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MITIGATING AMMONIA VOLATILIZATION LOSSES USING BIOCHAR AMENDMENTS IN AN UPLAND RICE SOIL IN YOLA, ADAMAWA STATE, NIGERIA

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ABSTRACT

Ammonia volatilization is a primary way of nitrogen (N) loss in tropical agriculture, particularly in neutral or alkaline soils. This study evaluated the potential of maize cob biochar (MCB), rice husk biochar (RHB), and locally sourced conventional charcoal (CCB) for reducing NH_3 loss in moist and submerged soils. MCB and RHB were pyrolyzed at 450 °C while CCB was sourced locally and applied at rates of 0–20 ton ha^{-1} to urea-treated soils. The experiment was layout in two-factor completely randomized design. Volatilization was monitored over 21 days in closed chambers under two moisture regimes: 80 % available water capacity (moist) and 2 cm standing water. Results revealed that in moist soils, high application rates (20-ton ha^{-1} MCB) significantly increased NH_3 loss to 0.64 g kg^{-1} due to elevated soil pH, while low rate CCB (5-ton ha^{-1}) matched the control (0.37 g kg^{-1}). Cumulative losses in moist conditions ranged from 2.21 to 3.5 g kg^{-1} with no consistent reduction across biochar rates. However, in submerged soils, the control exhibited the highest cumulative losses (4.36 g kg^{-1}). Application of 5-ton ha^{-1} CCB reduced volatilization by 46 %, likely through O-H adsorption and CO_2-carbonic acid buffering. While losses peaked between 10 and 14 days across both regimes, high pH porous biochars often increased volatilization in moist soils. The study concludes that 5 ton ha^{-1} of CCB is a practical, low-cost strategy for reducing N loss in flooded savanna systems. Effective N management remains highly dependent on feedstock type and soil moisture conditions.

Keywords: Ammonia Volatilization, Biochar, Conventional Charcoal, Nigerian Savanna, Nitrogen Use Efficiency

INTRODUCTION

Soils in the Nigerian savanna often have low organic matter and are usually moderately to strongly acidic. However, repeated fertilization and burning of crop residues can make the topsoil nearly neutral or even alkaline (Shehu et al., 2015; Salako, 2004). These conditions make it easier for ammonia to escape from surface-applied urea. Ammonia volatilization (AV) is a major way nitrogen is lost from soils, which lowers nitrogen use efficiency and crop yields, especially in tropical and savanna regions (Hearn et al., 2023; Miyazawa et al., 2020). This creates challenges for both farming productivity and the environment. Nitrogen fertilizers, especially, urea based are widely used to boost crop yields in these soils. However, ammonia volatilization from these fertilizers reduces nitrogen use efficiency and can harm the environment (Ofori et al., 2025; Zhong et al., 2021). As agriculture expands to feed more people, the use of nitrogen fertilizers is increasing, making this issue even more important. To reduce these losses and improve nitrogen use, new solutions like soil amendments must be considered.

Biochar is a low-cost, eco-friendly, carbon-rich soil amendment made by pyrolysis of plant material in the absence or limited oxygen. It has been widely studied for its ability to reduce ammonia volatilization (AV) because it can change soil pH, affect microbes, and influence how nitrogen moves in the soil (Kohira et al., 2024; Mandal et al., 2018). In agriculture, biochar can help lower ammonia loss by trapping ammonia gas and preventing it from escaping into the air, which reduces the negative effects of nitrogen fertilizers (Puga et al., 2020; Liang et al., 2017). However, the effectiveness of biochar depends on several factors, including the type of material used, the temperature at which it was produced, the amount applied, and the soil's properties (Abubakar and Nabayi, 2025; Sha et al., 2019; Mandal et al., 2018). In acidic soils, which are common in the savanna, biochar with a high pH can actually increase ammonia loss unless it is used with urea or organic fertilizers, or applied at the right rates (Sha et al. 2019).

Biochars that are modified or enriched with nitrogen have been shown to reduce ammonia losses more effectively by holding onto more nitrogen and releasing less of it (Egyir et al., 2022; Puga et al., 2020). Application of biochar to soils can also help plants use nitrogen more efficiently by supporting nitrification and immobilization, while reducing nitrogen lost as gas. This is important for sustainable farming in the Nigerian savanna (Kohira et al., 2024; Mandal et al., 2018). However, even though many studies show that biochar is effective in reducing nutrients losses (Ali et al., 2025; Solomon, 2022; Idowu and Brewer, 2018; Clough et al., 2013), new types of engineered biochar made with special processes or nanotechnology are often too complex and expensive for smallholder farmers, especially in countries like Nigeria where most farming activities is still at the subsistence level. Regular wood charcoal, which is widely produced and used as household fuel in Nigeria, including rural and peri-urban savanna areas, could be a good alternative because it is easy to find in local markets and homes (Łaska and Ige, 2023; Adio et al., 2022; Abdallah et al., 2016). Evaluation of charcoal as a soil amendment alongside biochar from farm waste is practical and economical. Farmers can reuse leftover charcoal fines or ash that would otherwise be discarded, lowering the cost of these processing methods. Comparing biochar from crop residues with common fuel charcoal in the same soil helps determine if easily available charcoal can reduce ammonia loss as well as specially made biochars. This comparison will help make recommendations that are both practical and effective for smallholder farmers in the Nigerian savanna. This study was carried out to test how well maize cob biochar (MCB), rice husk biochar (RHB), and conventional charcoal (CCB) can

reduce ammonia loss from moist and submerged soils in the semi-arid savanna of Yola, Adamawa State, Nigeria.

MATERIALS AND METHODS

Soil samples for the laboratory study were collected at the Modibbo Adama University Teaching and Research Farm (MAUTRF) in Yola, Adamawa State, Nigeria. Located on latitude 9.355905°–9.356225° N, longitude 12.50531°–12.49425° E at an altitude of 200 m above sea level. The site is located in the Northern Guinea savannah zone and experiences a tropical climate with distinct wet and dry seasons. The dry season spans November to March, and the wet season extends from April to October. The study location receives an average annual rainfall of 956 mm (Adebayo et al., 2020). Temperatures can reach up to 40°C in April, while the lowest temperatures, around 18°C, occur between December and January (Adebayo et al., 2020). Relative humidity is lowest (20–30%) from January to March and peaks at approximately 83 % in August. Evaporation rates remain low due to high solar radiation (Adebayo et al., 2020). The landscape is characterized by woody savannah vegetation with a mix of grasses and herbaceous plants. Major crops cultivated include rice (Oryza sativa), maize (Zea mays), cowpea (Vigna unguiculata), soybean (Glycine max), and sorghum (Sorghum bicolour).

Experimental Materials

Three types of biochar were used: maize cob biochar (MCB), rice husk biochar (RHB), and conventional charcoal biochar (CCB) from timber, a common local fuel.

Soil Sampling and Preparation

Soil samples were collected from rice fields using stratified random sampling at 30 points (0–20 cm depth) with a soil auger and combined into a composite sample. Samples were air-dried, crushed, and sieved (2 mm) for laboratory analysis. The remaining soil samples were used for pot experiments. Ten (10) undisturbed samples were collected with core samplers for bulk density and moisture content measurement.

Determination of Soil Physical and Chemical Properties

Soil properties were analyzed using standard methods. Particle size was measured by hydrometer (Jaiswal, 2011). Bulk density was determined by drying undisturbed samples at 105 °C and dividing the dry weight by sample volume. Total porosity was calculated as:

$$\text{Total Porocity} = \left(1 - \frac{\text{Db}}{\text{Dp}}\right) X\ 100 \quad (1)$$

Where Db = bulk density, Dp = particle density.

Water holding capacity (WHC) (%) was calculated as:

$$\text{WHC (\%)} = \left({}^{w3 - w2}/_{w4 - w1}\right) X\ 100 \quad (2)$$

Where, W1 = weight container, W2 = weight of container + dry soil, W3 = weight of saturated sample, W4 = weight of oven-dried sample.

Soil pH was measured in a 1:2.5 soil-water ratio using a glass electrode (Jaiswal, 2011). Electrical conductivity (EC) was measured with an EC meter using the same suspension (Black, 1965; Jaiswal, 2011). Organic carbon content was determined by the Walkley-Black method. Total nitrogen was measured using micro-Kjeldahl digestion as described by Jaiswal (2011). Available nitrogen was analyzed by the alkaline potassium permanganate method while and available phosphorus was measured using Olsen method (Olsen, 1954) as described by (Lyons et al. (2023). The effective cation exchange capacity (ECEC) was determined by summing total exchangeable bases and acidity (Black, 1965). Exchangeable acidity was measured using 1N KCl extraction and titration (Jaiswal, 2011). Exchangeable bases were extracted with 1N neutral ammonium acetate; Ca and Mg were measured by EDTA titration, K and Na by flame photometry (AAS, MEDTECH). Base saturation (%) was calculated by dividing total exchangeable bases by CEC and multiplying by 100 (Jaiswal, 2011).

Biochar Production

Biochars were produced from maize cob (MC) and rice husk (RH) collected from MAU farms. Conventional charcoal (CCB) was purchased from a local vendor. The MC and RH were placed in airtight stainless steel containers and pyrolysed in a furnace at 450°C for one hour. The furnace was then turned off, and the biochar cooled inside. The biochar was ground and sieved (2 mm) for uniform mixing with soil.

Biochar Characterization

Biochar pH and EC were determined in 1: 10 char to water ratio. The point of zero charge was measured using the pH drift method of Calvete *et al*. (2009). Fixed carbon, bulk density, specific surface area, and micropore volume were measured using Brunauer–Emmett–Teller (BET) method and Dubinin-Radushkevich respectively through N_2 gas adsorption according to the procedure of Jindo et al. (2014) as described by Solomon (2022); Abdu et al. (2021). The surface morphology and microstructural integrity of the produced biochars were investigated using Scanning Electron Microscopy (SEM). Before imaging, samples were mounted onto aluminium stubs with conductive carbon adhesive tape. To prevent charging effects and ensure high-resolution secondary-electron imaging, samples were sputter-coated with a thin gold/palladium layer. Micrographs were acquired using a point-mode SEM system at 15 kV to balance surface sensitivity and depth of field. Imaging was performed in a low-vacuum chamber at 60 Pa and approximately 300x magnification. A calibrated scale bar of 200 μm was used for all representative micrographs to facilitate comparative size analysis of the particles. Surface functional groups were identified through fourier transmission Infrared Spectroscopy (FTIR) (Spectrum 2, Perkin Elmer Model C98663) at Modibbo Adama University.

Experimental Design

The experiment used a two-factorial completely randomized design (CRD) with three replications. Treatments were six (6) sampling times (2, 4, 7, 10, 14 and 21 days) and three biochars (MCB, RHB, CCB) at four (4) application rates (5, 10, 15, and 20 ton ha-1) plus an absolute control (0 ton ha-1).

Data Collection (Ammonia Volatilization Studies)

Ammonia volatilization was measured using the enclosure chamber method (Yang et al., 2018). The soil (250 g) was mixed with each biochar at 0, 5, 10, 15, or 20 tons/ha and placed in airtight glass jars. Urea was applied at the recommended rate to simulate field conditions. After application, soils were kept at 80 % water holding capacity (WHC) and fewer than 2 cm of standing water for moist soils and submerged soils, respectively. In each jar, a 50 mL beaker with 20 mL of 2 % boric acid (with indicators) was used to trap volatilized ammonia, replaced on days 2, 4, 7, 10, 14, and 21. The trapped ammonia was titrated with 0.1 N H_2SO_4. Ammonia volatilized (mg) and cumulative volatilization (CAV (g kg^{-1})) were calculated as:

$$\text{AV (mg)} = \text{Tv} \times 0.0014 \times 1000 \quad (3)$$

Where, Tv = titre value,

$$\text{CAV (g/kg)} = \text{Ammonia volatilized over period (g)} / \text{N applied (kg)} \quad (4)$$

Data Analysis

Data collected were analyzed using the Generalized Linear Model (GLM) in Statistix 8.0. Significant means were separated at 5% significance using Tukey's HSD test (Gomez and Gomez, 1984). Cumulative ammonia volatilization over time was plotted using OriginPro 2019b (version 9.65).

RESULTS AND DISCUSSION

Table 1 shows the physical and chemical properties of the soil before the experiment. The soil at the study site is sandy loam in texture, with 66 % sand, 26.4 % silt, and 7.6 % clay. This high sand content is typical of many savanna soils and allows for good aeration, but it also means the soil does not retain water well. The soil has a bulk density of 1.60 Mg/m³ and a total porosity of 36 %. According to Hunt and Gilkes (1992), this bulk density is high for sandy loam and is close to the point where roots have difficulty growing and water movement is reduced. The low porosity also means the soil can be easily compacted, which is a common problem in the Northern and Southern Guinea savanna. tThe pH was 7.15, indicating a neutral soil reaction. Although many soils in the Nigerian savanna are naturally acidic due to intense leaching of basic cations, this neutral pH is beneficial because it falls within the optimal range for the solubility and availability of most essential plant nutrients. The Electrical Conductivity (EC) was 0.14 dS m^{-1}, well below the 4.0 dS m^{-1} threshold of saline soils, so the soil is non-saline. The soil had 12.17 g kg^{-1} of organic carbon and 1.10 g kg^{-1} of total nitrogen. Based on the critical levels for

Table 1: Physical and Chemical Properties of Soil before the Experiment

S/N	Parameters	Values
1	pH (1.2.5 soil to water)	7.15
2	EC (dS m^{-1})	0.14
3	Sand (%)	66.00
4	Silt (%)	26.40
5	Clay (%)	7.60
6	Textural Class	Sandy loam
7	Bulk Density (Mg m^{-3})	1.60
9	Porosity (%)	36.00
10	Organic Carbon (g kg^{-1})	12.17
12	Total N (g kg^{-1})	1.10
13	Available N (mg kg^{-1})	22.00
14	Available P (mg kg^{-1})	13.60
15	Ca^{2+} (cmol (+) kg^{-1})	2.85
16	Mg^{2+} (cmol (+) kg^{-1})	1.46
17	K^{+} (cmol (+) kg^{-1})	0.38
18	Na^{+} (cmol (+) kg^{-1})	0.30
19	TEB (cmol (+) kg^{-1})	4.99
20	TEA (cmol (+) kg^{-1})	1.40
21	ECEC (cmol (+) kg^{-1})	6.39
22	Base Saturation (%)	78.09

Nigerian soils established by Esu (1991), organic carbon is rated moderate, while total nitrogen is rated low to moderate. The available nitrogen was 22.00 mg $kg^{-1,}$ which is considered low, indicating that the soil may not meet the high nitrogen needs of cereal crops without extra fertilization. The soil recorded a mean AVP value of 13.60 mg kg^{-1}, which is rated as moderate according to Esu (1991). This suggests a reasonable P reserve, though a positive response to P fertilization remains likely for high-P-demanding crops. The exchangeable bases were dominated by calcium (2.85 cmol (+) kg^{-1}) and magnesium 1.46 cmol (+) kg^{-1}). However, the effective cation exchange capacity (ECEC) was 6.39 cmol (+) kg^{-1}, which is rated as low. Although the soil has a high base saturation (78.09 %), its low effective cation exchange capacity (ECEC) means it cannot retain nutrients well and is likely to lose them through leaching.

Physical and Chemical Properties of Biochar

The physical and chemical properties of the biochars used in the study are presented in Table 2. The results revealed that the pH values ranged from 7.25 to 9.40, indicating that all biochars were alkaline in nature. The highest pH of 9.40 was observed in MCB, while CCB and RHB recorded pH values of 8.95 and 7.25 and were moderately and slightly alkaline respectively. This pH values recorded by RHB and CCB may favors ammonium retention, whereas the high pH of MCB may increase soil alkalinity and enhance ammonia volatilization. Electrical conductivity values ranged from 1.18 – 1.43 dS m^{-1} which is an indication of moderate soluble salt levels across the biochars. The PZC measured in both NaCl and KCl were higest for MCB with values of 8.00 and 8.16 repectively. Similarly, lowest PZC of 6.91 and 6.90 measured in NaCl and KCl electrolytes respectively were recorded by RHB. The higher PZC of 8.00 in NaCl and 8.16 in KCl recorded by MCB means its surface remains positively charged above pH 8, favouring anion adsorption, while lower PZC of 6.90 recorded by RHB implies a positive charge above that pH range and it is better suited for cation retention but less effective for anions. Onokebhagbe et al. (2021) and Appel et al. (2003) reported that if the pH of a soil is above its PZC, the soil surface will have a net negative charge and predominantly exhibit an ability to retain cations, while the soil will mainly retain anions if its pH is below its PZC.

The fixed carbon content was highest in MCB (65.61 %), while CCB (35.93%) and RHB (39.02%) contained more reactive carbon beneficial for soil nutrient improvement. The higher fixed carbon recorded by MCB indicates that it will persists longer in soils, sequestering carbon effectively and reducing mineralization rates over years. In contrast, lower values in CCB and RHB imply faster breakdown, releasing

carbon as CO_2 but providing sustained energy for microbial activity. Chen et al. (2022); Bilias e al. (2021) reported that the magnitude of fixed carbon in a material in a direct reflection of its persistence, nutrient cycling, and remediation efficacy in degraded soils.

Table 2: Some Physical and Chemical Properties of Biochar

Parameters	Maize Cob Biochar (MCB)	Rice Husk Biochar (RHB)	Conventional Charcoal Biochar(CCB)
pH (1:10 Biochar: H2O)	9.40	7.25	8.95
EC (dS m^{-1})	1.43	1.18	1.39
PZC (NaCl)	8.00	6.91	7.98
pHzpc (KCl)	8.16	6.90	8.01
Bulk density (Mg m^{-3})	0.41	0.41	0.52
Micropore volume (cm^3 g^{-1})	0.257	0.318	0.04
Moisture content (%)	1.88	1.24	1.19
Fixed Carbon (%)	65.61	39.02	35.93
Silicon (%)	2.54	35.21	3.11
Specific surface area (m^2 g^{-1}) (BET)	285.02	325.49	275.76

The bulk density of the biochar materials ranged from 0.41 to 0.52 Mg/m³, indicating that all were light and porous materials suitable for improving soil aeration and water retention. Moisture content was low (1.19–1.88%), confirming that the biochars were well carbonized and stable. The specific surface area varied among the biochars, with RHB recording the highest value of 325.5 m^2 g^{-1}, followed by MCB with 285.0 m^2 g^{-1}while CCB recorded the lowest specific surface area of 210.7 m^2 g^{-1}. The large surface area of RHB and MCB suggests a higher adsorption capacity and potential for nutrient retention.

Scanning Electron Microscope Micrograph of Biochar, Maize Cob Biochar and Rice Husk Biochar and Conventional Charcoal Biochar

The scanning electron microscope **(**SEM) micrograph of CCB, MCB and RHB are presented in Figures 1. The micrographs reveal significant structural variations in the physical structure of the different biochar materials. Large, asymmetrical aggregates and uniformly distributed tiny particles produce a heterogeneous surface in the CCB sample. These aggregates exhibit minor areas of surface irregularity as well as a relatively compact and dense matrix. The scans show a limited amount of macro and micro porosity, making the entire sample appear more compact than other biochar samples. This suggests that either the CCB was produced at a much higher temperature than the others were, resulting in a high mineral content and/or greater localized coalescence throughout, as indicated by the nearly complete lack of clearly defined macro and micro pore structures. Lehmann and Joseph (2024); Khan et al., 2024; DeLuca et al. (2024); Steiner et al. (2018) opined that structural characteristics of biochar influenced by the interplay of production temperature, feedstock type, particle coalescence and mineral content.

The MCB (Fig. 1b), revealed a more intricate structure that resembles a "honeycomb-type" porous structure. There is clear evidence of the original plant cellulose's longitudinal channels throughout the vascular system. As a result, this extremely porous structure has a substantially higher specific surface area, offering a better potential for cation exchange and moisture retention for environmental application. Xiao, et al. (2018) also reported that the intricate, porous morphology enhances biochar's surface area, facilitating superior moisture retention by capillary action within vascular channels and promoting cation exchange capacity (CEC) for nutrients like K^+ and heavy metals. Fig. 1c shows the RHB micrograph, which exhibits a flaky, broken shape resembling thin sheets or long glass shards. Similar to the MCB, the RHB's surfaces are quite uneven. Despite their rough surfaces, the RHBs appear more brittle and fragmented than the MCBs, which may be due to their higher surface area and silicon contents. These suggest that the RHB may provide numerous active sites for adding new chemical groups. Hamidu et al. (2025); Morales et al. (2021) linked the flaky, shard-like morphology with brittle, fragmented sheets in rice husk biochar primarily to the high silica content which forms rigid SiO_2 networks during pyrolysis.

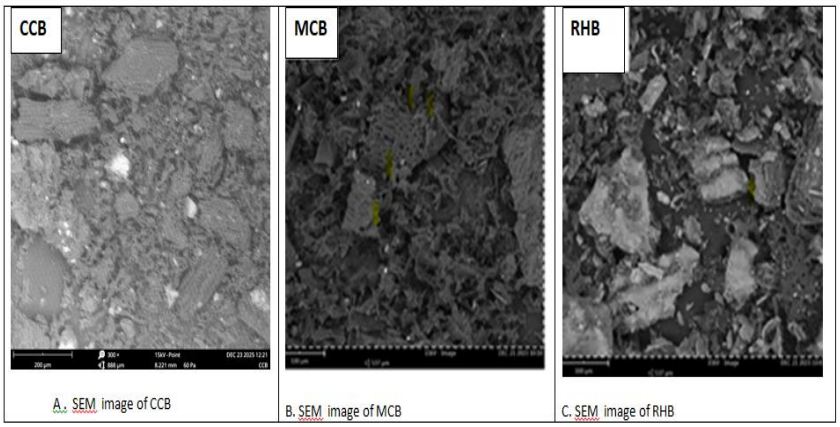

Figure 1: Scanning Electron Microscope (SEM) Image of (A) CCB (B) MCB and (C) RHB

Similarly, Gautam et al. (2025); Sales Alba (2022) attributed the brittle surfaces of their RHB to high surface area driven by rice husk's silica content, providing abundant active sites for pollutant trapping and functionalization in soil remediation.

All three biochar materials show irregular shapes that were produced during pyrolysis, according to SEM images, however their microstructure patterns are very different. The MCB seems to offer the best internal porosity properties of the three materials for adsorption. In terms of fragmentation and possibly accelerated surface reactions, RHB falls between these two distinct types of materials, whereas CCB seems to be more akin to a collection of aggregates with a significant amount of structure.

The Fourier Transmission Infrared Spectroscopy Overlay of Biochar, Maize Cob Biochar and Rice Husk Biochar and Conventional Charcoal Biochar

The result of Fourier transmission infrared spectroscopy (FTIR) is presented in Figure 2. The results revealed that the CCB exhibits a broad, shallow dip that corresponds to O-H stretch vibrations at the 3298 cm^{-1}. It also exhibits significant peak activity in the 1500–1600 cm^{-1} range; however, these peaks are larger and less distinct. This implies that the CCB sample has more complicated or disorganized carbon structures than the other samples. In addition, the CCB shows numerous tiny peaks in the fingerprint region, suggesting that it contains a variety of functional vibrations of the C-O stretching type or vibrations related to minerals in relation to mitigating ammonia volatilization. Zhang et al. (2026); Padilla et al. (2024) reported broad O-H peak signals abundant hydroxyls (-OH) and linked it to incomplete carbonization, while indistinct 1500-1600 cm^{-1} peaks reflect amorphous carbon domains rather than crystalline aromatics dominant in high-heat biochars.

The RHB exhibits significant peak activity in the 1500–1600 cm^{-1} range as well, indicating that the RHB material has a more complex or disordered carbon structure. The RHB spectra also shows a very sharp concentrated transmittance band around 800–1000 cm^{-1}, which is indicative of Si-O-Si stretch vibrations and may point to the relatively high silica content that is frequently seen in rice husk feedstocks. With respect to MCB, high transmittance in the 3500 cm^{-1} area was observed, suggesting a more hydrophobic surface or a greater level of dryness after pyrolysis. However, there is a noticeable, sharp peak that represents C=O stretching in conjugated ketones/carboxylic groups or C=C aromatic skeletal vibrations near 1600. This implies a sophisticated aromatic structure. A high degree of aromatic substitution is confirmed by the presence of multiple sharp peaks below 1000 cm^{-1}, which indicate specific out-of-plane aromatic C-H bending. The absence of O-H stretching reflects extensive deoxygenation, creating a non-polar carbon matrix resistant to hydrolysis, contrasting CCB's hydroxyl-rich profile. The sharp 1600 cm^{-1} peak confirms aromatic ketones/carboxyls or skeletal C=C vibrations, hallmarks of graphitic stability that correlate with MCB's honeycomb SEM structure and high fixed carbon (65.61 %). Similar findings were reported by McCall et al. (2025); Younis et al. (2021); Padilla et al. (2024).

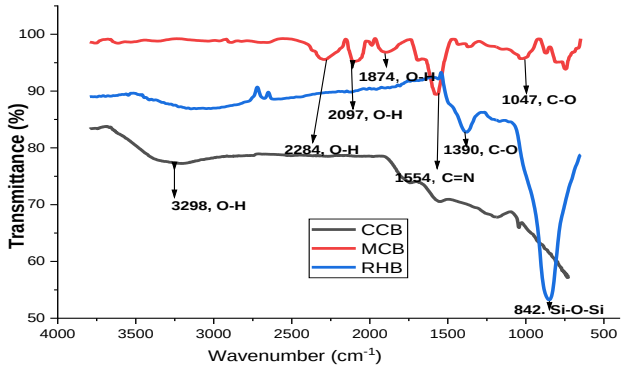

Figure 2: The Fourier Transmission Infrared Spectroscopy Spectra Overlay of CCB, MCB and RHB

The FTIR results confirm the SEM findings by revealing that MCB is chemically the most aromatic despite having a highly developed porous structure. On the other hand, the silica content of RHB dominates its chemistry, which probably contributes to the fragmented shard-like morphology observed in the SEM. These characteristics imply that RHB might perform well in applications requiring high thermal resistance or particular mineral interactions, while MCB might be better for organic pollutant adsorption via π-π interactions.

Effects of Biochar Type on Ammonia Volatilization in Moist and Submerged Soils

The effects of biochar rate on ammonia volatilization in moist and submerged soils are presented in Figure 3a and 3b respectively. Data obtained revealed significant differences ($p< 0.05$) among treatments under moist condition while no significant differences were observed in submerged soil conditions. In moist soils, highest ammonia volatilized of 0.64 g kg^{-1} was recorded by 20-ton ha^{-1} MCB, but was not significantly different from the rest of the treatments. However, it was significantly higher ($P<0.05$) than 0.37 g kg^{-1} each recorded by the control and 5 ton ha^{-1} CCB. Higher volatization by 20 ton ha^{-1} MCB may be attributed to its high pH (9.40) of MCB, which promoted ammonia volatilization by increasing soil alkalinity and accelerating urea hydrolysis. This observation agrees with the findings of Liu et al. (2025); Amin (2023); Cui et al. (2022) who reported that in saline-alkali or high pH soils, biochar application can increase NH_3 volatilization by up to 70 % if the material's basicity overrides its cation exchange capacity. Although MCB offers good physical structure, its high-dosage application in moist soils may be counterproductive due to alkalinity-induced volatilization. Therefore, the order of ammonia volatilization among the biochar material in moist soils followed the trend MCB >RHB >CCB = Control.

No significant differences were observed among biochar rates under the submerged soil condition. However, the highest NH_3 volatilized of 0.53 g kg^{-1} was recorded by 20-ton ha^{-1} RHB but was not significantly different from the rest of the treatments. Although Cayuela et al. (2014) and Sha et al. (2019) reported that moderate biochar rates effectively reduce nitrogen losses by improving soil structure and nutrient adsorption, while excessive use can alter soil pH and reduce efficiency. The observed resistance of the submerged soil to significant variations across biochar application rates may be due to the overwhelming influence of redox soil chemistry, which imposes a robust buffering effect that masks incremental biochar-mediated changes. Submergence triggers a pH convergence that masks the effect of biochar. While biochar typically introduces alkalinity, the accumulation of biogenic carbondioxide in the flooded environment produces carbonic acid, which drives the pH downward toward neutrality in a series of reaction:

$$CO_2 + H_2O \rightleftharpoons HCO_3^- \quad (5)$$

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \quad (6)$$

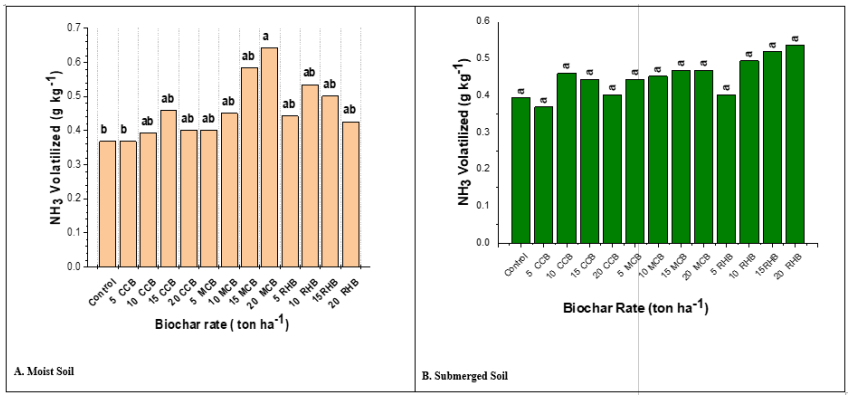

Figure 3: Effects of Biochar Rate on Ammonia Volatilized from (A) Moist Soil and (B) Submerged Soils

$$CaCO_3 + CO_2 + H_2O \rightleftharpoons Ca^{2+} + 2HCO_3^- \quad (7)$$

In addition, the physical saturation of biochar's internal pore network with water and the potential clogging of active surface sites by mobilized dissolved organic matter (DOM) may limit the functional differentiation between application rates. This finding is consistent with the geochemical equilibrium described by Ponnamperuma (1972), where the accumulation of biogenic CO_2 exerts a dominant downward pressure on the pH of slightly alkaline systems (Kirk, 2004). Joseph et al. (2021) obtained similar findings and opined that the buffering effect can effectively masked the alkaline contribution of the biochar, creating a physicochemical equilibrium where incremental application rates yielded no significant functional differentiation

Effect of Time on Ammonia Volatilization in Moist and Submerged Soils

The effects of time on ammonia volatilization in moist and submerged soils are presented in Figure 4. Results obtained revealed that there were differences ($P<0.05$) among the different time of sampling on ammonia volatilization. In both moist and submerged soils, highest ammonia volatilized of 0.68 g kg^{-1} and 0.58 g kg^{-1} for moist and submerged soils respectively were recorded at 10 days of incubation. Ammonia volatilization increased progressively after urea application and reached its peak between 10 and 14 days for both soils after which it gradually declined. This pattern corresponds to the urea hydrolysis process, where urea is enzymatically converted into ammonium (NH_4^+), followed by its transformation into ammonia gas (NH_3) under favorable pH and temperature conditions. Although both soil moisture conditions showed this temporal trend, the submerged soil consistently recorded higher ammonia losses than moist soil up to day 7. The higher losses under continuous submergence for the first week may be attributed to the accumulation of ammonium near the water surface, which promotes gaseous escape. In both soils, ammonia losses declined after day 14 due to reduced urease activity, lower ammonium availability, and possible adsorption by soil colloids. This observation is in line with the findings of Beeman et al. (2018) who reported that ammonia volatilization from urea-fertilized soils typically peaks within the first two weeks after application before decreasing as hydrolysis stabilizes.

Interaction Effect of Time and Biochar Rate on Ammonia Volatilization in Moist Soil

Figure 5 shows the significant interaction effect between time and biochar rate under moist soil conditions. There was an initial lag phase during the first 7 days of sampling. The soil exhibited a relative resistance to variations irrespective of biochar rate, with most treatments including the control showing statistically similar, low-level of volatilization. Means with the same letter for the same soil type are not significantly different at $P< 0.05$

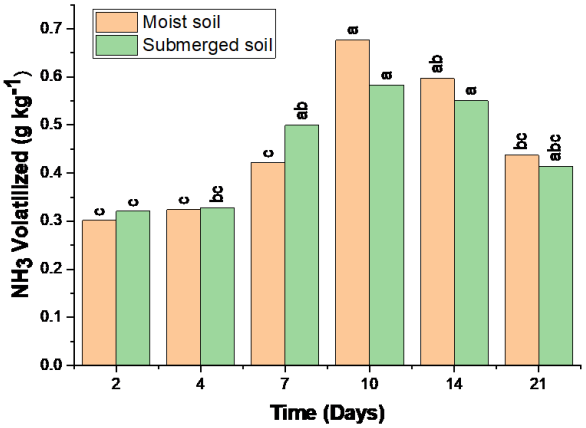

Figure 4: Effects of Time on Ammonia Volatilization in Moist and Submerged Soils

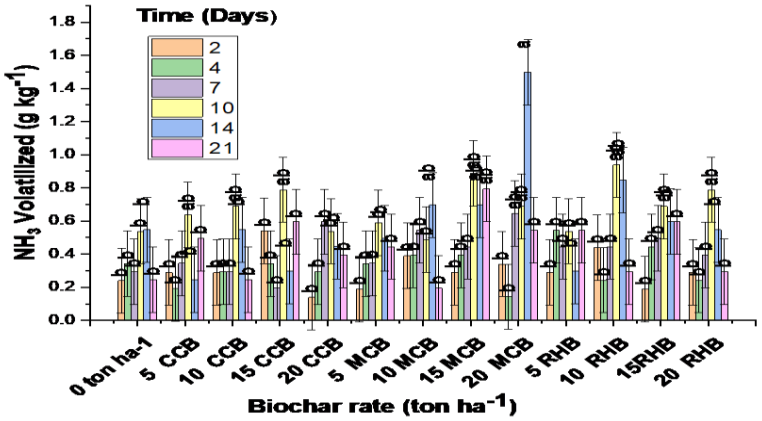

Figure 5: Interaction Effects of Time and Biochar Rate on Ammonia Volatilization in Moist Soil

This initial stability may be attributed to the robust indigenous buffering capacity of the soil and a temporal delay in urea hydrolysis. However, a critical divergence in NH_3 volatilization occurred at Day 14, where the 20 ton ha^{-1} MCB recorded the highest volatilization rate of 1.50 g kg^{-1}. Interestingly, despite this peak, many other treatments such as 5 CCB (0.25g kg^{-1}.) and 20 RHB (0.55) remained statistically equivalent to the control (0.55) at the same time interval. This lack of linear response to increasing biochar rates suggests a physicochemical equilibrium. In moist, high respiration environments, the accumulation of biogenic CO_2 generates a powerful carbonate-bicarbonate buffer. This system acts as a geochemical driver, where the production of H^+ from CO_2 hydration effectively neutralizes the alkaline ash content of the biochar, stabilizing the NH_3/NH_4^+ ratio and masking the expected effects of higher application rates. The highest volatilization observed in MCB at 14 days compared to the relative stability of CCB and RHB indicates that while the soil's redox-driven buffering is the dominant driver, specific biochar properties play a secondary, modulating role. The decline in volatilization observed by Day 21 across nearly all treatments suggests the exhaustion of the labile nitrogen pool or the physical masking of biochar's active surface sites by mobilized dissolved organic matter (DOM), which limits the long-term functional differentiation between application rates. Cayuela et al. (2014) also noted that biochar's mitigation effect is most pronounced during peak hydrolysis.

Cumulative Ammonia Volatilization in Submerged and Moist Soils

The cumulative ammonia volatilization in submerged and moist soils is presented in Figures 6 and 7 respectively. Cumulative ammonia volatilization under continuous submergence was markedly higher in the control pot, reaching 4.36 g kg by the end of the experiment. Ammonia volatilization increased sharply between the day 7 and 14, after which the rate of volatilization became more gradual irrespective of treatment (Fig. 6). The high volatilization under submergence may be attributed to the elevated soil pH at the soil–water interface and sustained urea hydrolysis, which enhanced the conversion of ammonium (NH_4^+) to ammonia (NH_3) gas. At Day 2, all biochar treatments first reduced volatilization in comparison to the control. However, across the 21 days study, only CCB at 5 tons ha^{-1} maintained the lowest cumulative loss of 2.34 g kg^{-1}. This resulted in about 46 % decrease in ammonia loss compared to the control pot and may be due the oxygen-rich surface of the biochar, which excels at ammonia (NH_3) adsorption throuhg hydrogen bonding and protonation of -OH/C-O groups, reducing volatilization losses. McCall et al. (2025); Younis et al. (2021) reported similar findings and opined that Biochar's oxygen-rich surface may support adsorption through hydrogen bonding and protonation of -OH/C-O groups. However, they also reported that multiple functional sites in biochar can support heavy metal complexation over simple cation

exchange. Interestingly, by Day 21, the cumulative loss increased from 2.41 to 3.21 g kg^{-1} when the dosage of RHB was increased from 5 to 20 tons ha^{-1}. This suggests that higher rates of biochars may unintentionally promote volatilization in anaerobic environments.

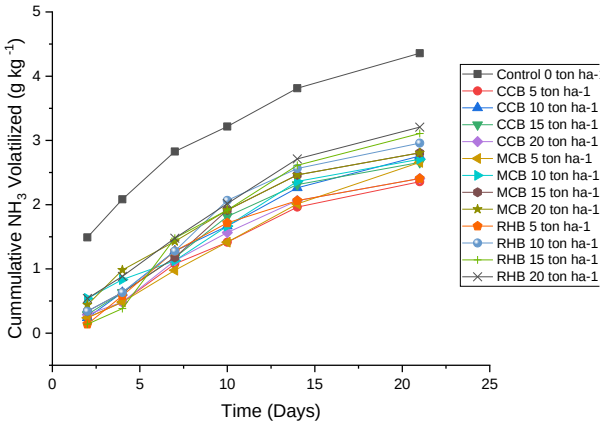

Figure 6: The Cumulative Ammonium Volatilization in Submerged Soil

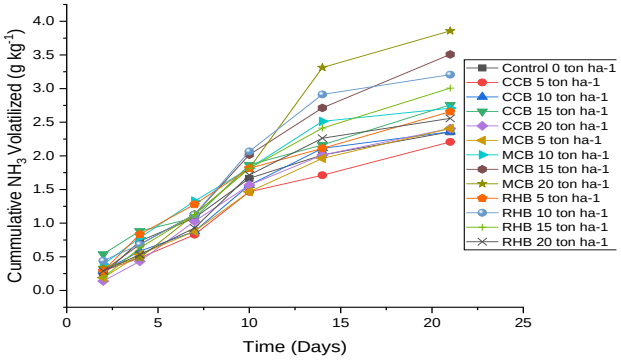

Figure 7: The Cummulative Ammonium Volatilization in Moist Soil

In moist soil, results revealed relatively lower cumulative losses and reflect the moderating influence of soil aeration and microbial activity which support nitrogen retention. This suggests that maintaining soil under moist rather than water-saturated conditions can minimize gaseous nitrogen losses. Moist soils exhibited lower baseline losses of 2.21 g kg^{-1} by the control at 21 days, while amendments yielded neutral to adverse effects, with increases up to 58.9 % by 20 ton ha^{-1} MCB and rare reductions of 0 % by 5 ton ha^{-1} CCB. The neutral to negative effects of biochar in moist soil may be due to enhanced aeration, accelerated nitrification, and microbial priming under oxic conditions. Unlike submerged systems, moist soils conditions increase O_2 availability, promoting NH_4^+ oxidation to NO_3^- via nitrifiers. This may promote the conversion of NH_4^+ to NO_3^-, decoupling organic N mineralization while accelerating gross nitrification, potentially elevating NH_3 via pH shifts and/or microbial stimulation despites biochar's properties. Kumar et al. (2024); Canatoy et al. (2024); Ge et al. (2023) reported that high-rate biochars may intensify N losses by priming organic N turnover or releasing sorbed N under oxic conditions. Similarly, Ma et al. (2024) reported the displacement of sorbed NH_4^+ in soil amended with biochar unlike flooded low-Eh retention, oxic moisture enables competitive cation exchange or desorption. These findings suggest a strong interaction between biochar type and the water-holding capacity of the soil. The CCB at low application rates (5-ton ha^{-1}) appears to be the most stable amendment for mitigating NH_3 volatilization loss across both moisture regimes.

CONCLUSION

In conclusion, this study shows that while MCB, RHB, and CCB variably influence ammonia volatilization from urea-applied soils, 5-ton ha^{-1} CCB provides a low-cost, practical strategy that smallholder farmers can consider. It offers the most consistent mitigation, reducing cumulative losses by up to 46% in submerged conditions through its O-H rich surface functional groups, without the pH elevation observed with high-rate MCB under moist conditions. These findings highlight the importance of soil moisture interactions in nitrogen retention. Future research should therefore, focus on field validation and exploring synergies with urease inhibitors to build confidence in these approaches for sustainable agriculture in semi-arid tropics.

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