

**EFFECT OF CONSERVATION AGRICULTURE AND
BIOCHAR ON NITROGEN CYCLING IN PIGEON PEA-MAIZE
ROTATION ON FERRALSOL IN GULU**

BY

WOKORACH SAMUEL OPIYO

(BSc. Agric UMU)

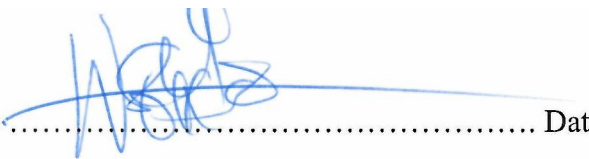
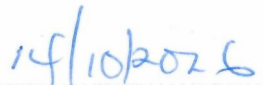
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DECLARATION

I, Wokorach Samuel Opiyo (23/U/0618/MAS/PS), attest that this work has not been published or submitted for any academic award in any University.

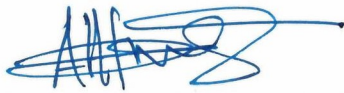
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APPROVAL

This dissertation, right from development of research ideas, design and establishment of the experiment, collection of data and analysis has been carried out in full adherence to research ethics and professionalism. According to the established guidelines, this work is hereby approved for submission.

1. Dr. Alfred Obia

Senior lecturer, Department of Agronomy, Faculty of Agriculture and Environment, Gulu University

Signature..........Date.....14.10.2026.....

2. Mr. David Akodi

Research Officer, National Coffee Research Institute, National Agricultural Research Organisation.

PhD Fellow, Norwegian University of Life Sciences (NMBU)

Signature..........Date.....14/10/2026.....

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DEDICATION

Indeed, charity begins from home, and that has been manifested through this success. I dedicate this work to my beloved wife, Milly Wokorach and our children; Lamaro Clara, Lanyamoi Jeremy Keith and Laloyo Shadrach Josiah. You gave me the time to focus, you sacrificed short-term comfort for long term ambitions like priority for school fees plus other expenses. More so, intercession for God's protection and blessing all the time. I remain deeply grateful and indebted for all that you have contributed to this achievement.

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LISTS OF ACRONYMS

AEC	Anion Exchange Capacity
ANOVA	Analysis of Variance
AOA	Ammonia Oxidizing Achaea
AOB	Ammonia Oxidizing Bacteria
ATP	Adenosine Triphosphate
AMF	Arbuscular Mycorrhizal Fungi
COVID-19	Corona Virus Disease
conc.	Concentrated
CA	Conservation Agriculture
CEC	Cation Exchange Capacity
CDO	Community Development Officer
Cu	Copper
DNA	Deoxyribose Nuclei Acid
DPO	District Production Officer
DM	Dry Matter
FAO	Food and Agricultural Organization
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GUREC	Gulu University Research Ethics Committee
IFAD	International Fund for Agricultural Development
CA	Conservation Agriculture
Cmol	Centimole
MAAIF	Ministry of Agriculture Animal Industry and Fishery

Mo	Molybdenum
NARO	National Agricultural Research Organization
NUE	Nutrient Use Efficiency
N ₂ O	Nitrous Oxide
NO	Nitric Oxide
NDPIII	National Development Plan Three
PPL	Pigeon Pea Litter
PP	Pigeon Pea
RCBD	Randomized Complete Block Design
SDGs	Sustainable Development Goals
SSA	Sub-Saharan African
SOM	Soil Organic Matter
UBOS	Uganda Bureau of Statistics

ABSTRACT

Low soil fertility is a global challenge frustrating efforts of enhancing crop productivity. One of the most important plant nutrients often in short supply is nitrogen (N). Crops commonly suffer from N deficiency due to high N lost as nitrous oxide (N₂O) gas, low nutrient absorption and accumulation in plant. Farmers who use conservation practices such as use of leaf litter to improve soil fertility suffer poor timing of application or slow mineralization process. Thus, objectives of the study were (i) to determine the effect of conservation agriculture (CA) planting basin, biochar and pigeon pea leaf litter on N₂O emission, (ii) to determine the effect of CA planting basin and biochar on the quantity and quality of pigeon pea leaf litter, (iii) to determine the effect of variation of nutrient content of pigeon pea leaf litter on mineralization. For objective 1, field experiment consisting of four treatments; CA + biochar, CA + biochar + leaf litter, CA + leaf litters and control. The experiment was organized in completely randomized design with four replicates to determine effect on N₂O emission. There was N₂O emission of 10–40 µg N₂O-N m⁻² h⁻¹ on average across different conservation agriculture practices that did not differ significantly (p=0.137). For objective 2, an experimental design of randomized complete block design was established to test the effect of conservation agriculture, conservation agriculture plus single application of 4 t/ha biochar, conservation agriculture plus double application of biochar at 2 t/ha followed by 1 t/ha and conventional farming on quantity and quality of leaf litters of pigeon pea. Before treatment, quantity of litter and N content on average was 240 kg/ha and 40 g/kg respectively. However, there was no significant effect of treatments on quantity of leaf litters and amount of N in leaf litters. However, leaf P and K content was affected by treatments. Leaf litter from conservation agriculture and conventional practice had lower content of P and K at 2.7 mg/kg and 39 mg/kg, respectively (p<0.001). The P and K content of litter from conservation agriculture with single and double application of biochar was higher at ~3.9 mg/kg and ~62 mg/kg, respectively. For objective 3, incubation experiment on N mineralization rate of leaf litter from different soil nutrient content was conducted over 14-16-day period. Furthermore, the leaf litter significantly stimulates soil microbial activity, with peak CO₂ evolution occurring at day 12 (p < 0.001). This indicates that most active microbial activity is confined to the initial two weeks of application of the litter. Last, ammonium concentrations peaked at day 12 and then dropped sharply as nitrate levels

surged between days 13 and 16 ($p < 0.001$), confirming the typical mineralization-nitrification sequence, with significant result. This study demonstrates that integrating CA with biochar enhances nutrient retention and availability. Furthermore, understanding variation in the nutrient content of the organic litter is important in planning its application to allow time for mineralization. Thus, mainstreaming pigeon pea as part of soil management will be alternative approach that boosts soil health, nutrient level and productivity of soil.

CHAPTER ONE: INTRODUCTION

1.1 Background

Sustaining soil fertility is becoming a very serious contemporary challenge for both researchers and policymakers. This follows the urgent need to meet the ever-growing global need to increase agricultural production to solve the problem of food and energy for the world's 8 billion people (Laekemariam & Elka, 2022; Nepal et al., 2023). Unfortunately, there is already massive soil fertility decline which has reduced crop yield by 27-41% (Grzebisz et al., 2022). The evidence of low soil fertility is manifested in both biological and physio-chemical properties (Javed et al., 2022). It includes low microbial diversity and abundance, low soil moisture, low cation exchange capacity and low soil nutrient content among others. Poor agricultural practices have catalyzed the decline of those parameters. For example, global nutrient deficit is estimated to be 5.5 million tons of nitrogen (N) (31% of the total nutrient deficit), 2.3 million tons of phosphorous (P) (13%), and 12.2 million tons of potassium (K) (56%) (Johnson Jeyaraj & Sankararajan, 2024). This effect is much higher in Sub-Saharan Africa.

Sub-Saharan Africa has continuously accessed very promising cultivars and good agronomy to solve low productivity bottlenecks. However, little success has been achieved as shown by the reduced crop productivity of staple cereal crops such as maize. Maize productivity is estimated to be at only 30% of its potential and this is attributed partly to low soil nutrients (Zingore et al., 2022). Among the nutrients, N remains very critical since it has numerous biomolecular components in plants. These biomolecules are building blocks of hormones and enzymes among others. All those molecules directly affect crop physiology (Daly et al., 2021) and productivity, hence yield declines.

Nitrogen is one of the most limiting nutrients in the entire agrarian systems. The root cause of its inadequacy is low capacity of farmers to apply the recommended amount of fertilizer. This was reported researcher on the fertilizer recommendation for an hectare (100), yet application is only at 5kg/Ha (Masso et al., 2024). Furthermore, losses of almost 50% occur once applied by the farmers on the soil (Kabasiita et al., 2022). The loss can be through leaching, erosion or

nitrous oxide (N₂O) emission among others (Ayaz et al., 2023; Harindintwali et al., 2021). In addition, farmers who attempt to apply do not realize nutrient absorption from the soil by the plants due to unfavorable physio-chemical properties of the soil which should have supported absorption (Hearn et al., 2023; Xu et al., 2023).

For example, pH affects soil nutrients solubility of nutrients such as P within the soil systems when it is too high or too low. Furthermore, pH has effects on solute concentration that directly contribute to N losses in many forms. For example, in low pH (acidic soil), NH₃ gas protonates to form NH₄⁺ ions, thus promoting their adsorption onto the cation exchange sites of soil and biochar (Jabin, 2023). Unfortunately, acidity predisposes soil to weathering. Meanwhile, increasing alkalinity in soil which can cause loss of NH₄⁺ through ammonia volatilization after deprotonation of weak acids from variable charged surfaces (Hearn et al., 2023).

In addition, low cation exchange capacity (CEC) affects adsorption, base saturation and availability of the nutrient in the soil solution. This predispose base cations (NH₄⁺, K⁺, Ca²⁺, Mg²⁺, and Na⁺) to leaching followed by the replacement of the base cations with Al³⁺, Fe²⁺, and H⁺ ions at the soil adsorption site (Ng et al., 2022; Prekop et al., 2023).

Moreover, slow mineralization process is another cause of low N. Mineralization is the process of how microbes break down organic matter to release nutrients for the plants. But some are not broken down by the soil microbial activities timely. This occurs where the timing for crop demand and nutrient release is not synchronized, hence the nutrient is not utilized by the crop (Alkharabsheh et al., 2021; Baksinskaite et al., 2024; Wang et al., 2022).

The findings from this work supplement the regional advocacy strategy on agricultural and food security policies in East African Community. It is also in line with Maputo declaration to support sustainable land management to complement the low fertilizer and nitrogen usage reported at only 2kg/ha/year (Policies & Community, 2014).

It is therefore important to devise a robust nutrient cycling design, that holistically consider various nutrient sources, manages nutrient within the soil and ensure reduced losses. Affordable sources like leaf litter retention/application, can address nutrient gaps among the poor communities. Also, understanding how the nutrients behave within the soil systems including nutrient release kinetics from organic matter can help farmers in farm planning of designing itinerary of applying the soil amendment. This allows correct timing of application to coincide

with crop nutrient demand. Furthermore, how the nutrient is lost to the environment through various mechanisms is important in devising means of reducing the losses. Nonetheless, this effort could be frustrated by climate vagaries. Consequently, affecting productivity and livelihood of the communities. Thus, information is particularly urgent for countries like Uganda that rely on rain-fed agriculture and use maize as staple food crop.

Based on the above, two contexts are very important to put in the agenda. To begin with, climate change detrimental to agricultural productivity and entire livelihood (Okolie et al., 2023; Dawid et al., 2023; Kumar et al., 2024). Second, climate smart agriculture (CSA) has been shown to be part of the sustainable solution (Begna, 2025; (Okoronkwo et al., n.d.). CSA has various tools that include; CA, biochar amongst others (Kabato et al., 2025). Previous studies have reported conservation agriculture and biochar to have positive effect on soil physio-chemical and biological soil properties (Cornelissen et al., 2013; Ellingsen; Hematimatin et al., 2024; Obia et al., 2017, 2019, 2020). But limited information is available from bi-modal rainfall climate systems dominated by Ferralsol like Uganda. Availability of such information may contribute to enhanced productivity and livelihood of the people, especially those who are deriving livelihood from crops such as maize.

Ugandan maize productivity is performing at only 30% compared to the world potential: 1.8 ton/ha vs 5.5 tons/ha (Epule et al., 2022; Kisaame, 2023; Zingore et al., 2022). Beyond being a staple crop, it is also used as animal feeds despite yield decline. The low yield may lead to failure in achieving the national and international goal like Sustainable Development Goals (SDG) 2 of zero hunger, NDP IV of sustainable increase in household income and quality of life and malnutrition among the vulnerable sections of the population (Fahad et al., 2022; Viana et al., 2022).

1.2 Problem statement

Low soil fertility is one of the main causes of low maize productivity in Uganda. Currently, maize productivity in Uganda stands at only 30% compared to global productivity (Epule et al., 2022; Kisaame, 2023; Zingore et al., 2022). The causes are low level of essential nutrients in soil, especially N. These are compounded by low application of fertilizer which stand at only 5% (W. Paper et al., 2024). In addition, losses of nutrients existing within the soil system

estimated at 50% (Singh et al., 2026). As if that is not enough, some plants poorly uptake nutrient from the soil. This is because of poor timing of microbial mineralization process that affects nutrient availability for absorption by the crops and losses of N in form of ammonium and nitrate (Ayiti & Babalola, 2022). In recent years, use of conservation agriculture and biochar have been considered as part of the solution to low soil fertility (Chen et al., 2023). For example, CA enhances N availability directly through biological N fixation from legumes included in rotation and through leaf litter fall of N-rich leaves. Likewise, biochar has been reported to reduce N loss in form of N_2O and influence microbial activity that increases mineralization and nutrient release (Cornelissen et al., 2013; Obia et al., 2019). However, there are contradictory reports on factors that affect loss of N in form of N_2O (Alkharabsheh et al., 2021; S. Joseph et al., 2021; Tea et al., 2023). Conservation and biochar are known to be beneficial in some soil environment and yet in other setting was found to negatively affect N_2 -fixing Rhizobium bacteria and P-mobilizing mycorrhiza fungi (Ringer, 2022). Meanwhile, conservation agriculture and biochar was found to affect crop growth, plant uptake of soil nutrients and their accumulation in leaf litters and nutrient recycling during mineralization (Bai et al., 2023; Jabin, 2023; Joseph et al., 2022; Murtaza et al., 2023). It has received limited research attention in maize cropping and production. Hence, conducting this study aimed at contributing to scientific understanding of managing soil fertility with aim of increasing productivity to alleviate food insecurity.

1.3 Objectives

1.3.1 General objective

The general objective of the study is to evaluate effect of conservation agriculture and biochar on nitrogen cycling in pigeon pea-maize rotation in Ferralsol of Gulu.

Specific objectives

- To determine the effect of CA planting basin, biochar & pigeon pea leaf litter on N_2O emission under pigeon pea-maize rotation.
- To determine the effect of CA planting basin and biochar on the quantity and nutrients content of pigeon pea leaf litter.

- To determine the rate mineralization of pigeon pea leaf litter taken from different farming practices

1.4 Hypotheses

- Conservation agriculture, biochar and application of biochar affects nitrogen loss inform of nitrous oxide (N₂O) emission under pigeon pea-maize rotation in the field.
- CA planting basin and biochar application increase pigeon pea leaf litter and its N, P and K contents.
- Variation in nutrient content in the pigeon pea leaf litter from different farming practices influences the rate of N mineralization.

1.5 Justifications

Low soil fertility has not only threatened farmers' livelihood and food security, but directly contributed to bottlenecks to attain the Country's national goal in Uganda's NDP III and IV. Therefore, the limited research in the areas of nutrient management within the soil system through integration of both CA and biochar, has catalyzed the establishment of this study to bridge productivity gaps in most staple crops grown in the Northern region of Uganda. Similarly, pigeon pea is embedded in the CA because of its main contribution on soil enhancement strategy, while other benefits such as food is secondary in the general terms. Finally, this study has provided insights to innovation and practices suitable for soil health and productivity improvement with potential to guide policy makers on allocation of resources and overall priority direction.

CHAPTER TWO: LITERATURE REVIEW

2.0 Overview of conservation agriculture and biochar

Conservation agriculture is a farming practices that is widely practiced globally to cope with climate change (Layek et al., 2022). It is a concomitant application of three fundamental pillars consisting of continuous minimum mechanical soil disturbance, permanent soil cover, and crop diversification (Dur et al., 2022). The low soil disturbance may include no-tillage, reduced or minimum tillage as the farmer uses other means to manage the weeds like herbicide application. The disturbed area is always less than 15 cm wide furrows for planting or less than 25% of the cropped area. Sometimes, strip tillage is allowed if the disturbed area is less than the set limits (Agriculture & Management, 2022; Dur et al., 2022; Suman et al., 2022). In permanent soil cover, more than 30% of the ground area is commonly covered immediately after the direct seeding operation (Dur et al., 2022). In crop species diversification on the other hand, crops are planted by varying rotation, sequences and associations to take advantage of nutrient utilization and management (Domeignoz-horta et al., 2022).

Conservation agriculture has many positive attributes according to some scholars (Kabato et al., 2025; Suman et al., 2022). For example, soil erosion is reduced by the retention of organic residue on the soil surface that protects soil aggregates from raindrop impact plus reduction of soil compaction. In addition, improvement of soil biodiversity and greenhouse gas (GHG) emissions mitigation has been reported in conservation agriculture systems (Kabato et al., 2025), and can contribute to pollution control. Furthermore, conservation agriculture has been reported to enhance symbiosis relationship among the microbes, improves moisture retention, enhance carbon: nitrogen ratio and improve pH among others (Francaviglia, 2023; Suman et al., 2022) reported that numerous microbes plus their associated benefits are seen in soil with CA practices. For example, beneficial fungi that include over 66 operational taxonomic units and bacterial community were found soils under conservation agriculture. From their study, a reduction of pathogenic fungi was observed while saprophytic fungi and AMF which are known for solubilization of major nutrients (nitrogen, phosphorus, zinc, and magnesium) increased. Additional benefits of conservation agriculture practices includes green manuring which improves soil organic matter, crop residues that enhances accumulation of bacteria like

comammox organisms which completely oxidize ammonia to nitrate and useful for plants nutrition (Domeignoz-horta et al., 2022).

Nonetheless, conservation practices have got some negative outcome. These includes no-till practices which promotes use of herbicides that was reported to cause herbicides resistant weeds (Parven et al., 2025) due to repeated application of a single herbicide over long time. Consequently, target-site resistance (resistance to ACCase inhibitor, ALS inhibitor, and PSII inhibitor) arises because of repeated mutation due to repeated application of herbicide. In addition, exposure to herbicides such as glyphosate have been associated with endocrine disruption, liver and kidney damage, DNA damage, reproductive problems, and various neurodegenerative disorder in human being (Mazuryk et al., 2024; Parven et al., 2025). Atrazine has also been reported to cause low sperm counts in men. Furthermore, consumption of herbicides and other agro-chemicals in food is very worrying at 4.10 million tons of pesticides (Parven et al., 2025) where herbicides account for 47.50% followed by insecticides (29.50%), fungicides (17.50%), and others (5.50%).

Meanwhile, biochar is known as a carbonaceous product prepared by subjecting biomass materials to heat in an oxygen-limited environment (pyrolysis). Pyrolysis is the thermal depolymerization of biomass at elevated temperatures without the participation of oxygen. The end products of pyrolysis are syngas, bio-oil, and char (Layek et al., 2022). Biochar was found to have many benefits to the soil systems including improvement in soil physical properties (bulk density, water holding capacity, permeability and hydraulic conductivity), chemical properties (nutrient retention, nutrient availability) and biological properties (microbial population, earthworm, enzyme activities). This improvement in soil characteristics improves plant growth and development (Layek et al., 2022).

In conclusion, the CA and biochar have shown significant positive and negative attributes. This varies by practices, type, biochar application and type of biochar prepared.

2.1 Effect of conservation and biochar on nitrous oxide emission

Among the greenhouse gases, nitrous oxide (N_2O) forms an important component. N_2O is produced in soil system, mainly through biological processes such as heterotrophic bacterial denitrification, autotrophic nitrification, nitrifier denitrification, fungal denitrification, and

heterotrophic nitrification (Guo et al., 2023). The gas has 121 years of atmospheric lifetime, contribute to destruction of stratospheric ozone, and is also 294 times in global warming potential than carbon dioxide (Gallarotti et al., 2021; Hussain & Park, 2021). N_2O emission directly contribute to soil nitrogen loss, climate change and reduction in agricultural productivity. Following those negativities, innovations and practices have been devised to control and mitigates N_2O production and predisposing factors through conservation agriculture and biochar.

Biochar has registered success in controlling the loss of nitrogen in form of nitrous oxide within the soil systems. This is by minimizing the predisposing factors to loses (Hu et al., 2023). Those predisposing factors controlled in soil systems are leaching of soil nutrient below root zone, denitrification and nitrification. All those are due to biochar's attributes such as specific surface area, porosity, surface charge, carboxylate esterification and aromatization structure, high pH, ash content, high carbon content, very low solubility, high stability couple with strong resistance to physical, chemical and biological degradation.

Similarly, several scholars (Alkharabsheh et al., 2021; Hu et al., 2023; Li et al., 2021; Rasse et al., 2022) have reported increased adsorption of the ammonium ion (NH_4^+) to biochar functional groups. The functional groups are carboxyl, carbonyl, hydroxyl and alkyl functional groups. The functional groups diminished NH_4^+ availability resulting in a decreased rate of nitrification. Biochar application therefore minimizes the conversion process by adsorption of ammonium ion, hence, providing a positive attribute towards nutrient management. Furthermore, Guo et al. (2023) also explained that, without such control, nitrification would negatively influence N losses through two step conversions of ammonium to nitrate via nitrite that plays a critical role in the cycle of N. Similarly, biochar was reported to affect the ammonia oxidation microbes, hence reducing N loss. The normal process of ammonia oxidation is when ammonia (NH_3) is converted to nitrite ($\text{NO}_2\text{-N}$) and nitrate ($\text{NO}_3\text{-N}$) (Guo et al., 2023).

In addition, the increased retention of NH_4^+ by biochar may be an important mechanism for reducing N_2O by limiting nitrification. Thus, biochar plays a very important role in reducing availability of NH_4^+ to losses through leaching, and volatilization. Hence, amending soils with biochar has potential to mitigate N_2O emissions (Dawar et al., 2021).

Similarly, under high pH in soil due to biochar application, alteration of microbial structure of ammonia oxidizing bacteria and ammonia oxidizing archaea occurs in some agro-ecological condition such as yellow-brown soil, and purple soil. This caused reduction in the gene expressions of ammonia synthesis-related enzymes and the abundance of ammonia-oxidizing archaea in such soil, thus inhibit the ammonia oxidation of the soil (Hu et al., 2023; Zhang et al., 2021).

Similarly, previous studies conducted by Weldon et al. (2019) and Obia et al. (2015) related enzymes mediating N-transformations and diminished emission of the N_2O . Their investigation found that, assembly of functional enzymes called nitrous oxide reductase (N_2OR) is enhanced at high pH.

That enzyme causes reduction of N_2O to N_2 in denitrification process. Biochar application often increases soil pH due to its alkaline nature. Thus, biochar increases N_2OR activity due to pH rise and this is one of the major mechanisms behind the observed suppression of N_2O emission in biochar treated acid soils. It can therefore be deduced that, as biochar increases the soil pH and so the activity of N_2OR enzyme leading to reduction of emission of N_2O . However, the loss of nitrogen in other forms may persist such as NO and N_2 . For example, a trade-off effect of full organic substitution on N_2O and NO emissions has been reported (Pan et al., 2022). The study attributed the effect to favorable conditions for N_2O production due to the stimulated activity of nitrifiers and denitrifiers. The suppression of N_2O emission following biochar amendment was probably due to promoted further reduction of N_2O (Han & Zou, 2021).

Meanwhile, there are numerous effects of CA practices such as leaf litter on N behavior within the soil system. Leaf litter materials was observed to cause emission based on quantity of leaf litter, moisture level, microbial activity, mineralization, nitrification and ammonification processes among others (Lazcano et al., 2021). The quantity of leaf litter is an important factor that influence the emission of N_2O as reported by Hussain & Park (2021). The researchers found that, N_2O emission increased significantly by increasing leaf litter from 370 to 730 g m⁻² in Pakistan's forest ecosystem. The release of N from organic materials is influenced by soil moisture and that relate to the level of N loss (Cotrufo et al., 2022). Thus, high moisture means high N loss, compared to low moisture condition. The study further noted that, leaf litter may act as a mulching material, hence increasing moisture contents that aid N losses.

Based on the two parameters of CA practices and leaf litter, in summary, leaf litter quantity drives N₂O emissions in CA, with higher levels of both increasing N losses through enhanced microbial activity (Lazcano et al., 2021; Hussain & Park, 2021; Cotrufo et al., 2022). Thus, low-emission practices must therefore integrate litter and water management to mitigate these trade-offs. However, contrary views exist on how certain types of biochar affect nutrient cycling. Biochar with C:N ratios >30 have been suggested to decrease N₂O emissions by temporarily immobilizing soil N. Biochar with a higher C:N ratio, higher CEC, and larger surface area reduces soil mineral N concentration because of the increased N immobilization and adsorption (Li et al., 2021).

Furthermore, biochar produced from some biomass materials such as neem tree was found to be more effective in the controls of net loss of N due presence of nitrification inhibitor (Abbas et al., 2021). Application of nitrification inhibitors such as 2-chloro-6-(trichloromethyl)-pyridine to reduce nitrification may be a good mitigation measure to N₂O emission.

In addition, Gallarotti et al. (2021), Martinsen et al. (2022, 2023), Slesak et al. (2023) and Wu et al. (2023) conducted study in both China and Zambia. The research observed negative contribution of biochar instead by increasing net nitrification rates by up to four-fold after biochar application. In China, more biochar material was needed to cause an effect e.g. more biochar from pines. It was found that, NH₃ volatilization and N₂O emission from poultry litter compost could not be reduced unless the amount of pine chips biochar was more than 20% (w/w)

Also, Martinsen et al. (2022) linked the biochar to increased soil porosity and soil moisture. It was reported that well-aerated soils could stimulate the populations of ammonia-oxidizing archaea and ammonia-oxidizing bacteria. This stimulates the process of nitrification which may lead to N₂O emission in the ideal situation. Martinsen et al. (2022) instead found an increase in N₂O production rate by AOA at low pH (pH less than 4.5) and as the pH increase, N₂O becomes lower (0 at pH more than 5.5). Thus, AOA production of N₂O increases as the pH tends towards acidity and lowers as the alkalinity increases. That is contradictory to normal biochar performance which could have increased the soil pH (Gallarotti et al., 2021; Han et al., 2021).

In contrast, in grass-legume mixtures, an increase in total plant productivity was found although there was no effect on ecosystem respiration and N₂O emissions from the soil (Song et al., 2023). The researchers found that losses are not entirely inform of N₂O emission but through other N forms during ammonification, denitrification, and biological immobilization. The ammonification is a is a microbial activity that decomposes organic nitrogen compounds to produce ammonia through hydrolysis of protein into peptide catalyzed by microbial protease, and followed by deamination, which primarily involves the separation of amino acids to produce NH₄⁺/NH₃. The process is later followed by nitrification (Song et al., 2023). Similarly, Barneze et al. (2020) reported no effect on N₂O emissions as a result of application of leguminous biomass as a result of high N content.

From the observation, the following were the identified gaps. First, previous findings reported few materials used to make biochar like neem tree and the effect on nitrification, hence nitrous oxide emission. Thus, this experiment explored the biochar material produced from pigeon pea stems and how it influences other soil chemical processes and consequently N₂O emission. Second, it was earlier found that not all legumes enhance emission of N₂O. Hence, this study validated whether pigeon pea leaf litter could influence N₂O emission. Third, some scholar indicated high immobilization and how it causes low N₂O emission due to more N immobilized in materials with properties of high carbon and nitrogen ratio. However, limited literature has explored whether similar attributes apply to pigeon pea leaf litter. Fourth, nitrification inhibitor such as neem tree was found to be more effective in the controls of net loss of N in form of N₂O. Nevertheless, it is not clear whether pigeon pea has similar behavior.

2.2 Effect of conservation agriculture and biochar on pigeon pea litter

Amidst climate change challenges, CA and biochar have tremendously enhanced the nutrient availability, utilization and use efficiency by crops (Mhlanga et al., 2022). This is because of how they moderates moisture contents, increase bacterial activity, enhance plant growth, reduce nutrients loss, increase nutrients absorption and buffer pH among others (Murtaza et al., 2023). Similarly, application of biochar to soil worldwide have been shown to improve crop yield by 30 to 100% in several crops such as soybeans, maize, carrots and beans (Coumar et al., 2016). Researchers linked this improvement to enhancement in nutrient availability to the crops, coupled with provision of favorable chemical, biological and physical properties.

Previous studies found that the quantity of biochar applied affects nutrient availability for plant uptake and use efficiency (Chew et al., 2022; Choudhary & Behera, 2020; Hematimatin et al., 2024; Martinsen et al., 2023). But the authors guided on the quantity of biochar to be added. For example, biochar applied at 5 tons/ha is required to achieve the desired crop growth response. This may also translate to the quantity of the leaf litter shed and the nutrient content in the litter.

In Ethiopia, Yaebiyo et al. (2023) reported that biochar enhanced survival and growth of agro-forestry under dry condition due to increase in soil moisture. The increase in moisture may have also increased the solubility of nutrients within the soil system. Consequently, this could be the reason behind the high nutrient contents in the leaf litter. Such higher nutrient content of litter from field amended with biochar may be due to improved Nutrient Use Efficiency (NUE) by neutralizing the saline, acidic and basic condition (Alkharabsheh et al., 2021). This is because, some nutrients were found to be favored when the pH of the soil is in neutral condition such as P, translating into nutrient accumulation in the leaf litter (Tadesse et al., 2021b; Zhu et al., 2022). Similarly, previous studies (Cornelissen et al., 2013; Guo et al., 2021; Rasse et al., 2022) confirmed that, biochar surface can exchange both anions and cations. The surface with cation exchange capacity (CEC) was found to increase with pH while the anion exchange capacity (AEC) increased with reduction in pH of the soil. Thus, since biochar attributes increases pH, that means high CEC due to increased pH causing the reduced nutrients loss through electrostatic adsorption, diminishing nutrients leaching and increasing uptake by the plants. Because of this, biochar can influence the physiology of plants e.g. increasing transpiration rate from 19 to 40% (Murtaza et al., 2024). Biochar increased net photosynthetic rate, transpiration rate, stomatal conductance, and water use efficiency during the plant growth period due to improved physio-chemical properties in soil (Naz et al., 2025).

Biochar has been shown to affect some important microbes that enhance the nutrients uptake by the plants. According to Li & Cai (2021), the hyphae of Arbuscular Mycorrhizal Fungi (AMF) was found to extend into the micropores of biochar and thus obtain phosphorus. Arbuscular mycorrhizal fungi hyphae acted as an extension of host plant roots and absorb nutrients from the soil, especially those with low mobility such as P, Cu, and Zn. In addition, several studies have shown that the addition of biochar improves AMF colonization rates (Vahedi et al., 2022). In line with that, other scholars have reported that there are good evidence that mycorrhizal fungi

produces enzymes that enable them to developed minerals and carbon from organic sources (Colpaerti & Tichelen, 1996; Osburn et al., 2022). Also, biochar has been reported to improve the performance of cowpeas (Adekiya et al., 2024). The yield increase was associated with improvement in Biological Nitrogen Fixation (BNF), soil aeration, water holding capacity, and higher plant nutrient uptake.

Similar to biochar, conservation agriculture practices influence both soil fertility and plant performance. Studies from Ethiopia report that CA enhances soil nitrogen and phosphorus levels (Belay et al., 2022; Masha et al., 2023). Belay et al. (2022) found annual increases of 0.5% in organic matter, nitrogen, and phosphorus, with organic matter rising from 3% to nearly 5%. Likewise, Masha et al. (2023) reported elevated total nitrogen (0.18%, 0.16%, and 0.17%) and available phosphorus (2.72, 2.77, and 1.94 ppm) under CA systems.

However, biochar effect was found to depend on the feedstock (Slesak et al., 2023). The feedstock with high levels of nutrients such as manure correspondingly produce biochar with greater nutrient content compared to feedstock of low nutrient level. Consequently, low nutrient biochar translates to low available nutrient to the plants.

Furthermore, Wan et al. (2023) found differences in the level of nutrients (N, P, K, Ca) in plants parts after biochar application. Low P content on the leaf of plants was found when biochar from wheat was applied to soil. The possible reason was that, since P is effective under neutral pH, addition of biochar could have increased the pH resulting to precipitation of P by Calcium and magnesium ion (Ca^{2+} and Mg^{2+}). P in soil may also be transformed due to hydrolysis, immobilization, mineralization, or amendment.

The feedstock source and pyrolysis conditions greatly influence important properties of the biochar and that translates to the overall performance of the plants. For wood biochar, high total C, low ash content, low total N, P, K, S, Ca, Mg, Al, Na, and Cu contents is commonly reported (Wan et al. 2023). In addition, low CEC and exchangeable cations as compared with manure-based biochar (Layek et al., 2022) may affect its effect on soil properties.

Similarly, other researchers (Chtouki et al., 2022; Li & Cai, 2021; Maftu & Nursyamsi, 2019) have demonstrated that P limitation in soil may be due to water limitation (e.g. arid and semi-

arid area), redox potential, chemical fixation of phosphorus, concentration of cations (Calcium, iron and Aluminum), and level of pH within the soil. Reduced P availability can be due to complexation and precipitation with soil cation. More so, orthophosphate anions react quickly with cations such as Fe and Al which significantly fix P through Al/Fe-P bonding in low pH soil.

Furthermore, contradictory view pointed that low N and P was recorded in biochar treated soil in study conducted on tomatoes plants due to higher microbial activity that normally dominates the biochar-treated substrate, leading to a major reduction of available nitrogen (Simiele et al., 2022). The researcher observed very low P at the beginning of vegetative stage and increase in the fruit stage. The explanation was linked to the biochar's ability to bring P into the substrate, which is dependent on the amount and form of phosphorous available in the substrate and biochar type.

Poor crop performance has been reported in biochar amended plot resulting to higher field capacity which affected AFM negatively (Li & Cai, 2021). Also, the type of soil affects the N loss in addition to soil amendments. For example, in Arenosol, Martinsen et al. (2022) reported high drainage capacity of the soil that could have leached out nitrate. That directly affects the level of nutrients within the soil system. Furthermore, some soil type affects the biochar nutrient level. Martinsen et al. (2023) conducted a study on sandy soil on how biochar affects K in the soil. Biochar was found to cause low level of K in sandy soil.

Nonetheless, previous studies have shown that biochar application increases yields of soybeans, maize, carrots, and beans. Yet, despite pigeon pea being a crucial crop in the region's farming systems under increasing climate stress, little attention has been given to this crop particularly concerning the quantity and quality of its leaf litter. While earlier research found that biochar enhanced soil N and P at two locations, no similar effect was observed for K, underscoring the need to examine biochar's impact on K availability and uptake by pigeon pea. Moreover, although low P accumulation has been reported in wheat, such findings have not been extended to pigeon pea leaf tissue. Given that biochar characteristics vary with feedstock (e.g., wood vs. manure biochars), their effects on nutrient absorption and overall pigeon pea performance likely differ as well.

2.3 Effect of variation on leaf litter nutrient content on mineralization

Mineralization is defined as the transformation of organic compounds into inorganic forms. The first stage of N mineralization is proteolysis. This is where proteins are broken down into amino acids to be taken up by microorganisms and plants. In addition, most amino acids undergo further changes during ammonification, where amino acids undergo deamination and are converted to ammonia (NH_3), and later to ammonium ion. Ammonium ions, which are made available to plants can undergo further microbiological process of nitrification to nitrate (NO_3^-) (Grzyb, Wolna-Maruwka, et al., 2020). Furthermore, mineralization is synonymous to immobilization, and it is a reverse process. This is so because microbes, sometimes instead of releasing N normally, keep up the minerals in its body parts (Grzyb, Wolna-maruwka, et al., 2020). Mineralization allows soil organic matter to release large amounts of macronutrients in a slow pace so that it favors a reduction in nutrient loss and presupposes more uptake by plants. It is a biological process that depends on many factors including time, physiochemical properties of soil (Daly et al., 2021; Grzyb, Wolna-Maruwka, et al., 2020; Islam et al., 2021; Motsomane et al., 2025).

As a case in point, the chemical traits of the organic materials and its influence on the mineralization varies across litter materials much as legumes like forb and graminoid (Bourget et al., 2023a). This finding indicates a relationship between capacities of microbial communities to degrade amino acids and the litter concentration of Mg at day 10. Furthermore, N and Mn concentrations were positively related to glucose and cellulose mineralization at day 38 or 157. To the contrary, Ca concentration; positive at day 157 and negative at day 367 (Bourget et al., 2023a).

Furthermore, Camelo et al. (2021) reported that, mineralization is favored in leguminous crops residues due to low carbon to nitrogen ratio which is always estimated to be below 20:1 ratio. Similarly, some research has shown the quality of organic residues can be influenced by C to N ratio couple with structure, and microbial activities (Nourou & Dominique, 2003; Yang et al., 2022). In addition, time is found to be a key factor in mineralization process. This is because, the existing literature found high microbial activity within 10 days when the N level in the litter is high such as in leguminous crop (Bourget et al., 2023b). The mineralization rate start in most

crops reducing after 10 days (Bourget et al., 2023b). The depth at which the materials are buried affects mineralization.

Another scholar reported the effect of pigeon pea root exudates in a crop rotation on microbial activity and diversity (Motsomane & Anathi, 2025). The root exudates were very critical in shaping soil microbial populations because it provide organic compounds that regulate microbial activity and decomposition. The study investigated bacterial genera such as *Novosphingobium*, *Croceicoccus*, *Paraburkholderia*, and *Pseudomonas* couple with increase in enzymes in soils, the nitrate reductase, β -glucosidase, acid, and alkaline phosphatase. The result presented a high amount under *C. cajan* than *E. curvula*.

Existing evidence on the link between mineralization and organic matter input remains inconclusive. According to Bourget et al. (2023b), for example, mineralization is mediated by the C and N composition of litter leachates and proceeds in sequential phase. Beginning with the release of N, P, and Mg, followed by lignin degradation. In a related study, Bourget et al. (2023a) observed that mineralization occurred between days 38 and 156 for substrates containing P and Mn.

In addition, it was found that difference in the mineralization rate varies according to the plants parts. For example, high microbial activities developed within 10 days in leaf litter materials compared to roots which occurred within 38 days (Kim & Isaac, 2022). Therefore, Korthals et al. (2021) and Akoto et al. (2022) also reported that mineralization is not only affected by carbon to nitrogen ratio. Plant litter with high N ($\geq 2.5\%$), low C/N ratio ($\leq 32:1$) and low lignin and polyphenol contents decompose relatively faster and can provide an adequate supply of nutrients in agroecosystems couple with the loss. Additionally, basal respiration and soil depth have been shown to influence microbial activity rates (Field et al., 2021).

Further studies indicate that activity of enzymes involved in C, N and P cycling is reflected by the equilibrium and stoichiometry of soil enzyme between C and N. This is shown when N and P addition significantly increased the non-labile soil oxidizable carbon (Bai et al., 2021; Zhai et al., 2024) This is because activities become more sensitive to the addition of nutrients than to the changes in the atmosphere and climate. Thus, bacteria and fungi influenced by weather and climate are the major producers of extracellular enzymes responsible for the degradation of complex, polymeric litter compounds to oligomers and monomers. Hence, increases

biogeochemical process especially cycling nutrient elements in soil by ingesting and destroying bacterial cells and excreting mineral nutrients (Bai et al., 2021).

In addition, mineralization was found to differ based on crop type and plant parts e.g. in jack bean (*Canavalia ensiformis*), pigeon pea (*Cajanus cajan*), dwarf mucuna (*Mucuna deeringiana*) and sunn hemp (*Crotalaria juncea*). The results presented on sunhemp and pigeon pea showed slowest rate of mineralization which highly affect subsequent crops (Carlos et al., 2023). The result showed that, quantity of N released from chicory leaves was averagely 25% more compared to that released from lucerne. The variation in nutrient release was within 7-14 days. After which, both leaves became similar in terms of mineralization. Thus, the researcher hypothesized that, it could be as a result of initial immobilization (Gardner et al., 2023).

Based on this review, the study identified several gaps; First, limited information is provided on the variation of mineralization within leaf of same species but different nutrient contents. Second, the literature reported CO₂ evolution at 14 days in pine tree during incubation experiment. Meanwhile, this study compared pigeon pea leaf litter with different nutrient contents and how it affects microbial activity, signified by soil respiration and that is carbon dioxide evolution. Third, previous study noted the chemical traits of legumes on mineralization such as forb and graminoid, but limited information was provided on pigeon pea legumes and how it could present itself with variation in mineral composition in the leaves.

CHAPTER THREE: MATERIALS AND METHOD

3.1 Description of study site

The study was conducted at Unyama Sub County, Gulu District in northern Uganda (Fig. 1), located at latitude 2°46'54.0" N and longitude 32°17'57.0" E (Maku et al., 2022). The climate is characterized by a bimodal rainfall pattern which starts in March to July (Partial dryness for about one month). The second rainfall period of August to November is followed by long dry season from December to March. The mean annual rainfall is between 1000 -1300 mm and mean annual temperature of 30 - 35 °C. The soil is classified as Ferralsol (WRB, 2014). The land cover is savannah grassland with few shrubs, and that determined the land use pattern. In addition, previous land use was characterized by common field crops such as maize, beans, cassava and pigeon pea grown in rotation (Namuyiga et al., 2022).

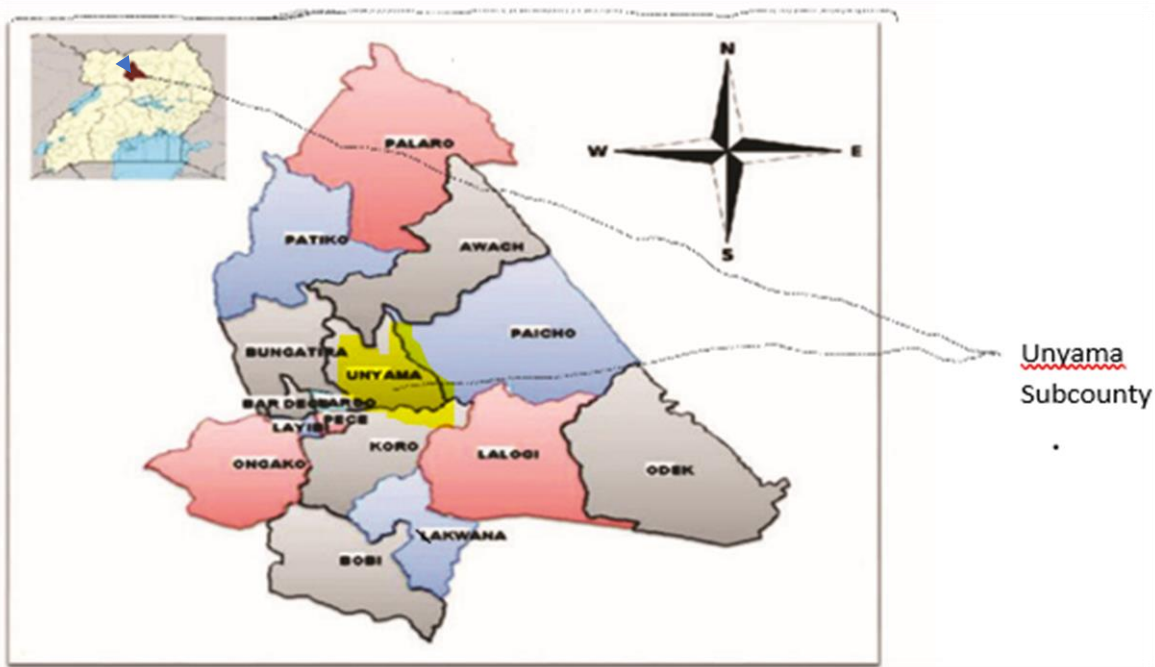


Figure 1: The study location at Unyama sub county in Gulu District.

3.2 Preparation of biochar material used in the study

Biochar was prepared from pigeon pea stems that was harvested from the previous season. Flame curtain Kon Tiki was used to prepare the biochar (Paper, 2026). It consisted of a conical

hole with diameter of 2 m and 1 m deep dug in the ground. The preparation processes involved placement of dry pigeon pea stems layer by layer during burning to allow continuous flame (flame curtain) on the surface. The syn gases were burnt by the flame curtain in the process. At the end of the burning, the flame died off when no more combustible syn gases were produced followed by quenching using water. The biochar was then covered using bananas leaves followed by soil. The biochar was harvested using hand hoe plus spade, three days after covering. The biochar was crushed before application to soil.

3.3 Determination of N loss in form of N₂O emission-Objective 1

3.3.1 Experimental design

The study on effect of CA with and without biochar and/or pigeon pea litter on N₂O loss adopted the Completely Randomized Design (CRD). The experimental layout is depicted in Figure 2. The study determined the level of N loss in form of N₂O emission. There were four treatments replicated 4 times. Treatments included (i) CA planting basin, biochar application (4 tons/ha) with pigeon pea litter (CA+BC+PPL), (ii) CA planting basin, biochar application (4tons/ha), without pigeon pea litter (CA+BC), (iii) CA planting basin with pigeon pea litter (CA+PPL) and (iv) CA planting basin without pigeon pea litter (CA). Each CA planting basin had a dimension of 35 cm long, 15 cm wide and 20 cm deep (10.5 L) with intra and inter row spacing of 35 cm and 70 cm, respectively. Soil collars made from PVC pipes and measuring 15 cm diameter and 10 cm height and surface area of 177 cm² was installed in each of the CA planting basins. This collar was place prior before planting the pigeon pea in the garden. A distance of 1 m was left between biochar treated basins and the non-biochar treated basins. Crushed biochar weighing 240 g (equivalent of 4 tons/ha) was added in the biochar treated basins; CA+BC+PPL and CA+BC. Fresh pigeon pea litter equivalent to 52.5 g of oven-dried pigeon pea leaf litter (1000 g litter m⁻² or 20 g N m⁻²) was spread homogeneously on the planting basins surface including soil collars after germination pigeon pea as seen in fig 2.

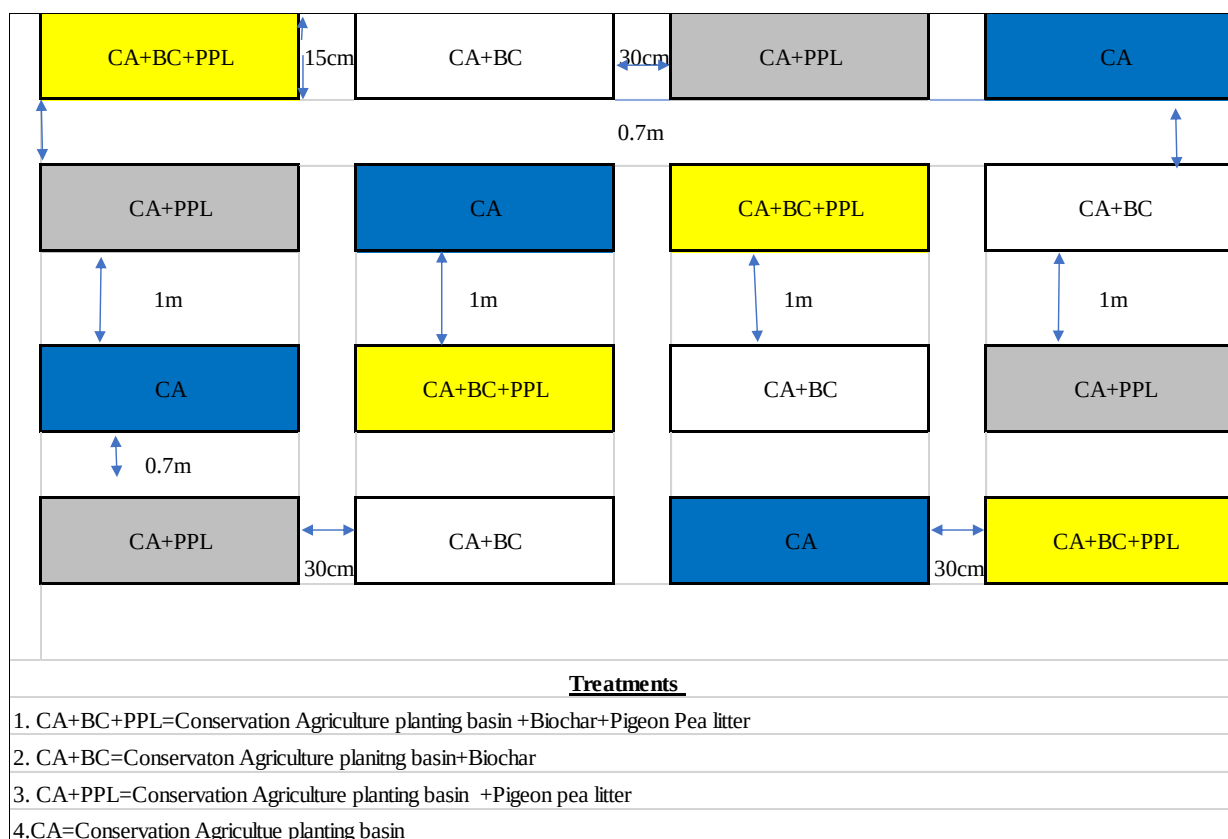


Figure 2: Experimental layout to determine N₂O emission.

3.3.2 Gas sampling

Gas sampling procedure was conducted in the experiment A. The procedures were characterized by putting structures that allow gas sampling without soil disturbance. Collars were installed in all the 16 experimental units before planting of pigeon pea. The collar consisted of polyvinyl chloride (PVC) of 17 cm diameter and 10 cm in height from which 7 cm, was inserted into the soil leaving 3 cm above ground. Pigeon pea crop was planted in all the experimental plot after installation of collars. Application of pigeon pea leaf litter as mulch was implemented in those specific treatments to serve as nutrient source.

The gas sampling was done before the leaf litter fall of pigeon pea after first planting of crop in 2025. Gas samples were collected during two rainfall episodes. During each episode, four frequent gas sampling campaigns were conducted; prior to forecasted relatively intensive rainfall, during the intensive rainfall, one week after the rainfall and two weeks after the rainfall event. Gas samples were collected from permanent collars installed in each of the basins (one in

each basin). During gas sampling, chambers were tightly placed on the collars (static base) and sealed from outside with a grease to avoid leakage of the gases. At each of the sampling event, samples were drawn at 4 different times for one hour (0 mins, 15, mins, 30 mins and 60 mins) using air-tight 20 ml syringes fitted with a 3-way valve. The gas samples were transferred to pre-evacuated clear glass vials sealed with a gas tight septum. The samples were labeled and stored in a dark room in a soil laboratory at Faculty of Agriculture and Environment, Gulu University. The gas samples were later analyzed for N₂O using gas chromatograph at Norwegian University of Life Sciences.

3.3.3 Experimental design

The study of effect of CA with single and split application of biochar on leaf litter quantity and quality adopted Randomized Complete Block Design (RCBD), set according to the layout in Figure 3. There were four treatments and four blocks / replicates. The treatments were implemented in plots measuring 6 by 5 meters. Treatment included (i) CA: planting basins with pigeon pea - maize rotation (CA). The variety used to establish the study was Sepi II (ii) CA planting basins with one-time 4t/ha biochar application, pigeon pea-maize rotation (CA+BC+PP), (ii) CA planting basins and biochar split application (2 t/ha at experimental set up & 1 t/ha per year) pigeon pea - maize rotation (CA+ BC+BC), (iv) Conventional agriculture with maize-pigeon pea rotation (Convent + PP). In CA plots, planting basins was measuring 35 cm long, 15 cm wide and 20 cm deep (10.5 L).

3.3.4 Data collection for litter quantity and NPK

a) Leaf litter quantity

A wooden frame measuring 120 cm by 60 cm was constructed by a strip of wood and nylon mesh. The mesh was fastened to allow collection of the leaf litter that falls from plants. The frame was laid under the plants and collected bi-weekly. The collection began immediately after 1 month from the time of planting of the crop to synchronize when the leaves start falling. The collection was conducted for 4 months starting from April 2025 to August 2025. To ensure uniformity using dry weight of the litter, a 1.6 kg litter was withdrawn and put in the oven to dry for a period of 24 hours at 65 °C and measured. The determined moisture content of the

sample of litter was used to correct the weight of the total leaf litters collected from different treatments from the field.

b) NPK contents in the leaf litter

The oven-dried leaf litter obtained from different treatments in the field were milled using a Wiley mill and passed through a 1 mm screen (Buthelezi et al., 2022). The milled litter was analyzed for nitrogen, phosphorous and potassium. Total N was determined using Kjeldal digestion (Allen, 1989). The analytical steps included heated acid digestion, Kjeldal distillation and titration. P was determined from the leaf litter as follows; 1 gm of the leaf litter were measured in a breakable crucible followed by oven drying at 105 °C degrees for 1 hour. The sample were ashed at 550 °C for 3 hours followed by digestion using concentrated nitric acid, filtration, and storage of filtrate. Furthermore, 2% nitric acid was reconstituted to make standard solution. It was prepared using stock solution using one parts per million: blank, 1 ppm, 2 ppm, 3 ppm, 4 ppm, 6 ppm, 7 ppm, 8 ppm and 10 ppm. The filtrate was analyzed for P using spectrometry techniques (Wieczorek et al., 2022)

3.4 Mineralization of pigeon pea litter from different Treatment-Objective 3

3.4.1 Experimental design

Mineralization experiment was performed in soil laboratory of Gulu University. The experiment investigated three variables that included the level of biological activity in soil (soil respiration) through measurement of carbon dioxide evolution. The experiment used the leaf litter drawn from various treatment in the field; CA, CA+BC, CA+BC+BC and conventional farming. The soil was opened daily for one hour to avoid anaerobic respiration condition from developing. Soil samples were incubated for 336 hours (14 days) in a closed chamber. A container was filled with soil drawn around the University field of 1gm and 300cm³. Thereafter, it was sieved and determined for its water field capacity. This was followed by connecting the container using a tube to a small container filled with 40mls of sodium hydroxide. Immediately, the evolution due to microbial activity was trapped by sodium hydroxide to form sodium carbonate. Subsequently, the solution is withdrawn and added with barium chloride to form precipitate. As the unreacted solution was titrated daily for 14 days with 0.01M HCl. The subtraction of the

titration value and the 40mls of sodium hydroxide indicated the carbon dioxide evolved in the experiment.

Second, the 10 gm of soil were taken from each container. KCl was added to stop the further reaction. This was followed by shaking the solution for 1 hour. It was sieved and stored in the fridge. This was followed by double titration to determine ammonium ($\text{NH}_4^+\text{-N}$) and nitrate ($\text{NO}_3^-\text{-N}$) build up within soil.

3.4.2 Data collection

The mass of CO_2 generated was calculated using the formula from Sariyildiz & Anderson (2003).

Second, $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ released during incubation experiment was determined as follows; (b) filtrate was analyzed for ammonium and nitrate ion using the double distillation.

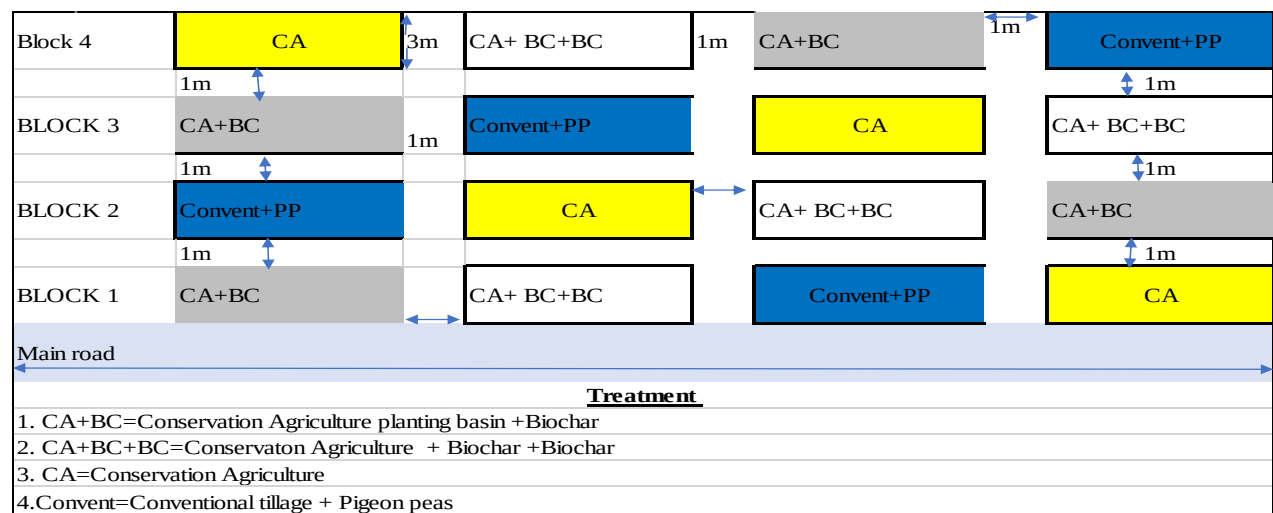


Figure 3: Experimental layout B to determine leaf litter quantity and nutrient content.

3.5 Statistical analysis

The experimental data was subjected to one-way Analysis of Variance (ANOVA) using R software to compare the effect of CA planting basin, biochar, and pigeon pea leaf litter on N-loss. In addition, two-way ANOVA for RCBD experiment for leaf litter quantity, nutrient content and carbon dioxide evolution in the mineralization experiment. Furthermore, three-way

ANOVA was conducted to assess the effect of variation of nutrient from different treatment on $\text{NH}_4\text{-N}$, $\text{NO}_3\text{—N}$ over 16 days.

Finally, all the text found to be significant were further conducted post hoc analysis to separate differences among treatments for those that presented a significant result. All statistical analyses were considered significant at $p < 0.05$..

CHAPTER FOUR: RESULTS

4.1 Effect of farming practices on N₂O emissions

4.1.1 N₂O emission trend during the season

The results presented is for effect of farming practices on N₂O emissions trend over the season (Fig 4). The treatments compared were conservation agriculture alone (CA), conservation agriculture plus application of biochar (CA + BC), conservation agriculture plus biochar and pigeon pea leaf litter (CA + BC + PPLL), and conservation agriculture plus leaf litter only (CA + PPLL). The N₂O emissions across the different farming practices ranged between 40 -120 $\mu\text{g N m}^{-2} \text{ h}^{-1}$. Furthermore, the result indicates that, all treatment had low emission in the third week of May. More so, CA + BC + PPLL amended with biochar the lowest N₂O emissions of compared to the other three treatments: 4-0 and 0 respectively. Finally, highest emissions were observed under CA + PPLL, followed by CA + BC + PPLL of average 120 $\mu\text{g N m}^{-2} \text{ h}^{-1}$.

In conclusion, all the farming practices predisposes the soil to N loss. In addition, month of April experienced the highest while the month of May experienced the lowest N-loss.

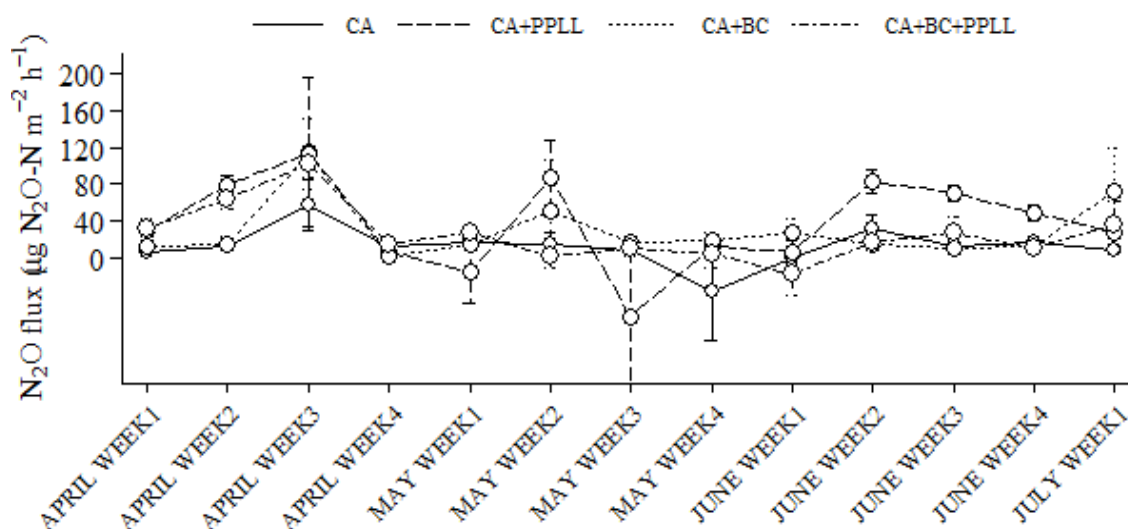


Figure 4: Variation in the N₂O emission across different farming practice over season. CA=conservation agriculture alone, CA + BC=conservation agriculture plus application of biochar, CA + BC + PPLL = Conservation agriculture plus biochar and leaf litter.

4.1.2 Cumulative N₂O emission during the season

The results presented is for effect of farming practices on cumulative emission of N₂O emissions over the season (Fig 5). The treatments compared were conservation agriculture alone (CA), conservation agriculture plus application of biochar (CA + BC), conservation agriculture plus biochar and pigeon pea leaf litter (CA + BC + PPLL), and conservation agriculture plus leaf litter only (CA + PPLL). The N₂O emissions across the different farming practices ranged between 0.040 – 0.1 kg N ha⁻¹. The result indicates that, CA amended with biochar and/or leaf litter exhibited greater N₂O emissions compared to CA without any amendment. The highest N₂O emissions were observed under CA + PPLL, while CA alone displayed the lowest emissions. It was also noted that, all treatments exhibited wide error bars, indicating substantial variability around the mean N₂O emissions within each farming practice.

Furthermore, analysis using one-way ANOVA (Appendix 7) revealed no statistically significant difference in N₂O emissions among the farming practices ($p = 0.416$). Meanwhile, the highest N₂O emissions observed under CA + PPLL are most likely attributable to priming effect, whereby the fresh, high-quality pigeon pea litter stimulated microbial denitrification. In addition, biochar may have modestly exacerbated this effect by retaining moisture and providing habitat for microbial activity. However, given the non-significant ANOVA result, these mechanistic explanations remain tentative and should be treated as hypotheses for further investigation rather than conclusive findings.

Finally, the wide error bars not only explain the non-significant ANOVA result but also highlight the need for increased replication, more frequent sampling, or the inclusion of covariates (e.g., soil moisture, temperature) to reduce residual variation and improve statistical power in future studies.

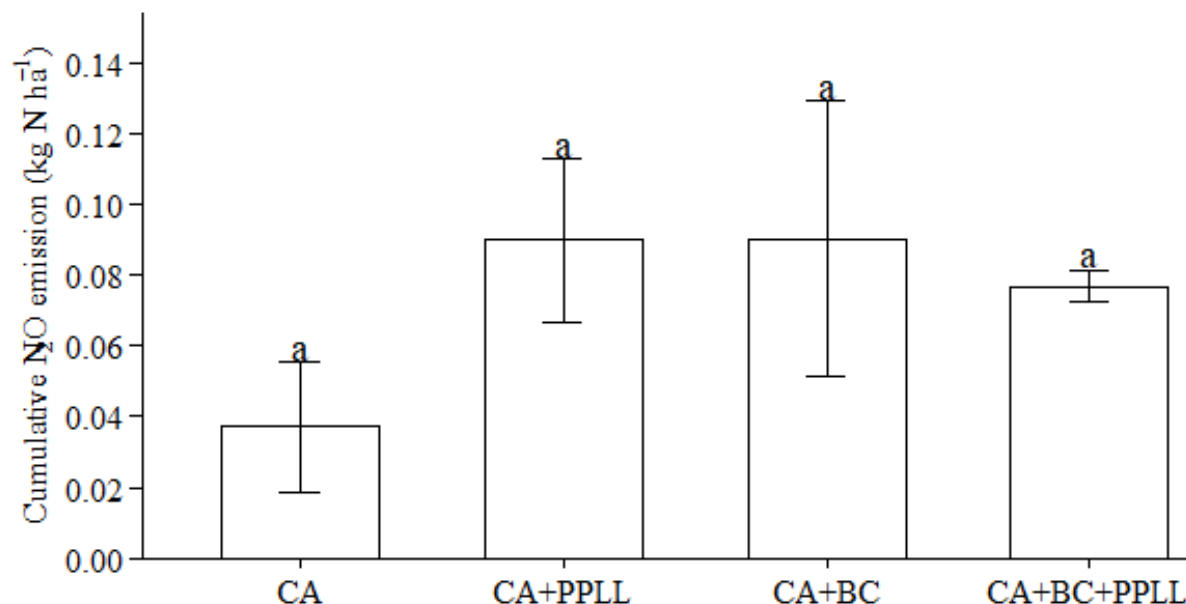


Figure 5: Cumulative variation in the N₂O emission across different farming practice over season. CA=conservation agriculture alone, CA + BC=conservation agriculture plus application of biochar, CA + PPLL = Conservation agriculture plus pigeon pea litter.

4.2 Effect of farming practices on leaf litter quantity and nutrient content

4.2.1 Effect of farming practices on quantity of leaf litter

The effect of farming practices on leaf litter quantity is presented in Figure 6. The treatments compared were conservation agriculture alone (CA), conservation agriculture plus application of biochar (CA + BC), conservation agriculture plus split application of biochar (CA + BC + BC), and conventional agriculture (Convent). The average leaf litter across all farming practices ranged between 240 and 260 kg/ha. Within this range, CA + BC showed the highest quantity of leaf litter, while CA and CA + BC + BC displayed closely similar values and conventional agriculture reported the lowest values. All treatments exhibited wide error bars, indicating substantial variability around the mean leaf litter quantity within each farming practice.

Furthermore, a one-way ANOVA was conducted (Appendix 8). There were no significant differences among treatment means (p-value of 0.997). The very large residual mean square (MS = 40,312) relative to the between-groups mean square (MS = 732) suggests considerable

variability within treatments, which may have obscured any potential treatment effect. Consequently, the observed differences are attributed to random variation rather than genuine treatment effects.

Finally, the wide error bars not only explain the non-significant ANOVA result but also highlight the need for increased replication, more controlled experimental conditions, or the inclusion of covariates (e.g., soil moisture, temperature, crop biomass) to reduce residual variation and improve statistical power in future studies.

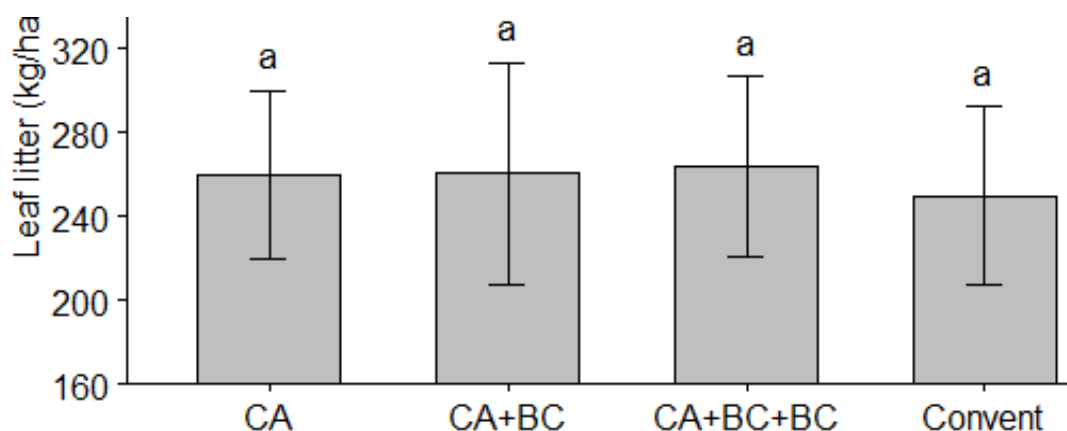


Figure 6: Effect of farming practices on leaf litter quantity. Farming practice.

CA=conservation agriculture alone, CA + BC=conservation agriculture plus application of biochar, CA + BC + BC=Conservation agriculture plus split application of biochar, and Convent.

4.2.2 Effect of farming practices on nutrient content in the leaf litter

4.2.2.1 Effect of farming practices on nitrogen content

The effect of farming practices on nitrogen (N) content in pigeon pea leaf litter was assessed across four treatments: conservation agriculture alone (CA), conservation agriculture plus single biochar application (CA + BC), conservation agriculture plus double biochar application (CA + BC + BC), and conventional agriculture (Convent) as seen in fig 7. The mean N content across all treatments was approximately 40 g/kg as seen in Fig. 7. Although the CA + BC + BC treatment exhibited the lowest N content and CA + BC the highest. Despite, there was no

significant difference ($p = 0.36$; Appendix 9). Meanwhile, a tentative inference is that the reduced N under double biochar application may result from temporary microbial immobilization driven by elevated carbon inputs. The high carbon-to-nitrogen ratio of biochar can stimulate microbial uptake of available soil N, rendering it temporarily unavailable for plant uptake and subsequently reducing N concentration in leaf litter.

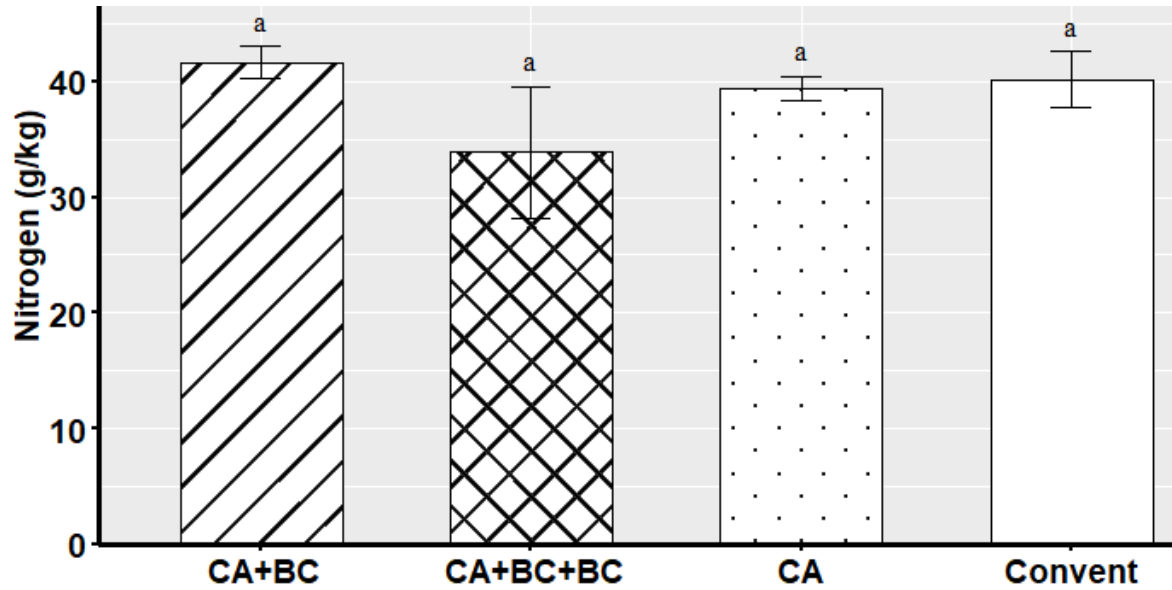


Figure 7: Effect of farming practices on nitrogen content in the leaf litter.

Farming practice: CA + BC=conservation agriculture plus application of biochar, CA + BC + BC=conservation agriculture plus double application of biochar, CA=conservation agriculture.

4.2.2.2 Effect of farming practices on phosphorus content

The result presented is for effect of farming practices on phosphorus (P) content in leaf litter (Figure 8). The treatments four farming practices; conservation agriculture alone (CA), conservation agriculture plus application of biochar (CA + BC), conservation agriculture plus double application of biochar (CA + BC + BC), and conventional agriculture (Convent). There was a visible difference in the phosphorus content of leaf litter collected from the four treatments. Within this range, the inclusion of biochar in CA as either a single (CA + BC) or split (CA + BC + BC) application enhanced the P content of leaf litter by 10% above

conventional practice. The overall spread of means indicated a clear separation among the farming practices, with biochar-amended treatments displaying higher P content than both CA alone and conventional agriculture.

Furthermore, a one-way ANOVA was conducted (Appendix 10) to separate the mean. The analysis revealed a significant difference in the phosphorus content of leaf litter among the four farming practices ($p < 0.001$). Subsequently, post-hoc test conducted to separate which means caused the differences as seen in appendix 11.

Finally, several mechanisms may account for this effect. First, biochar has a high surface area and cation exchange capacity, which can enhance phosphorus retention in the soil and reduce leaching losses, thereby increasing phosphorus availability for plant uptake and subsequent deposition in leaf litter. Second, biochar may stimulate microbial activity and phosphatase enzyme production, which mineralize organic phosphorus into plant-available forms. Third, biochar's capacity to moderate soil moisture and temperature may create favorable conditions for root growth and phosphorus acquisition, leading to higher phosphorus concentrations in plant residues. The fact that both single and split biochar applications produced similar enhancements suggests that the total amount of biochar applied may be less important than its presence in the system.

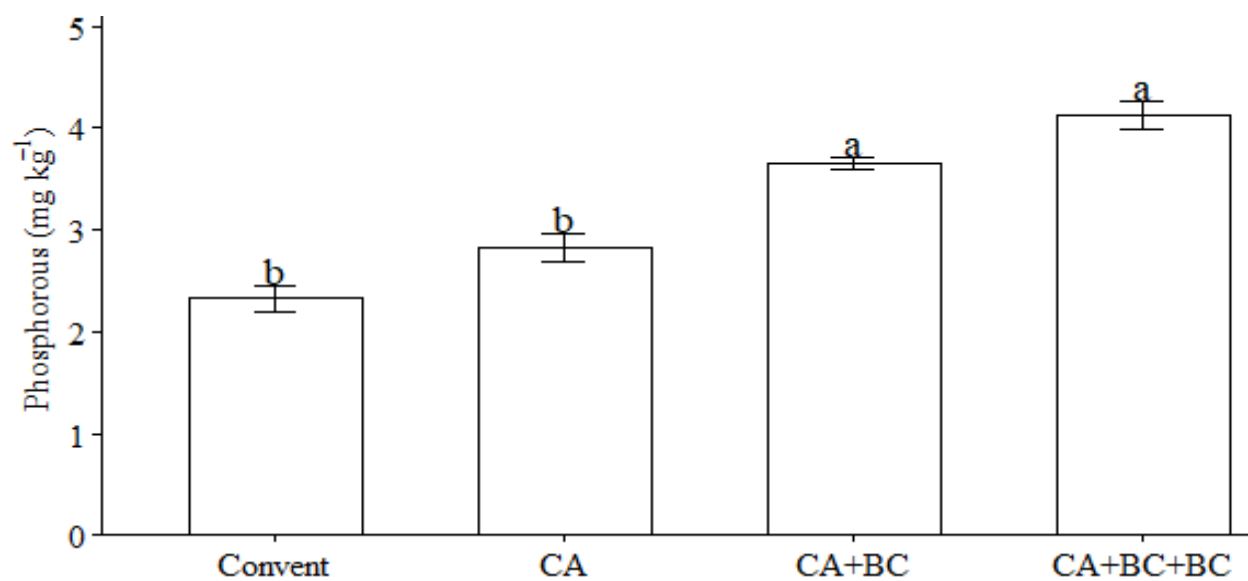


Figure 8: Effect of farming practices on phosphorous content in the leaf litter.

Farming practice: CA + BC=conservation agriculture plus application of biochar, CA + BC + BC=conservation agriculture plus double application of biochar, CA=conservation

4.2.2.3 Effect of farming practices on potassium content

The result here presented the effect of farming practices on potassium (K) content in leaf litter (Figure 9). The treatments compared were conservation agriculture alone (CA), conservation agriculture plus application of biochar (CA + BC), conservation agriculture plus double application of biochar (CA + BC + BC), and conventional agriculture (Convent). There was a visible difference in the mean potassium content of leaf litter among the four treatments. Within this range, conservation agriculture with single and split application of biochar substantially increased K content in leaf litter, rising from approximately 30 mg/kg under conventional practice to 65 mg/kg under biochar-amended treatments. Thus, representing an increase of up to 100% relative to conventional practice.

Furthermore, a one-way ANOVA output is presented in Appendix 11 to separate the mean. The analysis revealed a statistically significant difference in the potassium content of leaf litter among the four farming practices ($p < 0.001$).

Finally, the result confirms that farming practices had a statistically meaningful effect on the potassium content of leaf litter. A post hoc was conducted as seen in appendix 13. The CA + BC and CA + BC + BC increased K content by up to 100% relative to conventional practice. This finding suggests that biochar amendment under conservation agriculture positively influences potassium accumulation in leaf litter. Several mechanisms may account for this effect. First, biochar is itself a source of potassium, particularly when produced from potassium-rich feedstock, and can release K into the soil solution over time. Second, biochar's high cation exchange capacity can retain potassium ions and reduce leaching losses, thereby increasing potassium availability for plant uptake and subsequent deposition in leaf litter. Third, biochar may enhance root development and soil microbial activity, improving potassium acquisition by plants.

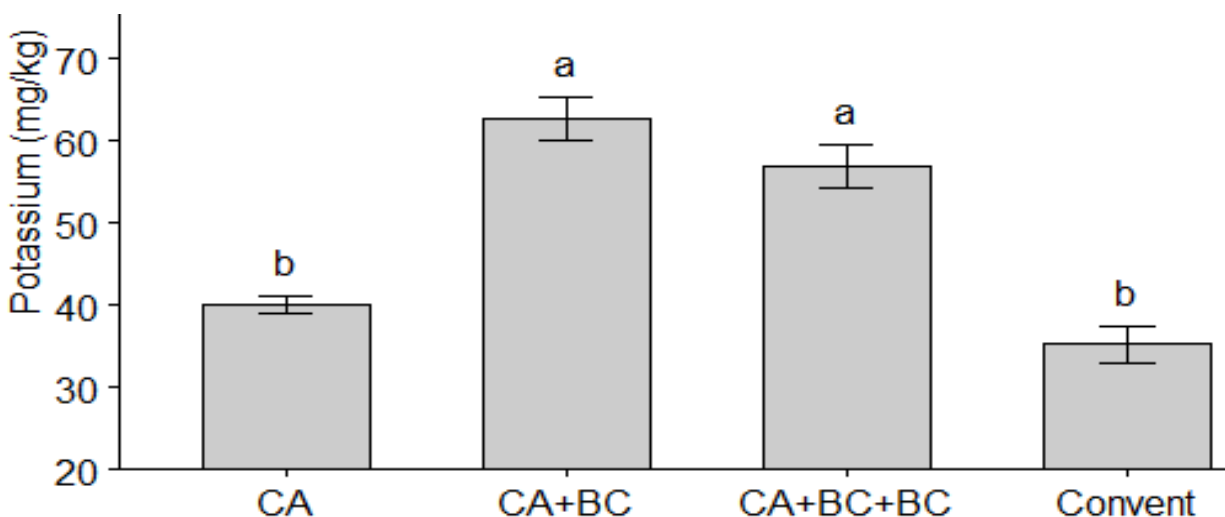


Figure 9: Effect of farming practices on phosphorous content in the leaf litter.

Farming practice: CA+BC = conservation agriculture plus application of biochar, CA+BC+BC= conservation agriculture plus double application of biochar, CA = conservation agriculture

4.3 Effect of variation in mineral content on mineralization

4.3.1 Carbon dioxide as a measure of microbial activity

The result here presented the effect of variation of nutrient in the leaf litter on carbon dioxide evolution as seen in (Figure 10). The leaf litter compared were from conservation agriculture alone (CA), conservation agriculture plus application of biochar (CA + BC), conservation agriculture plus double application of biochar (CA + BC + BC), and conventional agriculture (Convent). The result revealed the carbon dioxide evolution was between 700-1250 mg/m². There was significant of the findings ($p < 0.001$) as seen in the ANOVA table in (appendix 14) as seen in the table was a gradual decline in CO₂ accumulation observed (Fig. 10). Therefore, the findings demonstrate that litter incorporation substantially enhances microbial activity within the soil system during the initial 12 days of application.

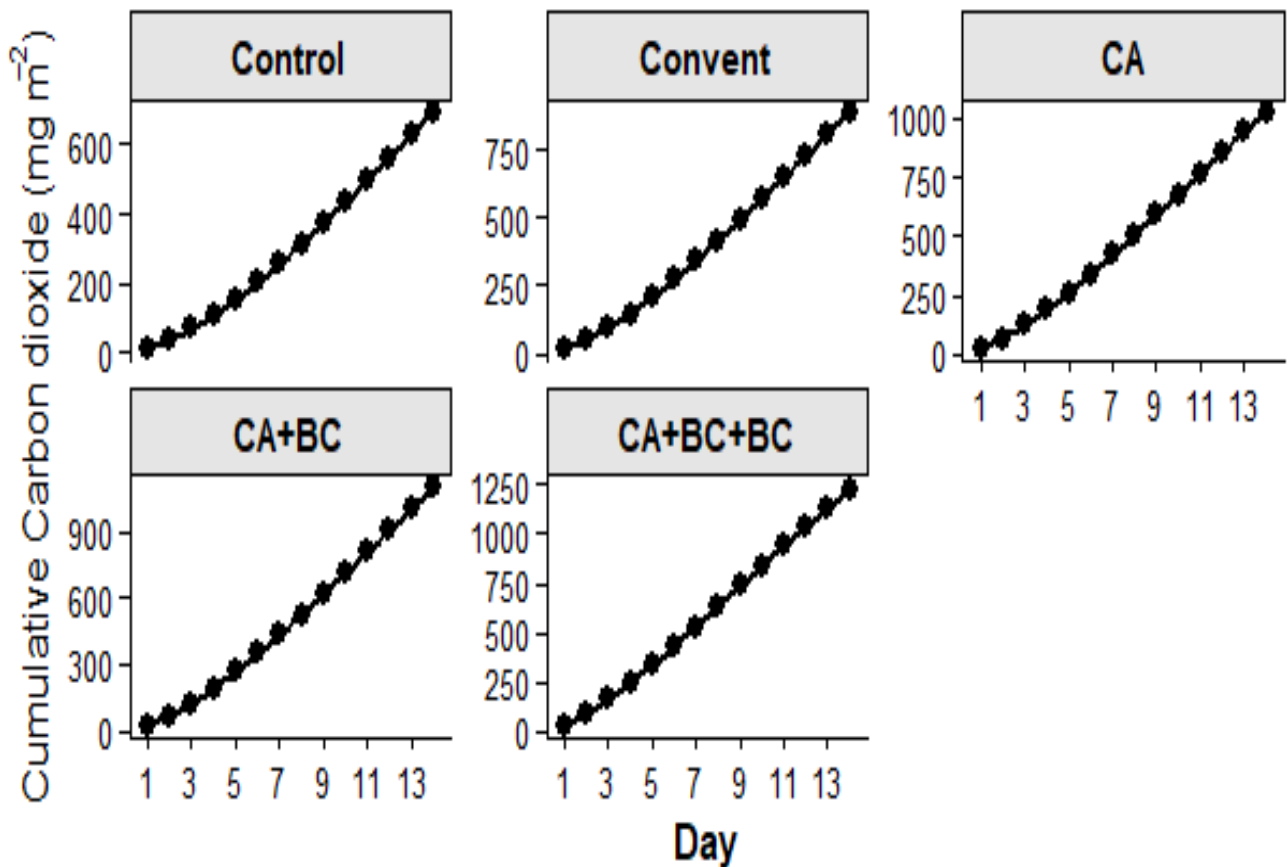


Figure 10: Changes in carbon dioxide evolution over time under different treatments.

Conservation agriculture, conservation agriculture with single application, conservation agriculture with double application, and conventional farming.

4.3.2 Effect of different nutrient contents in the leaf litter due to climate smart practices on the N-mineralization as ammonium and nitrate build up in the soil

The result presented is from the laboratory incubation experiment over a period of 16 days. The confidence level was set at 95% and the result indicated that there was significance difference ($p=0.003$) in the concentration of ammonium during incubation with leaf litters obtained from different farming practices over time (Fig. 11). The ammonium concentration increased in soil amended with litters from different farming practices until day 12 and decreased sharply to a level below the concentration present in the soil before incubation on day 16. Control that did not receive leaf litters had lower concentration of ammonium compared to the rest of treatments, but its ammonium concentration similarly dropped below pre-experiment state. Generally,

mineralization started in the first 12 days, immediately followed by immobilization/nitrification (days 12–16).

treatment without litter ($p < 0.001$). In summary, nitrate dynamics portray the typical sequence of mineralization to nitrification.

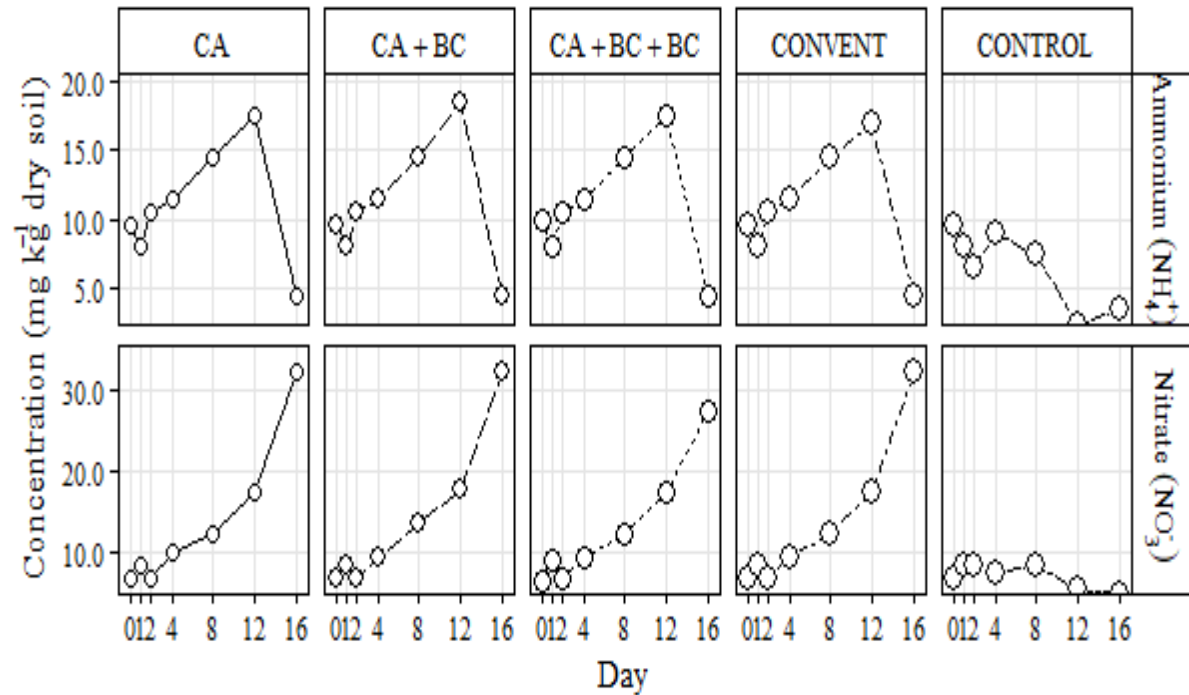


Figure 11: Effect of different nutrient in the leaf litter due to variation in treatments.

Conservation agriculture, conservation agriculture plus single biochar application, conservation agriculture plus biochar double application, and conventional farming on ammonium and nitrate

CHAPTER FIVE: DISCUSSION

5.1 Effect of CA planting basin and biochar on N₂O emission

Nitrous oxide (N₂O) emission represents a critical pathway of nitrogen loss and a greenhouse gas with 294 times the global warming potential of carbon dioxide and an atmospheric lifetime of 121 years (Gallarotti et al., 2021; Hussain & Park, 2021). The results of this study revealed that all agricultural practices studied remained net sources of N₂O emissions. There was no statistically significant difference ($p = 0.416$) in N₂O emissions across the four treatments: CA alone, CA + biochar, CA + biochar + pigeon pea leaf litter, and CA + pigeon pea leaf litter. This suggests that all practices provided conditions that favored N₂O production in a similar manner, with emissions ranging from 0.040 to 0.1 kg N ha⁻¹ over the season. This finding aligns with previous research that reported emissions between 1.93 ± 0.11 kg/ha (Bougma et al., 2025). It also agrees with other scholars who found no significant effect of organic amendments on N₂O emissions (Barneze et al., 2020; Song et al., 2023). However, it contrasts with studies that identified biochar as an effective mitigator of N₂O emissions (Dawar et al., 2021; Hu et al., 2023). It is also below the emission experienced in other ecological situations such as ponds, which were reported at 0.42 kg N ha⁻¹ y⁻¹ (Fan et al., 2022).

The high but non-significant increase in N₂O emissions observed in treatments amended with biochar and/or pigeon pea leaf litter can be explained by a temporary priming effect. Fresh pigeon pea litter, being a leguminous residue with a relatively low C: N ratio, likely provided readily available carbon and nitrogen substrates that stimulated microbial activity, particularly denitrifying bacteria (Lazcano et al., 2021). Additionally, biochar may have exacerbated this effect by improving soil moisture retention, creating conditions favorable for denitrification (Martinsen et al., 2022). The absence of a significant biochar-induced reduction in N₂O emissions contradicts studies that reported suppression due to increased soil pH favoring N₂O reductase activity (Obia et al., 2015; Weldon et al., 2019). However, such effects are more pronounced in strongly acidic soils. The ferralsol at the study site, while inherently acidic, did not experience sufficient pH elevation from a single 4 t/ha biochar application to trigger measurable N₂O reduction. This suggests that the biochar application rate may have been below the threshold required to elicit significant changes in soil pH and associated microbial processes in this specific agro-ecological context.

The wide error bars observed in the cumulative N₂O emissions data indicate substantial spatial and temporal variability, which likely obscured any potential treatment effects. This variability underscores the need for increased replication, more frequent sampling, or the inclusion of covariates such as soil moisture and temperature to reduce residual variation and improve statistical power in future studies. Furthermore, the lack of significant differences in N₂O emissions among treatments suggests that the mechanisms governing N₂O production in these ferralsol may be more strongly influenced by environmental factors (e.g., rainfall events, soil temperature) than by the agricultural practices tested. This is consistent with the observation that the highest N₂O emissions occurred during April, coinciding with the onset of the rainy season, while the lowest emissions were recorded in May. These temporal patterns highlight the overriding influence of soil moisture dynamics on N₂O fluxes in tropical environments.

5.2 Effect of CA and biochar on quantity and nutrient of pigeon pea leaf litter

5.2.1 Effect of CA and biochar on quantity of pigeon pea leaf litter

The amount of leaf litter collected ranged from 240 to 260 kg/ha and did not differ between treatments. This amount could provide multiple benefits for crop production, including mulching that regulates soil temperature and evaporation, coupled with nutrient release upon mineralization. This is similar to other findings done in Lira and Kitgum that found the average to be 250 kg/ha (Simplice et al., 2026). This aligns with other previous successes of the practices in other locations (Rajesh et al., 2023) where pigeon pigeon was used to supplement crop production because of its leaves.

However, this finding contradicts previous studies that have reported yield increases of 30–100% following biochar application (Coumar et al., 2016). The reason for the lack of effect is likely that the biochar application rate used in the study may have been below the threshold required to cause measurable growth responses in pigeon pea under the specific soil and climatic conditions of northern Uganda. Furthermore, some researchers have suggested that 5–10 t/ha is necessary for significant crop response (Chew et al., 2022).

The lack of significant treatment effects on leaf litter quantity also suggests that pigeon pea litter production may be more strongly influenced by genetic factors and environmental conditions (e.g., rainfall, temperature) than by soil amendments. This is consistent with the observation that all treatments exhibited wide error bars, indicating substantial variability around the mean litter quantity within each farming practice. The high variability in litter quantity within treatments highlights the need for increased replication, more controlled experimental conditions, or the inclusion of covariates such as soil moisture, temperature, and crop biomass to reduce residual variation and improve statistical power in future studies.

5.3 Effect of CA and biochar on nutrient content of pigeon pea leaf litter

5.3.1 Nitrogen content in leaf litter

The average nitrogen content from the leaf litters across different farming practices was 40 g/kg. This finding aligns with previous studies on green manure and the different nutrient content (Carlos et al., 2023) and could add a significant quantity of N to the soil to meet crop N requirements. The different farming practices tested did not affect leaf litter N content. Despite the absence of a significant effect, there was an observed trend of CA + BC (single biochar) having the highest N, while CA + BC + BC (repeated biochar application) had the lowest. This has provided some insight into the effect of biochar on nitrogen. Furthermore, the lower N content under double biochar application was most likely due to temporary microbial nitrogen immobilization associated with the high carbon-to-nitrogen ratio of biochar. Therefore, the soil microbes generally utilize available nitrogen to decompose the high carbon content, consequently immobilizing N in microbial biomass and rendering it temporarily unavailable for plant uptake (Simiele et al., 2022). Possibly, pigeon pea plants experience transient N deficiency, producing leaves with lower N concentration. The single biochar application (4 t/ha) likely provided optimal benefits without triggering immobilization. The biochar improved soil aeration, water holding capacity, and cation exchange capacity (CEC), enhancing N uptake efficiency without causing N scarcity (Alkharabsheh et al., 2021; Jabin, 2023).

5.3.2 Phosphorus content in leaf litter

The study found a significant treatment effect on leaf litter P content where CA combined with biochar substantially enhanced the uptake and accumulation of P in pigeon pea leaf litter. A possible reason for the positive effect of biochar on P may be due to increased soil pH closer to neutrality (pH 6.5–7.0) where phosphorus solubility is maximized (Tadesse et al., 2021b). This finding agrees with other explanations that biochar's high surface area and functional groups may have caused adsorption of P, reducing fixation by Al^{3+} and Fe^{3+} in acidic ferralsols (Zhu et al., 2022). In addition, biochar also promotes arbuscular mycorrhizal fungi (AMF) colonization, where AMF hyphae extend into biochar micropores, accessing P that would otherwise be unavailable to plant roots (Li & Cai, 2021; Vahedi et al., 2022).

The fact that both single and split biochar applications produced similar enhancements suggests that the total amount of biochar applied may be less important than its presence in the system. This is consistent with the observation that the lack of significant difference between single and split biochar applications for P content indicates that a total biochar dose of 3–4 t/ha is adequate to achieve measurable improvements in P cycling. These findings have important implications for smallholder farmers in northern Uganda, as they suggest that a single application of biochar at 4 t/ha may be sufficient to enhance P availability and uptake by pigeon pea, thereby improving litter quality and subsequent nutrient cycling in the pigeon pea-maize rotation.

5.3.3 Potassium content in leaf litter content in leaf litter

The study found a significant treatment effect on leaf litter K content demonstrating that CA combined with biochar substantially enhanced the uptake and accumulation of K in pigeon pea foliage. This finding is in line with previous research findings which indicated that improved K accumulation results from biochar's high cation exchange capacity (CEC), which retains K^+ ions against leaching, especially in sandy or highly weathered soils (Martinsen et al., 2023). Furthermore, biochar acts as a slow-release reservoir for K, sustaining plant availability throughout the growing season. This is particularly important in the bimodal rainfall system of northern Uganda, where heavy rains can otherwise leach mobile cations from the root zone. However, the lack of significant difference between single and split biochar applications for nutrients suggests that a total biochar dose of 3–4 t/ha is adequate.

The post-hoc analysis revealed that CA + BC and CA + BC + BC increased K content by up to 100% relative to conventional practice, with both treatments being statistically significant ($p < 0.001$). These findings demonstrate that biochar amendment under conservation agriculture positively influences potassium accumulation in leaf litter, with important implications for soil fertility management in K-deficient ferralsols. The enhanced K content in leaf litter from biochar-amended plots suggests that biochar not only improves K availability in the soil but also enhances plant uptake and subsequent recycling of this essential nutrient through litter fall, contributing to long-term soil fertility maintenance.

5.4 Effect of leaf litter nutrient variation on nitrogen mineralization

5.4.1 Carbon dioxide evolution as a measure of microbial activity

There was a significant difference in CO₂ evolution between leaf litter-amended soil and the control figure. The result preempts that organic matter addition stimulates microbial respiration. The peak CO₂ evolution observed around day 10–12 aligns with findings from Bourget et al. (2023b). The reason given for the observation was likely based on the maximum microbial activity that occurred within 10 days of adding leguminous residues. This peak corresponds to the rapid decomposition of labile carbon compounds (e.g., soluble sugars, hemicellulose) by copiotrophic microorganisms (Zhang et al., 2025). In addition, the decline in CO₂ evolution after day 12 likely indicates depletion of readily available carbon substrates, leaving more recalcitrant compounds (lignin, cellulose) that decompose more slowly. This pattern is typical for legume residues with moderate C: N ratios (Camelo et al., 2021; Nourou & Dominique, 2003). The consistently low CO₂ evolution from control soil without litter addition reflects reliance on native soil organic matter, which is more stable and less accessible to microbial attack (Almendros & González-Pérez, 2025; Ridgeway et al., 2022).

The findings demonstrate that litter incorporation substantially enhances microbial activity within the soil system during the initial 12 days of application. This has important implications for nutrient management, as it suggests that the most active period of microbial decomposition and nutrient release occurs within the first two weeks after litter application. Farmers can exploit this knowledge by timing the application of pigeon pea leaf litter to coincide with the period of maximum crop nutrient demand, thereby maximizing nutrient use efficiency and

minimizing losses. The significant treatment $\times$ day interaction indicates that the magnitude and temporal pattern of CO₂ evolution varied among litter sources, reflecting differences in litter quality (e.g., C: N ratio, lignin content) and nutrient composition. These findings underscore the importance of considering litter quality and timing of application in designing effective nutrient management strategies for conservation agriculture systems.

5.4.2 Ammonium dynamics

There was a significant treatment effect on ammonium concentration according to concentration figure and appendix, with a peak at day 12 followed by a sharp decline, revealing the classic sequence of mineralization to nitrification. The observation agrees with earlier work that explains that during the first 12 days, net mineralization dominated as heterotrophic microbes decomposed leaf litter proteins and amino acids, releasing NH₄⁺ into the soil solution (Grzyb, Wolna-Maruwka, et al., 2020).

On the other hand, the sharp decline after day 12 indicates the onset of nitrification (Di et al., 2025). Where NH₄⁺ is oxidized to NO₃⁻ by ammonia-oxidizing bacteria and archaea as the labile carbon pool becomes depleted. The fact that ammonium dropped below pre-incubation levels by day 16 suggests that nitrification outpaced mineralization in the later phase. The control treatment where no leaf litter was added to the experimental unit, while consistently showing lower ammonium concentrations, followed a similar temporal pattern. This indicates that even unamended soil contains native organic matter that undergoes the same transformation sequence, although at a slower rate and lower magnitude.

The peak ammonium concentration at day 12 provides a critical temporal window for farmers to synchronize litter application with crop planting. Specifically, incorporating pigeon pea leaf litter approximately 10–16 days before planting maize would allow ammonium concentrations to peak just as the crop begins active nitrogen uptake, thereby maximizing nitrogen use efficiency and minimizing losses through leaching or volatilization. This recommendation is particularly relevant for smallholder farmers in northern Uganda, who often struggle with poor timing of organic amendment application, leading to asynchrony between nutrient release and crop demand. The significant treatment $\times$ day interaction indicates that the magnitude and timing of ammonium peaks varied among litter sources, reflecting differences in litter quality

and nutrient composition. These findings highlight the importance of considering litter quality and timing of application in designing effective nutrient management strategies for conservation agriculture systems.

5.4.3 Nitrate dynamics

There was a significant effect of treatment on nitrate dynamics as indicated in the figures and appendix. During the initial phase (days 0–12), nitrate concentrations increased slowly and steadily. Finding, coinciding with the progressive accumulation of ammonium. This aligns with previous research that links the lag phase to the activation and population build-up of ammonia-oxidizing microorganisms, which require time to oxidize the available ammonium (Domeignoz-Horta et al., 2022).

A distinct inflection point occurred between days 13 and 16, marked by a sharp surge in nitrate that directly paralleled the abrupt decline in ammonium over the same interval. This inverse relationship confirms that the ammonium peak at day 12 served as the primary substrate for rapid nitrification, with the magnitude of nitrate increase being stoichiometrically proportional to the ammonium decrease (Figures 10 and 11). Leaf litter-amended treatments consistently supported significantly higher nitrate concentrations than the unamended control throughout the incubation period. This outcome demonstrates that organic matter inputs not only augment total nitrogen pools but also accelerate the transformation of nitrogen into the highly plant-available nitrate form. However, this enhanced nitrification potential carries an environmental trade-off: under field conditions, particularly during the intense rainfall events characteristic of Uganda's bimodal rainy season, the elevated nitrate reserves are more susceptible to leaching losses below the rooting zone, posing risks to both crop nitrogen use efficiency and groundwater quality (Gallarotti et al., 2021). This finding underscores the importance of synchronizing litter application with crop demand to minimize the period during which nitrate is vulnerable to leaching. Specifically, applying litter 10–14 days before planting, as recommended based on ammonium dynamics, would allow nitrate to accumulate just as the crop begins rapid nitrogen uptake, thereby reducing the window of vulnerability to leaching losses. The significant treatment $\times$ day $\times$ ion interaction indicates that the temporal dynamics of ammonium and nitrate varied among litter sources, reflecting differences in litter quality and nutrient composition.

5.5 Conclusion and Recommendations

5.5.1 Conclusion

This study provides critical evidence on the integration of conservation agriculture (CA) with biochar as a viable pathway for enhancing specific nutrient cycles within pigeon pea-maize rotations on Ugandan Ferralsols. The findings demonstrate that CA planting basins combined with a 4 t/ha biochar application constitute a promising climate-smart agriculture (CSA) strategy for Ugandan Ferralsols. Its climate-smartness is strongly supported by the substantial enhancement of phosphorus (P) and potassium (K) cycling, which builds long-term soil fertility, and by the potential to optimize nitrogen (N) supply through the synchronization of mineralization with crop demand. Specifically, the study revealed that biochar amendment under CA significantly increased P content in pigeon pea leaf litter by approximately 10% and K content by up to 100% relative to conventional practice. Furthermore, the incubation experiment identified a critical temporal window of 10–14 days during which ammonium concentrations peak and nitrate levels begin to rise, providing an evidence-based recommendation for synchronizing litter application with crop planting to maximize nitrogen use efficiency.

However, the climate-smart credentials of this practice are tempered by the lack of a significant reduction in N₂O emissions. Biochar at the applied dose (4 t/ha) did not act as a direct mitigator of greenhouse gas emissions in these specific acidic soils, challenging its role in climate change mitigation in the short term. The absence of a significant biochar-induced reduction in N₂O emissions contradicts studies that reported suppression due to increased soil pH favoring N₂O reductase activity, suggesting that the biochar application rate may have been below the threshold required to elicit significant changes in soil pH and associated microbial processes. Additionally, the study found no significant effects of treatments on leaf litter quantity or nitrogen content, indicating that biochar application rates may have been below the threshold required to cause measurable growth responses in pigeon pea under the specific soil and climatic conditions of northern Uganda.

Nonetheless, the key productivity gains derived from improved nutrient cycling—particularly the enhanced recycling of P and K and the tactical management of N release—could contribute to greater food security and farm profitability. These benefits may moderately counterbalance

the lack of direct N₂O mitigation, making the practice a valuable component of a broader integrated soil fertility management strategy for smallholder farmers in the region, provided that residue application is carefully timed to maximize agronomic efficiency. The study underscores the importance of considering both the agronomic and environmental dimensions of climate-smart agriculture practices and highlights the need for context-specific recommendations that account for local soil, climate, and management conditions.

5.5.2 Recommendations

- 6 To optimize maize yields, extension services should promote the soil incorporation of pigeon pea leaf litter during the two-week gap (10–14 days) before planting. This practice is scientifically timed to exploit a natural nitrogen peak: ammonium levels maximize at day 12, with nitrates rising sharply thereafter, ensuring that nutrients are released precisely when the emerging maize crop needs them most. To further enhance this system, farmers should adopt the combined use of conservation agriculture (CA) and biochar. This combination not only improves soil structure but also boosts the phosphorus and potassium content of the litter by 10% and up to 100%, respectively, making biochar a cost-effective intervention for farms facing P and K shortages. Farmers should be trained on the correct application rates (4 t/ha) and timing of biochar application to maximize benefits and minimize potential nitrogen immobilization. Additionally, farmers should be encouraged to retain pigeon pea leaf litter on the soil surface as mulch, as this practice regulates soil temperature and evaporation, and releases nutrients upon mineralization.

7 Recommendations for policy makers

Policy makers should promote small-scale biochar production using locally available pigeon pea stems and flame curtain kilns (Kon Tiki). Since the study confirms that locally produced biochar enhances P and K cycling, reducing dependence on expensive mineral fertilizers, this practice should be cascaded to the masses through national agricultural extension messages. Pigeon pea should be integrated into national agricultural extension messages not only as a food and feed crop but also for soil fertility management via conversion of its large biomass to biochar. Furthermore, policy makers should support farmer education on residue application timing, as the 14-16-day mineralization phase identified in this study provides an evidence-

based recommendation that extension services can disseminate to improve nutrient use efficiency. Finally, policy makers should consider subsidizing biochar production and distribution to make this technology accessible to resource-poor smallholder farmers, thereby contributing to the achievement of Sustainable Development Goal 2 (Zero Hunger) and the National Development Plan (NDP III and IV) objectives of sustainable increase in household income and quality of life couple with agro-industrialization.

Recommendations for future research

Future research should investigate the relationship between soil pH, and microbial community composition and AMF colonization influence on P and K improvements in biochar-affected soil. Additionally, researchers should quantify N₂O emissions over a full cropping cycle, including multiple rainfall events and the post-harvest period, to capture temporal variability that may obscure treatment effects. Furthermore, future studies should examine nitrogen losses through alternative pathways (leaching, ammonia volatilization, NO) since N₂O emissions alone did not differ significantly; a total N balance may reveal treatment effects not captured by N₂O measurements. Long-term studies (multiple seasons) are needed to assess the cumulative effects of biochar on soil fertility, crop productivity, and greenhouse gas emissions, as biochar effects are known to increase over time. Finally, research should explore the optimal biochar application rates and frequencies for different soil types and cropping systems in sub-Saharan Africa, to provide context-specific recommendations for smallholder farmers.

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APPENDICES

APPENDIX 1: CONSENT FORM

Title of the study: effect of conservation agriculture and biochar on nitrogen cycling in pigeon pea-maize rotation in Uganda

Investigator(s): Wokorach Samuel Opiyo, and Supervised by Dr Alfred Obia and David Akodi

Institution: Gulu University, Faculty of Agriculture and environment

Introduction

I am conducting research on effect of various climate smart agriculture practices on nutrients cycling and how it affects nutrients level and control pollution.

The research specifically will study the following;

To determine the effect of conservation agriculture planting basin, biochar & pigeon pea litter on N₂O emission under pigeon pea-maize rotation.

To determine out the effect of conservation agriculture planting basin and biochar on the quantity and nutrients content of pigeon pea litter.

To determine the effect of conservation farming planting basin and biochar on rates of mineralization of nutrients from pigeon pea litter.

A brief description of the sponsors of the research project

The study will be privately sponsored by the student for academic purpose.

Purpose:

The study seeks to address the challenges of nutrient loss within the soil system. The findings of this study will help to improve crop yield through nutrient conservation and reduced losses.

Procedures:

Your participation in this study will involve land preparation, digging planting basin, biochar preparation, biochar application, planting, weeding and collection of the leaf litter.

Who will participate in the study?

You have been chosen to participate in this study because you are one of the participants who stays within the experimental site, part of the farmer group and part of the farming household within the sub county. The experiment will last for approximately 4 months and you will be 20 in numbers.

Risks/discomforts:

There is no foreseeable risk of harm or discomfort that will arise from your participation in this study. The only risk or discomfort will be the inconvenience in terms of time spent during the experiment, dust in halation, cutting of toe by hoe, burn during bicohar preparation, carbondioxide inhalation, snake bite and prick by old stamps. All these shall be addressed by;

Protective wear such as overall, gumboots and musk shall be provided. in addition, all shall be provided with hard arm length gloves. In cases injury, the participating farmers shall be taken to government medical facilities and provided with transport and overhead expenses.

Benefits:

The benefits shall be as followings; capacity building for all the technology that the research find shall be used to improve their farming practices. The study will inform the farmers on enterprise selection, farm planning, soil and nutrient management. To add more, it would help to develop resilience and enhance productivity amidst the climate change.

In addition, the student and academia in the higher institution of learning shall use the published papers to enhance their careers and research gaps that shall be recommended by this study. In line with that, it will solve problems in area of soil physical, chemical and entire agro-ecosystem.

Finally, this paper will inform policy that shall help areas of agricultural insurance, simulation and modeling for crop subsidy and plan for country food sovereignty.

Confidentiality:

Your identity will not be revealed to any one as we shall only use codes to identify participants. Information obtained will only be accessible by the research team. Soft copies of the data will be protected by password and hard copy files will be kept under lock and key. Confidential information will only be accessed by the principal investigator.

Alternatives:

You do not have to participate in this study if you are not interested. You will not lose any benefit in case of no participation.

Questions:

If you have any questions related to the study as a research participant, you can contact the principal investigator, Wokorach Samuel Opiyo on telephone number 0774-397026 or via email on owokorachsamuel@yahoo.com or Dr Alfred Obia on Tel 0771-421124 (Academic Supervisor)

Statement of voluntariness:

Participation in the research study is voluntary and you may join on your own free will. You have a right to withdraw from the study at any time without penalty.

If you have any issues pertaining to your rights and participation in the study, please contact the Chairperson, Gulu University Research Ethics Committee, Dr. Julaina A. Obika Tel: No., 0772964491; email: j.obika@gu.ac.ug ; or the Uganda National Council for Science and Technology, on plot 6 Kimera road, Ntinda, Kampala on Tel 0414705500.

Statement of consent

..... has described to me what is going to be done, the risks, the benefits involved and my rights as a participant in this study. I understand that my decision to participate in this study will not affect me in any way. In the use of this information, my identity will be concealed. I am aware that I may withdraw at any time. I understand that by signing this form, I do not waive any of my legal rights but merely indicate that I have been informed about the research study in which I am voluntarily agreeing to participate. A copy of this form will be provided to me.

NameSignature/thumbprint of participant.....Date

Name..... Signature of witness.....Date.....

Name..... Signature of interviewer/investigatorDate.....

Data collection schedule for gas sampling

Month	April				May				June				July				August	Sept	October
Weeks	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	Analysis using gas chromatography		
Gas sampling																			

APPENDIX 2: STANDARD CALCULATION USED IN THE STUDY

Variables measured were; Total: N (g/kg), CO₂ (%), NH₄⁺-N (mg/kg), NO₃⁻-N (mg/kg)

$$V_2 - V_1 = V_A$$

Where;

V₂=Final volume of the acid used

V₁=Initial volume of the acid used

V_A =Volume of HCl acid used in the titration in liters

This was followed by determining the amount of N in the samples

$$N = (V_A \times N \times 14) / W$$

Where;

V_A =Volume of acid used in the titration

N=Normality of HCl

14=atomic weight of nitrogen (in g/mol)

W=weight of sample in grams

Calculation for carbondioxide

$$CO_2 = (V_1 - V_0) \times N \times 44$$

V_1 =Volume of acid used to titrate remaining NaOH

V_0 = Volume of acid used to titrate blank NaOH

N=Normality of acid

44=Molecular weight of CO_2

Calculations for N in a ammonium and nitrate

The following were the calculation undertaken.

First, water content of a fresh sample (fresh soil - dry soil)

$$H_1 = \frac{\text{bulk weight (fresh soil-dry soil)}}{\text{Weight of fresh bulk sample-tare}}$$

Second, amount of ammonium N in mgml^{-1} of the extract

$$NH_4^+ - N = \frac{(V_2 - V_1) \text{ ml} \times 0.01 \text{ meq} \times 14 \text{ mg N} \times \frac{1}{25 \text{ ml extract}}}{\text{ml meq}}$$

Where; V_2 =Volume of 0.01 eq l^{-1} acid added to the sample

V_1 = Volume of 0.01 eq l⁻¹ acid added to the blank

Third, amount of the ammonium-N in mg kg⁻¹ of dry soil

$$\text{NH}_4^+ \text{-N} = 0.0056(V_2 - V_1) \frac{\text{mgN}}{\text{ml extract}} \times \frac{25 \text{ ml extract}}{10 \text{ g soil}} \times \frac{1000 \text{ g soil}}{1 \text{ kg soil}}$$

Fourth, amount of the ammonium-N in mg kg⁻¹ of dry soil

$$\text{NH}_4^+ \text{-N} = \frac{14 (V_2 - V_1)}{(1 - H_1)}$$

Fifth, amount of nitrate-N in mg kg⁻¹ of dry soil

$$\text{NO}_3^- \text{-N kg}^{-1} = \frac{14(V_2 - V_1)}{(1 - H_1)}$$

Calculation to determine the amount of litter and soil to use in the incubation experiment

Total leaf litter = 93 g

Area of trap = 0.6 x 1.2 = 0.72 m²

Volume of soil = 0.72 x 0.2

$$= 0.144 \text{ m}^3$$

The bulk density = 1300 kg/m³ (1.3 g/cm³)

Mass of soil for the 0.72 m² x 0.2 m depth x density

$$= 0.72 \times 0.2 \times 1300$$

$$= 187.2 \text{ kg}$$

For area of leaf litter trap,

- 93g litter releases nutrient to 187.2 kg of soil if 20 cm depth is considered.

- 93g of litter in 0.144 m³.
- Hence, the study used 1gm leaf litter in a 300 cm³ soil.

APPENDIX 3: ETHICAL CONSIDERATION

The research studies were done in a respectful and responsible manner in order achieve to its intended goal. That made it imperative for these studies to undertaken the following processes. To begin with, approval of protocol by GUREC before data collection. This was done through submitting of the protocol, defending it and adhering to all the recommendation made. That was meant to conform to the international standards. Second, the investigations were done through involvement of local leaders to provide ownership and security of the site. Third, Memorandum of Understanding (MOU) was signed with the farmers who hosted the experimental plot. In that MOU, each plot was hired to a tune of 80,000 per season. Fourth, Personal protective Requirements (PPE) such as gumboots were provided for those participating in the study. Lastly, both time and labor compensation in buying pigeon stems, preparing land, making planting basin, real planting and managing of the plot. The details of the payment for each activity in indicated in the table below.

Table below show the amount of payment and each activity plus item

S/N	PARTICULARS	DESCRIPTION	Amount
1	Hire land	Per season	80,000
2	Community meeting	Refreshment	5,000
3	Digging planting basin	Digging of each hole	1,000
4	Transport	Each individual	5,000
5	Planting	Each day worked	10,000

6	Weeding	Each day worked	10,000
7	Buying pigeon pea stems	Each bundle	20,000

APPENDIX 4: RESEARCH DISSEMINATION PLAN

To enhance utilization of the technology from the studies and inform policy direction, the study was disseminated after concluding the findings. The process ensured that, the participants discussed findings and implication of the study. Thus, the following category of stakeholders were invited; first, farmers who were the primary user of the knowledge to improve on their farm planning, productivity and quality of life. Second, the district technical team who forms part of knowledge cascaded in the lower local government. These comprised of the Community Development Services (CDO), Extension Officers and the political leaders who are the policy makers.

APPENDIX 5: DATA MANAGEMENT

As a bid to ensure quality, integrity and usability of the data, the research carried out the following process in the data management. To begin with, planning was done on how the data would be handled, stored and shared. Followed by, collection was done by qualified people using standard tools approved by GUREC with the input of the academic supervisor. In addition, documentation was carried out in consideration of study variables, and R data analysis package. Lastly, sharing of while ensuring confidentiality and intellectual property.

APPENDIX 6: PHOTOS



Figure 12: Pigeon pea well established.



Figure 13: Fastened nylon bag on the wooden frame under pigeon pea for leaf litter collection



Figure 14: L-R Kjeldal experiment, and laboratory incubation experiment and right is filtration for K analysis

APPENDIX 7: ANOVA TABLE FOR NITROUS OXIDE EMISSION

SOURCE OF VARIATION	DF	SS	MS	F	P
Treatment	3	0.0078	0.002600	1.018	0.416
Residuals	13	0.0332	0.002554		
Total	16	0.0410			

APPENDIX 8: ANOVA TABLE FO QUANTITY OF LEAF LITTER

SOURCE OF VARIATION	DF	SS	MS	F	P
Between groups (Treatment)	3	2,197	732	0.018	0.997
Within groups (Residuals/Error)	76	3,063,716	40,312		
Total	79	3,065,913			

APPENDIX 9: ANOVA TABLE AMOUNT FOR NITROGEN IN THE LEAF LITTER

SOURCE OF VARIATION	DF	SS	MS	F	P
Treatment	3	244	81.35	1.113	0.36
Residuals	28	2046	73.06		
Total	31	2,290	154.41		

APPENDIX 10: ANOVA TABLE AMOUNT FOR P IN THE LEAF LITTER

SOURCE OF VARIATION	DF	SS	MS	F	P
Treatments	3	444.3	694.9	35.56	3e-06
Errors (residual)	12	234.5	19.5		
Total	15	678.8	714.4		

APPENDIX 11: POST HOC TABLE FOR COMPARING WHICH TREATMENT IS CAUSING SIGNIFICANCE IN P ANALYSIS.

Treatment	Difference	Lower	Upper	P adjusted	Comments
CA-Conv	2.1	1.2	3	0.0005	Significant
CA+BC-Conv	3.4	2.5	4.3	0.0001	Significant
CA+BC+BC-Conv	4.8	3.9	5.7	0	Not significant
CA+BC-CA	1.3	0.4	2.2	0.004	Significant
CA+BC+BC-CA	2.7	1.8	3.6	0.0002	Significant
CA+BC+BC-CA+BC	1.4	0.5	2.3	0.0025	Significant

APPENDIX 12: ANOVA TABLE AMOUNT FOR POTASSIUM IN THE LEAF LITTER

SOURCE OF VARIATION	DF	SS	MS	F	P
Treatments	3	444.3	694.9	35.56	3e-06
Errors (residual)	12	234.5	19.5		
Total	15	678.8	714.4		

APPENDIX 13: POST HOC TABLE FOR COMPARING WHICH TREATMENT IS CAUSING SIGNIFICANCE IN K ANALYSIS.

Treatment comparison	Results				Comments
CA+BC-CA	22.725	13.444	32.006	0.0000508	It is significant
CA+BC+BC-CA	16.9	7.61902	26.181	0.0007884	It is significant
Convent-CA	-4.775	-14.056	4.50598	0.4523861	Not significant
CA+BC+BC- CA+BC	-5.825	-15.106	3.45598	0.2931375	Not significant
Convent-CA+BC	-27.5	-36.781	-18.219	0.0000073	It is significant
Convent- CA+BC+BC	-21.675	-30.956	-12.394	0.0000806	It is significant

APPENDIX 14: ANOVA TABLE FOR VARIATION IN NUTRIENT ON CARBON DIOXIDE EVOLUTION.

Source of Variation	DF	SS	MS	F-value	P-value
Treatment	4	2,675,740	668,935	22,887.60	< 0.001
Day	13	26,957,256	2,073,635	70,949.20	< 0.001
Treatment × Day	52	926,053	17,809	609.30	< 0.001
Residuals	210	6,138	29		
Total	279	30,565,187			

APPENDIX 15: TABLE POST HOC FOR CARBONDIOXDE EVOLUTION

Comparison	Mean Diff	LSD (7.51)
CA+BC+BC vs CA+BC	89.58	a. CA+BC+BC=598.9829
CA+BC+BC vs CA	112.73	b. CA+BC =509.4034
CA+BC+BC vs Convent	192.46	c. CA=486.2555
CA+BC+BC vs Control	288.98	e. Control= 310.0008
CA+BC vs CA	23.15	
CA+BC vs Convent	102.88	
CA+BC vs Control	199.40	
CA vs Convent	79.73	
CA vs Control	176.26	
Convent vs Control	96.52	

APPENDIX 16: ANOVA TALBE FOR AMMONIUM AND NITRATE BUILD UP

Source	Df	Sum Sq	Mean Sq	F-value	P-value
Treatment	4	12.25	3.064	8.75	< 0.001

Source	Df	Sum Sq	Mean Sq	F-value	P-value
Day_fac	6	22.61	3.768	10.77	< 0.001
Ion	1	3.13	3.129	8.94	0.003
Treatment:Day_fac	24	14.42	0.601	1.72	0.025
Treatment:Ion	4	0.49	0.123	0.35	0.843
Day_fac:Ion	6	45.80	7.634	21.81	< 0.001
Treatment:Day_fac:Ion	24	10.88	0.453	1.29	0.175
Residuals	140	49.00	0.350		
Total	209	158.58			

APPENDIX 17: POST HOC ANOVA TALBE FOR AMMONIUM AND NITRATE BUILD UP

Treatment	Mean N (mg/kg)	Grouping
CA+BC+BC	3.85	A
CA+BC	3.65	A
CA	3.37	B
Convent	3.23	Bc
Control	3.00	C

APPENDIX 18: ORIGINALITY CERTIFICATE

GULU
P.O. Box 166
Gulu, Uganda



UNIVERSITY

Tel: +256-471-32924
Fax: +256 471343095
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