rice straw biochar had been increased significantly upon enrichment with chicken slurry. Besides, it has higher pH of 9.2, which is alkaline.

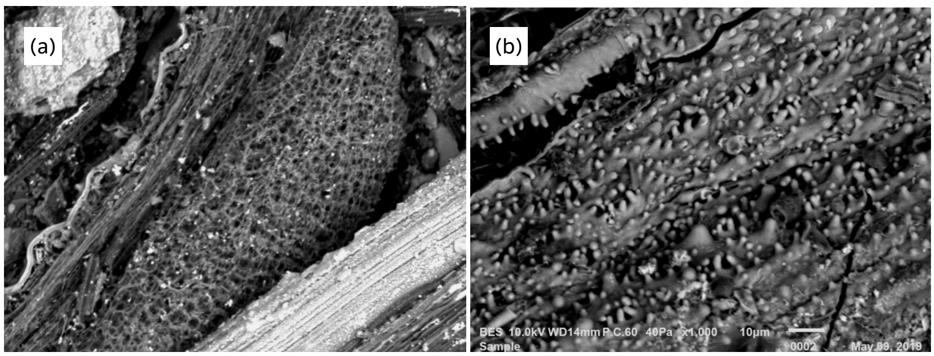

Figure 1. Surface area and porosity of (a) rice straw biochar and (b) enriched rice straw biochar, under Scanning Electron Microscope.

Source: Elaborated by the authors.

Effect of enriched rice straw biochar in minimizing NH_3 volatilisation

The daily NH_3 loss over a period of 26 days incubation is shown on Fig. 2. There was no activity of NH3 volatilisation for T0 (soil only), and the volatilisation started on 2nd day for T1 (soil + urea). The NH_3 loss starts on 4th day for T2, T4 and T5, meanwhile T3 started on 5th day. NH_3 loss in T1 increased sharply on 5th day and declines steeply from 6th day on daily basis up to 26 days. T2, T4 and T5 have shown maximum NH_3 loss on 11th day, meanwhile T3 loss peaks up on 10th day. To conclude, enriched rice straw biochar effectively delayed and slow down the NH_3 loss about 4 - 10 days consecutively over T1 before it reaches its peak of volatilisation. Overall, all the treatments showed a positive effect in reducing NH_3 loss compared to T1.

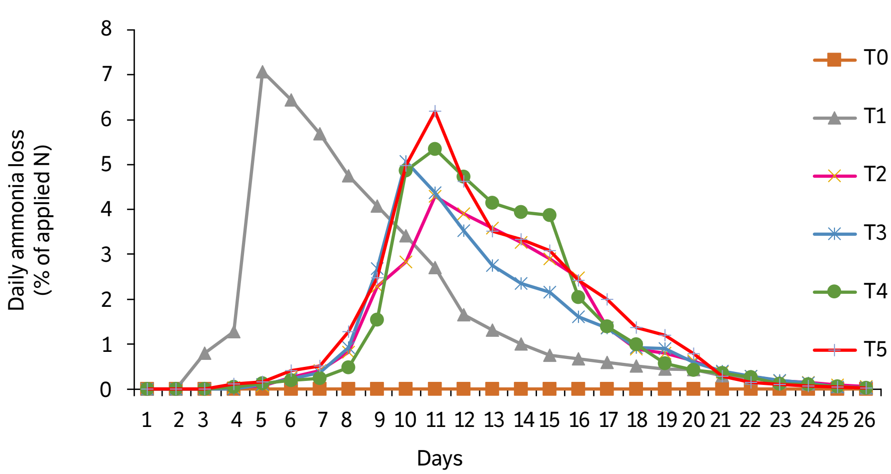

Figure 2. Daily ammonia loss for a period of 26 days of incubation study.

Source: Elaborated by the authors.

Besides, the total mean changes in soil pH during incubation study with the control and biochar incorporated treatments were shown in Table 4. All the treatments with enriched rice straw biochar increased the soil pH over T0 and T1.

Table 4. Effects of enriched rice straw biochar on soil N, NH_4^+ and NO_3^- in NH_3 volatilisation study.

Treatments	Total ammonia loss (%)	Soil pH	NH_4^+ (ppm)	NO_3^- (ppm)
T0	0.0 ± 0.00^a	0.06 ± 0.02^a	106.67 ± 12.01^a	39.67 ± 5.49^a
T1	44.52 ± 2.04^d	6.23 ± 0.01^b	256.67 ± 29.63^b	36.00 ± 4.62^a
T2	31.96 ± 0.26^b	7.62 ± 0.01^c	425.00 ± 16.07^d	38.00 ± 6.08^a
T3	31.06 ± 0.17^b	7.80 ± 0.02^c	428.00 ± 7.57^d	45.00 ± 6.08^b
T4	35.88 ± 0.59^c	7.94 ± 0.01^c	385.00 ± 8.08^{cd}	81.67 ± 4.67^b
T5	39.15 ± 0.84^d	7.98 ± 0.02^c	371.33 ± 22.81^c	72.33 ± 6.17^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. Source: Elaborated by the authors.

The capability of biochar to retain NH_4^+ and NO_3^- is presented in Table 4. All treatments with biochar (T2, T3, T4 and T5) have shown positive significant retention NH_4^+ over T0 and T1. The T2 and T3 significantly retained more NH_4^+ ions in soil by 65.37% and 66.54%, respectively in comparison to T1 (soil + urea). Treatments T4 and T5 had significantly retained more NO_3^- ions in the soil in comparison to T1.

Effect of enriched rice straw biochar in improving soil N, NH_4^+ and NO_3^- in pot experiment

At 70 DAT, the soil pH of the treatments applied with enriched rice straw biochar (T2 and T3) was significantly increased compared to treatments without enriched rice straw biochar (T0 and T1) (Table 5). The addition of enriched rice straw biochar had significantly improved soil organic and inorganic N. Treatments T2 and T3 had significantly increased N, NH_4^+ and NO_3^- compared to T0 and T1 (Table 5).

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

Treatments	Soil pH	Total N (%)	NH_4^+ (ppm)	NO_3^- (ppm)
T0	5.81 ± 0.13^a	0.07 ± 0.02^a	23.35 ± 2.34^a	25.69 ± 6.18^a
T1	6.17 ± 0.03^a	0.15 ± 0.01^b	31.35 ± 5.24^a	38.52 ± 2.02^b
T2	6.96 ± 0.09^b	0.20± 0.01^c	73.53 ± 2.01^b	66.55 ± 2.02^c
T3	6.88 ± 0.14^b	0.22 ± 0.02^c	94.57 ± 2.02^c	89.06 ± 2.01^d

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. Source: Elaborated by the authors.

Effect of enriched rice straw biochar in improving rice plant growth and N uptake in pot experiment

The rice plant growth upon addition of enriched biochar is presented in Table 6. The treatment with enriched rice straw biochar had significantly increase rice plant dry weight compared to control. The rice plant dry weight treatment T3 was found out to be the highest. Similarly, the tiller number, and panicle number was significantly higher in T2 and T3 compared to T0 and T1. The rice plant height in T3 is the highest among the treatments. Besides, the rice plant in treatment T3 absorbed the highest N compared to other treatments (Fig. 3a). The N uptake in treatments amended with enriched rice straw biochar at 5-10 $t{\cdot}h^{a-1}$ (T2 and T3) was the highest compared to T0 and T1 (Fig. 3b).

Table 6. Effects of enriched rice straw biochar on physical growth performance of rice plant.

Treatments	Dry weight (g)	Height (cm)	Tiller number	Panicle number
T0	7.64 ± 0.84^a	41.94 ± 0.19^a	2.00 ± 0.33^a	1.00 ± 0.02^a
T1	22.97 ± 2.99^b	76.18 ± 2.92^{bc}	3.00 ± 0.34^a	2.00 ± 0.33^a
T2	28.30 ± 1.99^c	81.47 ± 0.72^c	7.00 ± 0.35^b	5.00 ± 0.57^b
T3	37.43 ± 0.87^d	97.13 ± 1.16^d	7.00 ± 0.58^b	9.00 ± 0.58^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. Source: Elaborated by the authors.

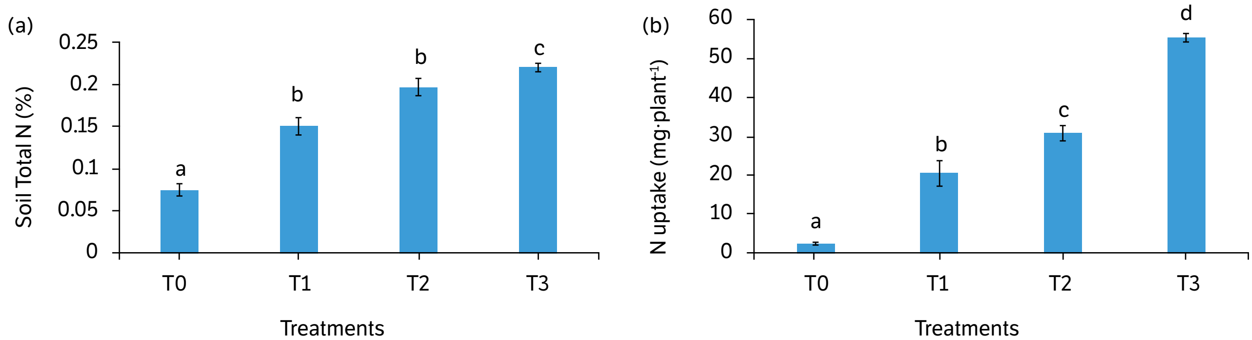

Figure 3. (a) Total N and (b) N uptake in rice plant. Mean values with different letter(s) indicate significant difference between treatments by Tukey's test at $p \leq 0.05$. Bars represent the mean values ± SE.

Source: Elaborated by the authors.

Surface morphology and selected chemical properties of enriched rice straw biochar

Enriched rice straw biochar offers a wide variety benefit for agricultural sector. Knowledge on its structure and properties is highly crucial for effective utilization in agricultural sector. Activation of biochar contributes to agronomical benefits. It has been documented that activation increases the surface area and porosity of biochar (Downie et al. 2009). Higher surface area of biochar benefits soil environment the most. Soil surface area is very important since it influences the fertility, microbial activity, and nutrient cycling. However, soil surface area depends on the structure and nature of the soil. Most of the soil has lower surface area due to acidity. Addition of organic matters has demonstrated to overcome this problem. Biochar as one of the organic amendments will similarly alters the physical nature of the soil to some extent since it has larger surface area (Chan et al. 2007). Further, Dai et al. (2020) and Sakhiya et al. (2021) stated that rice straw derived biochar has larger surface area and pore volume. Besides, enriched rice straw biochar has higher CEC (75.6 $cmol_c \cdot kg^{-1}$) where it possesses strong affinity in binding ions to its surface exchange sites (Table 7). Hence, biochars aids higher adsorption of nutrients from being volatilised or leached.

Table 7. Selected chemical properties of rice straw biochar and enriched rice straw biochar

Property	Rice straw biochar	Enriched rice straw biochar
pH (water)	8.1 ± 0.06^a	9.2 ± 0.05^b
CEC ($cmol \cdot kg^{-1}$)	65.3 ± 0.17^a	75.6 ± 0.19^b
Total Nitrogen (%)	0.42 ± 0.01^a	0.45 ± 0.03^a
Available P (%)	10.4 ± 0.12^a	14.3 ± 0.17^b
Exchangeable Ca ($cmol_c \cdot kg^{-1}$)	3329 ± 1.15^a	3599 ± 5.77^b
Exchangeable Mg ($cmol_c \cdot kg^{-1}$)	1744 ± 2.31^a	809 ± 0.33^b
Exchangeable K ($cmol_c \cdot kg^{-1}$)	4841 ± 0.50^a	12030 ± 0.01^b
Exchangeable Na ($cmol_c \cdot kg^{-1}$)	226.4 ± 0.01^a	246.3 ± 0.02^b

Note: Means between columns with different letters indicate significant difference between enriched and non-enriched rice straw biochar by independent t-test $p \leq 0.05$. Columns represent the mean values ± SE. Source: Elaborated by the authors.

In addition, activation of biochar showed positive effect in increasing the nutrient contents of the biochar. This gives a clear indication that biochar was able to adsorb the ions and compact the pores with nutrients. The enrichment turns the biochar to activated nutrient-packed biochar. Besides, it has higher pH (9.2), and it helps to reduce the soil acidity and directly contributes to lesser liming practices in agricultural field at a certain application rate.

Effect on NH_3 volatilisation upon enriched rice straw biochar application

Application of enriched rice straw biochar as additives to soil (T2, T3, T4, and T5) had significantly minimized NH_3 loss compared to urea without additives (T1) (Table 4). Evidently, T2 and T3 significantly minimized NH_3 loss over T1.

Averaged across enriched rice straw biochar application rate, T3 (10 t·ha^{-1}) has shown significant effect in minimizing NH_3 loss, however there was no significant difference in between T2 and T3. Hence, T2 (5 t·ha^{-1}) can be applied in agricultural field to overcome losses from urea. Lower application rate of biochar is cost effective and eases farmers to utilize it in agricultural field. Biochar application at rate of 5-10 t·ha^{-1} is highly recommended to avoid plant phytotoxicity, to retain nutrients and water retention in soil (Gale et al. 2016; Maraseni 2010). The effectiveness of enriched rice straw biochar in reducing NH_3 loss could be attributed to its larger surface area that facilitates nutrient capture and the ability to adsorb NH_3 onto its oxygen surface functional group. Besides, biochar in soil is very stable and resilient which only break down sparingly over the long term (Li and Tasnady 2008), so captured nutrients were being released slowly. The slow-release process delays the NH_3 volatilisation and is ready for plant uptakes. Enriched rice straw biochar acting as a slow-release fertilizer would minimize N loss and benefits the plant.

Additionally, enriched rice straw biochar can naturally lower the acidity of soil. One of the most prominent features of enriched rice straw biochar is its alkalizing effects in soil which affects directly the volatilisation of NH_3. Biochars are alkaline due to their ash content which release base cations; hence biochar addition neutralizes soil acidity and increases CEC (Obia et al. 2015). Biochars have abundant soluble and exchangeable base cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) which can be released into acid soil easily where it directly helps in improving soil fertility. Once the biochar is incorporated to the soil, the base cations exchanged with exchangeable Al^{3+} and H^+ on soil negative-charge sites, thus decreases the soil acidity (Yuan et al. 2011). It has been said that volatilisation of NH_3 is rapid on alkaline soil and this will be detrimental for crop. Schomberg et al. (2012) reported that soil added with biochar increased NH_3 volatilisation because high pH ammonification process accelerates volatilisation. Contrastingly, alkaline nature of biochar does not affect the NH_3 loss in this study. This might be due to the enriched rice straw biochar has high sorption capacity due to high surface area (Mandal et al. 2016). Kelly (2015) stated that pH increase with biochar is not high enough to enhance NH_3 volatilisation. Taghizadeh-Toosi et al. (2012) also found out that biochar application has successfully reduced NH_3 volatilisation. Since biochar enhances the soil pH value, so enriched rice straw biochar can be used as an alternative option to liming practices. Most tropical soil is acidic and it has limitation to crop growth because of Al toxicity which leads to less phosphate availability for plant uptake (Yuan and Xu 2011). Liming practice is costly and not easily accessible to all areas especially in developing countries. Attention has been given to alternatives such as biochar because it has significant carbonaceous components due to incomplete combustion of various organic components, hence biochar will remain in soil for long term and the effects offered by biochar is highly beneficial for soil and plant (Novak et al. 2009; Sohi et al. 2010).

Biochar application rate at 5-10 t·ha^{-1} shows the greatest effect in retaining more NH_4^+ and NO_3^- ions in the soil. This is possible due to the dual adsorption capacity of biochar. Biochar comes in zwitterion-like properties where it has both charges to adhere negative and positive charged ions on its surface (Ahmad et al. 2022). The enriched rice straw biochar high capacity to adsorb both charged ions has resulted in more NH_4^+ and NO_3^- ions in the soil. Chen et al. (2013) also reported that biochar application played vital role in enhancing the adsorption of NH_4^+ and NO_3^- ions by reducing NH_3 volatilisation. The higher retention of NH_4^+ and NO_3^- ions in soil could be associated to the higher CEC of enriched rice straw biochar (75.6 cmol·kg^{-1}) which adsorbs the ions and release it slowly. It is important to stress that the uptake rate of NH_4^+ and NO_3^- is higher among plants (Bolan and Kemp 2003), especially NH_4^+ ions is highly favourable for plant uptake due to the ease of assimilation. Hence, addition of enriched rice straw biochar acts as a soil ameliorant to retain more nutrients in soil.

Effect of soil improvements upon enriched rice straw biochar application

The soil pH in treatment T2 and T3 was near to neutral. This was due to the initial high pH of the enriched rice straw biochar. The increase in soil pH can also be partly relates to the exchange of proton in between soil and organic amendments used in this study. Besides, due to the weathering process, part of biochar subjected to oxidation and hydration, and transformed itself into material known as humic acid (Hiemstra et al. 2013). The increase in soil pH could be due to the formation of humic like materials during the initial decomposition of organic amendments leads to formation of organic anions, which consumes protons on the soil. The increase of soil pH in T1 might be due to the application of fertilizer (CIRP) which contributes Ca. It has been said that higher soil pH enhances the NH_3 loss. But in this study, it is contrast to the statement. Kelly (2015) stated that pH increased following the application of biochar is not high enough to enhance NH_3 volatilization. This statement is further proven by the finding of this research. The soil amended with enriched rice straw biochar minimized NH_3 volatilization and enhanced the retention of N, NH_4^+, and NO_3^- in both NH_3 volatilization study and pot study.

The treatment amended with enriched biochar also had shown significant increase in N, NH_4^+ and NO_3^- of the soil. The finding is consistent with the NH_3 volatilisation laboratory incubation study. The added urea-N successfully mineralized to the form of NH_4^+ and NO_3^- rather than NH_3. The enriched rice straw biochar adsorption capacity of both inorganic ions (NH_4^+ and NO_3^-) was due the higher CEC, larger surface area, and porosity of enriched rice straw biochar. This was in agreement with a study conducted by Fidel et al. (2018).

Effect on rice plant growth and N uptake in pot experiment upon enriched rice straw biochar application

The rice plant growth performance was improved significantly in treatments amended with enriched rice straw biochar. The increased of rice plant growth directly correlated to the increment of soil N. The rice plant in treatments with enriched rice straw biochar had significantly utilized the N and NH_4^+ for efficient growth. Due to efficient N absorption, the rice plant total N concentration in rice plant tissue increased. The rice plant in T3 had significantly absorbed the highest N content compared to other treatments (Fig. 3a). The increment of total N in rice plant tissue triggers successful N uptake. The finding was in agreement with Si et al. (2018) and Selvarajh et al. (2020b) who stated that addition of biochar increase overall rice plant growth and nutrient uptake. This shows that the addition of biochar with urea reduces NH_3 loss from being volatilised and the applied urea fertilizer was sufficient to meet the rice plant nutrient demand.

CONCLUSION

Application of enriched rice straw biochar into a tropical acid soil had significantly minimized NH_3 volatilisation, increase soil pH and retain more nutrients such as NH_4^+ and NO_3^- in soil. This suggest that co-application of enriched rice straw biochar prior to addition of urea highlights the role of biochar in improving inorganic N in the soil and rice plant growth. This is possible due to the efficacy of enriched rice straw biochar to integrate well in soil and adsorb nutrients efficiently. The rice straw converted to biochar are available abundantly and if the enriched rice straw biochar application practice was adopted, this will reduce the economic cost of applying large amount of urea fertilizer alone. Longer term studies is necessary and currently field experiment was being conducted to further ascertain the effects of enriched rice straw biochar on improving soil N and rice plant growth.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS' CONTRIBUTION

Conceptualization: Ch'ng H.Y., Zain N.B.M.; **Methodology:** Ahmed O.S., Jalloh M.B., Damrongrak I., Liew J.Y.; Selvarajh G.; **Investigation:** Ahmed O.S., Zain N.B.M., Jalloh M.B., Damrongrak I., Liew J.Y.; **Supervision:** Ch'ng H.Y.; **Writing – Original Draft:** Selvarajh G., Ch'ng H.Y.; **Writing – Review and Editing:** Nuurul S., Azmin H.M., Naher L.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

FUNDING

Malaysia Ministry of Higher Education, Fundamental Research Grant Scheme
Grant No.: FRGS/1/2018/WAB01/UMK/02/1

University Malaysia Kelantan, Community Impact Research Grant
Grant No.: R/COM/A0700/01459A/003/2021/00989

ACKNOWLEDGMENTS

The authors would like to thank Malaysia Ministry of Higher Education and Universiti Malaysia Kelantan for providing the financial support and research facilities.

REFERENCES

Ahmad, A., Chowdhary, P., Khan, N., Chaurasia, D., Varjani, S., Pandey, A. and Chaturvedi, P. (2022). Effect of sewage sludge biochar on the soil nutrient, microbial abundance, and plant biomass: A sustainable approach towards mitigation of solid waste. Chemosphere, 287, 132112. https://doi.org/10.1016/j.chemosphere.2021.132112

Ahmed, O. H., Aminuddin, H. and Husni, M.H.A. (2006a). Effects of Urea, Humic Acid and Phosphate Interactions. International Journal of Agricultural Research, 50, 25-31. https://doi.org/10.3923/ijar.2006.25.31

Ahmed, O.H., Aminuddin, H. and Husni, M.H.A. (2006b). Reducing ammonia loss from urea and improving soil-exchangeable ammonium retention through mixing triple superphosphate, humic acid and zeolite. Soil Use and Management, 22, 315-319. https://doi.org/10.1111/j.1475-2743.2006.00040.x

Basso, A.S., Miguez, F.E., Laird, D.A., Horton, R. and Westgate, M. (2013). Assessing potential of biochar for increasing water-holding capacity of sandy soils. Gcb Bioenergy, 5, 132-143. https://doi.org/10.1111/gcbb.12026

Bremner, J.M. (1965). Organic nitrogen in soils. Soil Nitrogen, 10, 93-149.

Bolan, N.S. and Kemp, P.D. (2003). A review of factors affecting and prevention of pasture-induced nitrate toxicity in grazing animals (Doctoral dissertation, New Zealand Grassland Association Incorporated).

Bouyoucos, G.J. (1962). Hydrometer method improved for making particle size analyses of soils 1. Agronomy Journal, 54, 464-465. https://doi.org/10.2134/agronj1962.00021962005400050028x

Chan, K.Y., Van, Zwieten, L., Meszaros, I., Downie, A. and Joseph, S. (2007). Agronomic values of greenwaste biochar as a soil amendment. Soil Research, 45, 629-634. http://doi.org/10.1071/SR07109

Chen, C.R., Phillips, I.R., Condron, L.M., Goloran, J., Xu, Z.H. and Chan, K.Y. (2013). Impacts of greenwaste biochar on ammonia volatilisation from bauxite processing residue sand. Plant and Soil, 367, 301-312. https://doi.org/10.1007/s11104-012-1468-0

Cottenie, A. (1980). Soil and plant testing as a basis of fertilizer recommendations. Soils Bulletin, 38, 70-73.

Dai, J., Meng, X., Zhang, Y. and Huang, Y. (2020). Effects of modification and magnetization of rice straw derived biochar on adsorption of tetracycline from water. Bioresource Technology, 311, 123455. https://doi.org/10.1016/j.biortech.2020.123455

Downie, A., Chia, C. H. and Munroe, P. (2009). Characteristics of Biochar: Physical and Structural Properties. In J. Lehmann and S. Joseph (Eds). Biochar for Environmental Management: Science and Technology. Earthscan, London, 13-29.

Fidel, R. B., Laird, D. A. and Spokas, K.A. (2018). Sorption of ammonium and nitrate to biochars is electrostatic and pH-dependent. Scientific reports, 8, 1-10. https://doi.org/10.1038/s41598-018-35534-w

Gale, N. V., Sackett, T. E. and Thomas, S. C. (2016). Thermal treatment and leaching of biochar alleviates plant growth inhibition from mobile organic compounds. PeerJ, 4, e2385. https://doi.org/10.7717%2Fpeerj.2385

Gamage, A., Basnayake, B., De Costa J. and Merah, O. (2021). Effects of rice husk biochar coated urea and anaerobically digested rice straw compost on the soil fertility, and cyclic effect of phosphorus. Plants, 11, 75. https://doi.org/10.3390/plants11010075

Haefele, S. M., Konboonc, Y., Wongboon, W., Amarantea, S., Maarifatb, A., Pfeifferb., M. and Knoblauch, C. (2011). Effects and fate of biochar from rice residues in rice-based systems. Field Crops Research, 121, 430-440. https://doi.org/10.1016/j.fcr.2011.01.014

Hiemstra, T., Mia, S., Duhaut, P. B. and Molleman, B. (2013). Natural and pyrogenic humic acids at goethite and natural oxide surfaces interacting with phosphate. Environmental Science & Technology, 47, 9182-9189. https://doi.org/10.1021/es400997n

Jadon, P., Selladurai, R., Yadav, S. S., Coumar, M. V., Dotaniya, M. L., Singh, A. K., Bhadouriya, J. and Kundu, S. (2018). Volatilization and leaching losses of nitrogen from different coated urea fertilizers. Journal of Soil Science and Plant Nutrition, 18, 1036-1047. http://doi.org/10.4067/S0718-95162018005002903

Kapoor, A., Sharma, R., Kumar, A. and Sepehya, S. (2022). Biochar as a means to improve soil fertility and crop productivity: a review. Journal of Plant Nutrition, 45, 2380-2388. https://doi.org/10.1080/01904167.2022.2027980

Keeney, D. R. and Nelson, D. W. (1982). Nitrogen-Inorganic Forms. In A.L. Miller and Keeney D. R. (Eds). Methods of Soil Analysis part 2: chemical and microbiological properties, 2nd ed. (p. 643-698), Madison:American Society of Agronomy.

Kelly, C. N., Calderón, F. C., Acosta-Martínez. V., Mikha, M. M., Benjamin, J., Rutherford, D. W. and Rostad, C. E. (2015). Switchgrass biochar effects on plant biomass and microbial dynamics in two soils from different regions. Pedosphere, 25, 329-342. https://doi.org/10.1016/S1002-0160(15)30001-1

Kew, K. K. and How, S. S. (2020). Design and construction of mobile Biochar Kiln for small farmers. IOP Conference Series: Materials Science and Engineering, 788, 012075. https://doi.org/10.1088/1757-899X/788/1/012075

Lija, M., Haruna, A. O. and Kasim, S. (2014). Maize (*Zea Mays* L.) nutrient use efficiency as affected by formulated fertilizer with clinoptilolite zeolite. Emirates Journal of Food and Agriculture, 284-292. https://doi.org/10.9755/ejfa.v26i3.16183

Lehmann, J., Czimczik, C. I., Laird, D. and Sohi, S. (2009). Stability of Biochar in the Soil. In J. Lehmann and J. Stephen (Eds.), Biochar for Environmental Management: Science and Technology (p. 169-182). London: Earthscan.

Lehmann, J. and Joseph, S. (2015). Biochar for Environmental Management: an introduction. (p. 33-46). London: Routledge.

Li, S. and Tasnady, D. (2023). Biochar for Soil Carbon Sequestration: Current Knowledge, Mechanisms, and Future Perspectives. C Carbon Journal of Research, 9, 67. https://doi.org/10.3390/c9030067

Mandal, S., Thangarajan, R., Bolan, N.S., Sarkar, B., Khan, N., Ok, Y.S. and Naidu. R. (2016). Biochar-induced concomitant decrease in ammonia volatilization and increase in nitrogen use efficiency by wheat. Chemosphere, 142, 120-127. https://doi.org/10.1016/j.chemosphere.2015.04.086

Mansor, A.M., Theo, W.L., Lim, J.S., Nasir, A.F., Hashim, H. and Ho, W.S. (2018). Potential commercialisation of biocoke production in Malaysia—A best evidence review. Renewable and Sustainable Energy Reviews, 90, 636-649. https://doi.org/10.1016/j.rser.2018.03.008

Maraseni, T.N. (2010). Biochar: maximising the benefits. International Journal of Environmental Studies, 67, 319-327. https://doi.org/10.1080/00207231003612225

Mariano, E, Sant Ana Filho, C. R., Bortoletto-Santos, R., Bendassolli, J.A. and Trivelin, P. C. O. (2019). Ammonia losses following surface application of enhanced-efficiency nitrogen fertilizers and urea. Atmospheric Environment, 203, 242-251. https://doi.org/10.1016/j.atmosenv.2019.02.003

Mehlich, A. (1953). Determination of P, Ca, Mg, K, Na and NH4. Releigh, North Carolina State University Soil Test Division.

Murphy, J. and Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta, 27, 31-36. https://doi.org/10.1016/S0003-2670(00)88444-5

Narzari, R., Bordoloi, N., Chutia, R.S., Borkotoki, B., Gogoi, N., Bora, A. and Kataki, R. (2015). Biochar: An Overview on its production, properties and potential benefits. Biology, Biotechnology and Sustainable Development, 1, 13-40.

Novak, J. M. (2009). Impact of biochar amendment on fertility of a southeastern coastal plain soil. Soil science, 174, 105-112. http://dx.doi.org/10.1097/SS.0b013e3181981d9a

Obia, A., Cornelissen, G., Mulder, J. and Dörsch, P. (2015). Effect of soil pH increase by biochar on NO, N2O and N2 production during denitrification in acid soils. PloS One, 10, e0138781. https://doi.org/10.1371%2Fjournal.pone.0138781

Palanivell, P., Ahmed, O. H. and Majid, A. N. (2016). Minimizing ammonia volatilization from urea, improving lowland rice (cv. MR219) seed germination, plant growth variables, nutrient uptake, and nutrient recovery using clinoptilolite zeolite. Archives of Agronomy and Soil Science, 62, 708-724. https://doi.org/10.1080/03650340.2015.1077229

Peech, H. M. (1965). Hydrogen-ion Activity. In C. A. Black, D. D. Evans, L. E. Ensminger, J. L. White, F. E. Clark and R. C. Dinauer. (Eds.). Methods of Soil Analysis, Part 2, Madison, W.I.: American Society of Agronomy.

Rosmiza, M. Z., Davies W. P., Rosniza, A. C. P., Mazdi, M. and Jabil, M. J. (2014). Farmers' knowledge on potential uses of rice straw: an assessment in MADA and Sekinchan, Malaysia. Geografia-Malaysian Journal of Society and Space, 10, 30-43. [Accessed Jun. 15, 2022]. Available at: https://www.researchgate.net/publication/305470005_Farmers%27_knowledge_on_potential_uses_of_rice_straw_An_assessment_in_MADA_and_Sekinchan_Malaysia

Rowell, D. L. (1994). Soil Science, Methods and Applications. Longman Group UK Limited, 86–87.

Sarkar, N., Kumar, G. S., Bannerjee, S. and Aikat, K. (2012). Bioethanol production from agricultural wastes: An overview. Renewable Energy, 37, 19-27. https://doi.org/10.1016/j.renene.2011.06.045

Sakhiya, A. K., Baghel, P., Anand, A., Vijay, V. K. and Kaushal, P. (2021). A comparative study of physical and chemical activation of rice straw derived biochar to enhance Zn+ 2 adsorption. Bioresource Technology Reports, 15, 100774. https://doi.org/10.1016/j.biteb.2021.100774

Schomberg, H. H., Gaskin, J. W., Harris, K., Das, K. C., Novak, J. M., Busscher, W..J, Watts, D. W., Woodroof, R. H., Lima, I. M., Ahmedna, M., Rehrah, D. and Xing, B. (2012). Influence of biochar on nitrogen fractions in a coastal plain soil. Journal of Environmental Quality, 41, 1087-1095. https://doi.org/10.2134/jeq2011.0133

Selvarajh, G., Ch'ng, H. Y. and Zain, M. D. (2020a). Effects of rice husk biochar in minimizing ammonia volatilization from urea fertilizer applied under waterlogged condition. AIMS Agriculture and Food, 6, 159-171. https://doi.org/10.3934/agrfood.2021010

Selvarajh, G., Ch'ng, H. Y., MdZain, N. M., Sannasi, P. and Azmin, S. N. H. (2020b). Improving soil nitrogen availability and rice growth performance on a tropical acid soil via mixture of rice husk and enriched rice straw biochars. Applied Sciences, 11, 108. https://doi.org/10.3390/app11010108

Selvarajh, G., Ch'ng, H.Y., Zain,, N. M. and Damrongrak, I. (2021). Enriched Rice Husk Biochar Minimizes Ammonia Loss from Applied Urea Fertilizer Under Waterlogged Environment [RESEARCH NOTE]. The Philippine Agricultural Scientist, 104, 5. http://doi.org/10.3934/agrfood.2021010

Selvarajh, G. and Chng, H.Y. (2022). Reducing Ammonia Volatilization from Urea Fertilizer Applied in a Waterlogged Tropical Acid Soil via Mixture of Rice Straw and Rice Husk Biochars. Journal of Agricultural Sciences, 28, 269-277. https://doi.org/10.15832/ankutbd.836980

Si, L., Xie, Y., Ma, Q. and Wu, L. (2018). The short-term effects of enriched rice straw biochar, nitrogen and phosphorus fertilizer on rice yield and soil properties in a cold waterlogged paddy field. Sustainability, 10, 537. https://doi.org/10.3390/su10020537

Singh, R. and Patel, M. (2022). Effective utilization of rice straw in value-added by-products: A systematic review of state of art and future perspectives. Biomass and Bioenergy, 159, 106411. https://doi.org/10.1016/j.biombioe.2022.106411

Siva, K. B., Aminuddin, H., Husni, M. H. A. and Manas, A. R. (1999). Ammonia volatilization from urea as affected by tropical-based palm oil mill effluent (Pome) and peat. Communications in Soil Science and Plant Analysis, 30, 785-804. https://doi.org/10.1080/00103629909370246

Sohi, S.P., Krull, E., Lopez-Capel, E. and Bol, R. (2010). A Review of biochar and its use and function in soil. Advances in Agronomy, 105, 47-82. Academic Press.https://doi.org/10.1016/S0065-2113(10)05002-9

Sun, X., Zhong, T., Zhang, L., Zhang, K. and Wu, W. (2019). Reducing ammonia volatilization from paddy field with rice straw derived biochar. Science of The Total Environment, 660, 512-518. https://doi.org/10.1016/j.scitotenv.2018.12.450

Taghizadeh-Toosi, A. (2012). Biochar adsorbed ammonia is bioavailable. Plant and Soil, 350, 57-69. https://doi.org/10.1007/s11104-011-0870-3

Tan, K.H. (2005). Soil sampling, preparation, and analysis (2nd ed). Boca Raton, Florida, USA.

Venkatesh, G, Rao CS, Gopinanth KA, Reddy S. (2015). Low-cost portable kiln for biochar production from on-farm crop residue. Indian Farming, 64, 9-12. [Accessed Jul. 5, 2023]. Available at: https://www.researchgate.net/publication/280105300_Low-Cost_Portable_Kiln_for_Biochar_Production_from_On-Farm_Crop_Residue

Xu, J., Liu, B., Wang, H., Liu, W., Li, Y., Dai, Y. and Lu, T. (2019). Ammonia volatilization and nitrogen leaching following top-dressing of urea from water-saving irrigated rice field: impact of two-split surge irrigation. Paddy and Water Environment, 17, 45-51. https://doi.org/10.1007/s10333-018-0682-7

Yeboah, E., Patrick, O., Gabriel, Q., Emmanuel, D. and Saran, S. (2009). Improving soil productivity through biochar amendments to soils. African Journal of Environmental Science and Technology, 3, 34-41. [Accessed Jun. 15, 2022]. Available at: https://www.researchgate.net/publication/230583059_Improving_soil_productivity_through_biochar_amendments_to_soils

Yuan, J.H. and Xu, R.K. (2011). The amelioration effects of low temperature biochar generated from nine crop residues on an acidic Ultisol. Soil Use and Management, 27, 110-115. https://doi.org/10.1111/j.1475-2743.2010.00317.x

Yuan, J.H., Xu, R.K., Qian, W. and Wang, R.H. (2011). Comparison of the ameliorating effects on an acidic ultisol between four crop straws and their biochars. Journal of Soils and Sediments, 11, 741-750. https://doi.org/10.1007/s11368-011-0365-0

Zheng, J., Mmari, W.N., Funakawa, S. (2018). Ammonia volatilization following urea application at maize fields in the East African highlands with different soil properties. Biology and fertility of soils, 54, 411-422. https://doi.org/10.1007/s00374-018-1270-0