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Health Assessment in Water-Logged Soil Cultivated to Rice Under Amendment With Rice Straw Biochar, Magnetic Rice Straw Biochar and their Urea Intercalated Derivatives

Atere*, C. T., Akinyemi, O. T. and Adesanwo, O. O.
Department of Soil Science and Land Resources Management, Faculty of Agriculture, Obafemi Awolowo University, PMB 13, Ile-Ife, Nigeria
*Corresponding author: cornelatere@oauife.edu.ng

Abstract

The study assessed health status of water-logged soil under rice production with application of rice straw biochar, magnetic rice straw biochar, and their urea-intercalated derivatives, using various chemical and biological indicators. Three kilogramme soil (Gleysol) each was amended according to treatments and planted with three-week-old rice seedlings in a screenhouse. The experiment was a non-factorial design laid out in completely randomized design with three replicates. After rice harvesting, the amended soil was subjected to chemical and biological analyses. Results revealed significantly higher ($p<0.05$) organic carbon (OC) contents in biochar-based treatments compared to sole urea and unamended soil. Particularly, treatments involving 30 t magnetic rice straw biochar ha^{-1} intercalated with 40 and 60 kg N ha^{-1} as urea (UMRB1 and UMRB2) exhibited significantly higher OC values than those involving rice straw biochar intercalated with urea at 40, 60, and 80 kg N ha^{-1} (URB1, URB2, and URB3). The treatments also led to significant increases in soil total nitrogen (TN) and available phosphorus (P) relative to the control, with significant increase in TN observed with URB1 and UMRB1. Application of magnetic biochar, with or without urea intercalation increased Ca and Mg concentrations. Amendments also increased soil urease activity at both 7 and 14 days post-rice transplanting by 9-57% and 8-54%, respectively, with UMRB2 giving the highest values. Furthermore, UMRB3, UMRB1 and UMRB2 significantly increased microbial biomass carbon (420-481%) and nitrogen (425-625%) levels. The highest values of dissolved organic carbon and nitrogen were recorded with URB3 and UMRB2, respectively. Overall, rice straw biochar and its derivatives, especially urea-intercalated magnetic rice straw biochar at 40 kg N ha^{-1}, demonstrated significant potential for enhancing soil health in lowland-rice production systems.

Keywords: Microbial biomass carbon, microbial biomass nitrogen, dissolved organic carbon, dissolved organic nitrogen, urease.

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Introduction

Rice is one of the most widely cultivated cereals globally (≈ 480 million MT annually), serving as a staple food for more than half of the world's population (Muthayya *et al*. 2014; Fukagawa and Ziska 2019). Rice has high requirement for nutrient, especially nitrogen (N), and the yields are often proportional to fertilizer amounts. The crop's N need is majorly met via application of inorganic fertilizer. However, production and use of N fertilizers have both environmental and cost implications. Production of nitrogen fertilizer through Haber-Bosch *process* consumes lots of fossil energy with attendant consequences on the cost of final product and global carbon emission (International Fertilizer Industry Association 2009). Furthermore, poor N management under waterlogged condition in lowland rice cultivation is a major contributor to groundwater pollution (via runoff) and greenhouse gas (CH_4 and N_2O) emission due to N loss through volatilization and denitrification (Qiao *et al*. 2022; Islam *et al*. 2022).

Another environmental challenge associated with rice production is open burning of the rice straw after grain harvest in order to get rid of the massive waste generated. This practice is still popular in Nigeria amidst many other developing countries, and it releases toxic gases into the atmosphere, contributing to air pollution and greenhouse gas emission (Jenkins *et al*. 2003; Chukwudebelu *et al*. 2015). Rice straw has also been incorporated into the rice field to serve as manure for subsequent rice crop; although this helps in a way to manage the huge biomass waste and reduce annual emissions of N_2O, the practice has been associated with CH_4 emission if not properly managed (Li *et al*. 2021).

Consequently, to better manage nutrient N and straw waste in lowland rice production, a number of innovative techniques have been adopted such as converting rice straw to biochar or impregnating magnetism on rice straw and subsequently converting to biochar to form the iron-modified biochar (Ruthiraan *et al*., 2014) which has been found to improve the adsorption efficiency of the biochar (Oladipo and Ifebajo 2018; Li *et al*. 2020; Luo *et al*. 2021). Biochar from ordinary rice straw or magnetic rice straw has also been chemically combined (intercalated) with N fertilizer such as urea whereby the ammonia (NH_4^+) is absorbed and released slowly into the soil for plant uptake during rice growth (Fang *et al*. 2016), thereby, increasing rice yield.

The bulk of rice cultivated in Nigeria is done on water-logged soils, representing 43–53% of the country's absolute rice production (Akpokodje *et al*. 2001; Imolehin and Wada 2005; UNEP, 2005). However, many Nigerian soils, typical of tropical soils, are low in activity clay, percentage base saturation and organic matter; and as such, they are highly degraded and poor in nutrient and health. Soil nutrient replenishment and health maintenance have been considered key tools for achieving food security in Africa, including the Sahel (Vanlauwe *et al*. 2023). Hence, application of biochar and magnetic biochar can positively impact on the nutrient and health status of the degraded tropical soils. Biochar addition to soil has been reported to enhance organic carbon sequestration (Hayes 2013), improve soil structure, fertility, water retention and crop yield (Liu *et al*. 2018; Sun *et al*. 2022). While a few previous studies in China have reported positive response of paddy rice to biochar and magnetic biochar application (Li *et al*. 2020; Luo *et al*. 2021), data remain limited on such studies on lowland rice cultivation, especially as it affects the health and nutrient status of Nigerian tropical soils.

Various soil physical, chemical and biological indicators have been used to assess soil health. Few among such indicators are soil pH, organic carbon (OC), total N, available P, exchangeable cations (Ca, Mg, K) and biological indicators such as enzymes (e.g., urease), microbial biomass carbon (MBC) and nitrogen (MBN), as well as dissolved organic carbon (DOC) and nitrogen (DON). Soil enzymes are associated with biochemical cycles occurring in the soil environment which involve but not restricted to mineralization of soil organic matter and other biogeochemical cycling of nutrients (Makoi and Ndakidemi 2008). For instance, urease is an enzyme found to be linked with nitrogen cycling in the soil. The MBC, MBN, DOC and DON on the other hand, constitute a key part of biogeochemical cycles of C and N in terrestrial and aquatic ecosystems (Michalzik 2001; Gong *et al*. 2022). Therefore, the aim of the current study was to assess the health of gleysol cultivated to rice under application of rice straw and magnetic rice straw biochar intercalated with urea fertilizer in a rainforest ecological zone of Nigeria.

Materials and Methods

Collection and determination of the properties of soil used for the screenhouse study

Bulk soil samples were randomly collected from a wet valley bottom at the Obafemi Awolowo University (OAU) (longitudes 4º20' E and 4º31' E and latitudes 7º29' N and 7º49' N), Ile-Ife, Osun State, Nigeria. The soil, after thorough homogenization and air-drying was passed through 4 mm and 2 mm sieves for the screenhouse and laboratory studies, respectively. The physical and chemical properties of the soil are as follows: textural class of loamy sand with sand, silt and clay percentages of 797, 80 and 123 g kg^{-1}, respectively; pH (0.01M $CaCl_2$) of 3.8; total N content of 0.4%; OC of 2.4%; C/N ratio of 6; available P content (Bray-1 method) of 22.4 mg kg^{-1};

exchangeable Ca, K, Mg and Na contents of 1.57, 1.22, 0.65 and 0.02 mg kg^{-1}, respectively; and extractable Fe of 14.35 mg kg^{-1}.

Preparation and determination of the properties of rice straw biochar, magnetic rice straw biochar and their urea-intercalated derivatives

Rice straw which was collected from the Africa Rice Center, International Institute of Tropical Agriculture (IITA), Ibadan, Oyo State, Nigeria was rinsed in distilled water and air-dried. As already described and referenced in Akinyemi *et al*. (submitted for publication), the air-dried rice straw was subjected to pyrolysis at a temperature of 450°C (Ruthiraan *et al*. 2014) at the Department of Mechanical Engineering, University of Ibadan, Ibadan, Nigeria.

To obtain the magnetic rice straw biochar, rice straw was soaked in a 0.6 M $FeCl_3$ solution at ratio 1:8 (w/v) for 2 hours and then removed, drained, oven dried for 48 hours at 60°C and pyrolyzed (Ruthiraan *et al*. 2014).

Urea intercalated rice straw biochar and magnetic rice straw biochar were each obtained by dissolving urea fertilizer in distilled water at ratio 1:1 (w/v), and then adding and mixing the biochar in the ratio 1:1 (g/ml) (Manikandan and Subramanian 2013). The mixture of the biochar and urea solution was oven dried at 65°C till constant weight. The oven-dried mixture was set by adding one gram (1 g) of adhesive polymer (e.g., starch) and air-drying. The chemical properties of the biochar: rice biochar (RB), urea intercalated rice straw biochar (URB), magnetic rice straw biochar (MRB) and urea intercalated magnetic rice straw biochar (UMRB) are as follows: pH – 9.5, 9.4, 6.6 and 7.1, respectively; OC – 49.9, 36.5, 56.8 and 44.5%, respectively; total N – 1.22, 29.8, 1.54, and 35.6%, respectively; and total P – 58.4, 49.1, 22.6 and 19.7 mg kg^{-1}, respectively.

Treatment combination and screenhouse experiment

Screenhouse set-up included 12 treatments as follows: urea at 0 kg N ha^{-1} and 80 kg N ha^{-1}, 30 t ha^{-1} rice straw biochar ha^{-1} (RB), 30 t magnetic rice straw biochar ha^{-1} (MRB), 30 t rice straw biochar ha^{-1} + two split applications of urea at 80 kg N ha^{-1} (RBU), 30 t rice straw biochar ha^{-1} intercalated with urea at 40, 60 and 80 kg N ha^{-1} (URB1–3), 30 t magnetic rice straw biochar ha^{-1} + two split applications of urea at 80 kg N ha^{-1} (MRBU), 30 t magnetic rice straw biochar ha^{-1} intercalated with urea at 40, 60 and 80 kg N ha^{-1} (UMRB1–3). Fifteen-day-old rice (FARO 52) seedlings raised from seeds obtained from the Africa Rice Center, IITA, Ibadan, Nigeria, were transplanted into pots filled with 3 kg air-dried, 4 mm - sieved soil that had been mixed according to treatments. The soils were wetted and allowed to wait for 24 hours prior to transplanting. Application of treatments involving sole urea was done in two splits: at planting and panicle formation stages. The experiment was replicated three times and laid out in a completely randomized design. The pots were maintained at water level of 5 cm above the soil surface throughout the experiment. Soil samples were collected at 0, 7 and 14 days after rice transplanting to determine urease activities. Further, soil samples were collected across treatments after rice harvest for the determination of the following chemical and biological soil health indicators: soil pH, OC, TN, available P, exchangeable cations (Na, K, Ca, Mg and Fe), urease activity, microbial biomass C and N, and dissolved organic C and N.

Analytical techniques

The following soil chemical properties were determined following standard procedures: soil particle size analysis, pH (0.01 M $CaCl_2$), organic carbon (Walkley and Black 1934; Allison 1965), TN using micro-Kjeldahl digestion, distillation, and titration processes (Bremner, 1996), available P extracted using the Bray-1 method and colorimetrically determined at 660 nm wavelength after the development of the molybdenum blue color (Bray and Kurtz 1945); exchangeable cations extracted using 1 N neutral ammonium acetate solution (Soil Survey Staff 2003) and the concentrations of Na and K determined using S-935/ Micro-processor Flame Photometer while Ca, Fe and Mg were determined using 230ATS Atomic Absorption Spectrometer (AAS). The DOC and DON were determined following the procedures of Ciavatta *et al*. (1991) and Kolthoff and Sandell (1952), respectively. The MBC and MBN were determined as described by Witt *et al*. (2000). Urease enzyme analysis was determined by the method of Tabatabai and Bremner (1972).

Statistical analyses

The data obtained from the study were subjected to Analysis of Variance (ANOVA) using SAS statistical package (SAS System 9.0). Treatment means were separated using the Duncan's multiple range test at 0.05 probability level.

Results

Chemical properties of the soil after rice harvesting

Although the soil pH after plant harvesting ranged from very strongly acid to moderately acid, slight improvement was observed with biochar application except in pots treated with UMRB1, UMRB2 and UMRB3 and Urea, where the pH slightly reduced compared with the control (Table 1). All the treated soils containing biochar in any form had higher organic C content than the sole urea-treated soil and the control. The increases in the OC contents of the biochar-based treatments over those of urea and the control ranged from 14–

107% and 7–93%, respectively, with the MRB-treated soil having the highest value of OC (2.9% higher than the control). It was also observed that introduction of magnetism (Fe) into the biochar enhanced the soil OC compared with the non-magnetic biochar e.g., soils treated with UMRB1 and UMRB2 had significantly higher organic C values than those treated with URB1, URB2 and URB3 ($p<0.05$). The results on soil TN showed that it was increased in the various treatments over the control by 23–79%, with the highest increase obtained with URB1 and UMRB1. The available P in the soil was increased by the treatments (except RB) over the control by between 12 and 41%.

The exchangeable cation concentrations after rice harvesting, as presented in Table 2, were increased by some of the soil amendments over the control. The soil Na concentration was increased over the control mostly in the soils treated with sole urea or biochar/magnetic biochar co-applied or intercalated with urea. While the treatments did not significantly affect the K concentrations in the soils, magnetic biochar with or without urea intercalation increased Ca (33–106%) and Mg (14–57%) concentrations compared with the control. Fe concentration was, however, increased by all amendments (except UMRB1) by 1-263% over the control.

Table 1: Some chemical properties of soil amended with rice straw biochar, rice straw magnetic biochar and their urea intercalated derivatives after rice harvest in the screenhouse

Treatments	pH (0.01 M $CaCl_2$)	OC (%)	TN (%)	Avail. P (mg kg^{-1})
Control	4.33	1.5i	0.43d	17g
Urea	3.99	1.4j	0.53cd	21e
RB	5.10	2.5b	0.63bc	17g
MRB	4.38	2.9a	0.53cd	21e
RBU	5.18	1.7g	0.63bc	19f
MRBU	4.36	2.2d	0.57bc	19f
URB1	4.06	1.6h	0.77a	21e
URB2	4.12	1.9f	0.64b	22c
URB3	4.02	2.0e	0.53cd	24a
UMRB1	3.16	2.3c	0.77a	22d
UMRB2	3.33	2.5b	0.67ab	23b
UMRB3	3.76	1.6h	0.67ab	21e

Means in a column with the same alphabet(s) are not significantly different from each other at probability level (α) of 0.05. OC – organic carbon, TN – total nitrogen, Avail. P – Available phosphorus, Control-No RB, Urea at 80 kg Nha^{-1}, RB-Rice straw biochar at 30 t ha^{-1}, MRB-Magnetic rice straw biochar at 30 t ha^{-1}, RBU-Rice straw biochar (30 t ha^{-1}) + two split applications of urea at 80 kg N ha^{-1}, MRBU-Magnetic rice straw biochar (30 t ha^{-1}) + two split applications of urea at 80 kg N ha^{-1}, URB1-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 40 kg N ha^{-1}, URB2-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 60 kg N ha^{-1}, URB3-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 80 kg N ha^{-1}, UMRB1--Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 40 kg N ha^{-1}, UMRB2--Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 60 kg N ha^{-1}, UMRB3–

Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 80 kg N ha^{-1}.

Table 2: Exchangeable cations in soil amended with rice straw biochar, rice straw magnetic biochar and their urea intercalated derivatives after rice harvesting in the screenhouse

Treatments	Na	K	Ca	Mg	Fe
		(cmol kg^{-1})			(mg kg^{-1})
Control	0.01c	0.02f	1.8i	0.7d	8.7k
Urea	0.02b	0.03e	1.9h	0.8c	24.9c
RB	0.01c	0.08b	2.0g	0.9b	19.8e
MRB	0.01c	0.07c	2.4d	0.9b	26.8b
RBU	0.02b	0.09a	1.7j	0.9b	20.7d
MRBU	0.02b	0.07c	2.8c	0.8c	31.6a
URB1	0.03a	0.03e	1.8i	0.7d	10.1h
URB2	0.02b	0.02f	2.1f	0.8c	9.0i
URB3	0.02b	0.03e	2.2e	0.7d	12.7f
UMRB1	0.03a	0.02f	3.7a	1.1a	6.9l
UMRB2	0.03a	0.04d	2.4d	0.9b	8.8j
UMRB3	0.03a	0.02f	2.9b	0.8c	11.9g

Means in a column with the same alphabet(s) are not significantly different from each other at probability level (α) of 0.05. Na- Sodium, Mg- Magnesium, Ca-Calcium, Fe-Iron, K-Potassium, Control-No RB, Urea at 80 kg Nha^{-1}, RB-Rice straw biochar at 30 t ha^{-1}, MRB-Magnetic rice straw biochar at 30 t ha^{-1}, RBU-Rice straw biochar (30 t ha^{-1}) + two split applications of urea at 80 kg N ha^{-1}, MRBU-Magnetic rice straw biochar (30 t ha^{-1}) + two split applications of urea at 80 kg N ha^{-1}, URB1-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 40 kg N ha^{-1}, URB2-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 60 kg N ha^{-1}, URB3-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 80 kg N ha^{-1}, UMRB1-Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 40 kg N ha^{-1}, UMRB2–Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 60 kg N ha^{-1}, UMRB3--Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 80 kg N ha^{-1}.

Urease activity in soil under application rice straw biochar, rice straw magnetic biochar and their urea intercalated derivatives

The urease activity in the soil from day 0 to 14 after transplanting the rice seedling are presented in Table 3. The urease activity was significantly lower in the amended soils than the control at day 0. At days 7 and 14, however, the various amendments when compared with the control, significantly increased the soil urease activity by 9–57% and 8–54%, respectively ($p<0.05$), with the urea-intercalated magnetic biochar giving the highest values in the order of UMRB2 > UMRB1 > UMRB3.

Microbial biomass and dissolved organic matter in soil under application of rice straw biochar, rice straw magnetic biochar and their urea intercalated derivatives

The MBC and MBN were significantly increased majorly by UMRB3, UMRB1, UMRB2 and MRB over the control ($p<0.05$, Fig. 1). The increases recorded by the specified treatments over the control ranged from 420–481% for MBC, and 425–625% for MBN. No consistent trend was observed in the DOC and DON values for the various treatments relative to the control, except that the highest values of DOC and DON were obtained with URB3 and UMRB2, respectively.

Table 3: Urease activities in soils amended with rice straw biochar, rice straw magnetic biochar and their urea intercalated derivatives at days 0, 7 and day 14 after rice transplanting in the screenhouse

Treatment	Day 0	Day 7	Day 14
	mg $NH_4^+N\ g^{-1}d^{-1}$		
Control	8.74a	5.96l	6.24l
Urea	8.59b	6.52k	6.73k
RB	6.37i	6.99i	7.02j
MRB	6.87d	7.12h	7.36i
RBU	6.79e	6.82j	7.57h
MRBU	6.93c	7.56g	7.90g
URB1	5.90l	8.05f	8.11f
URB2	6.70f	8.10e	8.23e
URB3	6.65g	8.36d	8.60d
UMRB1	5.99k	9.28b	9.36b
UMRB2	6.56h	9.35a	9.63a
UMRB3	6.05j	8.69c	8.76c

Means in a column with the same alphabet(s) are not significantly different from each other at probability level (α) of 0.05. Control – No RB, Urea at 80 kg Nha^{-1}, RB-Rice straw biochar at 30 t ha^{-1}, MRB-Magnetic rice straw biochar at 30 t ha^{-1}, RBU-Rice straw biochar (30 t ha^{-1}) + two split applications of urea at 80 kg N ha^{-1}, MRBU-Magnetic rice straw biochar (30 t ha^{-1}) + two split applications of urea at 80 kg N ha^{-1}, URB1-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 40 kg N ha^{-1}, URB2-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 60 kg N ha^{-1}, URB3-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 80 kg N ha^{-1}, UMRB1-Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 40 kg N ha^{-1}, UMRB2-Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 60 kg N ha^{-1}, UMRB3--Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 80 kg N ha^{-1}.

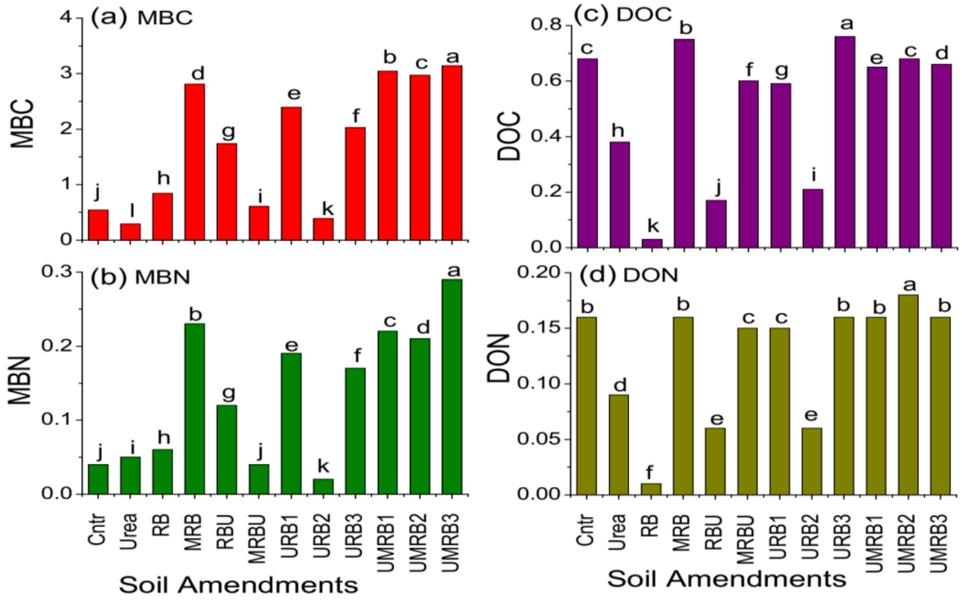

Fig. 1: The MBC (a), MBN (b), DOC (c) and DON (d) in soil amended with rice straw biochar, rice straw magnetic biochar and their urea intercalated derivatives in the screenhouse. Values are means of three replicates. Treatments that share common alphabet(s) are not significantly different from each other at probability level (α) of 0.05. MBC-Microbial biomass carbon, MBN- Microbial biomass nitrogen, DOC-Dissolved organic carbon, DON- Dissolved organic nitrogen, Control-No RB, Urea at 80 kg Nha^{-1}, RB-Rice straw biochar at 30 t ha^{-1}, MRB-Magnetic rice straw biochar at 30 t ha^{-1}, RBU-Rice straw biochar (30 t ha^{-1}) + two split applications of urea at 80 kg N ha^{-1}, MRBU-Magnetic rice straw biochar (30 t ha^{-1}) + two split applications of urea at 80 kg N ha^{-1}, URB1-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 40 kg N ha^{-1}, URB2-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 60 kg N ha^{-1}, URB3-Rice straw biochar (30 t ha^{-1}) intercalated with urea at 80 kg N ha^{-1}, UMRB1--

Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 40 kg N ha^{-1}, UMRB2--Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 60 kg N ha^{-1}, UMRB3--Magnetic rice straw biochar (30 t ha^{-1}) intercalated with urea at 80 kg N ha^{-1}.

Discussion

The slight improvement observed in the soil pH of pots treated with biochar with the exception of URMB, could be due to the presence of high ash content in biochar, and hydrolysis of soluble minerals (e.g., K and Na oxides) which favored a high electron activity and low free H^+ level (Yin *et al*. 2017). Biochar-based treatments, except the urea intercalated magnetic rice straw biochar and sole urea, increased soil pH compared with the control, indicating their potentials for soil pH management (Rinklebe *et al*. 2016). The higher organic C in biochar than sole urea treatments could be attributed to the carbonaceous nature of biochar (Lehmann *et al*. 2007a, b). Further, the significantly higher organic C content in pots treated with UMRB than those with URB could arise from the capacity of Fe metal in biochar to reduce the conversion of carbon to methane in waterlogged soils. The higher value of total N concentrations observed with UMRB could be as a result of an improvement in the absorptive potential of biochar due to the presence of Fe (Güereña *et al*., 2013; Zhao *et al*., 2014). Biochar has high adsorptive surface for nutrient retention, while magnetic biochar has also been reported to possess higher surface area (up to 12 folds) and contribute to increase of around 10-fold in CEC than the non-magnetic biochar (Silva *et al*. 2020). Hence, the added biochar and the magnetic biochar in the current study increased the available P and exchangeable cation (Na, Ca, Mg and Fe) contents of the soil.

The urease enzyme activity indicates the nutritional status of the soil and the efficiency of N mineralization in soil (Mierzwa-Hersztek *et al*. 2018). Specifically, urease is responsible for the conversion of urea to ammonia (NH_3) and carbon dioxide (CO_2) (Koçak 2020).

At day 0 after rice transplanting, the microbial mineralization of nutrients, especially N in the amended soils was not yet conspicuous. There might also be temporary nutrient (N) immobilization from the soils, arising from the addition of biochar – a highly carbonaceous material with high C:N ratio, resulting in low urease activity. However, the sharp increase in urease activity at days 7 and 14 indicated active microbial mineralization of N from the added non-magnetic biochar, magnetic biochar and their urea-intercalated derivatives. Previous study had reported an increase in the rate of urease activity in soil, following the application of biochar, thus leading to an increase in the availability of soil NH_4^+-N for plant uptake (Teutscherova *et al*. 2018; Khan *et al*. 2019; Wu *et al*. 2020; Lopes *et al*. 2021). The highest values of urease activity recorded with urea-intercalated magnetic biochar in the current study indicated that intercalating urea on magnetic biochar further enhanced N release in the soil. The significantly high microbial biomass C and N contents observed in pots treated with urea intercalated rice straw magnetic biochar (UMRB1, UMRB2 and UMRB3), could be attributed to positive effect of the amendments on soil microbial community, which could trigger their diversities, population and activity, resulting in increased assimilation of C and N and other nutrients into their cells (Mierzwa-Hersztek 2020; Wu *et al*. 2023). Microbial biomass carbon is an important component of soil carbon dynamics with medium to long mean resident time. Liu *et al*. (2019) suggested co-application of biochar with fertilizer for increasing soil microbial biomass. The lower contents of DOC and DON with many of the amendments than the control could be due to the recalcitrant nature of biochar, reducing DOC and causing temporary microbial N immobilization and consequently, low DON. Since DOC and DON are a labile organic matter source readily available for microbial uptake (Farrell *et al*. 2014), their concentrations could reduce due to the heightened microbial diversity and activity in the biochar-based treatments than in the control. The reduction in the DOC could also mean that much of the carbon in the biochar-based amendments was not metabolized by the soil microbial community, indicating that biochar addition could enhance soil organic carbon sequestration (Prommer *et al*. 2014).

In conclusion, soils receiving rice straw biochar, magnetic rice straw biochar and their intercalated derivatives had significantly higher organic C content in comparison with those receiving sole urea and no amendment. Introduction of magnetism (Fe) into the biochar further increased the soil organic C content when compared with the non-magnetic biochar. Similarly, soil total N content was significantly increased by the biochar-based amendments, with the highest increases obtained with rice straw biochar and magnetic rice straw biochar each intercalated with 40 kg N ha^{-1} urea. While the soil available P and Fe concentration were increased by most of the treatments, the Ca concentrations were mainly increased by magnetic biochar with or without intercalation with urea, when compared with the unamended control. The soil urease activity was also markedly increased by the rice-straw-biochar-based amendments. The highest values of urease activity as well as of soil microbial biomass C and N were obtained with urea-intercalated magnetic biochar. The highest values of DOC and DON were similarly obtained with rice straw biochar intercalated with urea at 80 kg N ha^{-1} and magnetic rice straw biochar intercalated with urea at 60 kg N ha^{-1}, respectively. While rice straw biochar, magnetic rice straw biochar and their urea-intercalated derivatives have been primarily targeted towards improved nitrogen use efficiency and rice yield in lowland rice production, soil incorporation of these organic amendments inadvertently enhances soil health, and should therefore, be considered for soil health management in sustainable lowland rice cultivation.

Authors' Contributions

Olusola Olajumoke Adesanwo conceptualised the study the study while all authors contributed to the study's design and execution. Material preparation, data collection and analysis were performed by Olatundun Titilope Akinyemi under the supervision of Cornelius Talade and Olajumoke Adesanwo. The manuscript draft was written by Cornelius Talade Atere and revised by Olajumoke Adesanwo. All authors read and approved the final version.

Ethics approval: This work has not been published elsewhere in any form or language (partially or full).

References

Akpokodje, G., Lançon, F. and Erenstein, O. 2001. Nigeria's rice economy: state of the art. Project report – The Nigerian Rice Economy in a Competitive World: Constraints, Opportunities and Strategic Choices, Bouake: WARDA. ii-55 pp.

Allison, L.E., Bollen, W. B. and Moodie, C. D. 1965. Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties. Agronomy Monographs, American Society of Agronomy, Agronomy Monographs 9 (1), Madison, Wisconsin, 1188 pp.

Bray, R. H. and Kurtz, L. T. 1945. Determination of total, organic, and available forms of phosphorus in soils, *Soil Science*, 59(1), 39-46.

Bremner, J. M. 1996. Nitrogen total, Methods of soil analysis: Part 3 Chemical methods, Madison, WI: SSSA Book Series 5, pp. 1085-1121.

Ciavatta, C., Govi, M., Antisari, L. V. and Sequi, P. 1991. Determination of organic carbon in aqueous extracts of soils and fertilizers, *Communications in Soil Science and Plant Analysis*, 22(9-10), 795-807.

Chukwudebelu, J. A., Igwe, C. C. and Madukasi, E. I. 2015. Prospects of using rice husk for the production of dense and hollow bricks, *African Journal of Environmental Science and Technology*, 9(5), 493-501.

Fang, C., Zhang, H., Wan, J., Wu, Y., Li, K., Jin, C., Chen, W., Wang, S., Wang, W. and Zhang, H. 2016. Control of leaf senescence by a MeOH-jasmonates cascade that is epigenetically regulated by OsSRT1 in rice, *Molecular Plant*, 9, 1366-1378.

Farrell, M., Prendergast-Miller, M., Jones, D. L., Hill, P. W. and Condron, L. M. 2014. Soil microbial organic nitrogen uptake is regulated by carbon availability, *Soil Biology and Biochemistry*, 77, 261-267.

Fukagawa, N. K. and Ziska, L. H. 2019. Rice: Importance for Global Nutrition. *Journal of Nutritional Science and Vitaminology*. (Tokyo). 65 (Supple-ment): S2-S3. doi: 10.3177/jnsv.65.S2. PMID: 31619630.

Gong, S., Feng, Z., Qu, A., Sun, J., Xu, X., Lai, Y. and Kong, Y. 2022. Effects of land-use types on the temporal dynamics of soil active carbon and nitrogen in the rocky mountainous of North China, *Soil Science and Plant Nutrition*, 68(1), 72-80.

Güereña, D., Lehmann, J., Hanley, K., Enders, A., Hyland, C. and Riha, S. 2013. Nitrogen dynamics following field application of biochar in a temperate North American maize-based production system, *Plant and Soil*, 365(1), 239-254.

Hayes, 2013. Relationships Between Biochar and Soil Humic Substances. In: J. Xu et al. (eds.), Functions of Natural Organic Matter in Changing Environment. Zhejiang University Press and Springer Science+Business Media Dordrecht, pp. 959-963.

Imolehin, E. D. and Wada, A. C. 2005. Meeting the rice production and consumption demands of Nigeria with improved technologies, International rice commission newsletter, 49, FAO, Rome.

International Fertilizer Industry Association, 2009, Fertilizers, climate change and enhancing agricultural productivity sustainably, Paris, France: International Fertilizer Industry Association.

Islam, S. M. M., Gaihre, Y. K., Islam, Md. F., Ahmed, Md. N., Akter, M., Singh, U. and Sander, B. O. 2022. Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management, *Journal of Environmental Management*, 307, 114520.

Jenkins, J., Chojnacky, D. C., Heath, L. S. and Birdsey, R. A. 2003. National scale biomass estimators for united state tree species, *Forest Science*, 49(1), 12-35.

Khan, A., Szulejko, J. E., Samaddar, P., Kim, K. H., Liu, B., Maitlo, H. A. and Ok, Y. S. 2019. The potential of biochar as sorptive media for removal of hazardous benzene in air, *Chemical Engineering Journal*, 361, 1576-1585.

Koçak, B. 2020. Importance of urease activity in soil. International Scientific and Vocational Studies Congress – Science and Health (BILMES SH 2020), 12-15 December 2020, Turkey.

Kolthoff, I. M. and Sandell, E. B. 1952. Textbook of Quantitative Inorganic Analysis, 3rd Edition, New York: The Macmillan Company, p. 759.

Lehmann, J. 2007a. Bio-energy in the black, *Frontiers of Ecology Environ-ment*, 5, 381-387.

Lehmann, J. 2007b. A handful of carbon, *Nature*, 447, 143-144.

Li, J., Wang, S. L., Zhang, J., Zheng, L., Chen, D., Wu, Z. and Wu, W. 2020. Coconut-fiber biochar reduced the bioavailability of lead but increased its translocation rate in rice plants: elucidation of immobilization mechanisms and significance of iron plaque barrier on roots using spectroscopic techniques, *Journal of Hazardous Materials*, 389, 122117.

Li, S. H., Guo, L. J., Cao, C. G. and Li, C. F. 2021. Effects of straw returning levels on carbon footprint and net ecosystem economic benefits from rice-wheat rotation in central China, *Environmental Science and Pollution Research*, 28, 5742-5754.

Liu, L., Li, J., Yue, F., Yan, X., Wang, F., Bloszies, S. and Wang, Y. 2018. Effects of arbuscular mycorrhizal inoculation and biochar amendment on maize growth, cadmium uptake and soil cadmium speciation in Cd-contaminated soil, *Chemosphere*, 194, 495-503.

Liu, S., Li, J., Xu, S., Wang, M., Zhang, Y. and Xue, X. 2019. A modified method for enhancing adsorption capability of banana pseudostem biochar towards methylene blue at low temperature, *Bioresource Technology*, 282, 48-55.

Lopes, É. M. G., Reis, M. M., Frazão, L. A., da Mata Terra, L. E., Lopes, E. F., dos Santos, M. M. and Fernandes, L. A. 2021. Biochar increases enzyme activity and total microbial quality of soil grown with sugarcane, *Environmental Technology & Innovation*, 21, 101270.

Luo, W., Qian, L., Liu, W., Zhang, X., Wang, Q., Jiang, H., Cheng, B., Ma, H. and Wu, Z. 2021. A potential Mg-enriched biochar fertilizer: excellent slow-release performance and release mechanism of nutrients, *Science Total Environment*, 768, 144454.

Makoi, J. H. and Ndakidemi, P. A. 2008. Selected soil enzymes: Examples of their potential roles in the ecosystem, *African Journal of Biotechnology*, 7, 181-191.

Manikandan, A. and Subramanian, P. A. 2013. Urea Intercalated Biochar-a Slow Release Fertilizer Production and Characterisation, *Indian Journal of Chemistry Technology*, 6, 5579-5584.

Mierzwa-Hersztek, *et al.* (2018). Biochar changes in soil based on quantitative and qualitative humus compounds parameters, *Soil Science Annual*, 69(4), 234-242.

Mierzwa-Hersztek, M., Gondek, K., Kopeć, M. and Ukalska-Jaruga, A. 2020. Effect of Coapplication of Biochar and Nutrients on Microbiocenotic Composition, Dehydrogenase Activity Index and Chemical Properties of Sandy Soil, *Waste Biomass Valorization*, 11, 3911-3923.

Michalzik, B., Kalbitz, K., Park, J. H., Solinger, J. and Matzner, E. 2001. Fluxes and concentrations of dissolved organic carbon and nitrogen – A synthesis for temperate forest, *Biogeochemistry*, 52, 73-205.

Muthayya, S., Sugimoto, J. D., Montgomery, S. and Maberly, G. F. 2014. An Overview of Global Rice Production, Supply, Trade, and Consumption: Global Rice Production, Consumption, and Trade, *Annals of the New York Academy of Sciences*, 1324, 7-14.

Oladipo, A. and Ifebajo, A. 2018. Highly efficient magnetic chicken bone biochar for removal of tetracycline and fluorescent dye from wastewater: Two-stage adsorber analysis, *Journal of Environmental Management*, 209, 9-16.

Prommer, J., Wanek, W., Hofhansl, F., Trojan, D., Offre, P., Urich, T., Schleper, C., Sassmann, S., Kitzler, B., Soja, G. and Hood-Nowotny, R. C.

2014. Biochar decelerates soil organic nitrogen cycling but stimulates soil nitrification in a temperate arable field trial, PLoS One, 9(1), e86388.

Qiao, J. Wang, J., Zhao, D., Zhou, W., Schwenke, G., Yan, T. and Liu, D. L. 2022. Optimizing N fertilizer rates sustained rice yields, improved N use efficiency, and decreased N losses via runoff from rice-wheat cropping systems, *Agriculture, Ecosystems & Environment*, 324, 107724.

Rinklebe, J., Shaheen, S. M. and Frohne, T. 2016. Amendment of biochar reduces the release of toxic elements under dynamic redox conditions in a contaminated floodplain soil, *Chemosphere*, 142, 41-47.

Ruthiraan, M., Mubarak, N. M., Thines, R. K., Abdullah, E. C., Sahu, J. N., Jayakumar, N. S. and Ganesan, P. 2014. Comparative kinetic study of functionalized carbon nanotubes and magnetic biochar for removal of Cd^{2+} ions from wastewater, *Korean Journal of Chemical Engineering*, 32(3), 446-457.

Silva, T. C. F., VergÜtz, L., Pacheco, A. A., Melo, L. F., Renato, N. S. and Melo, L. C. A. 2020. Characterization and application of magnetic biochar for the removal of phosphorus from water, *Anais da Academia Brasileira de Ciências*, 92(3), e20190440.

Soil Survey Staff (2003). Keys to Soil Taxonomy. 9th Edition, United States Department of Agriculture, United States Department of Agriculture Natural Resources Conservation Service, 322p.

Sun, Q., Yang, X., Meng, J., Lan, Y., Han, X., Chen, W. and Huang, Y. 2022. Long-Term Effects of Straw and Straw-Derived Biochar on Humic Substances and Aggregate-Associated Humic Substances in Brown Earth Soil, *Frontiers in Environmental Science*, 10, 899935.

Tabatabai, M. A. and Bremner, J. M. 1972. Assay of Urease Activity in Soils, *American Journal of Soil Science Society*, 41, 350-352.

Teutscherova, N., Houška, J., Navas, M., Masaguer, A., Benito, M. and Vazquez, E. 2018. Leaching of ammonium and nitrate from Acrisol and Calcisol amended with holm oak biochar: A column study, *Geoderma*, 323, 136-145.

UNEP. 2005. Integrated Assessment of the Impact of Trade Liberalization: A Country Study on the Nigerian Rice Sector, 107pp. United Nations environment programme. Retrieved from https://wedocs.unep.org/rest/bitstreams/11296/retrieve on 12th December, 2023.

Vanlauwe, R., Amede, T., Bationo, A., Bindraban, P., Breman, H., Cardinael, R., Couedel, A., Chivenge, P., Corbeels, M., Dobermann, A., Falconnier, G., Fatunbi, W., Giller, K., Harawa, R., Kamau, M., Merckx, R., Palm, C., Powlson, D., Rusinamhodzi, L., Six, J., Singh, U., Stewart, Z., van Ittersum, M., Witt, C., Zingore, S. and Groot, R. 2023. Fertilizer and Soil Health in Africa: The Role of Fertilizer in Building Soil Health to Sustain Farming and Address Climate Change, International Fertilizer Development Center Po Box 2040 | Muscle Shoals, Al 35662 |USA, 76pp.

Walkley, A. and Black, C. A. 1934. An estimation of methods for determining organic carbon and nitrogen in the soils, *The Journal of Agricultural Science*, 25, 598-609.

Witt, C., Gaunt, J., Galicia, C. C., Ottow, J. C. G. and Neue, H. U. 2000. A rapid chloroform-fumigation extraction method for measuring soil microbial biomass carbon and nitrogen in flooded rice soils, *Biological Fertility Soils*, 30, 510-519.

Wu, L., Zhang, S., Wang, J. and Ding, X. 2020. Phosphorus retention using iron (II/III) modified biochar in saline-alkaline soils: Adsorption, column and field tests, *Environmental Pollution*, 261, 114223.

Wu L., Zhang K., Zhu X., Lu T. and Wang X. 2023. Effects of amendments on carbon and nitrogen fractions in agricultural soils of Yellow River Delta, *Geoscience Letters*, 10, 22.

Yin, D., Wang, X., Peng, B., Tan, C. and Ma, L. Q. 2017. Effect of biochar and Fe-biochar on Cd and As mobility and transfer in soil-rice system, *Chemosphere*, 186, 928-937.

Zhao, X., Wang, J., Wang, S. and Xing, G. 2014. Successive straw biochar application as a strategy to sequester carbon and improve fertility: A pot experiment with two rice/wheat rotations in paddy soil, *Plant and Soil*, 378(1), 279-294.