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Assessing the Nitrogen Leaching Potential of the Njala Soil Series Amended with Biochar

Alie Kamara [a*], Foday Saidu Sesay [a] and Adama Moses Kanu [b]

[a] Soil Science Department, Njala University, Sierra Leone.
[b] Kambia District Development and Rehabilitation Organization (KADRO), Kambia District, Sierra Leone.

Authors' contributions

This work was carried out in collaboration among all authors. Author AK designed the study, performed statistical analysis and final editing and submission of the manuscript. Author FSS wrote the protocol and the first draft of the manuscript. Author AMK set up the lab experiment and collected the data. All authors read and approved the final manuscript.

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ABSTRACT

Upland gravelly soils of Sierra Leone pose serious challenges to agriculture due to their low ability to retaining nutrients and water. Their highly weathered states, dominance of low activity clays and low organic matter content exacerbates their nutrient retention capabilities leading to high leaching of essential nutrients. However, there little knowledge about the magnitude of nutrient loss on Njala soils. This study was therefore conducted to quantify leaching losses of nitrogen from urea fertilizer in soils treated with and without biochar. In this study, four treatments were used to set up leaching columns: (i) Soil without Biochar (Control), (ii) Soil+Biochar, (iii) Soil+Fertilizer, and (iv) Soil+Biochar+Fertilizer. Each treatment was replicated three times. Leaching experiment was

**Corresponding author: E-mail: aliekamara@njala.edu.sl;*

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conducted daily for seven days. Leachates were collected daily and analyzed for total Nitrogen. The results showed a high rate of nutrients loss in soils not treated with biochar than soils treated with biochar. Hence, the study has revealed the magnitude of nitrogen loss from applied urea fertilizer is 74.1% while the addition of biochar can reduce the loss significantly to 40% on the gravelly upland soils of Njala. The study showed the vulnerability of nitrogen loss on the Njala uplands and the role of biochar in minimizing such loss.

Keywords: Leaching column; acacia biochar; leachates; Njala University campus; upland gravelly soils; Sierra Leone.

1. INTRODUCTION

Soils of the Njala Area, like most of Sierra Leone soils, have low nutrient retention capacities due to their highly weathered state as well as the dominance of low activity clays (Batiano et al., 2006; Dijkerman, 1969). Moreso, the high gravel content (60-80%) in them makes them more porous with high infiltration rate, consequently aggravating nutrient loss by leaching (van Vuure et al,. 1976). These properties negatively impact their ecosystem services especially in terms of crop productivity and environmental quality.

Nutrient loss from leaching is of increasing concern especially in the tropics. This is because nutrient loss through leaching can reduce nutrient use efficiency (Zhang, 2015) and thus limit crop production, pollute underground water (Ascott et al., 2017) with economic implications and thus increase the use of fossil fuel-based fertilizers (Gu et al., 2013). Furthermore, the leaching of inorganic fertilizers like urea can cause pollution of surface and underground water resources (Kanter et al., 2020; Waring et al., 2020).

One of the approaches for improving nutrient retention and lowering nutrient leaching rates in highly weathered tropical soils is the use of soil amendments such as soil organic manures (livestock and poultry litter), compost, and green manures. However, soil organic matter has high turnover rates in humid tropical soils due to high temperature of the region leading to shorter residence times (Sanchez, 2019; Cotrufo et al., 2019; Dignac et al., 2017; Crowther et al., 2016). In order to sustain their effectiveness, there may be the need for their frequent addition which is uneconomical and laborious. In recent years, studies have shown that the application of biochar to agricultural soils has the unique quality of retaining nutrients and water for plant nutrition over longer periods due to the more stable carbon it contains (Shi et al., 2023; Lehmann et al., 2021; Joseph et al., 2021; El-Naggar et al., 2019). Biochar has positive effects on physical, chemical and biological processes in the soil which appear to enhance nutrient and water retention capacity thereby contributing to reduction in nutrient leaching. For instance, studies suggest that the application of biochar can increase soil fertility and productivity (El-Naggar et al., 2019, Jeffery et al., 2017) by reducing the leaching of nutrient (Jeffery et al., 2017; Hagemann et al., 2017; Yao et al., 2012;) or even supplying nutrient to the plants (Hagemann et al., 2017, Joseph et al., 2021; Glaser & Lehr, 2019).

Urea fertilizer is the most common nitrogen fertilizer used in Sierra Leone agriculture (MAFFS 2017; World Bank, 2017). Under well drained conditions, urea can readily be converted to nitrate via ammonium (Haynes et al., 2021; Kopittke et al., 2019; Coskun et al., 2017) and leached, especially in soil with low nutrient retention capacities like the Njala Series typical of gravelly upland soils in Sierra Leone (Sanchez, 2019; Moormann & Van Wambeke, 1978; Smithson, 1965)., Very little studies have been conducted to understand the magnitude of nutrient leaching in Sierra Leone soils. It is therefore necessary to conduct a study that will shed light on the potential of nutrient leaching in well-drained, gravelly upland soils of Sierra Leone. Such knowledge will contribute to raising awareness on the relevance of development of effective soil management strategies aimed at reducing nutrient leaching, increase crop production and ensure a healthier environment. Hence, the objectives of this study were to compare nitrogen leaching in soils amended with and without biochar under (i) unfertilized condition and (ii) fertilized condition.

2. METHOD

2.1 Description of the Study Area

The study was conducted in the Njala University Quality control Laboratory in Njala Campus of the Njala University in Moyamba District, Southern Sierra Leone. Njala is about 205km from Freetown, the capital city of Sierra Leone, and is located at an elevation of 128m above sea level (altitude), on Latitude 8ºN and Longitude 12ºW. The soil used in this study, The Njala Soil Series, belong to Soil Province G: Soils from the Rokel River Series under secondary bush (van Vuure et al,. 1976). The Njala Soil Series is the dominant soil in The Njala Area covering about 5,833ha (Odell & Dijkcrman, 1967; van Vuure et al,. 1976). The climate is characterized by two distinct seasons, rainy and dry. The rainy season lasts from May to November and the dry season from December to April. The average annual rainfall is about 2500 mm most of which falls in July and August (World Bank Group, 2021; SLMet, 2018; Wadsworth et al., 2019).

2.2 Soil Sampling and Processing

Three composite soil samples of the Njala Soil Series were collected from three different locations at a depth of 30cm. The samples were taken to the Njala University Quality Control Laboratory for preparation and storage. The collected samples were air dried, thoroughly mixed and sieved through a 2mm sieve. The three composite samples from the three different locations on the Njala Soil Series represented three replications.

2.3 Biochar Preparation

The biomass used for biochar production was acacia tree branches. Smaller branches were cut off from trees, and split into smaller sizes and sun dried. The sun-dried biomass was later cut into small chips, placed in a Top-Lit-Up-Draft pyrolysis stove for conversion into biochar. The pyrolyzed biochar was removed from the stove, spread on the floor and quenched with water to prevent it from burning into ashes. The acacia biochar was dried under sun for three days then crushed to pass through a 2mm sieve. The processed biochar was stored in a polythene container.

2.4 Soil Porosity Determination

The soil porosity was determined using a simple lab method (Dane & Topp, 2020). A clean dry 100ml graduated measuring cylinder was weighed and recorded as w_1. The weighed cylinder was filled with 2.0mm sieved air-dry soil and tapped gently to the 100ml mark. The cylinder with soil was weighed and recorded as w_2. The dry soil weight (w_3) was determined by the formula;

$$w_3 = w_2 - w_1$$

The bulk density was determined using the formula below:

BD = weight of dry soil/volume of cylinder = $w_3/100$

The process was repeated four times and the average was taken. With an assumed particle density (PD) of 2.65g/cm^3, the percentage of soil volume occupied by solids was calculated as:

% Solids = (BD/PD) x 100

The result obtained was used to determine the percent soil porosity as follows

%Porosity = 100 - %Solids

Hence, the soil porosity was given by;

Soil Porosity = %Porosity/100

The pore volume (*Vp)* of the soil that will fill a 50cm x 5cm leaching column to the 30cm mark was determined by the formula;

$$Vp = (\pi r^2 L)\ (\text{porosity})$$

Where;
r = radius of the leaching column and
L = length of the leaching column filled with soil = 30cm.

2.5 Leaching Column Set Up

2.5.1 Column preparation

Leaching studies were conducted using a modified approach to the standard method (Skjennum et al., 2023). A PVC pipe of 50cm length and 5cm diameter was sealed at one end with a piece of cotton cloth to prevent soil particles from running out. The sealed pipe was weighed to obtain the empty weight (w_1). The sealed pipe was filled with dry soil to the 30cm mark. The column was gently tapped and topped to the 30cm mark with soil. The leaching column filled with soil was weighed again (w_2). The weight of soil required to fill the column to the 30cm mark was calculated (w_2-w_1).

2.5.2 Experimental design and layout

The laboratory experiment consisted of four soil treatments with three replications arranged in complete randomized design. The four treatments used are described in Table 1:

Table 1. Experimental treatments used in the study

Treatment	Description
1	Control Soil; no biochar, no fertilizer
2	Soil+Biochar only; No fertilizer
3	Soil+Fertilizer; no biochar
4	Soil+Biochar+Fertilizer

Biochar Application: The amount of soil required to fill the leaching column to the 30cm mark (as determined in 2.5.1) was weighed separately into twelve containers arranged in three sets or replications. Biochar was applied at a rate of 20g/kg soil and mixed thoroughly for Treatments 2 and 3 as indicated in Table 1. The columns (total = 12) were filled with the appropriate soil treatment. Each column was clamped and suspended on a wooden platform.

Fertilizer Application: Urea fertilizer granules (applied at a rate of 0.2g/kg soil) were carefully placed on the top of the soil in the suspended columns receiving fertilizer treatments (as indicated in Table 1). The urea granules were carefully mixed with soil to the top 5cm depth using a spatula. The column was tapped gently to allow the particles to settle to the 30cm mark.

2.6 Column Leaching

A filter paper was placed at the surface of the soil in each column to minimize soil particle movement at the top of the column whilst the water is poured. Distilled water (¾ pour volume) was slowly poured onto each column from a tap at a rate of 10ml/min to wet the column without leaching it. The mouth of the column was covered with parafilm to prevent moisture loss through evaporation and left overnight. This was done to initialize the column before running the actual leaching studies. The following day, two pore volumes of distilled water were leached through the column. The leaching process was repeated every 24 hours for seven days with the mouth being covered with parafilm after every leaching period. The volumes of daily leachates collected were measured and the leachates were analyzed for total nitrogen content using the Kjeldahl method.

2.7 Data Analysis

The results obtained from this experiment were subjected to analysis of variance in RStudio. Where significant differences were observed, mean separation was done by Tuckey's post-hoc test.

3. RESULTS AND DISCUSSION

3.1 Effect of Biochar on Nitrogen Leaching in Soil without Fertilizer Application

Rapid nitrogen loss was observed in the first three days for both control soil and biochar treated soil (Fig. 1). However, the leaching loss of nitrogen was significantly higher ($p<0.05$; $F=202.9$, $p=0.0$) in the control soil without biochar compared to the soil treated with biochar. Also, the daily leaching losses of nitrogen for each treatment differed significantly ($p<0.05$; $F=77.26$, $p=0.0$).

Post-hoc analysis of the significant differences in leaching losses between control and biochar treated soils observed for each day reveals that the nitrogen leaching losses were significant at Days 1 and 2 only (Fig. 1). At Day 3 and thereafter, there were no significant differences in nitrogen leaching losses between the control and biochar-treated soils. Also, post-hoc analysis of the daily leaching losses of nitrogen showed that, for the biochar treated soil, there were significant differences between Day 1 and all other days; leaching losses at Day 2 did not differ significantly from Days 4 and 5 but differed significantly from Days 5,6 and 7. On the other hand, for the control soil (without biochar), leaching losses differ significantly among Days 1-4. Thereafter, leaching did not differ among the rest of days (Day4-7). Thus, it is clear that leaching losses of nitrogen approached a steady state at Day 3 for biochar treated soil and at Day 4 for the control soil. The lower leaching losses of nitrogen from the biochar treated soil indicated the ability of biochar to minimize leaching losses even under no fertilizer input conditions. Cumulative leaching losses reached a maximum of 29.5mg N/kg soil for the control soil without biochar and 17.1mg N/kg soil for the soil treated with biochar. Thus, the presence of biochar resulted in the significant ($p<0.05$) reduction of nitrogen losses by 12.4mg N/kg soil.

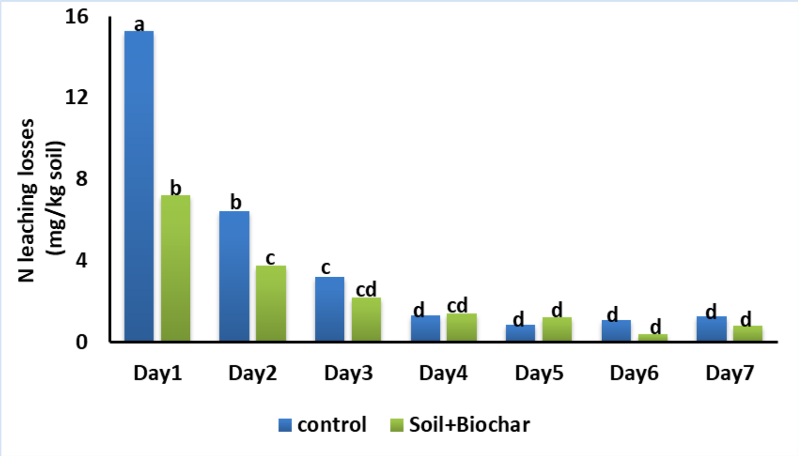

Fig. 1. Daily leaching losses of nitrogen in the absence of fertilizer application for control soil without biochar and soil treated with biochar

3.2 Effect of Biochar on Nitrogen Leaching in Soil with Fertilizer Application

Fig. 2 shows the daily leaching losses of nitrogen applied as urea on soil without biochar and soil treated with acacia biochar. There was an initial rapid loss of nitrogen in the first four days for soils with and without biochar, but the loss was much rapid for the soil without biochar than soil with biochar. Nitrogen leaching loss was significantly higher ($p<0.05$; $F=2115.4$, $p=0.0$) in the soil without biochar (Soil+Fertilizer) than in the soil treated with biochar (Soil+Fertilizer+Biochar). The daily leaching losses of nitrogen for each treatment differed significantly ($p<0.05$; $F=832.8$, $p=0.0$). At Day 4 and thereafter, leaching losses did not differ significantly between treatments. This showed that biochar can minimize rapid leaching losses of fertilizers in soil thereby improving fertilizer nutrient retention.

In the presence of urea fertilizer, the cumulative nitrogen leaching losses from the soil without biochar (Soil+Fertilizer) reached a maximum of 165.9mg N/kg soil while for the soil treated with biochar (Soil+Fertilizer+Biochar) it reached a maximum of 103.5 mg N/kg soil. Thus, in the presence of biochar, the amount of nitrogen lost from applied urea fertilizer was significantly reduced by 62.4mg N/kg soil. These losses were calculated to represent 74.1% of applied urea fertilizer for soil without biochar and 40% for soil with biochar. Thus, acacia biochar has the potential to reduce leaching losses from urea fertilizer application on Njala soils.

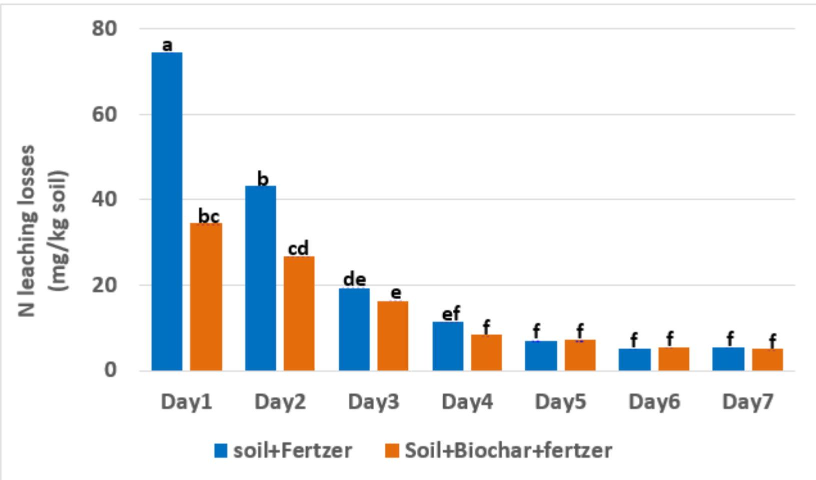

Fig. 2. Daily leaching losses of nitrogen in the presence of fertilizer application for control soil without biochar and soil treated with biochar

4. DISCUSSION

The study clearly revealed the vulnerability of upland soils in the Njala area (dominated by the Njala soil series) to nutrient loss by leaching especially after fertilizer application. The observed reduction in amount of nitrogen loss by leaching in the presence of acacia biochar (Fig. 2) corroborated by the reports of biochar capacity to adsorb and retain nitrogen species (Jeffery et al., 2017). Jeffery et al. (2017) specifically showed that biochar can adsorb nitrate from the soil solution and release it in a slow-release manner, a process that directly explains the reduced rate of leaching reported in this study (Fig. 2). Instead of a rapid loss of N, the biochar-treated soil retained the fertilizer-derived N, slowing its release over time. This mechanism is vital for enhancing the synchrony between nutrient availability and plant uptake.

The reduction in amount of nitrogen loss by leaching in the presence of acacia biochar could be explained by the nutrient retention capacity of acacia biochar. Several studies have shown the ability of acacia biochar and other biochar derived from woody residues to improve nutrient retention and reduce nutrient leaching (Dane & Topp, 2020; Tomczyk, et al., 2020; Mukherjee & Lal, 2014). In particular, (Yao et al., 2012) reported that biochar amendment to a sandy soil significantly reduced the leaching of nitrate, ammonium, and phosphate, which was attributed to the high surface area and porosity of biochar that provides numerous sites for adsorption. This is particularly relevant for the Njala series, as its high gravel content (coarse texture), the dominance of low activity clays, high infiltration capacity, low CEC and acidity (Odell & Dijkcrman, 1967; van Vuure et al,. 1976) make them highly susceptible to leaching losses of nutrients. High leaching losses of nutrients can have great impacts on crop productivity and bring losses to farmers due to high input cost. Additionally, the leaching of some inorganic fertilizers like urea, can impact water quality.

The long-term implications of the findings of this study are accentuated in several field studies, such as Major et al. (2010), who, in a seminal field trial, found that biochar application to a highly weathered tropical soil reduced nutrient leaching and sustained higher crop yields over multiple seasons. They attributed their observation to the persistent nature of biochar in soil, which provides a long-term improvement in soil cation exchange capacity (CEC). Also, a review report by Joseph et al. (2021), indicated that the "aging" process in soil, where biochar surfaces oxidize and develop functional groups, enhances its CEC over time, leading to longer-lasting improvements in nutrient retention. This suggests that the leaching reduction observed in this study shows the potential of acacia biochar as to enhance nutrient retention and a valuable long-term investment for soil health.

Furthermore, the effectiveness of using biochar produced from woody residues, such as acacia residues, used in this study, and given the local availability of acacia residues, is supported by the work of Vaccari et al. (2015). They reported that biochar produced from forest wood chips was highly effective at reducing nitrate leaching and improving nitrogen uptake by plants. This indicates that biochars derived from readily available forest residues in Sierra Leone are a vital resource for developing localized solutions to soil fertility challenges posed by nutrient leaching losses.

5. CONCLUSION

This study has shown that application of urea fertilizer on upland soils of the Njala area (or Njala soil series) without a soil amendment like biochar could lead to significant losses (74.1%) of nitrogen due to leaching. In the presence of biochar, leaching losses of urea fertilizer can be reduced from 74.1% to 40%. The reduction in nitrogen leaching observed in this study is firmly supported by mechanistic and field-level studies across different soil types and regions around the globe. Thus, the application of biochar is a scientifically grounded strategy for mitigating the problem of nitrogen leaching in the gravelly Njala Soil Series, thereby indicating the potential to enhance agricultural sustainability and reduce environmental impact.

Thus, acacia biochar is very promising for use as a soil conditioner for minimizing nutrient leaching from soils. Hence, farmers are encouraged to clear and char biomass instead of clear and burn for sustainable crop production and a healthy environment.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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