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MINERAL NITROGEN DYNAMICS OVER TIME INFLUENCED BY PEANUT-WASTE BIOCHAR APPLICATION IN ALKALINE SOIL

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ABSTRACT

Soil fertility in arid to semi-arid regions is constrained by extreme temperature fluctuations. Soils of such regions typically have low fertility levels, nitrogen (N) availability (due to ammonia volatilization and denitrification), and soil organic carbon (SOC) content. An incubation experiment was conducted to assess how a peanut-waste biochar (PB), produced at 300°C, influences the mineral N and chemical properties of an alkaline soil. The treatments included five PB rates (control, 5, 10, 15, and 20g PB kg^{-1} soil) and two fertilizer rates [no fertilization without additions of N and phosphorus (P) and fertilization with addition of 120kg N ha^{-1} and 90kg P ha^{-1}]. The soil was incubated for various durations (0, 14, 28, 42, and 56days). There were significant temporal shifts in the mineral form of N in the incubated soil. Following 56days of incubation under fertilization, the treatment with 20g kg^{-1} PB revealed soil nitrate-N and ammonium-N levels of 15.8mg kg^{-1} and 21.1mg kg^{-1}, respectively. With no fertilization, 20g kg^{-1} PB increased mineral N by 2.3-fold over the treatment without PB. This increase was 2.6-fold with fertilization. After 56days of incubation, in the presence of 20g kg^{-1} PB, there was a 19% increase in cation exchange capacity under fertilization and a 21% increase under no fertilization, compared to the respective treatments without PB. Immediately after the PB application, SOC was significantly increased, corresponding to PB rates. However, substantial increases were observed only in treatments with 15 and 20g PB kg^{-1} soil. In conclusion, the addition of 15 and 20g PB kg^{-1} to alkaline soil significantly increased N availability in soil, demonstrating the importance of biochar for N management in agricultural soils.

KEYWORDS: Peanut-waste biochar, mineral nitrogen, nitrate, ammonium, alkaline soil

INTRODUCTION

Aridisols are present in various countries across arid to semi-arid regions, including Ireland, Iran, the United Kingdom, central Saudi Arabia, Iraq, Afghanistan, Yemen, Pakistan, Lebanon, Jordan, central Sudan, and Syria (FAO 2011, 2015). These soils typically exhibit low levels of SOC and N. One important factor determining soil fertility is the contents of organic matter in soils, constituting at least 95% of the total N (Steiner *et al.* 2007; Liu *et al.*, 2020). Low contents of organic matter and low levels of soil fertility are key characteristics of alkaline soils, presenting a severe hurdle to soil productivity. Previous research has suggested the addition of mulches, compost, cover crops, farmyard manures, and other organic amendments to soils to enhance soil fertility and SOC, however, the efficacy of such amendments is often limited, particularly in semi-arid to arid regions (Saleem *et al*., 2020; Zhang *et al*., 2022). Fast decomposition of these amendments leads to temporary benefits, as SOC contents are rapidly converted into methane and carbon dioxide (Tomczyk *et al*., 2020). In contrast, the remarkably stable aromatic structure of biochar renders it an increasingly crucial soil amendment, primarily because of its capacity to improve soil nutritional, biological, and chemical properties. Thus, biochar can sustainably improve productivity from problem soils.

In areas with arid to semi-arid climates, such as Pakistan, the effectiveness of N fertilizer application in agricultural soils is significantly lower compared to moderate climates. There are considerable N losses following the application of nitrogenous fertilizers, attributed to factors like denitrification, nitrate leaching, and ammonia volatilization. For alkaline soils of Pakistan, urea is used as a primary source of N. However, the recovery efficiency of urea ranges from 30% to 50% only, the rest is lost in the environment and contributes to environmental problems (Ladha *et al*., 2005). The primary cause of this low efficiency is the loss during and after fertilizer application. The research on increasing the efficiency of applied N fertilizers is urgently needed both to boost agricultural output and to ensure environmental safety.

Nitrogen content in biochar ranges from 2 to 78g kg^{-1}, contingent on the type of feedstock and pyrolysis temperature/conditions (Chan and Xu, 2009). Using low pyrolysis temperature-produced biochar in soils may directly supply N and other nutrients to soils and, indirectly improve soil fertility by increasing ion exchange capacity and ammonium adsorption on the surfaces of biochar (Aon *et al*., 2023). The biochar can also stimulate the N-fixing activity of microorganisms (Gou *et al*., 2023) as well as improve the capacity of soil to hold moisture (Li *et al*., 2021).

The use of biochar having alkaline pH values has been noted for its ability to ease soil acidity (Yuan *et al*., 2011). In fact, the effects of biochar have been extensively studied on acidic or neutral soils. However, it is possible to prepare biochar having neutral to alkaline pH values. Such a type of biochar has the potential for use on alkaline soils (Abbas *et al*. 2010), and its benefits have also been documented (Aon *et al*., 2015). Moreover, carboxylic functional groups are produced as a result of slow oxidization of biochar (Cheng *et al*., 2006). Thus, because of formation of the acidic functional groups, soil application of such type of biochar may neutralize alkalinity factor. With varying types of feedstock and conditions of pyrolysis, it is possible to produce biochar having pH ranging from 4 to 12 (Lehmann, 2007). Moreover, for biochar production, during pyrolysis, processing temperatures less than 500°C favor nutrient retention (Chan and Xu, 2009). With all the above in view, this study evaluated the effects of peanut-waste biochar (PB), produced at low temperatures, on chemical properties and mineral-N dynamics in alkaline soil.

MATERIALS AND METHODS

Experimental materials: For the preparation of biochar, we used peanut waste collected from a peanut processing factory present at Rajbah Road, Faisalabad. This specific type of biochar was produced in a muffle furnace at the temperature of 300°C, as detailed by Sanchez *et al*. (2009). The characteristics of PB used in this study are given by Aon *et al*. (2018). The PB had 551g C kg^{-1}, 50g H kg^{-1}, 235g O kg^{-1}, 26g N kg^{-1}, 6g S kg^{-1}, 12g K kg^{-1}, 7g P kg^{-1}, 21g Ca kg^{-1}, 14g Mg kg^{-1}, 261mg Zn kg^{-1}, 51mg Cu kg^{-1}, 418mg Fe kg^{-1}, and 442mg Mn kg^{-1}. To ascertain its environmental safety, we also analyzed the biochar for selected non-essential heavy metals. The biochar had 0.07mg Cd kg^{-1}, 0.11mg Pb kg^{-1} and 0.62mg Cr kg^{-1}. In terms of physicochemical characteristics, PB had a CEC 49cmol$_c$ kg^{-1}, surface area of 39m^2 g^{-1}, and pH 6.91. Regarding proximate composition, PB had 138g ash kg^{-1}, 343g volatile matter kg^{-1}, and 642g yield kg^{-1} (conversion efficiency). In PB, carboxylic functional groups were present at a concentration of 0.14mol$_c$ kg^{-1}, phenolic functional groups at 0.16 mol$_c$ kg^{-1}, and lactonic functional groups at 0.13 mol$_c$ kg^{-1}, all of which contain oxygen. The elemental ratios of C:N, C:P, and C:S, were 21.1, 81.9, and 92.6, respectively. The elemental molar ratios of PB were 1.09 for the H:C ratio, 0.32 for O:C ratio, and 0.34 for (O+N): C ratio.

In this study, a soil specimen was collected from the Experimental area of the Institute of Soil and Environmental Science, Agriculture University, Faisalabad, sourced from the surface layer at a depth ranging from 0 to 15cm. The soil sample underwent air-drying and subsequent grinding to achieve a particle size suitable for passage through a 2mm sieve. Post-sieving, sandy clay loam was composed of 212g clay kg^{-1}, 225g silt kg^{-1}, and 563g sand kg^{-1}. The texture of the soil was measured by the hydrometer method, as outlined by Gee and Bauder (1986).

The pH of the soil was 8.23, measured in saturated soil paste. Electric conductivity was measured in saturated soil extract, and it was 1.13dS m^{-1}. Soil organic matter, determined by the Walkley-Black method (Nelson and Sommers 1982), was 5.3g kg^{-1}. A cation exchange capacity of 6.75cmol$_c$ kg^{-1} soil was measured following Rhoades (1982). The determination of soil total N followed the Kjeldahl method (Jackson, 1962). It was 0.7g N kg^{-1}. The extractable K, determined by the method of Richards (1954) was 127mg kg^{-1}. Olsen P, determined by extracting the soil with a sodium bicarbonate solution (Olsen and Sommers, 1982), was 4.3mg kg^{-1}. The content of calcium carbonate was determined using the method proposed by Leoppert *et al*. (1984), resulting in 34.3g kg^{-1}. For the evaluation of soil NH_4^+-N content, a potassium sulfate extraction method was applied, recording 3.18g kg^{-1} soil. This was analyzed using the indophenol blue method (Clare and Stevenson, 1964). Soil NO_3^--N was determined by the ammonium bicarbonate-DTPA method (Soltanpour and Schwab, 1977). Subsequently, the hydrazine reduction procedure was applied, leading to a value of 2.40mg kg^{-1} soil. This measurement was conducted on a spectrophotometer at a wavelength of 540nm (Kamphake *et al*., 1967).

Incubation experiment: A soil incubation study was conducted in a laboratory of the University. The aim was to evaluate the impact of various PB rates (control, 5, 10, 15, and 20g PB kg^{-1} soil on a weight/weight basis) on N dynamics and chemical properties in alkaline soil. This assessment was conducted with and without fertilization and at sampling times of 0, 14, 28, 42, and 56days. Hence, there were five PB rates, two fertilization levels, and five incubation periods. The treatments in this experiment were arranged according to 3-factorial CRD and replicated three times.

Plastic pots, measuring 15cm in depth and 20cm in diameter, were each filled with 500grams of soil. The designated amounts of PB were blended with the soil as per the treatment plan. In a signle split, initial applications of N and P fertilizers were administered in their designated treatments at a rate of 120kg N ha^{-1} and 90kg P ha^{-1}, using urea for N and single superphosphate for P. Moreover, a uniform application of 60kg K ha^{-1} was made in all pots as sulfate of potash. A plastic film covered all the pots, with small holes created to facilitate gaseous exchange and regulate moisture loss. Subsequently, the pots were placed in an incubator at 25°C. Every three days, the weight of each cup was recorded, and de-ionized water was used for irrigation to maintain a consistent moisture level throughout the experimental period.

Sampling and analysis: After incubation periods of 0, 14, 28, 42, and 56days, three plastic pots from each treatment were collected for analysis. Following each sampling, the soil samples were collected in sealed zip bags and stored at 4°C until analysis. Soil samples were analyzed for SOC, CEC, NH_4^+-N, and NO_3^--N as per the details given above for pre-sowing soil analysis. Total mineral-N content was taken as the sum of NO_3^--N and NH_4^+-N.

Statistical analysis: The determination of significant differences because of treatment factors was based on a 3-way ANOVA run on Statistix 8.1 software. Tukey's HSD test (*P≤0.05*) was used for pair-wise comparisons between the treatments.

RESULTS

Soil chemical characteristics: The soil CEC was significantly affected (*P≤0.05*) by fertilization, PB application, and sampling days, as illustrated in Figure 1. Figure 1a displays the treatment effects without fertilizer. Comparing the results of the first sampling, a substantial increase (*P≤0.05*) of 7%, 12%, and 15% in soil CEC occurred, after 14days at PB rates of, respectively, 10, 15, and 20g kg^{-1} soil. After 56days of incubation, in the presence of 10g PB kg^{-1} soil, there was a 5% increase in soil CEC compared to observed at 14days. With fertilization, after 42days, the treatment with 10g PB kg^{-1} soil showed a maximum increase of 23% in soil CEC compared to the first sampling of the control rate.

Figure 1b demonstrates that with fertilization, soil CEC experienced increases of 2%, 16%, 20%, 19%, and 16% compared to their corresponding control treatments after 0, 14, 28, 42, and 56days of adding 20g PB kg^{-1} soil, respectively. The highest soil CEC (8.11cmol$_c$ kg^{-1}) with fertilizer was observed in the 20g PB kg^{-1} soil amended treatment after 42days. After 56days, a significant rise (*P≤0.05*) of 20% in soil CEC was noted where 10g PB kg^{-1} soil was added. At 20g PB kg^{-1} soil, the maximum increase of 21% occurred after 42days.

Figure 2 illustrates the impact of PB addition, fertilizer, and sampling days on SOC. Significant differences (*P≤0.05*) in SOC content were noted due to varying rates of PB, fertilizer, and diverse sampling durations. With no fertilization, immediately after PB application (as observed in the initial sampling), all treatments displayed significant differences (*P≤0.05*) from each other (Figure 2a). Immediately after applying treatments, the SOC content showed a 1.6-, 2.8-, 3.2-, and 3.8-fold increase compared to the control with the addition of 5, 10, 15, and 20g of PB kg^{-1} of soil, respectively. After 42 and 56days of incubation, at 10, 15, and 20g PB kg^{-1} soil, a substantial increase (*P≤0.05*) in SOC content was noticed. With no fertilization, however, SOC content at the control PB rate remained statistically consistent across all samplings.

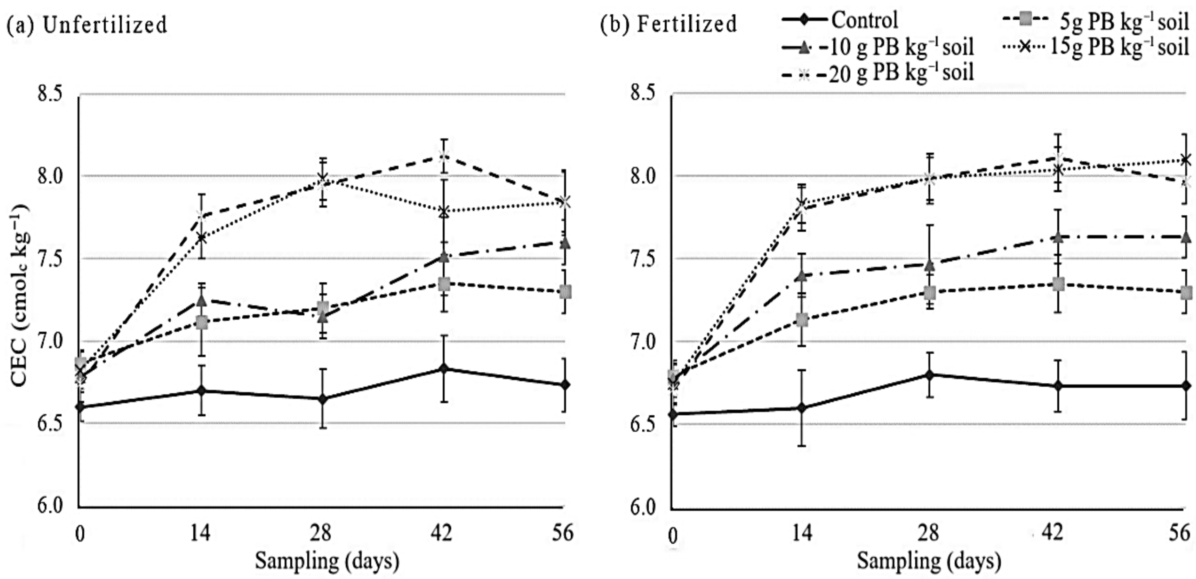

Figure 1. Temporal shifts in cation exchange capacity at peanut-waste biochar (PB) additions under unfertilized and fertilized conditions (error bars depict standard deviations, n = 3)

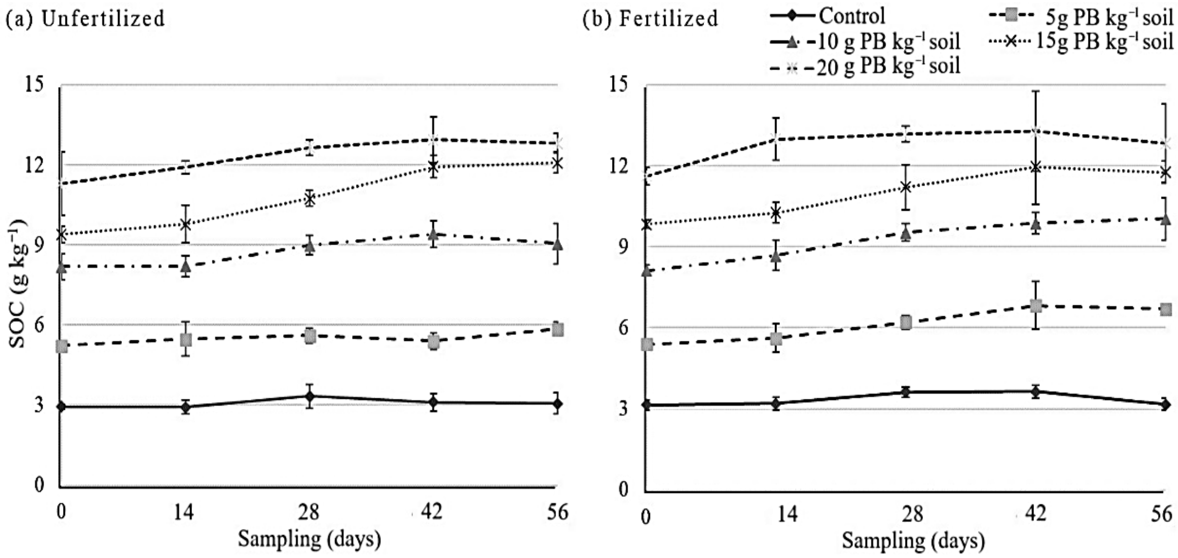

Figure 2. Temporal shifts in soil organic carbon at peanut-waste biochar (PB) additions under unfertilized and fertilized conditions (error bars depict standard deviations, n = 3)

With fertilization (Figure 2b), compared to the initial sampling results, there was an increase of up to 24%, 23%, 15%, and 10% in SOC content after 56days of incubation for, respectively 5, 10, 15, and 20g PB kg^{-1} soil-amended treatments. The fifth sampling (after 56days of treatment application) illustrated a noteworthy increase (*P≤0.05*) of 20% and 10% in SOC content for 15 and 20g PB kg^{-1} soil-amended treatments, respectively, compared to the initial sampling results of treatments. After 42days of incubation, the peak SOC content (13.3g kg^{-1} soil) was attained with 20g PB kg^{-1} soil with fertilizer.

Characteristics of nitrogen dynamics: Figure 3 demonstrates the influence of different rates of PB on the dynamics of soil NH_4^+-N in the presence and absence of fertilizer. The interaction effect of treatments (PB × fertilizer × sampling) was determined to be statistically significant (*P≤0.05*) for soil NH_4^+-N content. In Figure 3a, without fertilizer, 20g PB kg^{-1} soil led to a notable increase (up to 5.58mg kg^{-1} soil) in soil NH_4^+-N content, in comparison with the respective control. At 10g PB kg^{-1} soil, there were substantial increases of 28%, 36%, 64%, and 79% in soil NH_4^+-N content after 14, 28, 42, and 56days, respectively, compared to the content found immediately after the addition of 10g PB kg^{-1} soil. The highest soil NH_4^+-N content (8.23mg kg^{-1} soil) was observed after 56days of incubation with 10g PB kg^{-1} soil. Relative to the initial sampling, there were increases of 4%, 26%, 79%, 78%, and 34% in soil NH_4^+-N content after 56days of 0, 5, 10, 15, and 20g PB kg^{-1} soil, respectively. Figure 3b illustrates the impact of different treatments on NH_4^+-N content under fertilized conditions. Right after the application of treatments (0day sampling), an NH_4^+-N content of 36.5mg kg^{-1} soil was recorded for the treatment without PB, with no significant difference (*P≤0.05*) observed in the NH_4^+-N content among various PB rates. After 14days, treatments with 1.5% and 20g PB kg^{-1} soil demonstrated significantly better NH_4^+-N content (*P≤0.05*) compared to the control and 0g PB kg^{-1} soil. Between the second and third samplings (after 14 and 28days, respectively), there were decreases of 41%, 47%, 35%, 32%, and 31% in soil NH_4^+-N content for treatments with 0, 5, 10, 15, and 20g PB kg^{-1} soil, respectively. Following a 56-day incubation study, the soil treatment with 20g PB kg^{-1} soil exhibited the highest NH_4^+-N content at 21.1mg kg^{-1} soil. In comparison, the soils treated with 15g PB kg^{-1} soil and 10g PB kg^{-1} soil recorded NH_4^+-N contents of 20.1mg kg^{-1} and 15.2mg kg^{-1}, respectively. The treatments exerted a noteworthy influence on the soil NO_3^--N content, yielding a statistically significant result (*P ⩽0.05*).

Figure 4 summarizes the time-based effect of various PB rates on soil NO_3^--N status with and without fertilizer. Without fertilization, throughout the experimental duration, control and 0g PB kg^{-1} soil could not exhibit any significant changes (*P≤0.05*) in soil NO_3^--N, compared to results of 0days sampling (Figure 4a). Notably, at 10g PB kg^{-1} soil, after 56days, there was a substantial increase (*P≤0.05*) in soil NO_3^--N content, over the results of the first sampling of treatment having a similar rate of PB. The treatment with 10g PB kg^{-1} soil reached the maximum NO_3^--N content value (6.13mg kg^{-1} soil) after 56days, while the addition of 20g PB kg^{-1} soil immediately resulted in 3.30mg NO_3^--N kg^{-1} soil, followed by subsequent increases of 33%, 103%, 97%, and 120% after 2, 4, 6, and 56days, respectively. After 56days, as compared to the control PB treatment, there were increases of 12%, 70%, 141%, and 184% in NO_3^--N content for 5, 10, 15, and 20g PB kg^{-1} soil, respectively.

As shown in Figure 4b, 3.74mg NO_3^--N kg^{-1} soil was observed following treatment with 10g PB kg^{-1} soil having fertilizer. After 14days, the treatment without PB showed the highest NO_3^--N content. By the 28-day mark, the soil treated with 10g PB kg^{-1} soil exhibited the highest content at 20.6mg kg^{-1} soil, followed by the treatment with 20g PB kg^{-1} soil, which recorded 19.8mg NO_3^--N content per kg^{-1} soil. In the fourth sampling, there were 37% and 34% higher NO_3^--N content in the soil of treatments with 15 and 20g PB kg^{-1} soil, respectively, over control. Following the 56-day incubation study, the NO_3^--N content in soils treated with 0, 5, 10, 15, and 20g PB kg^{-1} soil was recorded at 8.12, 9.01, 12.9, 14.6, and 15.8mg kg^{-1} soil, respectively. This reflects a significant increase of 95% in NO_3^--N content of soil treated with 20g PB kg^{-1} soil, over control treatment.

The significance of the 3-way interaction effect in impacting soil mineral-N content is evident ($P \leq 0.05$) in Figure 5. In Figure 5a, without fertilization, the soil treated with 20g PB kg^{-1} soil exhibited the highest mineral-N content at 8.88mg kg^{-1} soil after 14days. This was followed by 7.71mg kg^{-1} soil and 6.30mg kg^{-1} soil in the treatments amended with 10g PB kg^{-1} soil and 10g PB kg^{-1} soil, respectively. After 14days, the mineral-N content witnessed a substantial 92% surge when 20g PB kg^{-1} soil was added compared to the control treatment. At the 28-day mark, the highest mineral-N content, measuring 12.8mg kg^{-1} soil, was observed in the treatment with 20g PB kg^{-1} soil. Following closely, the treatment was amended with 10g PB kg^{-1} soil recorded content of 12.3mg kg^{-1} soil. Compared to the control treatment after 42days, there were increases of 17%, 58%, 109%, and 105% in mineral-N content of 5, 10, 15, and 20g PB kg^{-1} soil amended treatments, respectively. After 56days, at 05, 10, 15, and 20g PB kg^{-1} soil, soil mineral-N content was up to 20%, 78%, 128%, and 134% higher, respectively, than the control treatment. significant result ($P \leq 0.05$).

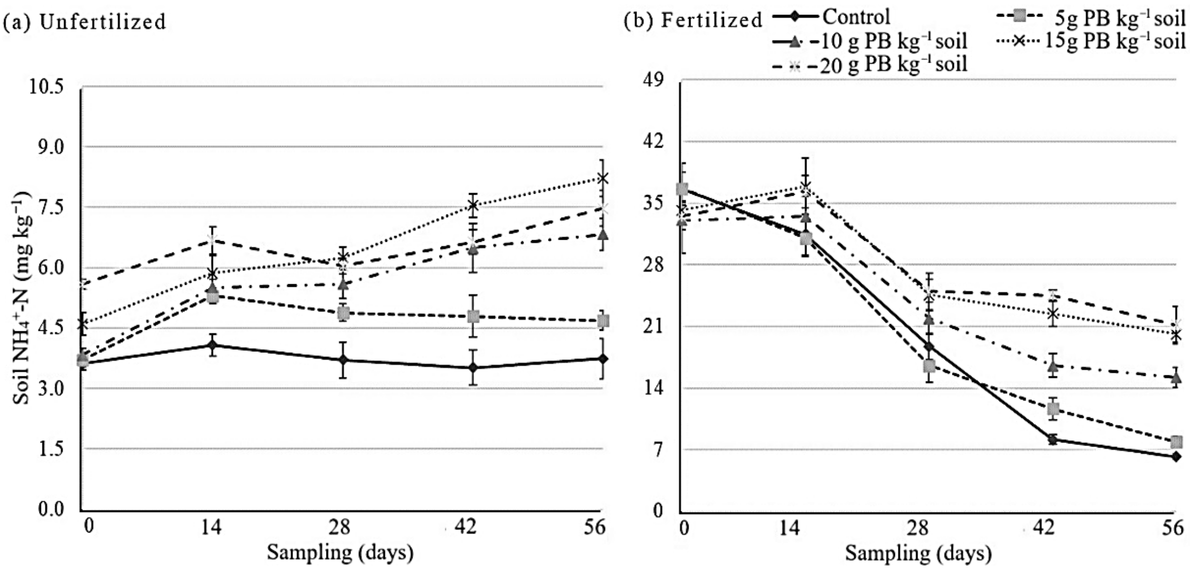

Figure 3. Temporal shifts ammonical-nitrogen at peanut-waste biochar (PB) additions under unfertilized and fertilized conditions (error bars depict standard deviations, n = 3)

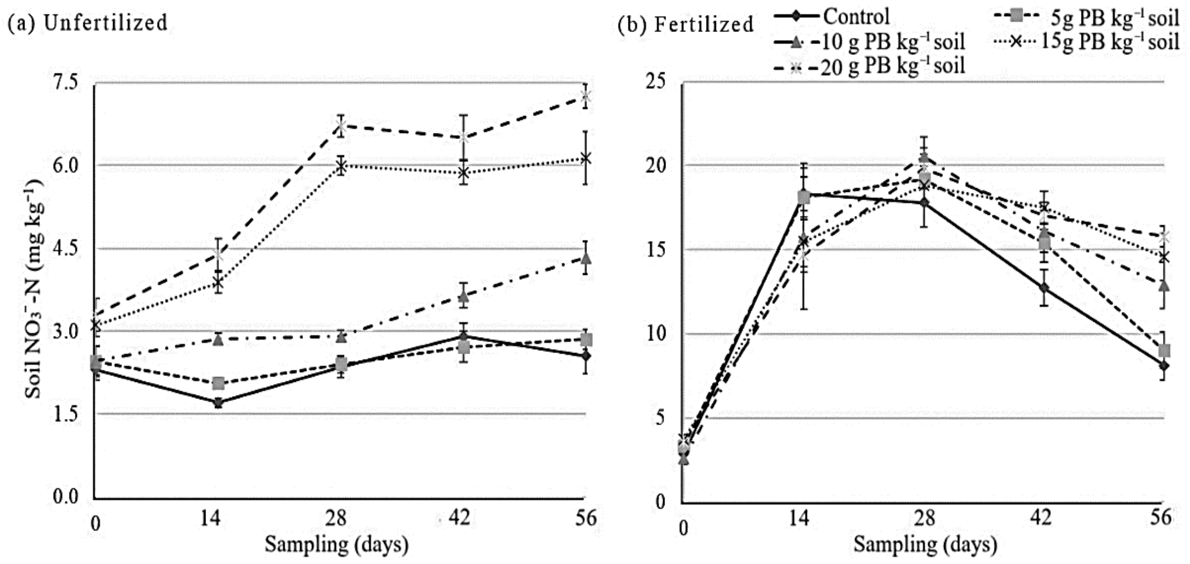

Figure 4. Temporal shifts in nitrate-nitrogen at peanut-waste biochar (PB) additions under unfertilized and fertilized conditions (error bars depict standard deviations, n = 3)

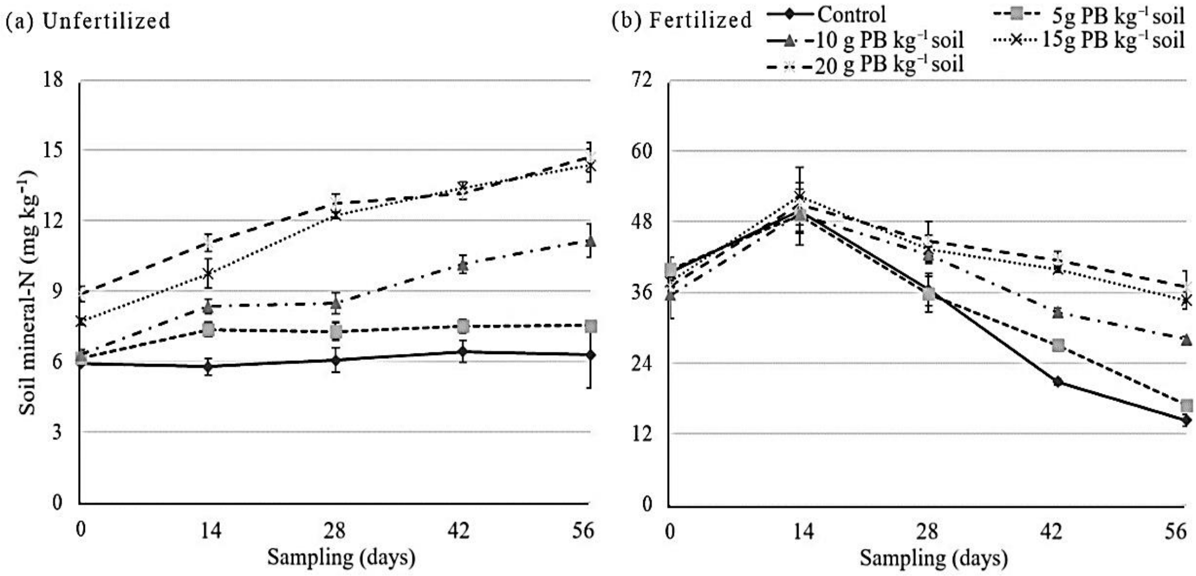

Figure 5. Temporal shifts in mineral-nitrogen at peanut-waste biochar (PB) additions under unfertilized and fertilized conditions (error bars depict standard deviations, n = 3)

Figure 5b displays the data under fertilization. Immediately following incorporating PB, no noticeable differences were observed in the mineral-N content across different treatments. Even after the 14-day incubation period, there were no noteworthy differences ($P \leq 0.05$) detected in the mineral-N content across the various treatments. By the 28days, relative to the control treatment, there were increases of 16%, 19%, and 23% in soil mineral-N content for the treatments with 10, 15, and 20g PB kg^{-1} soil, respectively. With fertilization, after 42days of incubation, the soil of treatment amended with 20g PB kg^{-1} exhibited the maximum mineral N content (41.6mg kg^{-1}). Concluding the incubation study, the treatments with 5, 10, 15, and 20g PB kg^{-1} soil exhibited up to 1.2-, 2.0-, 2.4-, and 2.6-fold higher soil mineral-N content, respectively, compared to the control treatment.

DISCUSSION

In this controlled incubation experiment, the effectiveness of different PB rates was examined to track the temporal changes in mineral-N dynamics and the chemical characteristics of alkaline soil, both in the absence and presence of fertilizer. Biochar, characterized by its highly aromatic composition, can persist in soils for extended periods (Joseph *et al.*, 2021). Unlike other organic soil amendments, biochar's extensive surface area allows it to retain a greater amount of nutrients (Weber and Quicker, 2018). Furthermore, on a long-term basis, biochar holds the potential to boost nutrient availability for plants through its contribution to organic matter and enhancement of soil chemical properties. In the current incubation study, the application of PB, both with and without fertilizer, led to a significant improvement ($P \leq 0.05$) in soil chemical properties, encompassing CEC and SOC (depicted in Figures 1 and 2) as well as mineral-N (depicted in Figure 5), by retaining soil NH_4^+-N and NO_3^--N (depicted in Figure 3 and 4).

Soil CEC is a pivotal soil property governing nutrient desorption/adsorption and availability. The addition of biochar to soil has been reported to increase the CEC of soils (Jiang *et al.*, 2014; Weber and Quicker, 2018). This characteristic of biochar is associated with its small particle size and large surface area having unsettled charges in its structure. In the present study, soil CEC was investigated for the effects of various PB rates added to alkaline soil. After the immediate application of different PB rates, no statistically significant ($P \leq 0.05$) shifts were observed in soil CEC. However, a noteworthy enhancement in soil CEC was observed after just 14days of PB addition at rates of 10, 15, and 20g PB kg^{-1} soil (illustrated in Figure 1). This confirms previous findings on the increase in CEC of biochar with aging (Cheng *et al.*, 2008; Kharel *et al.*, 2019). With time, positive charge decreases, and negative charge increases on biochar surfaces (Cheng *et al.* 2008), mainly linked with oxidation of carboxyl and other functional groups (Gundale and DeLuca, 2006). High CEC of biochar can help retain plant nutrients, such as $NH_4^{+,}$ in soils (Cheng *et al.*, 2006; Cao *et al.*, 2022).

A noticeable increase in SOC content was observed with increasing PB rates, reaching the highest point at 20g PB kg^{-1} soil. A recent study by Gou *et al.* (2023) highlighted a significant boost in microbial activity within the soil attributed to biochar addition, leading to an improvement in soil organic matter content. The application of biochar introduces a considerable amount of organic carbon into the soil, ultimately enhancing the soil's organic carbon status on a sustainable basis (Aon *et al.*, 2023). Peanut-waste biochar exhibited a higher total carbon content of 57.1%. Consequently, an evident ($P \leq 0.05$) increase in SOC content was observed upon introducing PB into the soil (refer to Figure 2). The heightened levels of organic matter in soils amended with biochar underscore the resistant nature of biochar against oxidation, indicative of its recalcitrant characteristics (Yaashikaa *et al*., 2020). Nigussie *et al*. (2012) conducted a study on diverse soils, incorporating biochar led to a notable upswing in total organic carbon content of soils.

In the present incubation study, the introduction of biochar triggered a change in soil N dynamics (refer to Figures 3, 4, and 5). A marked (*P≤0.05*) rise in soil NH_4^+-N was identified just 14days after incorporating PB. Compared to initial levels, the addition of PB at 10 to 20g kg^{-1} soil significantly (*P≤0.05*) enhanced soil NH_4^+-N content. Biochar might harbor bioavailable forms of N, and their mineralization and release are contingent on various factors, including the C:N ratio of biochar and soil, the characteristics of the studied ecosystems, and the relative size and recalcitrance of biochar (Woolf and Lehmann, 2012).

The rates of mineralization/immobilization in soil are influenced by the availability of N and C pools for soil microbiota. Generally, an increase in the C:N ratio accentuates N immobilization. Incorporating biochar into the soil adds an extra dimension to both C and N pools. Studies have indicated that integrating biochar into soils results in a more gradual mineralization of biochar compared to non-pyrolyzed biomass (Knoblauch *et al*., 2012). In the current context, there was likely a net mineralization effect because of the addition of 10, 15, and 20g PB kg^{-1} soil. The increased N mineralization can be attributed to the low C:N ratio (21.9) of the introduced PB biochar. In a study by Wang *et al*. (2012), it was revealed that the acid-hydrolyzable N content present in biochar increased with a reduction in pyrolysis temperature (up to 250°C). Peanut-waste biochar used in the incubation study was produced at 300°C, it is plausible that the resultant PB contained a substantial fraction of hydrolyzable N content, including ammonia, amino acids, and amino sugars. Consequently, the addition of PB into alkaline soil led to an augmented mineralization of N present in PB. Overall, improved NH_4^+-N content was noted in all treatments after 14days of incubation under fertilization.

Following 42 and 56days of incubation, it became evident that the decline in soil NH_4^+-N content was relatively subdued in treatments amended with 10, 15, and 20g PB kg^{-1} soil (refer to Figure 3). This may be attributed to NH_4^+-N adsorption (mainly generated from urea hydrolysis under fertilizer conditions) on the surfaces of biochar. The CEC of biochar is influential in the adsorption of NH_4^+-N. In the present incubation study, PB exhibited a CEC of 49.1cmol$_c$ kg^{-1}, and PB application ultimately led to an enhancement in soil CEC (refer to Figure 1). Due to the improved soil CEC, the decline in soil NH_4^+-N content was relatively gradual in soil amended with PB, compared to control treatment without PB.

With the addition of 15 and 20g PB kg^{-1} soil, soil NO_3^--N content increased significantly (*P≤0.05*) after 28days of treatment application (see Fig. 4). Although biochar can absorb NO_3^--N (Kameyama *et al*. 2012), this has been reported for biochar produced at temperatures ≥600°C (Kameyama *et al*. 2012). In this study, soil NO_3^--N content increased significantly (*P≤0.05*) because of higher PB rates (15 and 20g kg^{-1} soil). This increase can be attributed to the conversion of hydrolyzable N content to NH_4^+-N and finally to NO_3^- N form (Shi *et al*., 2017; Tsai and Chang, 2020).

CONCLUSIONS

We observed significant variations in mineral forms of N in an alkaline soil over the period of incubation. This was accompanied by changes in SOC and soil CEC. Such findings are important for the sustainable management of alkaline mineral soils that are low in organic matter and universally deficient in plant-available N. In conclusion, the present study suggested the addition of PB at 15 or 20g PB kg^{-1} to alkaline soils. However, the economic viability of such high rates of biochar additions remains a topic of future research.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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