

**EFFECT OF CLIMATE-SMART AGRICULTURAL PRACTICES ON SOIL
ORGANIC CARBON AND YIELD OF PIGEON PEA IN NORTHERN UGANDA**

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OCTOBER, 2026

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DECLARATION

I, ABER CINDERELLA (23/U/0599/MAS/PS) do declare that this dissertation is my own original work and, has never been submitted to any institution of higher learning by anyone for the award of any degree or diploma.

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APPROVAL

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DEDICATION

I dedicate this work to my parents, guardians, siblings and friends for their support and encouragement during my entire study programme.

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ACRONYMS

CA	Conservation Agriculture
CF	Conservation Farming
CF+PP	Conservation Farming plus Pigeon Pea
CH ₄	Methane
CO ₂	Carbon dioxide
CSA	Climate Smart Agriculture
GHG	Greenhouse Gas
NT	No- Tillage
POXC	Permanganate Oxidizable Carbon
RCBD	Randomized Complete Block Design
SDG 2	Sustainable Development Goal 2
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SSA	Sub- Saharan Africa

ABSTRACT

The current decrease in crop yield has elevated food insecurity with over a billion people affected across the globe and has been attributed to climate change and poor soil quality. This challenge is more pronounced in the developing countries with devastating economic constraints, which deprive people of food security. As such, better and sustainable interventions that improve the soil and contribute to climate change adaptation and mitigation for enhanced yield is needed. A two-season experiment was conducted at Gulu aiming at exploring the effect of conservation agriculture (CA) and biochar on soil carbon, greenhouse gas emission and grain yield of pigeon pea. The experiment followed Randomized Complete Block Design (RCBD) with four treatments replicated four times. The treatments included (i) CA with maize – pigeon pea rotation (CA+PP), (ii) CA with one time biochar application (4 tons/ha) and maize – pigeon pea rotation (CA+BC+PP), (iii) conventional agriculture with maize – pigeon pea rotation (Conv+PP), (iv) CA with half biochar (2t, 1t & 1t/ha per year) and maize – pigeon pea rotation (CA+BC+BC+PP), (v) conventional agriculture with maize monocropping (Conv+MM). The results from experiment showed that CA and biochar improved total soil organic carbon and readily oxidizable carbon and as well as increasing the biomass and grain yield of pigeon pea. The highest total soil organic carbon content of 1.6 – 1.99% and readily oxidizable carbon of 0.05 – 0.059% were recorded in CA+BC+PP compared to total soil organic carbon of 1.5 – 1.53% and readily oxidizable carbon 0.03 - 0.05% in conventional practice. Similarly, a reduction in CO₂ emission from 294 to 218 mg CO₂-C m⁻²h⁻¹ and CH₄ emission from 63.4 to 21.8 µg CH₄-C m⁻²h⁻¹ was registered in the treatments having climate smart agriculture practices. The biomass at harvest was highest at 13.69 tons/ha in CA+BC+PP in season 1 compared to that of conventional plot of 8.75 tons/ha with corresponding grains yield of 2.11 tons/ha and 1.76 tons/ha, respectively. This pattern of biomass and grain yield between the two treatments was also registered in the second growing cycle though with an overall lower yield. Therefore, CA and biochar can contribute to food security by increasing yield and climate change mitigation through soil C sequestration and reduced greenhouse gas emission. As such, CA practices and biochar application can be considered as sustainable and can contribute to climate resilience.

Key words: Conservation agriculture; biochar; greenhouse gas emission; pigeon pea; yield.

CHAPTER ONE: INTRODUCTION

1.1 Background

Globally, human population has been, and is still increasing drastically, and as such, global food need is predicted to rise by ~60% by 2050 (Ittersum et al., 2016). This rise in food demand is expected to be greater in Sub Saharan Africa (SSA) where the population is predicted to grow by 2.5 fold by 2050 (Ittersum et al., 2016). Climate change is also affecting food production (Knox et al., 2012) and aggravating the food security situation. The interplay between population growth, increasing food demand and climate change causing low productivity (Begna, 2020) is projected to continue affecting economic development in SSA (Liu et al., 2008). The situation in Uganda is precarious due to recurrent weather shocks affecting crop productivity of small holder farmers (Hubler et al., 2023), increasing food insecurity and lowering the purchasing power of farmers and economic development of the country (Mwaura & Okoboi, 2014).

In 2012, an estimated 1.5% of global crop yield loss were attributed to warming trends (Lobell & Gourdji, 2012), while in Africa, 8% yield loss or increase of food crop is predicted by 2050 (Knox et al., 2012). The models applied by Washington & Pearce (2012) during short rains in East Africa indicated that the distributions of crops might be affected by temperature and rainfall. These changes in precipitation and temperature has stronger effect on rain-fed agriculture and in arid regions, all of which are widespread in Uganda raising food security concerns more especially due to inadequate access to modern agriculture facilities (Mwaura & Okoboi, 2014). This shift in weather pattern has caused an increase in drought frequency and length, temperature, erratic rainfalls and floods (Mishra et al., 2017).

Severe drought has been reported to reduce grain yield of maize crop as well as harvest index (Sellamuthu et al., 2022; Ray et al., 2018). The drought damage depends on the stress duration and crop growth stages (Setter et al., 2001). Drought affects the root zone where moisture is reduced, and plant is unable to tap enough water for growth (Sellamuthu et al., 2022). Drought stress is physiologically similar as it induces unhealthy plant osmotic and metabolic activities (Sané et al., 2005). According to McWilliams (2001), drought stress increased level of nitrate in the grain causing lower grain quality of corn and sorghum. In this case, plants get difficulty under drought stress in tapping and transporting materials thus affecting access to nutrients.

The irregular pattern in rainfall has devastating effect on crop productivity. Impacts negatively on crops growth and yield, with stronger negative effect when it occurs during the flowering phase of the crop (Mar et al., 2018). Studies reported by Rahman et al. (2017) and Guttal & Jayaprakash (2007) showed an increase in rainfall amount from 31.5 to 32.2 mm during January, August, September and October (JASO). Furthermore, erratic rainfall has been shown to result into prolonged drought (And & Watanabe, 2015).

Climate smart agriculture has been proposed as a solution to climate challenges, with three goals of increasing yields, climate change adaptation and climate change mitigation (Thierfelder et al., 2017). It consists of array of practices such as use of drought tolerant crops and varieties, agroforestry and conservation agriculture (CA). (Thierfelder et al., 2017). It can be implemented to manage effect of climate change by using the components to ensure farmers manage soil fertility losses and water stresses (Begna, 2020) to improve crop yield. Therefore, climate smart agricultural practices like CA, biochar and climate resilient crops have been reported to increase yields, promote climate change mitigation and adaptation (Obia et al., 2020; Gwenzi et al., 2015; Cornelissen et al., 2013). These practices have been reported to increase water productivity and improved soil organic carbon (Abhishek et al., 2020; Bangroo et al., 2013) thus contributing to 4% initiative for climate change mitigation and improve crop productivity (Corbeels et al., 2018). Furthermore, Singh et al., (2022) noted that to improve productivity, better breeding strategies can also be employed to provide superior genotypes which is high yielding and suitable for African market and climatic conditions (Odeny, 2007).

Conservation agriculture, biochar, CA planting basins, is one of the CSA practices being promoted for improving agricultural sustainability while offering benefits to climate change (Powelson et al., 2016; Martinsen et al 2019; Obia et al ., 2019). The benefits of CA is used to mitigate climate change and increase soil organic carbon (Ackson et al., 2019; Paustian et al., 2016) and reduction in greenhouse gases (GHG) emission thus increasing soil carbon storage. The magnitude of carbon sequestration depends on management practices, soil types and adoption level of individual farmers (Martinsen et al., 2019).

Incorporation of biochar into CA may enhance positive effect of CA since biochar has been reported to lock-up carbon during its production process. Thus release of carbon to atmosphere would be reduced through storing in soils, hence mitigating climate change (Ahmed et al., 2016; Mashamaite et al., 2024). Biochar application has been shown to

increase soil carbon, a key soil property that influence soil quality ensuring agricultural and environmental sustainability of soils (Kätterer et al., 2019; Cornelissen et al, 2013; Schmidt et al, 2014). Report by Obia et al. (2019), Obia et al. (2020), Gwenzi et al. (2015) & Cornelissen et al. (2013) showed improvement in soil quality, increased yield, and mitigation and adaptation of climate change due to biochar application. Increase in SOC concentration in soil from CA causes improvement in soil physical conditions including soil hydraulic properties. Obia et al. (2020) and Gwenzi et al. (2015) also confirmed that CA in combination with biochar enhances plant-available water, moderates soil temperature which can contribute to climate change adaptation in case of erratic rainfall or drought. CA and biochar can also enhance nutrient availability for the crops. This results to increased biomass production and yields.

To enhance the benefits of climate smart agricultural practices, the choice of crop may be very important. Climate resilient crops may perform better in case of climate extremes. One of the most important climate resilient crop in Uganda is Pigeon pea (*Cajanus cajan*). Pigeon pea have been gaining importance in Uganda, majorly in northern Uganda. This is attributed to generally favorable growing conditions like good soil. The crop is deep rooted enhancing its ability to utilize soil water and nutrients. It also enhances nutrient availability due to nitrogen fixing ability. Low income earners therefore prefer pigeon pea because the crop is tolerant to drought, easy to harvest and has good nutrient recycling ability. It produces a lot of biomass, which may be utilize for biochar production (Namuyiga et al., 2022).

The current study focuses on the effect of CA and BC on soil organic carbon and yield of pigeon pea in smallholder farmers' settings in northern Uganda.

1.2 Problem Statement

Pigeon pea is a crop grown mainly in semi-arid areas with unreliable rainfall, and where crop failures are frequent. Even though pigeon pea is drought tolerant with great food and nutritional value, its yields has remained low and poor soil quality and drought are the main contributors. Currently national production is 93.000 tons, productivity is about 894 kg/ha. This yield is lower than the potential crop yield of 1500 kg/ha (Fatokimi & Tanimonure, 2022).

Low yield is due to poor agronomic practices, poor soils and climate extremes especially rainfall, droughts and temperature (Ray et al., 2018; Olesen & Bindi, 2002; Zhao et al.,

2020). Therefore soil organic carbon enhancement and good agronomic practices and attenuating effects of climate change through climate smart agricultural practices like conservation agriculture and biochar have been proposed as a solution (Obia et al., 2020; Thierfelder et al., 2017).

However, reported effects of CA by smallholder farmers on storage of SOC and soil fertility differ considerably amongst the difference studies (Martinsen et al., 2019). Likewise, results from incorporation of biochar into CA has conflicting research results (Thierfelder et al., 2017) effects on SOC. Such inconsistencies have also been reported for crop yields. In addition, soil carbon loss avenues like CO₂ and CH₄ emissions under CA with or without biochar has not been consistently reported. This variation may be because of different soil types and management practices e.g. the changes in position of CA planting basins yearly has made it difficult to estimate changes in SOC stock brought about by planting basins (Martinsen et al., 2019). An analysis of better understanding of the effect of CA practice and biochar on yield and soil carbon in pigeon pea farming, could help smallholder farmers to increase productivity and become climate resilient.

1.3 Research Objectives

1.3.1 Main objective

To determine the effect of CSA practices on soil carbon dynamics and yield of pigeon pea for improved climate change adaptation and mitigation in Uganda.

1.3.2 Specific objectives

- i. To determine the effect of conservation agriculture practices and biochar application on soil organic carbon and readily oxidizable carbon.
- ii. To determine the effect of conservation agriculture and biochar application on CO₂ and CH₄ fluxes.
- iii. To determine the effect of conservation agriculture practices and biochar application on biomass and grain yield of pigeon pea.

1.4 Research Hypothesis

- i. Conservation agricultural practices lead to higher SOC and readily oxidizable carbon than conventional agriculture practices, with their effects becoming stronger with biochar incorporation.
- ii. Conservation agriculture practice decreases CO₂ and CH₄ emissions from soil compared to conventional agriculture practices, and these reductions in the emissions becoming more pronounced when biochar is included in conservation agriculture.
- iii. Conservation agriculture practices increase biomass and grain yield of pigeon pea with even greater yields with biochar incorporation compared to conventional agriculture practice.

1.5 Justification of the study

Increase in global food demand due to population pressure is predicted to rise by 60% by 2050 compared with the 2005/2006 demand, and this trend remains a key concern for global agricultural sector. This is expected to be more in sub-Saharan Africa. However, many countries have not done enough to improve its productivity this study will contribute to Improving productivity of pigeon pea, a crop that is climate resilient will be a key contribution to meeting global food demand. Pigeon pea is highly nutritious and can contribute to improving livelihoods of smallholder farmers, who prefer it because it fixes nitrogen, is easy to harvest and produces more biomass than crops such bean, green gram (Namuyiga et al., 2022). Pigeon pea is cheap source of vegetable protein. It provides dietary requirements for quite a number of rural poor who do not obtain the required protein at critical stages of growth and development

In addition to promoting food security, and in effect contributing to SDG 2 “Zero hunger” Pigeon pea highly contributes toward economic development in term of food and nutrition security and its ameliorant effect in the soil (Soko, 2000) such as improving organic carbon within the soil, which can increase crop yields thus food security. Improvement of soil can enhance adaptation capacity like improving water storage in the soil, moderating temperature and mitigation hence climate resilience (Vinod Kumar Singh, 2023).

CHAPTER TWO: LITERATURE REVIEW

2.1 Climate smart agriculture

Climate-smart agriculture is considered as a sustainable approach to farming that aims to increase productivity, enhanced resilience to climate change, and reduce or remove greenhouse gas emissions. The principles of CSA: improve food security and agricultural productivity, increase resilience of farming systems to climate change and mitigation of greenhouse gas emissions (Rosenstock et al., 2015). It has given a great promise to increasing agricultural productivity in the changing climate situation and decreasing greenhouse gas emissions. CSA may stands to address the increasing production in agriculture and contributes to mitigation of GHG emissions (Petrál et al., 2020). Climate-smart agriculture highly improves total carbon storage thereby mitigating greenhouse gas emissions (Tadesse et al., 2021).

Some of the practices that constitute CSA may include CA implementation, biochar application and pigeon pea growing. Conservation agriculture useful for soil organic improvement, storage of moisture in the soil and temperature regulation make it a better technology preferred by farmers (Makate et al., 2019). Adoption of CSA practices at five different locations in Chinese provinces, showed that CSA practices increased yields by 1,410 kg/ha above in the control fields. It generally improves soil and yield through enhancing moisture and nutrient (Gwenzi et al., 2015). Climate smart agriculture practices helps in reducing challenging effect of climate e.g. high yielding crops varieties which are drought resistance increases yields and decreases the risk of climate impact (Begna, 2020). There was reduction in greenhouse gas emissions in the study done in central china, whereby methane emissions from conventional plot were higher than in CA plot ($1.75 \mu\text{g CH}_4\text{-C m}^{-2}\text{h}^{-1}$ to $1.64 \mu\text{g CH}_4\text{-C m}^{-2}\text{h}^{-1}$) (Li et al., 2013). From the same study, carbondioxide also reduced by between 40% - 33% in early planting and by between 47% - 22% in late planting. Thierfelder et al. (2017) also reported increased infiltration and soil moisture conservation that help in overcoming the drought, thus resulting to productivity and profitability improvement.

2.2 Climate smart agriculture research and practice by farmers

2.2.1 Conservation agriculture

Conservation agriculture is considered a sustainable farming system that ensures improved soil health and productivity while minimizing environmental damage. It has three core principles: minimal soil disturbance, residue retention and crop diversification/rotation (FAO, 2015; Naab et al., 2017). It has been seen as the main path to intensify sustainable environment (Hobbs et al., 2008; Pretty & Bharucha, 2014). Conservation agriculture may stand to address the loss of soil C through reduction of emissions of CO₂ and CH₄ (Hobbs, 2007). It has been identified as an effective practice for increasing soil aggregation and carbon sequestration (Vinod Kumar Singh, 2023). Agricultural soil carbon sequestration is considered as an important intervention in mitigating GHG emission. As such, adoption of CA as an improved agriculture land management practice has contributed to removal of 0.79 - 1.54 C/year from the atmosphere and enhancement of crop productivity (Vinod Kumar Singh, 2023)

2.2.2 Relevance of conservation agriculture to small holder farmers

Conservation Agriculture based system of cropping provides good agronomic and economic benefits through increase in productivity for smallholder farmers thus ensuring food security. Cost benefit / profit analysis has shown that no tillage systems is more profiting than the conventional cropping systems (Naab et al., 2017). Thierfelder et al. (2014) reported that CA reduces on-farm labor during land preparation. This can improve on the farmers' income hence income diversification. In contrast, smallholder farmers have social and economic problems that highly limit CA adoption (Powlson et al., 2016).

2.2.3 Effect of conservation agriculture on soil carbon

Conservation agriculture with its inherent principles has been reported to sequester carbon (Lal, 2015) and increase productivity (Six et al., 2004). As such, conservation agriculture supports in mitigation of climate change and providing food security (Landers et al., 2021) through crop yield increase and reducing on-farm labor (Thierfelder et al., 2014). The climate change mitigating potential of reducing GHG emission has been attributed to minimum tillage of CA, which may be as low as 10% of the entire land (Obia et al., 2019; Cornelissen et al., 2013). In addition, Powlson et al. (2016) reported improvement of physical

soil condition due to buildup of surface organic carbon in CA systems, that leads to sustainable agriculture and adaptation to climate change.

Conservation agriculture has been reported to improve soil properties such as water infiltration, soil aggregation and reduce soil erosion (Palm et al., 2013). CA has also been reported to promote biological tillage, which can lead to compaction reduction, increasing carbon content of the soil, regulating soil temperature, and reducing weeds growth (Ella et al., 2016). Combining reduced tillage with residues retention also improves soil chemical quality through improving SOC sequestration and as well as nutrient contents in the soil (Yadav et al., 2017).

It has also helped in reducing production cost, saving time, increasing yields, reducing pests and diseases through activating various diversity (Hobbs, 2007).

Conservation Agriculture contributes positively to sequestering carbon and improve soil organic matter content, increase in situ rainwater harvesting and crop yields. In addition, it also controls weeds through suppression by soil surface cover as well as conserves the environment. More so, it also contributes to improvement of soil structure and reduces up to 60% labor and time of farmers while providing times for another engagement (Mutua et al., 2014)

Pigeon pea is drought tolerant and produces high biomass that help improve soil moisture and nutrient retention (Odeny, 2007b). Low yield of pigeon pea has been associated with low organic carbon in the soil systems (Saxena et al., 2010). In a report by Nagar et al. (2015), CA highly increased yield by 18.5tons/ha as compared to conventional tilth. Namatsheve et al. (2025) reported increased grain yield of pigeon pea under biochar application and CA systems than conventional practices.

Soil contain the highest pool of carbon among other terrestrial ecosystems, amounting to 1502 Pg C for the upper 1 meter of soil (Jobbagy & Jackson, 2000), of which arable soil contain a tenth of C. Because of this C pool size, soil management especially conventional practices have impacted storage of carbon in the atmosphere. CA on the other hand reduces decomposition of organic matter, and in effect reduces carbon losses from soil. For instance, Havlin et al. (1990) reported higher soil organic carbon under no tillage combined with rotation of maize and soybeans in comparison to the conventional tillage even though it was under rotation systems. In contrast, Powlson et al. (2014) reported that soil carbon

sequestration through increase in SOC in no till practice is limited and any apparent increase in SOC may only be associated with soil depth distribution alteration. And such increase in SOC is often lost due to conventional ploughing which is necessary in no till systems after every few years for various agronomic reasons. A similar result was also reported by Baker et al. (2007) where storage of soil organic carbon was observed in soil surface layer under no tillage.

In addition, in 69 experiments reported by Luo et al. (2010), increased C under no tillage system within 10 cm was observed while decreases were observed at 20 to 40 cm depths. Generally, an overall net improvement in C under no-tillage was found. Another study also reported SOC content increase at 0-31 cm depth but was greater in the topsoil layer of 0-1 cm. This change was higher because the top layer received high organic inputs leading to increased SOC content (Novara et al., 2019). Additionally, 20% SOC increase was observed at 0 to 30 cm depth after rotating annual to perennial (Ledo et al., 2020). Increased SOC largely results from crop root exudates and it highly support crop growth. Increase in SOC concentration in soil from CA causes improvement in soil physical conditions (Ella et al., 2016). Thereby, organic carbon is the highly considered as indicator for healthy soil, and it help in mitigating greenhouse gas emission.

SOM has strong effect on the physical properties of soil, and this has been reported to be more prominent in the top soil layer of 0-20 cm. The aggregate stability, bulk density, water holding capacity, compaction characteristics and cation exchange capacity, and its interaction with SOM and other soil biology are the properties which are commonly improved due to SOM (Murphy, 2015). According to Yadav et al. (2017), improvement in physical properties represented by the aggregates, hydraulic conductivity as well as soil bulk density was stronger in CA more than conventional tillage. These improved the soil ability to store carbon and increases soil fauna.

According to Martinsen et al. (2019), 9.3% space occupied under CA with planting basins resulted to a rise in SOC. CA practices of no-tillage, residues retention and crop rotation provided higher soil carbon (Naab et al., 2017). Thereby, increasing SOC is helpful in agriculture for example through binding toxic heavy metals, hence making them unavailable for plant uptake (Gerke, 2022).

2.2.4 Effect of conservation agriculture on greenhouse gas emission

Limited studies have been done on greenhouse gas emissions under CA, and even fewer have been conducted in Africa. Additionally, majority of the studies so far been done have focused on effect of various fertilizers on greenhouse gas emission than on different CA practices and their contributions. However, there are few studies that have been done and had all the combination of CA components on greenhouse gas emission (Kimaro et al., 2015). Although, most studies have focused on various greenhouse gases individually, there is need to have tremendous assessment of the CA on emissions to fully understand potential cropping system mitigation strategies.

According to Six et al. (2004), the potential of no-tillage to mitigate greenhouse gas emission in temperate climate has been investigated and literature generated over time. Also, variation in N₂O emission over three decades in no tillage as well as tilled area was observed, even though emission proven lowest in no tillage than tilled area, more especially where rotations were practiced (Six et al., 2004). In addition, Sibila et al. (2019) reported CO₂ and CH₄ emission greater in between rows than within the crop canopy. This study concluded that CA contributed greatly in reducing GHG.

2.2.5 Effect of conservation agriculture on crop yield

Conservation agriculture practices have been shown to produce positive result through simultaneous implementation of its principles. Use of maize rotation with soybean alongside residue retention and minimum tillage has been reported to present a win to win situation because of improved soil fertility, increased yields and high economic return (Naab et al., 2017). Likewise, rotating maize with cowpea also increased yield in a CA system (Mupangwa et al., 2019).

According to Birhanu & Dereso (2021), surface mulch conserves moisture in the soil thus reducing evaporation and moderating in soil temperature, hence improving crop growth and increasing yields. A study done for Southern Africa found a positive result on adaptation and productivity from CA+BC, where greater infiltration and soil moisture conservation were observed overcoming the drought effect on crop growth, thus increasing productivity (Thierfelder et al., 2017). To the contrary, studies by Giller et al. (2015) and Castaldi et al. (2011) showed that the effect of CA on yield and built up of soil carbon were negative. Therefore, all three components of CA should be practiced to register positive effect.

2.3 Use of biochar in crop

2.3.1 Biochar production and properties

Biochar is a product of pyrolysis process achieved through combustion of organic material without or with limited oxygen (Wang & Brown, 2017). Several biochar production techniques exist but use of a simple flame curtain Kon-Tiki kiln has gained momentum due to low labor input, investment and knowledge requirements (Schmidt et al., 2014). The cone-shaped Kon-Tiki kiln is commonly constructed as soil pit dug using hand hoe (Cornelissen et al., 2016). Biochar production process require dry biomass feedstock that are added layer by layer to ensure constant burning flame until the pit is full with biochar. The biochar yield estimate from this method is $22 \pm 5\%$ on dry weight basis and $40 \pm 11\%$ carbon basis.

The pyrolysis temperature in Kon-Tiki kiln ranges from 650 to 800 °C where the biomass lignin is completely transformed to char (Schmidt et al., 2014). Biochar has elements such as carbon, hydrogen, phosphorus, nitrogen, cations, and heavy metals in various amounts (Jacobs & Sovacool, 2012). The variation of metal amount is determined by different feedstock types and pyrolysis conditions (Joseph et al., 2012). Novak et al. (2009) reported carbon content of 834.2 g/kg, potassium 4.15 g/kg, and nitrogen 3.41g/kg and phosphorous 263g/kg. pH values range from 4 to 12 depending on the pyrolysis temperature and feedstock.

Biochar has been reported to increase pH, P availability, improve soil organic carbon and reduce non carbondioxide greenhouse gas emission (Cowie et al., 2021) as well as increasing yields from 10% to 40%. The pH effect of biochar on soil is often attributed to inherent attributes of low pH, fertility and also limitd fertilizers (Jeffery et al., 2017). A report by Adekiya et al. (2020) recorded enhanced cocoyam yield after application of 30 tons/ha of biochar in degraded soil. Also Borchard et al. (2019b) reported reduced N₂O emission and NO₃⁻ leaching in the soil after biochar amendment. Biederman & Stanley Harpole (2013a) observed increased yield, above ground biomass and total soil carbon than in control field. In 14 months experiment done by Castaldi et al. (2011), increase in yield and soil microbial activities were recorded while GHG fluxes were not affected after incorporation of biochar. Application of biochar increased maize yield by 15% - 7% compared to control and also reduced GHG (methane and N₂O) by 9.8% - 41% compared to control (Zhang et al., 2012).

2.3.2 Advantages of biochar

Biochar has high pore size with good adsorption capacity and can thus increase water holding and nutrient retention capacity. This can increase water and nutrient availability for crop thus increasing productivity. Biochar, in addition, sequester carbon within soil contributing to improved soil quality (Ahmed et al., 2016). Report by Calderón et al. (2015) indicated great carbon sequestration after addition of biochar from crop residues other than leaving crop residues to decompose in the field. This is due to resistance of chars to decomposition after amendment in the soil, and as such, it offsets losses of carbon from soil (Sohi et al., 2009). Biochar also due to its high alkalinity can aid soil acidity amelioration and activates microbial activity within the soil.

2.3.3 Impact of biochar on soil physical properties

Biochar application has great influence on soil pH, soil colour, bulk density, aeration, cation exchange capacity, water holding capacity, nutrient balances as well as other soil parameters because of intrinsic structures and physiochemical characteristic (Obia et al., 2019). The effect of biochar on these soil properties and in effect on physical, chemical, and biological quality and fertility contributes to soil health (Alkharabsheh et al., 2021). This help crops meet their growth requirements including water, nutrients, oxygen, temperature in the soil for increased productivity and environmental sustainability (Alkharabsheh et al., 2021).

Biochar is very porous and has been reported to improve soil aeration and reduce the bulk density (Prajakta et al., 2021). Reduced bulk density has also been linked to the effect of biochar on soil aggregation, in which aggregate stability increased by 7-20% (Obia et al., 2016). The same author also reported increased total porosity and available water capacity. The improved water holding capacity may be associated with improved wettability of soil and water infiltration rate upon biochar application (Venkateswarlu, 2018). The improved porosity and hydraulic properties affect nutrients movement, root growth and yields and quality of the grains at harvest.

2.3.4 Impact of biochar on soil chemical properties

Biochar application has been reported to bring about a lot of changes in soil chemical properties like increased soil pH, CEC and organic carbon (Biederman & Stanley Harpole, 2013). Soil pH rises after biochar application varies and depend on soil type, feed stock of biochar (Tian, Tan, kasiulienė & Ai, 2017). Martinsen et al. (2015) reported increase in soil

pH from 4.7 to 5 after application of biochar that was derived from oil palm and cacao shell. Increased soil pH improves nutrient mobility and availability for crops and reduces mobility of toxic elements in acidic soils (Major, Rondon, Molina, Riha & Lehmann, 2010).

CEC is a clear indicator of fertility as it aids mineral nutrients and ions like Na^+ , Ca^{2+} , Mg^{2+} , K^+ , and NH_4^+ . The inherent natural soil property of the soil is not easily influenced with any soil management activities (Alkharabsheh et al., 2021). Despite this, a lot of studies have shown that biochar amendment improved soil cation exchange capacity. This has been associated with the negatively charged phenolic and carboxylic groups (Gao et al., 2017). Zhang et al. (2012) also reported an upsurge in CEC by 21% in biochar amended soil compared with unamended soil. Increase of 21% in the soil CEC was observed from various treatments with biochar applied at rate of 5 mg/kg of soil (Ndor et al., 2015). The high CEC and associated adsorption capacity of biochar has also been reported to reduce pollutants (Melo et al., 2016).

Biochar application also increased soil organic carbon level by up to 23% (El-Naggar et al., 2018). Brassard et al. (2016) also observed increased SOC content of sandy soil of 42% to 72% after biochar amendment. Jeffery et al. (2011) presented increased organic carbon after application of maize biochar. SOC is important for soil health, soil fertility enhancement, and soil ecosystem activities.

2.4 Pigeon pea production in Africa

World annual production of pigeon pea is estimated at 3.7 million metric tons, with estimated yield of 898kg/ha (FAOSTAT, 2010). Major pigeon pea producing countries in Africa are Kenya with 89.2 metric tons produced on 196,000 ha land size (Simtowe et al., 2012), Malawi with 79.3 metric tons produced on 123,000 ha of land size (Simtowe et al., 2016), Uganda with 77.3 metric tons produced on 86,000 ha of land size, Tanzania with 46 metric tons produced on 68,000 ha of land size, and Mozambique with 40 metric tons produced on 85,000 ha of land size

Mean while in Uganda, currently pigeon pea production is at 13,000 metric tons from 29,800 ha, mainly grown in Northern and North-Eastern regions. It is majorly grown in a mixed cropping system with sorghum and millet by the smallholder farmers. The average pigeon pea productivity in Uganda is from 0.5 to 0.7 tons/ha (UCA, 2010).

Pigeon pea is drought tolerant and produces high biomass that help improve soil moisture and nutrient retention (Odeny, 2007b). Low yield of pigeon pea has been associated with low organic carbon in the soil systems (Saxena et al., 2010). In a report by Nagar et al. (2015), CA highly increased yield by 18.5 tons/ha as compared to conventional tillage. Namatsheve et al. (2025) reported increased grain yield of pigeon pea under biochar application and CA systems than conventional practices.

2.4.1 Advantages of pigeon pea

Pigeon pea has many advantages including a unique tolerance to environment stresses, high biomass and adds nitrogen to the soil (Odeny, 2007) through biological nitrogen fixation (Namuyiga et al., 2022). Pigeon pea provides human with grains, fodders, shade and fuel wood. The grains are rich in protein, minerals and vitamins and is known for improving diets. Pigeon pea has ability to withstand variations in precipitation and temperature (Washington & Pearce, 2012) and has been reported to add SOC (Mandal et al., 2019; Brosgole, Lederer et al., 1976). In addition, it also provides feed for ruminant and non-ruminant animals. Generally pigeon pea dried grains, aerial portion and green pods are source of low cost food and feed for human livelihoods (Abebe, 2022).

2.4.2 Constraints in pigeon pea production

Pigeon pea has faced declining productivity due to fusarium wilt, pod borer pest, as well as soil fertility and lack of affordable and improved seeds. Its growth is highly disturbed by pests and diseases especially pod borer and fusarium wilt (Hillocks et al., 2000), respectively, which reduces its productivity (Nisa, 2020) in East Africa.

Availability of improved cultivars of pigeon pea which has a high productivity performance, seed replacement ratio, cultural practices, research and development priorities are the key factors that affect productivity of pigeon pea. Low seed availability and high prices (Audi et al., 2008) has prompted farmers to rely on the local seeds sowed from their farm after harvesting. Pigeon pea is also mostly neglected by researchers and extension service providers. Smallholder farmers receive low farm gate prices, market prices are high (Economics & Library; Fatokimi & Tanimonure, 2022).

Despite the fact that pigeon pea can adapt to wide range of growing conditions, the declining soil fertility coupled with low soil water storage and high infiltration leads to drought, that result into low yields, food insecurity and increased poverty (Johnston et al., 2009).

Therefore, the research aiming at increasing yield of pigeon pea by improving soil carbon seems imperative.

2.4.3 Strategies for increasing pigeon pea yields

A lot of interventions are being used to improve pigeon pea productivity which include breeding programs, crop rotation, mixed cropping, use of inorganic and organic fertilizers, conservation agriculture and biochar.

Intercropping of pigeon pea with cereals such as maize, millet or any low growing legumes like groundnut, bean, and soybean among others have been reported to contribute to high yield. This is because pigeon pea has ability and potential to fix up to 235 kg/ha/year of atmospheric nitrogen (Odeny, 2007). Pigeon pea roots also support in release of phosphorous to the soil, thus increasing P availability for proper plant growth and development. Although various legumes fix nitrogen, few do more than pigeon pea with potential that does not require inoculation (Odeny, 2007). The strong nitrogen fixation capability of pigeon pea has been reported to increase crop yield when intercropped with maize. In fact, Sogbedji et al. (2006) found 32% increase in maize yield when intercropped with pigeon pea in West Africa. In addition to intercropping, inclusion of pigeon pea in a rotation enhances soil fertility thus improving productivity of crop that follows it in a rotation. Adjei-Nsiah (2012) reported an increase of 75% to 200% in maize yield grown after pigeon pea. As such, rotation is a key principle of CA and can improve soil fertility and increases pigeon pea yield.

Although outside the scope of this study, breeding programs to developed superior varieties (Ojwang et al., 2016) and use of individual farmer to farmer seed delivery systems (Obuo et al., 2004) have been shown to increase pigeon pea productivity.

2.5 Effect of combined use of CA and biochar on soil carbon, greenhouse gas emission and yield

2.5.1 Total carbon, SOC and labile C

Biochar application in the soil increases the total soil carbon (Biederman & Stanley Harpole, 2013a). Additionally, biochar increases pH level, hence reduces its acidity. Furthermore, biochar also improves soil chemical properties like P, N and K content (Biederman & Stanley Harpole, 2013a). Laird et al. (2010) reported 69% increase in organic carbon and improved the soil quality and fertility.

Biochar addition increases the soil moisture content and SOC and has been appreciated as a good amendment for increased storage of carbon in the soil (Thammasom et al., 2016). Biochar reduces carbon mineralization rate, which results labile soil carbon stability (Borchard et al., 2019b). Increased labile carbon commonly expressed as Readily Oxidisable Carbon (ROC) as well as SOC after biochar addition in the soil has also been reported (Yang et al., 2017). Biochar improved SOC storage in the top soil (0 to 15 cm) by 37% and 15% in the first and second planting seasons (Yang et al., 2020). In another study, soil carbon storage and carbon pool were improved due to biochar use whereby 198.3% and 71.5% increased was observed (Wang et al., 2024; Gerke et al., 2022). A study by Munera-Echeverri et al. (2020) found increased amount of SOC in plots where biochar was incorporated in CA planting basins. Biochar contains humic substances which can contribute up to 50% soil carbon. These humic substances highly influence concentration of various soil-plant nutrients, and increase the solubility of P, Fe, and Cu hence availing them for plants uptake. In the same study, greater root biomass which enhanced buildup of SOM was also reported. Palm et al. (2013) also reported that CA improve soil organic matter as well as other properties of the soil hence reducing soil water runoff. Therefore, biochar improve levels of soil carbon in the farm and also reduces impact of drought while enhancing soil carbon storage (Vinod Kumar Singh, 2023). There were increased labile carbon from CA+Biochar (Major et al., 2010). CA basins recorded increased SOC and also labile carbon compared to conventional practices (Ellingsen, 2018). CA+Biochar contributed to reduced soil temperature. This was due reduced soil moisture however, in another laboratory tests where by only biochar led to reduced thermal temperature of the soil (Obia et al., 2020). CA in combination with biochar improved soil carbon due to residue retention, crop rotation and reduced soil disturbance (Zhang et al., 2012). Thierfelder & Wall (2009) and Thierfelder et al. (2014) observed increased soil moisture in the entire season in CA and biochar compared to conventional practice due to increased water infiltration and reduced surface evaporation. Climate smart agricultural practices like crop rotation, cover cropping, biochar application, minimum tillage e.g. rip lines and planting basins, organic manure could help to improve and conserve soil moisture and retain water for long period and support plant growth. Incorporation of biochar in CA planting basins, for example, was reported to increase water retention by up to over 100% (Obia et al., 2020).

The reported high soil moisture retention in combined use of biochar and CA practices including basins resulted into increased productivity during the dry times (Palm et al., 2013).

Due to increased water holding capacity, biochar and CA enhance biomass production and organic matter input into soil resulting to increased soil organic carbon by 3.8% (Joseph et al., 2021).

2.5.2 Effect of conservation agriculture and biochar on green house gas emission

A studies by Oladele & Adetunji (2021) and Cross & Sohi (2011) on application of biochar to soil found a reduction in CO₂, increased labile C and stored SOC with a great impact on mitigation. BC contributed to reduction of CH₄ emission and the general global warming (Thammasom et al., 2016). A metaanalysis by Jeffery et al. (2016) showed the potential of biochar in decreasing the soil CH₄ emission. Report by Shakoor et al. (2022) recorded reduced GHG emission majorly from CA than conventional tillage and improved soil organic carbon. Alam et al. (2019) reported reduced GHG emissions of 26% with added residues retention that has contributed to more storage of soil organic carbon. Joseph et al. (2021) recorded reduced CO₂ emission from 12 to 50% in the soil.

2.5.3 Effect of conservation agriculture and biochar on pigeon pea growth and yield

Conservation agriculture and biochar have wide range of benefits to the soil, growth and yield of different crops. When CA is combined with biochar, it can enhance plant available water as well as regulating temperature of the soil, which is a great avenue for productivity improvement (Obia et al., 2020). Biochar on its own has been reported to improve several properties of soil that directly contribute to improvement of plant available water. These soil properties improved by biochar include aggregate stability that increased by 7-9% and by 17-20% under maize and soybeans, respectively, increased soil porosity, soil aeration and reduced bulk density (Obia et al., 2016). The modification of soil structure indicated by changes in aggregation, porosity and bulk density and water holding capacity improvement is a key mechanism behind plant growth and yield improvement after biochar application. Although, increased productivity because of amendment of biochar to the soil is frequently presented, the increase is commonly stronger in coarse textured sandy soils compared to fine textured (Alkharabsheh et al., 2021). Cornelissen et al. (2013), reported increased maize yields of around 444% ± 114% and 352% ± 139% of control yields attributing this to improvements in soil water retention.

Jeffery et al. (2011) presented increased productivity from 28% to 39% in both biomass yield and crop yield after being planted using biochar amendment. These have been because of

liming effect of biochar and increased soil water hence increasing availability of nutrient in the soil. Biederman & Stanley Harpole (2013b) found increased soil pH in biochar amended soil. This change in soil pH influences nutrient solubility hence making it available for root uptake. Ferralsol that are common in tropics are acidic and biochar addition may help to neutralize the soil acidity for proper crop growth and yields. Yield increase in tropics due to biochar has been reported to at 25% on average associated with liming and fertilization. These soils have low pH and low fertility accompanied with low fertilizer inputs, as such, higher nutrient biochar input regulated yield substantially more than biochar with low nutrient (Jeffery et al., 2017).

Furthermore, CA and biochar has been reported to increase grain yield, biological N₂ fixation and nitrogen use efficiency (Namatsheve et al., 2024). Biochar have positive impact on abundance and multiplication of microbial communities in the soil thus enhancing nutrient utilization due to improved mineralization (Zhang et al., 2012). Many studies have proven that CA system, significantly improved the overall total carbon concentration in soil (Vinod Kumar Singh, 2023). The increased soil carbon may improve nutrient use efficiency due to increased nutrient retention.

2.6 Pigeon pea yield

Pigeon pea is one of the most commonly grown crop in Uganda especially Northern region. It contain high biomass, which can help to produce high biomass and later be converted into biochar that can improve soil fertility for increase yield of pigeon pea. However, its yield is highly affected by prolonged drought, erratic rainfall and temperature extremes

In East Africa, pigeon pea is cultivated in about 0.82 million ha, with production of 0.5 million tones. This production is low to feed the current growing population (ICRISAT, 2012, FAOSTAT, 2011).

CHAPTER THREE: MATERIALS AND METHODS

3.1 Description of the study area

The experiment was conducted at Unyama sub-county. Unyama is located in Gulu City, Northern Uganda, with geographical coordinates of 2° 49'14" North, 32° 22'8" East and terrain elevation of 1080 masl. The area receives rainfall of 227.1 mm per annum while the vegetation is tropical wet and dry or savanna. The area has highly weathered soils classified as ferralsols.

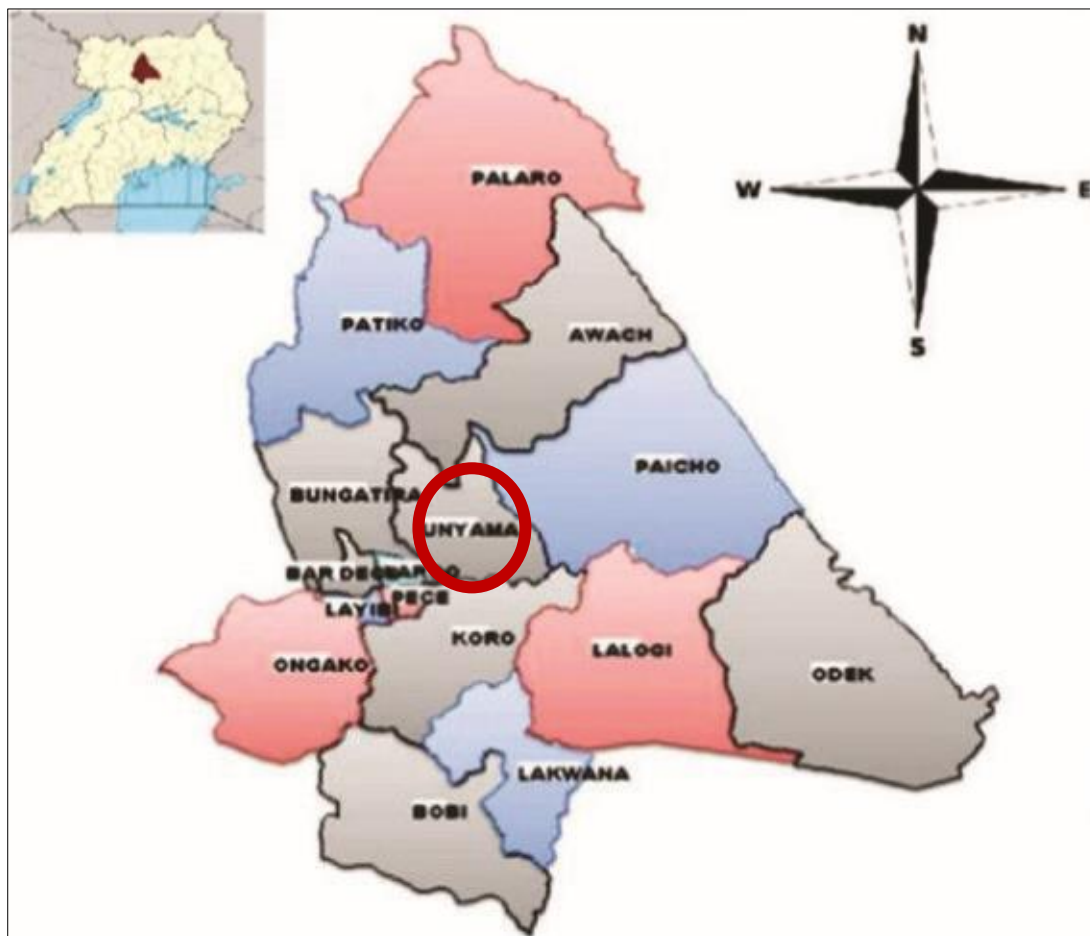


Figure 1: Location of Unyama where the study was conducted

3.2 The crops used in the experiment

Pigeon pea (SEPI 1 variety) was used for the experiment. This is a major crop widely grown in Northern Uganda by smallholder farmers. As a legume, it improves soil fertility by fixing nitrogen and contributes to food security. SEPI 1 variety takes only five months to maturity, hence it can be planted in all the two growing seasons of northern Uganda and was released by National Agricultural Research Organization (NARO) of Uganda in 1999. Maize (Longe

10H) is commonly grown in Uganda and was released by National Maize Research Program (NMRP) of NARO in 2009.

3.3 Experimental design

The experiments followed a RCBD with five (4) treatment, replicated 4 times. Treatments included; (i) conservation agriculture with maize-pigeon pea rotation (CA+PP), (ii) conservation agriculture with maize-pigeon pea rotation and one time biochar application of 4 tons/ha (CA+BC+PP), (iii) conventional farming consisting of overall ploughing with maize-pigeon pea rotation (C+PP), (iv) Conservation agriculture with maize-pigeon pea rotation and split biochar application (2t, 1t & 1t/ha per year) (CA+BC+BC+PP), (v) conventional farming consisting of overall ploughing with maize monocropping (Convent+MM). The plots measured 5 x 6 m with inter plot spacing within a block of 1m and inter block spacing of 1.5m. A permanent minimum tillage planting basins of 35 cm length x 20 cm depth x 15 cm width was opened. The inter row spacing of basins was 70 cm while within row spacing was 35 cm.

Therefore, CA+PP, CA+BC+PP, CA+BC+BC+PP, C+PP, were the treatments considered for total SOC, ROC, biomass and grain yield under pigeon pea growing seasons. The experiment addresss objective 2 also followed a RCBD, with CA+PP, CA+BC+PP, Conv+PP and Conv+MM as treatments considered for CO₂ and CH₄ that started on 22/April/2025 and end on December/2025. Then were considered for GHGs (CO₂ and CH₄ fluxes) under maize growing seasons.

Table 1: The experimental treatments

T NO.	Treatment	Treatment Descriptions
T1	CA+PP	Conservation agriculture with maize-pigeon pea rotation.
T2	CA+BC+BC+PP	Conservation agriculture with maize-pigeon pea rotation and split biochar application (2t, 1t & 1t/ha per year).
T3	CA+BC+PP	Conservation agriculture with maize-pigeon pea rotation and one time biochar application of 4 tons/ha.
T4	C+PP	Conventional farming consisting of overall ploughing with maize-pigeon pea rotation.
T5	Conv+MM	Conventional farming consisting of the overall ploughing with maize monocropping.

CA+PP	CA+BC+BC+PF	C+PP	CA+BC+PP
C+PP	CA+BC+PP	CA+PP	CA+BC+BC+PP
CA+BC+BC+PP	CA+PP	C+PP	CA+BC+PP
CA+BC+PP	CA+BC+BC+PP	CA+PP	C+PP

Figure 2: Experimental layout for experiment addressing objective 1 and 3.

CA+PP	Conv+MM	CA+BC	Conv+PP
Conv+PP	CA+BC	Conv+MM	CA+PP
Conv+MM	Conv+PP	CA+PP	CA+BC
CA+BC	CA+PP	Conv+PP	Conv+MM

Figure 3: Experimental layout for experiment addressing objective 2.

3.3.1 Fitting of collars in the field for gas sampling

A round cylindrical polyvinyl chloride (PVC) plastic pipes of 17 cm diameter and 10 cm height was locally cut using axe saw and used as collars. The collars were heated from one side using Bunsen burner and widened from the top using hand. The heating was done to enlarge the top to reduce the gas escape from the sides during gas sampling events. It was slowly driven into the soil using a hand to a depth of 7 cm in the soil leaving about 3 cm of the widened side above the soil surface (Fig. 2).



Figure 4: Fitting of collars in the plots

3.3.2 Soil sampling and gas extraction

At all the gas sampling events, small amounts of undisturbed soil samples were collected from each of the plots (outside the collars) using a mini auger (1 cm diameter) at 20 cm depth. Soil samples were transferred to zip-locks, labelled, and were stored in a cooler box and transported to soil laboratory at Gulu University for determination of ammonium and nitrate N. Extraction of mineral N was done on the same day of sampling by adding 11 g of the collected soil samples into a 100 ml plastic bottle containing 40 ml of 1M potassium chloride (KCl) (Collier et al., 2014). The suspension was shaken in the shaker for 200 rotation per minute for 1 hour, filtered and stored in a freezer at -20 °C until analysis.

3.3.3 Soil moisture and temperature

Soil moisture sensor (SM150 kit – Soil Moisture Meter, Denta-T Devices) was used for determination of soil moisture contents inside the gas sampling collars during all the gas sampling events. The remaining soil samples from section 3.2.1 from each of the sampling events were used for determination of soil moisture using gravimetric method in the soil laboratory at Gulu University. Soil samples were dried at temperature of 105 °C for 24 hours. The difference between moist and oven dried sample weight was divided by the oven dried sample weight (Collier et al., 2014) to obtain gravimetric moisture content.

3.3.4 Planting

Planting of pigeon pea was done on 22/April/2025. For gas emission studies, both pigeon pea and maize rotation was studied to see the difference in the gas fluxes (CO₂ and CH₄) when the crops are in the field. When planting pigeon pea, at least 5 seeds were placed in each basin and later thinned to 3 plants after germination. For maize, 3 seeds were dropped and thinned to 2 seedlings after germination. Plots under conventional overall ploughing followed regular farmers' planting practice. The plots for conventional treatment were ploughed with the hand hoe, and planting holes were dug in the plots in lines with inter row spacing of 60cm and within row spacing of 50cm. No fertilizer was applied to any of these plots.

3.3.5 Weeding

The first weeding was done 2-3 weeks after the emergence of pigeon peas. The second weeding was done at 6 weeks. Hand hoe was used to carry out weeding in the conventional

plots while hand picking of weeds was done in all the plots with basins. The same approach of weeding was used in the second season when maize was planted.

3.3.6 Pest and disease management

Pest control was conducted at maximum flowering stage. Pod borers, thrips were controlled using Dudu-Acelamectin contact pesticide in the field.

3.3.7 Harvesting

Harvesting of pigeon peas was done when the pods had dried but before it started shattering to prevent losses of the grains. Harvesting was conducted by cutting the whole plant using a machete followed by removal of pods from the branches. The harvested pods were sun dried to attain a specific moisture content and threshed followed by determining grain dry weight.

3.4 Data collection

3.4.1 Objective 1: Determination of total SOC and readily oxidizable carbon

Total SOC and readily oxidizable carbon were measured under the treatments; CA+PP, CA+BC+PP, CA+BC+BC+PP and C+ PP in each of the seasons. Soil samples were collected from the four treatments at the end of first seasons. The soil samples were collected randomly from 5 spots in each of the plots using mini auger to a depth of 20 cm. Samples were bulked by soil depth (5 cm interval) in each of the treatments. The soil samples from each plot were analyzed for total soil organic carbon and readily oxidizable carbon using Walkley and Black wet oxidation procedure (Weil et al., 2003; Jha et al., 2014) and potassium permanganate oxidizable carbon, respectively.

Total SOC was measured using wet oxidation method (Walkley-Black, 1934) whereby, 1 g of soil was added into a 500 ml conical flask. The sample was oxidized using 10 ml of a 0.1667 M potassium dichromate ($K_2Cr_2O_7$) in acid environment through addition of 20 ml of sulphuric acid (H_2SO_4). The suspension was mixed thoroughly and allowed to react for 30 minutes. The reaction mixture was diluted with 200 ml of deionized water and 10 ml of phosphoric acid (H_3PO_4) was added to it and 2 ml of diphenylamine indicator was later added to the solution. The suspension was titrated with standard 0.5 M iron sulphate ($FeSO_4$) solution until a brilliant green color was obtained. A blank sample was as well run simultaneously. Percentage organic carbon in each of the sample was determined following

the equation below and Organic Carbon recovery was estimated to be about 77% (Vos et al., 2007). Therefore, the amount of C was calculated by multiplying the obtained % C by 1.3:

$$Total\ SOC\ (\%) = [10 * (S - T) * 0.003 * 100] / (S * Wt)$$

Where, S = $FeSO_4$ solution required for the blank (ml), T = $FeSO_4$ solution required for the soil sample, 3 = equivalent weight (Eq W) of C (weight of C is 12, valency is 4 Eq W is $12/4 = 3$), 0.003 = Factor converting the volume of 0.167 M K_2CrO_7 to the mass of carbon (mg of C), Wt = Oven dried weight of the soil.

Readily oxidizable carbon (ROC) / Permanganate oxidizable carbon (POXC) was analyzed following procedures described by Weil *et al.* (2003) modified as follows. 2.5 g of air-dried soil was weighed into a polypropylene tube and 18 ml of demineralized water and 2.0 ml of 0.2 M K_2MnO_4 was added. The tube was shaken for 2 minutes at 120 rpm and there after left undisturbed for 8 minutes to continue the oxidation reaction. 0.5 ml of the solution was taken from the tube and placed in another tube with 49.5 ml of demineralized water, allowing the reaction to stop. The absorbance of each sample at 550 nm (Abs) was determined using a GENESYS 10S UV-VIS Spectrophotometer (mode). Permanganate oxidizable carbon was calculated following the equation below.

$$POXC\ (mg/kg\ soil) = [0.02\ mol/L - (a + b * Abs)] * (900\ mg\ C/mol) * (0.02\ L\ rx\ solution / Wt)$$

Where, 0.02 mol/L = initial solution concentration, a = intercept of the standard curve, b = Slope of the standard, Abs = Absorbance of the unknown, 900 = mg of carbon oxidized by 1 mole of MnO_4 changing from Mn^{7+} to Mn^{4+} , 0.02 Lrx 0.02 Lrx = volume of the stock solution reacted, Wt = Weight of the air-dried soil sample in kg.

3.4.2 Objective 2: Determination of CO₂ and CH₄ fluxes

The treatments that were considered for GHGs; CA+PP, CA+BC+PP, Conv + PP and Conv+MM in each of the seasons.

During gas sampling, chambers was tightly placed on the static base (collar) 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 using air-tight 20 ml syringes. Samples were transferred to pre-evacuated clear glass vials sealed with gas tight rubber septa and aluminum

crimp cup, labelled and stored in a dark room in the soil laboratory. The gas samples were later analyzed using gas chromatography (model 7890B, Agilent Technologies, USA)

3.4.3 Objective 3: Determination of biomass and grain yield of pigeon pea

Above and below-ground biomass and grain yield were measured under the treatments; CA+PP, CA+BC+PP, CA+BC+BC+PP and C+ PP in each of the seasons.

Biomass yield was determined at flowering stage. Five (5) pigeon pea plants were carefully dug out using a hand hoe during flowering stage and divided into below-ground (roots) and above-ground biomass (vegetative parts). The roots were carefully washed with clean water and these parts were oven-dried at 60 °C for 2 days. The fresh and oven-dried samples were weighed using a weighing scale and recorded. For grain yield, pigeon pea in each plot was harvested at the end of season and grain weight was determined.

3.5 Statistical Analysis

The effect of CSA practices on total soil organic carbon, permanganate oxidizable carbon/ readily oxidizable carbon, CO₂ and CH₄ fluxes and yield were analyzed using onw-way ANOVA and mean values was separated using Tukey test at 5% level of significance. All analyses were performed using R- software (**version 4.4.3**).

3.6 Ethical considerations

The administrative clearance was obtained from the local authorities and land owners/farmer group members where the experiment was conducted. The ethical approval was granted from Gulu University Research Ethics Committee (No. GUREC-2025-1178 (Appendix 13).

CHAPTER FOUR: RESULTS

4.1 Effect of CA practices on SOC and readily oxidizable carbon

The total SOC was generally high at >1.5% across farming practices and seasons. There was no significant difference in SOC across farming practices in the first season whereas in second season, CA with biochar inclusion especially 4 t/ha single application significantly increased SOC. CA without biochar did not affect SOC during the two seasons' experiment. CA with biochar application at 4 t/ha had a SOC of 1.99% compared to 1.53% SOC in conventional tillage practice (Figure 3).

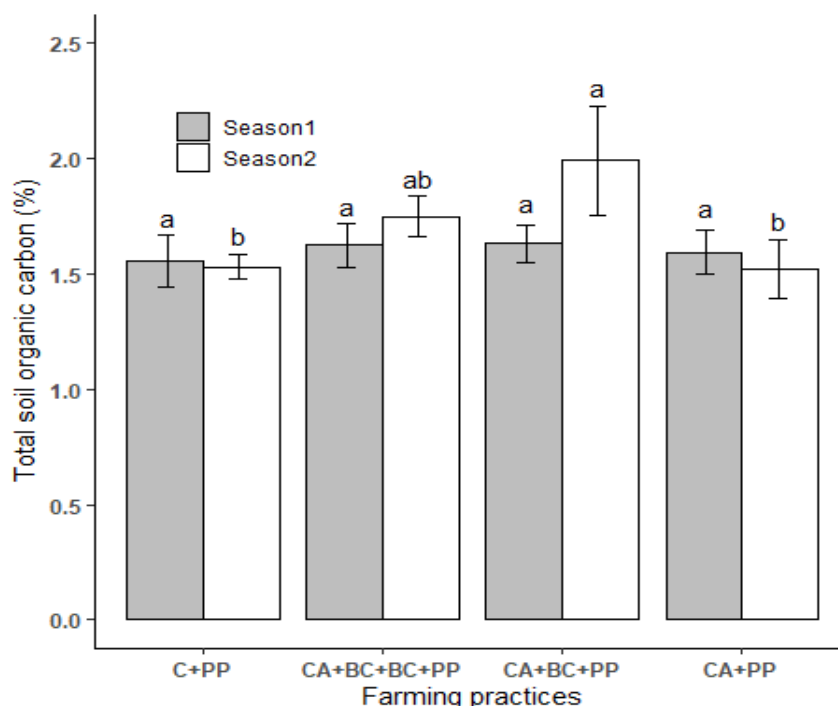


Figure 5: Effect of farming practices and biochar on total soil organic carbon. CA, conservation agriculture; BC, biochar; PP, pigeon pea; C, conventional. Error bars represents standard error. Different letters indicate significant differences ($P < 0.05$). NB: soil samples were collected from each farming practice after pigeon pea harvest.

When total SOC was tested across depth profile of 0–20 cm at 5 cm interval, there was a general decrease in the contents with depth. However, the decrease in SOC was significant only in the first season with 10–15 and 15–20 cm depth layers having lower SOC compared to 0–5 and 5–10 cm layers. Total SOC in first season for the depth of 0–5cm was 1.87% compared to 1.40% for the depth of 15–20 cm, representing a 25% decrease. The lack of significant decrease in SOC in the second season may be associated with biochar shifts from top soil to deeper soil depth when after rotation with pigeon pea and time duration of the experiment (Figure 4).

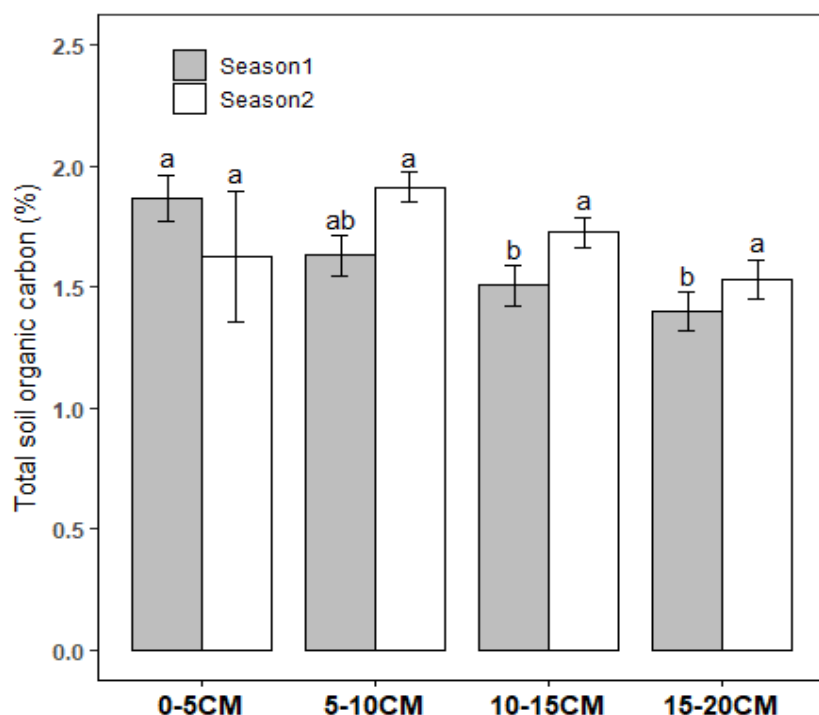


Figure 6: Effect of soil depths on total soil organic carbon. 0-5cm; 5-10cm; 10-15cm; 15-20cm are vertical soil depths. Error bars represent standard error. Different letters indicate significant differences ($P < 0.05$). NB: soil samples were collected from each depth after pigeon pea harvest.

The farming practices significantly affected readily oxidizable carbon (ROC) in both first and second season. CA combined with split application of biochar (CA+BC+BC+PP) recorded the highest ROC of 0.07% in the first season. CA together with single application of biochar at 4 t/ha on the other hand gave the lowest ROC of 0.05% in first season. Practices without biochar gave intermediate ROC values. In second season, practices with biochar inclusion (CA with single and split application of biochar) recorded higher ROC compared to CA without biochar and conventional practice (Figure 5). Conventional practice had the lowest value of ~0.035%.

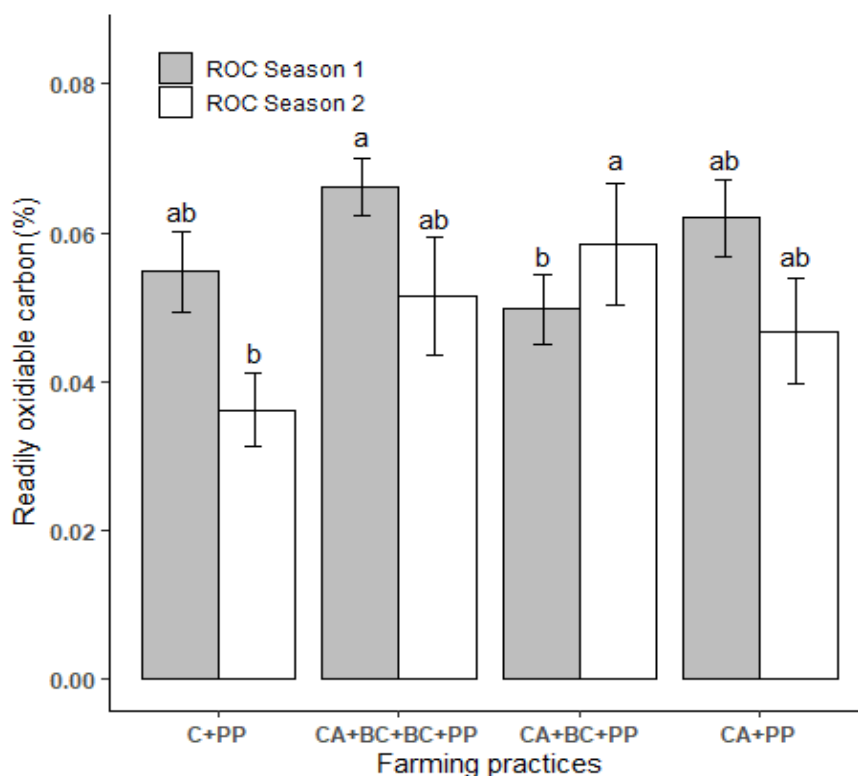


Figure 7: Effect of farming practices on readily oxidizable carbon. CA, conservation agriculture; BC, biochar; P, pigeon pea; C, conventional. Error bars represents standard error. Different letters indicate significant differences ($P < 0.05$). NB: soil samples were collected from each practice after pigeon pea harvest.

Soil depths affected ROC significantly ($P < 0.05$) in both season 1 and 2. Depth of 0-5 cm had the highest ROC of 0.07% compared to depth of 15-20 cm with lowest ROC of 0.052% in season 1 whereas, depth of 5-10 cm recorded higher ROC of 0.06% than depth of 15-20cm with 0.03%. (Figure 6). Generally, CA practices tended to improve total SOC and ROC thus increasing soil carbon contents.

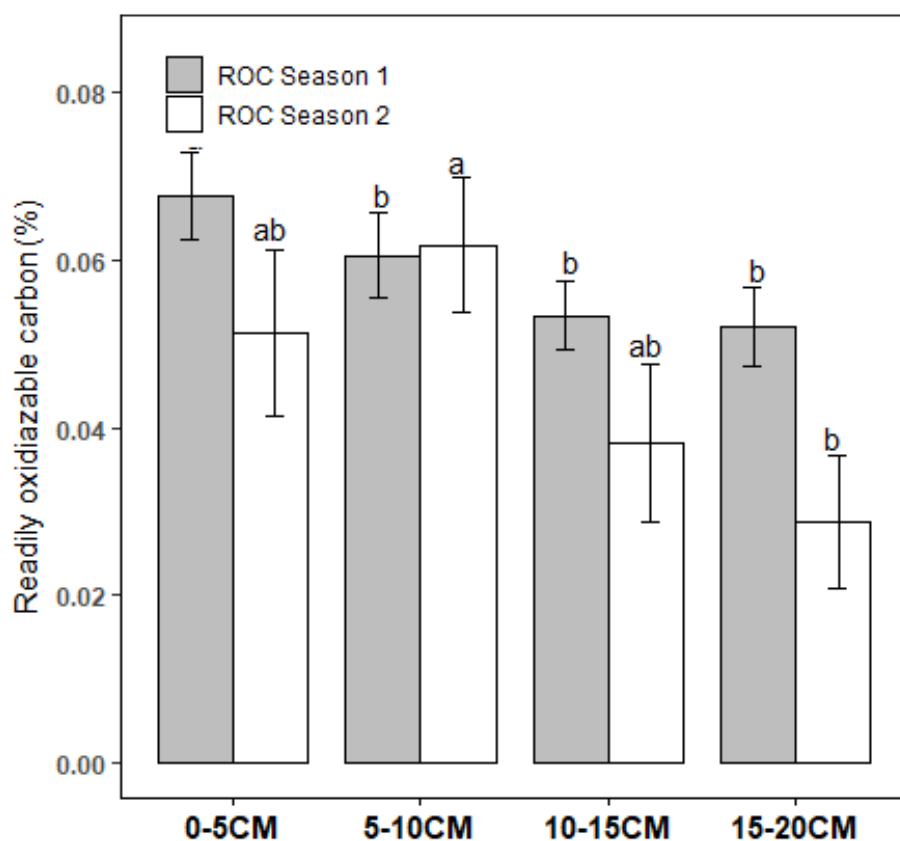


Figure 8: Effect of soil depths on readily oxidizable carbon. 0-5 cm; 5-10 cm; 10-15 cm; 15-20 cm are vertical soil depths. Error bars represent standard error. Different letters indicate significant differences ($P < 0.05$). NB: soil samples were collected from each depth after pigeon pea harvest.

4.2 Effect of conservation agriculture on CO₂ and CH₄ fluxes

Carbon dioxide was not significantly affected by the farming practices for both first season pigeon pea and second season maize ($P > 0.05$). The CO₂ flux varied from 260 – 308 and 179 – 223 mg CO₂-C m⁻² h⁻¹ in the first and second seasons, respectively (Figure 7).

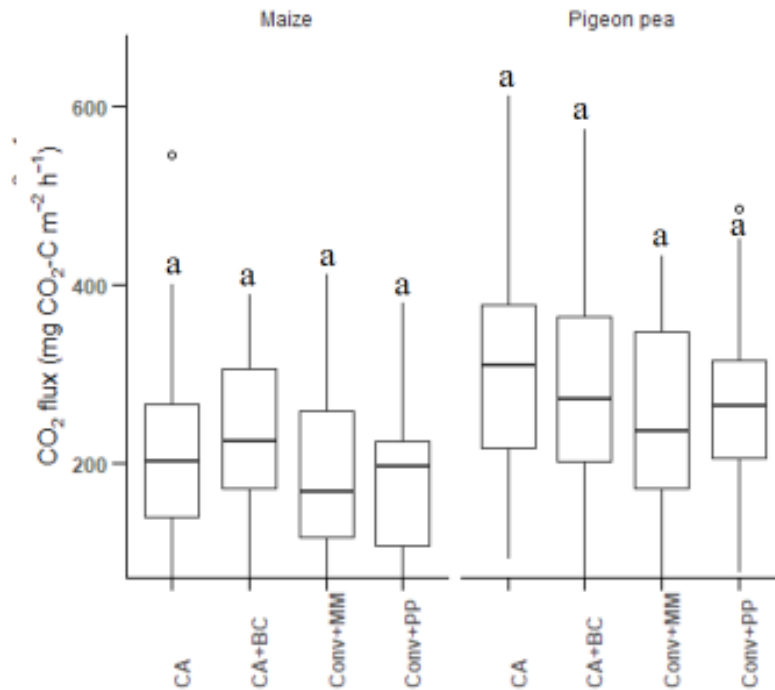


Figure 9: Effect of farming practices on methane flux. CA, conservation agriculture; BC, biochar; Conv, conventional tillage; MM, maize monoculture; PP, pigeon pea. Whisker bars represent 1.5 times the IQR from the top and bottom of the box. Dotted points below or above the whiskers are outliers. Same letters indicate no significant differences ($P > 0.05$) and different letters indicate significant differences ($P < 0.05$). NB: four sampling events were used during gas collection at 0, 15, 30 and 45 minutes.

CH₄ fluxes were significantly ($P < 0.05$) affected by farming practices in the first season when pigeon pea was planted but not ($P > 0.05$) in season 2 when maize was planted (Figure 8). In the second season, CH₄ flux varied between 10 – 25 $\mu\text{g CH}_4\text{-C m}^{-2}\text{h}^{-1}$. CH₄ emission in CA + biochar had lower fluxes of 28.3 $\mu\text{g CH}_4\text{-C m}^{-2}\text{h}^{-1}$ and 10.7 $\mu\text{g CH}_4\text{-C m}^{-2}\text{h}^{-1}$ in season pigeon pea and season maize, respectively, compared to CA, Conv+PP, Conv+MM with highest CH₄ emission in both pigeon pea and maize season. In general, CA+BC and Conv+MM had reduced CH₄ fluxes in both pigeon pea and maize season (Figure 8).

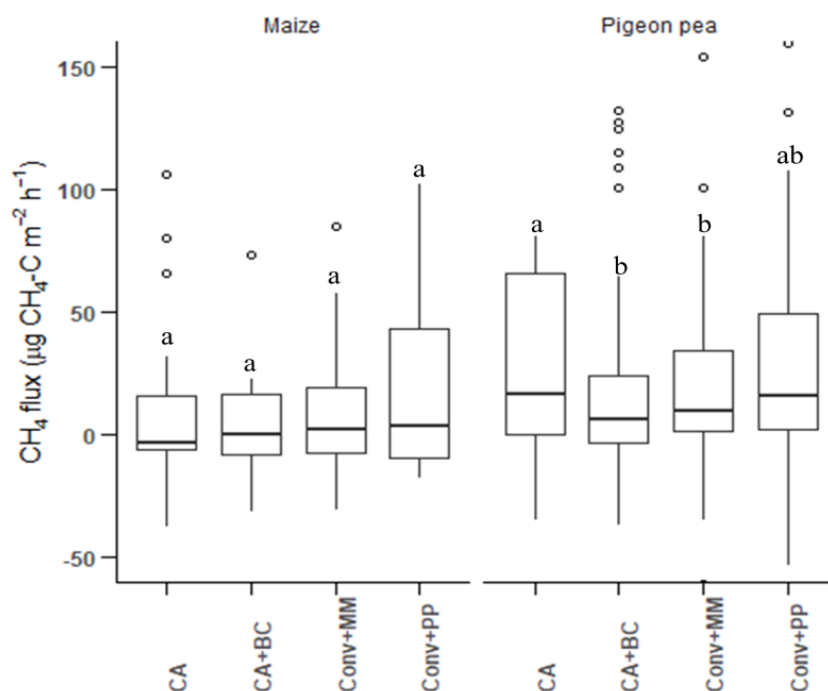


Figure 10: Effect of farming practices on methane flux. CA, conservation agriculture; BC, biochar; Conv, conventional tillage; MM, maize monoculture; PP, pigeon pea. Whisker bars represent 1.5 times the IQR from the top and bottom of the box. Dotted points below or above the whiskers are outliers. Same letters indicate no significant differences ($P > 0.05$) and Different letters indicate significant differences ($P < 0.05$). NB: four sampling events were used during gas collection at 0, 15, 30 and 45 minutes.

4.3 Effect of conservation agriculture and biochar on biomass and grain yield of pigeon pea

Below ground biomass at flowering stage were not significantly different across farming practices in both season 1 and 2 of pigeon pea growing ($P > 0.05$). There was, however, higher below ground biomass in season 1 compared to season 2 (Figure 9). There was also general tendency of higher biomass in CA practices compared to conventional practice.

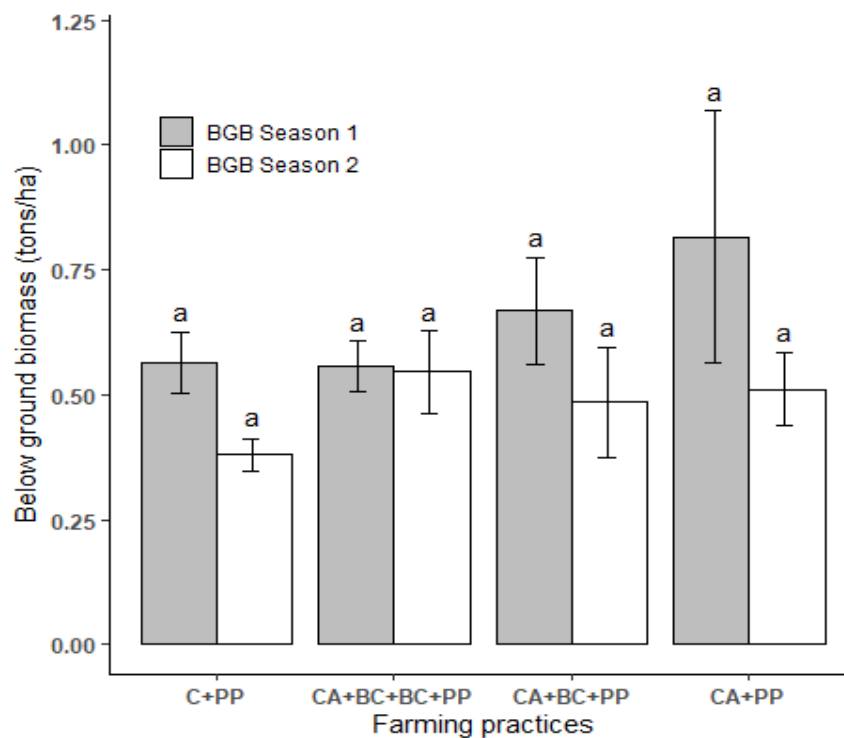


Figure 11: Effect of farming practices on below ground biomass of pigeon pea at flowering stage. CA, conservation agriculture; BC, biochar; C, conventional; PP, pigeon pea. Error bars represent standard error. Same letters indicate no significant differences ($P > 0.05$). NB: Three plants were randomly selected at flowering stage.

The above ground biomass at flowering stage also showed no significant difference across farming practices in season 1 and 2. There was a general tendency of higher above ground biomass in CA practices with or without biochar though these differences were significant (Figure 10).

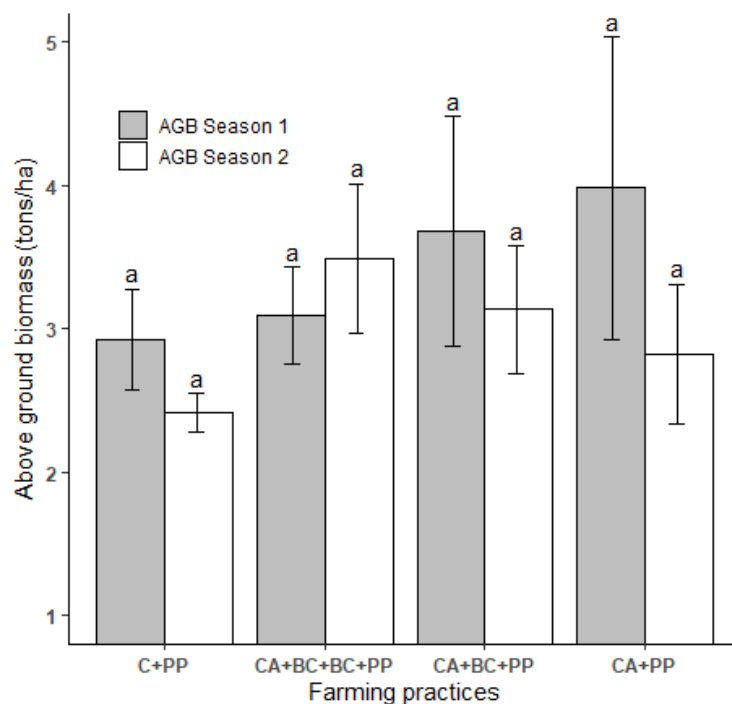


Figure 12: Effect of farming practices on above ground biomass of pigeon pea at flowering stage. CA, conservation agriculture; BC, biochar; C, conventional; PP, pigeon pea. Error bars represents standard error. Same letters indicate no significant differences ($P > 0.05$) and Different letters indicate significant differences ($P < 0.05$). NB: Three plants were randomly selected at flowering stage.

The total biomass at harvest were significantly affected ($P < 0.05$) by farming practices. CA with or without biochar included generally resulted to greater total biomass compared to conventional practice. There was also greater biomass in season 1 compared to season 2. In season 1, the highest total biomass at harvest was recorded in CA+BC+PP treatment at 13.68 tons/ha compared to 8.75 tons/ha in conventional practice, whereas, in season 2, CA+BC+BC+PP treatment gave the highest total biomass at 5.0 tons/ha compared to conventional practice which gave the lowest biomass at 3.76 tons/ha (Figure 11).

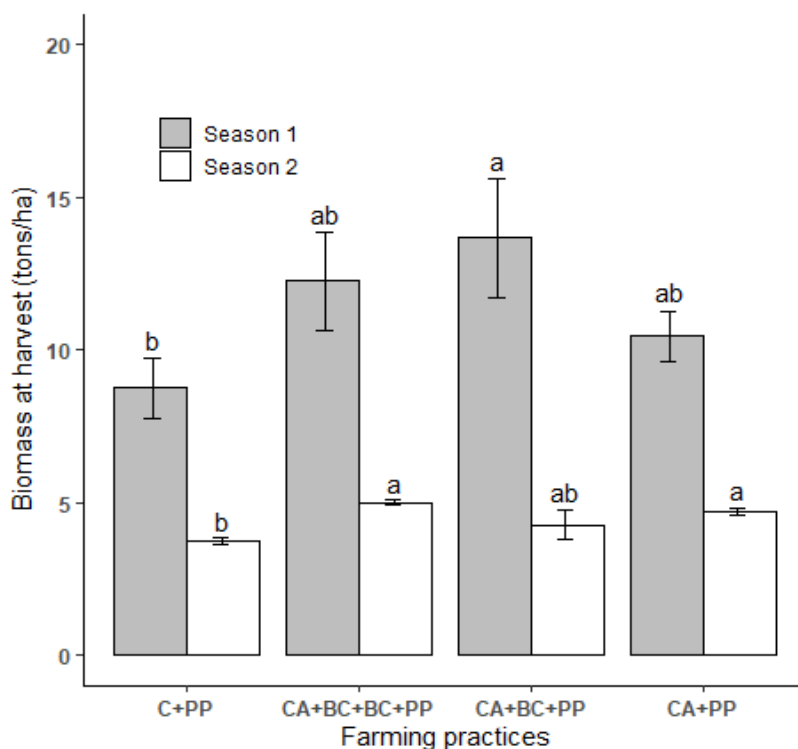


Figure 13: Effect of farming practices on biomass of pigeon pea at harvest. CA, conservation agriculture; BC, biochar; C, conventional; PP, pigeon pea. Error bars represents standard error. Same letters indicate no significant differences ($P > 0.05$) and Different letters indicate significant differences ($P < 0.05$). NB: biomass determined at harvest.

Farming practices significantly affected grain yield of pigeon pea in season 1 ($P < 0.05$) and not in season 2. CA+BC+PP registered the highest grain yields of 2.11 tons/ha in season 1 compared to conventional practice which gave the lowest yield at 1.7 tons/ha. In season 2, although there was no significant difference between farming practices, CA practices with or without biochar gave higher yields following the same pattern as for first season (Figure 12). Farming practices with biochar amendment registered higher yield of pigeon pea than conservation agriculture and conventional practice in both season 1 and 2.

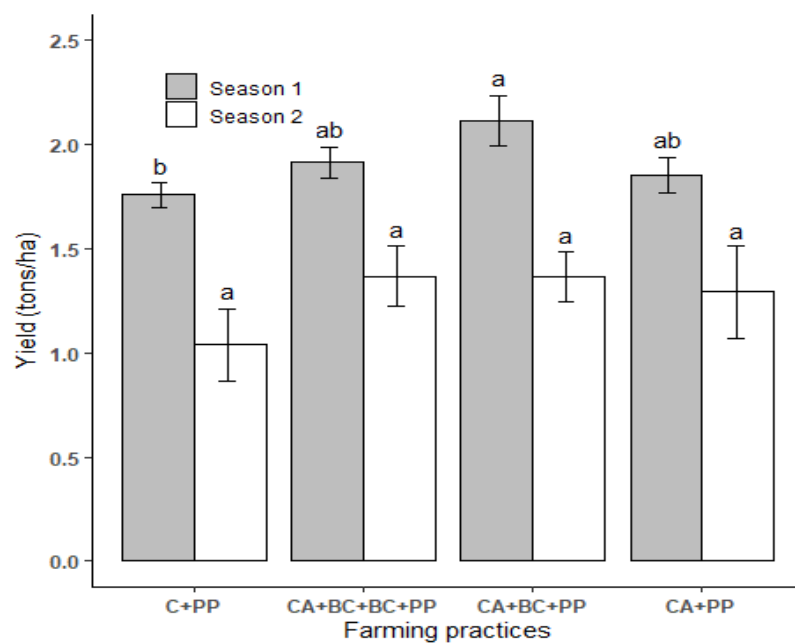


Figure 14: Effect of farming practices on grain yield of pigeon pea. CA, conservation agriculture; BC, biochar; P, pigeon pea; C, conventional. Error bars represents standard error means. Different letters indicate significant differences ($P < 0.05$). NB: pods were harvested, dried and threshed to determine the grain yields.

CHAPTER FIVE: DISCUSSIONS

5.1 Effect of conservation agriculture practices and biochar on SOC and readily oxidizable carbon

5.1.1 Soil organic carbon

Soil organic carbon is an important component of soil that indicates the level of fertility given its role in nutrient release and retention in soil amongst other benefits (Xinyu Ding, 2023). The farming practices tested in this study affected SOC although the effect was not consistent across the two seasons of the study. The CA with biochar single application of 4 t/ha increased SOC ($p < 0.05$) in the second season only. Such increase was not observed in the first season perhaps due field variability. This result is in agreement with Munera-Echeverri et al. (2020) who observed effectiveness of CA practices in increasing soil organic matter, mineralization of soil organic matter inside the planting basins than out of the basins. Additionally, Page et al. (2020) also registered increase in soil microorganism, CEC, high moisture and residue retention in CA practice, which had resulted into increased SOM in the soil. Likewise, biochar application rate and soil depth at rates of 0, 30, 60, 90 Mg ha⁻¹a increased SOC by 34%, 33% and 48% and dissolved organic carbon by 3.4%, 12.2% and 15.5%, respectively (Ding et al., 2023). Also, SOC increased by 31.75-83.62 and 29.90%-51.55% due to addition of biochar to coarse-textured soil (Yang et al., 2017). Therefore, increase in SOC due to increasing application rate of biochar can contribute to stability of SOC by reducing the labile organic carbon, creating oligotrophic members and activation of enzymes that is beneficial for storage of carbon as earlier reported by Qiu et al. (2023).

The SOC also varied with soil depth where total SOC decreased with increasing depth within the 20 cm depth sampled. The reason for the decrease may be associated with organic inputs and biological activity on new organic matter that occur at the surface. This result is in agreement with Ella et al. (2016) who observed increased soil organic carbon at depth of 0 - 5 cm in all the conservation practices and low organic carbon in the depth of 15-20 cm. Ding et al. (2023) reported more native SOC at 0-15 cm depth, thus biochar application rate led to increment of native SOC, which is recalcitrant resulting to SOC sequestration in the soil.

5.1.2 Readily oxidizable carbon

The farming practices significantly affected readily oxidizable carbon in both first and second season. Although CA with single application of 4 t/ha and split application of biochar

recorded higher ROC than the counter part. Readily oxidizable carbon is a sensitive indicator of early changes in soil quality and active organic matter, and it play vital role in nutrient cycling and soil structure. High ROC indicates high microbial activity and water retention which lead to improved soil fertility (Laird et al., 2010). CA plus biochar contributed to improved labile carbon in the soil (Major et al., 2010). Labile carbon was higher in conservation agriculture than conventional agriculture practice (Ellingsen, 2018). Additionally, increased readily oxidizable carbon of 29.90%-51.55% due to biochar application to coarse-textured soil has been reported by Yang et al. (2017). Therefore, biochar application to soil has proven to reduce on carbon mineralization thus contributing to stability of labile soil carbon (Borchard et al., 2019b). The biochar application rate of 30, 60 and 90 t/ha has increased readily oxidizable carbon by 34%, 33% and 48% (Ding et al., 2023).

Readily oxidizable carbon increased with soil depth. The highest and the lowest amount of ROC was observed at the depth of 0-5 cm in 15-20 cm in season 1 and depth of 5-10 cm and 15-20 cm in season 2, respectively. This was due to presence of organic materials within the surface soil layer of 0-5 cm and biochar addition within the depth of 5-10 cm. This result is in agreement with Ella et al. (2016) who observed increased soil organic carbon at depth of 0 - 5 cm and moderate fertility levels. Wei et al. (2021) also encountered increase in readily oxidizable carbon in the 0-10 cm depth in three tropical forest soil. Ding et al. (2023) found between 39 to 51% of the biochar to the top 30 cm after 11 yrs, and an increase in recalcitrant native SOC. The 0-15 cm depth more native SOC and readily oxidizable carbon, thus biochar application led to increment of recalcitrant native SOC with soil depth contributing to SOC sequestration in the soil.

5.2 Effect of conservation agriculture on CO₂ and CH₄ fluxes

Carbondioxide and methane are the major contributors to global warming, because they trap heat within the atmosphere from escaping to outer space (Thammasom et al., 2016). The farming practices did not affect CO₂ fluxes in both season 1 and season 2 when the field was planted with pigeon pea and maize, respectively. However, Franco-luesma et al. (2020) reported increased in daily CO₂ fluxes due to soil water fill pores after irrigation in the three maize planting seasons in tilled soil and regisetered cumulative seasonal average of 3.28 mg CO₂-C m⁻²h⁻¹ soil CO₂ emissions. From the same experiment, soil which was not tilled presented up to 42% lower CO₂ emissions compared to the tilled field. Li et al. (2013)

reported reduction in CO₂ emission from 19% to 33% from the field at early rice growth stage and 27% to 31% at late rice growth stage in no till field.

Generally, methane fluxes were reduced in the treatment with CA+BC and Conv+MM both in pigeon pea and maize season. This could be ascribed to CA and biochar's stability in the soil and recalcitrant structure which provide cementing and protective trait to organic carbon from mineralization, thus increase in total SOC contributing to reduced fluxes of CH₄. Biochar application to soil resulted into higher GHG mitigation by decreasing the emissions of CO₂ and CH₄ with CO₂ being reduced by upto 25% in first season and 41% in the second season (Yang et al., 2020). The unpuddled rice transplanting with higher residue retention were effective on green house gas mitigation during the rice production times, because excess organic carbon storage reduced CH₄ emissions compared to without residue retention (Alam et al., 2019). As such, both CH₄ and CO₂ emissions were disturbed by seeding effect. The result from another study indicated that the decreased root growth and aboveground biomass greatly contributed to GHG emissions that was majorly from CO₂ and CH₄ (Flores-macías et al., 2022), with result from reduced tillage having the highest emissions. However, in the conventional plus reduced tillage had also shown higher indirect emissions. Maize monocropping produced more emission than the practices under crop rotation. Therefore, reduced tillage under rotation with organic use is a bit expensive but it had the least emissions other than conventional. Conservation agriculture had little emission compared to conventional tillage meaning CA reduces the global warming potential (Dendooven et al., 2012). There are a lot studies that have reported greater GHG emissions under conservation agriculture compared to conventional tillage and others have found less or reduced emissions (Palm et al., 2013).

5.3 Effect of conservation agriculture and biochar on biomass and grain yield of pigeon pea

5.3.1 Below ground biomass, above ground biomass and biomass at harvest

Biomass plays a key role through providing soil covers, when decomposed improve soil organic carbon and activation of soil micro organisms that support plant growth while increasing yields (Zhang et al., 2012). The below ground biomass tested were not ($P > 0.05$) affected by the farming practices although there was a tendency of more below ground biomass under CA practices than conventional practice. This is because of biochar and CA

ability to improve both physical and chemical soil conditions like soil organic carbon, water holding capacity, moderate soil temperature and nutrient retention.

Above ground biomass were generally greater in CA practices with or without biochar though the differences were significant. Biomass yield increased by 28% after application of biochar (Jeffery et al., 2011).

Total biomass at harvest were affected ($P < 0.05$) significantly by farming practice. CA with or without biochar generally resulted to greater total biomass than conventional practice. CA and biochar contributes highly into biomass production through availing nutrients that support biomass growth. Musokwa & Mafongoya, (2021), reported highest dry biomass matter yield in sole pigeon pea, pigeon pea +maize compared to sole maize in growing year of 2016 and 2017 after addition of water use efficiency of pigeon pea intercropped with maize versus sole pigeon pea and maize.

5.3.2 Grain yields

High yields help combat hunger and poverty, support national import/export decisions and can minimize the environmental impact of farming by optimizing resource use (Thierfelder et al., 2014). The farming practices tested affected ($P < 0.05$) grain yield of pigeon pea in season 1 but not in season 2. CA with biochar single application 4 t/ha and split application 2 t/ha recorded higher grain yields of pigeon pea than conservation agriculture and conventional practice in both season 1 and 2. CA practices and biochar provide conducive environment for beneficial soil microorganisms that substantially contribute to recycling of nutrient and subsequent mineralization Munera-Echeverri et al. (2020). The improvement in soil organic carbon and readily oxidizable carbon (Fig. 3 and 5) contributes to soil fertility improvement and crop growth (Gurmu, 2019). The results in agreement with Obia et al. (2020) who reported an increase in rain water harvesting within the basins, adequate water retention of 59%-107% and 15%-65% in CA practices, thus increasing crop productivity. The result was also supported by finding from Namatsheve et al. (2024) who reported increased grain yield of pigeon pea. Additionally, Cornelissen et al. (2013) reported increased yield by 444% in CA practices. Page et al. (2020) also reported increase in soil microorganism, moisture retention and increased crop yield in CA practices. Borchard et al. (2019) also reported increased yield in maize accompanied with increased N and Ca in maize leaves after a 15 g/kg biochar addition into the soil. Hossain et al. (2010) reported the use of waste water sludge biochar of 10 t/ha increased cherry and tomato yield by 64% as it was applied to

chromosol soil because of its ability to availing nitrogen and phosphorous in the soil system. Martinsen et al. (2014) also recorded an increase in maize stover and grains at 232 to 60% and half at 128 to 6% of fertilizer application rates. It contributed to higher availability of K and P around the stover as it increases the CEC, pH and exchangeable K as well as improving water availability and reduces the Al in the soil (Alkharabsheh et al., 2021).

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The results from experiment showed that CA with biochar especially 4 t/ha single application significantly increased SOC upto 1.99%. Total SOC generally decreased with depth within the 20 cm depth profile that was studied. Readily oxidizable carbon, which is a measure of labile C followed similar pattern as total SOC. Therefore, CA practices with biochar inclusion can contribute to soil C sequestration despite lack of effect on CO₂ emission. The positive effect of co-implementation of CA and biochar application on C sequestration and in effect on climate change mitigation was further reinforced by reduced methane emissions by at least 20% in the current study. Similar positive effect of co-implementation of CA and biochar application was also observed in total biomass. For example, biomass in the second season increased above conventional practice by at least 40% compared to only 19% increase when CA is implemented without biochar. Likewise, grain yield increased above conventional practice by at least 9% in CA implemented together with biochar compared to an increase of 5% when CA is implemented alone. Therefore, CA with biochar amendment can be treated as a sustainable production system that if widely adopted can contribute improved yields, climate resilience and livelihoods.

6.2 Recommendations

6.2.1 Recommendation for farmer practice

Conservation agriculture practices with inclusion of biochar application is recommended for use where soil organic carbon is low for improving soil moisture and subsequent soil organic enrichment for increasing yields.

6.2.2 Recommendation for institutional / national development

There is need for inclusion of climate smart agriculture in the institutional training courses to increase adoption nationwide for sustainable development.

Climate smart agriculture practices should be included in national agriculture extension handbooks for wider dissemination and adoption across the farming communities.

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APPENDICES

Appendix 1: Effect of farming practices on total soil organic carbon.

(a) Total SOC content in the first pigeon pea growing season.

Treatments	Total SOC (%)
CA+BC+BC+PP	1.63 ±0.344 ^a
CA+BC+PP	1.63 ±0.313 ^a
CA+PP	1.59 ±0.412 ^a
C+PP	1.55 ±0.439 ^a

Same letters indicate no significance at $P > 0.05$.

(b) Total SOC content in the second pigeon pea growing season.

Treatments	Total SOC (%)
CA+BC+PP	1.99±0.944 ^a
CA+BC+BC+PP	1.75 ±0.345 ^{ab}
C+PP	1.53±0.221 ^b
CA+PP	1.52 ±0.052 ^b

Different letters indicate significance difference at $P < 0.05$, and same letters indicate no significance $P > 0.05$.

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	1.533	0.5108	2.119	0.101
Residuals	124	29.887	0.2410		

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	0.064	0.02121	0.147	0.931
Residuals	60	8.676	0.14459		

Appendix 2: Effect of farming practices on soil readily oxidizable carbon

(a) ROC in the first planting season of pigeon pea.

Treatments	ROC (%)
CA+BC+BC+PP	0.07 ± 0.015 ^a
CA+PP	0.06 ± 0.020 ^{ab}
C+PP	0.06 ± 0.022 ^{ab}
CA+BC+PP	0.05 ± 0.019 ^b

Different letters indicate significance difference at $P < 0.05$, and same letters indicate no significance $P > 0.05$.

(a i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	0.00383	0.0012780	1.986	0.12
Residuals	124	0.07979	0.0006435		

(b) ROC in the second planting season of pigeon pea.

Treatments	ROC (%)
CA+BC+PP	0.06 ± 0.031 ^a
CA+BC+BC+PP	0.05 ± 0.032 ^{ab}
CA+PP	0.05 ± 0.029 ^{ab}
C+PP	0.03 ± 0.021 ^b

Different letters indicate significance difference at $P < 0.05$, and same letters indicate no significance $P > 0.05$

(b ii)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	0.00521	0.001735	1.299	0.283
Residuals	60	0.08014	0.001336		

Appendix 3: Effect of farming practices and depth on total SOC and Readily Oxidizable Carbon.

(a) ROC and Total SOC by depth in the first growing season of pigeon pea.

Depth	ROC (%)	Total SOC (%)
5CM	0.068 ± 0.021 ^a	1.868 ± 0.377 ^a
10CM	0.059 ± 0.021 ^{ab}	1.644 ± 0.320 ^{ab}
15CM	0.053 ± 0.016 ^b	1.503 ± 0.335 ^b
20CM	0.052 ± 0.019 ^b	1.402 ± 0.308 ^b

Different letters indicate significance difference at $P < 0.05$, and same letters indicate no significance $P > 0.05$.

(a i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	0.002518	0.0008393	2.255	0.0909
Residuals	61	0.22701	0.0003721		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(a ii)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	1.952	0.6506	5.546	0.00199
Residuals	60	7.038	0.1173		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(b) ROC and Total SOC by depth in the second growing season.

Depth	ROC (%)	Total SOC (%)
0-5CM	0.053 ± 0.037 ^{ab}	1.625 ± 1.077 ^a
5-10CM	0.064 ± 0.026 ^a	1.913 ± 0.253 ^a
10-15CM	0.045 ± 0.026 ^{ab}	1.725 ± 0.262 ^a
15-20CM	0.035 ± 0.020 ^b	1.531 ± 0.314 ^a

Different letters indicate significance difference at $P < 0.05$, and same letters indicate no significance $P > 0.05$.

(b i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	0.01015	0.003383	2.698	0.0537
Residuals	60	0.07520	0.001253		
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					

(b ii)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	0.00254	0.0008485	2.293	0.0871
Residuals	60	0.022202	0.0003700		
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					

Appendix 4: Effect of conservation agriculture practices on CO₂ fluxes

(a) Carbondioxide fluxes during pigeon pea growing season.

Treatments	CO ₂ (mg CO ₂ -C m ⁻² h ⁻¹)
CA	308±123 ^a
CA+BC	280±118 ^a
Conv+MM	264±148 ^a
Conv+PP	260±96 ^a

Same letters indicate no significance at P > 0.05.

(a i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	68992	22997	1.523	0.21
Residuals	188	2838055	15096		

(b) Carbondioxide fluxes during maize growing season.

Treatments	CO ₂ (mg CO ₂ -C m ⁻² h ⁻¹)
CA	223±118 ^a
CA+BC	212±101 ^a
Conv+MM	196±109 ^a
Conv+PP	179±96 ^a

Same letters indicate no significance at P > 0.05.

(b i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	22138	7378	0.654	0.583
Residuals	76	76.857202	11279		

Appendix 5: Effect of conservation agriculture practices on CH₄ fluxes

(a) Methane fluxes during pigeon pea season.

Treatments	CH ₄ (µg CH ₄ -C m ⁻² h ⁻¹)
CA	80.09±159.78 ^a
Conv+PP	46.68±65.19 ^{ab}
Conv+MM	35.42±82.08 ^b
CA+BC	28.32±46.68 ^b

Different letters indicate significance difference at $P < 0.05$, and same letters indicate no significance $P > 0.05$.

(a i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	76564	25521	2.185	0.0913
Residuals	188	2196062	11681		

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(b) Methane fluxes during maize season.

Treatments	CH ₄ (µg CH ₄ -C m ⁻² h ⁻¹)
CA	10.52±35.465 ^a
CA+BC	10.74±28.952 ^a
Conv+MM	17.76±72.544 ^a
Conv+PP	25.87±37.009 ^a

Same letters indicate no significance at $P > 0.05$.

(b i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	2912	970.6	0.454	0.715
Residuals	71	151847	2138.7		

Appendix 6: Effect of farming practices on below ground and above ground biomass at peak flowering stage of pigeon pea

(a) Below ground biomass in the first and second season of pigeon pea growing.

Treatments	BGB (tons/ha)	BGB (tons/ha)
CA+PP	0.82 ±0.50 ^a	0.51 ±0.08 ^a
CA+BC+PP	0.67 ±0.21 ^a	0.48±0.22 ^a
CA+BC+BC+PP	0.56 ±0.10 ^a	0.55 ±0.17 ^a
C+PP	0.56 ±0.12 ^a	0.38 ±0.67 ^a

Same letters indicate no significance at $P > 0.05$.

(a i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	0.1768	0.05894	0.723	0.557
Residuals	12	0.9780	0.08150		

(a ii)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	0.04858	0.01619	0.826	0.504
Residuals	12	0.23516	0.01960		

(b) Above ground biomass in the first and season of pigeon pea growing.

Treatments	AGB (tons/ha)	AGB (tons/ha)
CA+PP	3.98±2.11 ^a	2.82±0.97 ^a
CA+BC+PP	3.68±1.61 ^a	3.14±0.89 ^a
CA+BC+BC+PP	3.09±0.68 ^a	3.49±1.04 ^a
C+PP	2.93±0.71 ^a	2.41±0.27 ^a

Same letters indicate no significance $P > 0.05$.

(b i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	2.939	0.9795	0.49	0.696
Residuals	12	23.986	1.9989		

(b ii)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	1.291	0.6572	1.165	0.364
Residuals	12	6.770	0.5642		

Appendix 7: Effect of farming practices on biomass at harvest.

(a) Biomass at harvest in the first season of pigeon pea growing.

Treatments	Biomass (tons/ha)
CA+BC+PP	13.69 ±3.89 ^a
CA+BC+BC+PP	12.26 ±3.24 ^{ab}
CA+PP	10.45 ±1.69 ^{ab}
C+PP	8.75 ±1.94 ^b

Different letters indicate significance difference at $P < 0.05$, and same letters indicate no significance $P > 0.05$.

(a i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	55.42	18.472	2.287	0.131
Residuals	12	96.94	8.079		

(b) Biomass at Harvest in the second season of pigeon pea growing.

Treatments	Biomass (tons//ha)
CA+BC+BC+PP	5.01 ±0.19 ^a
CA+PP	4.71 ±0.20 ^a
CA+BC+PP	4.26 ±0.96 ^{ab}
C+PP	3.76 ±0.25 ^b

Different letters indicate significance difference at $P < 0.05$, and same letters indicate no significance $P > 0.05$.

(b i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	3.538	1.1792	4.524	0.0242
Residuals	12	3.128	0.2607		

Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

Appendix 8: Effect of farming practices on grain yields of pigeon pea

(a) Grain yield in the first growing season of pigeon pea.

Treatments	Yield (tons/ha)
CA+BC+PP	2.11 ± 0.23 ^a
CA+BC+BC+PP	1.91 ± 0.15 ^{ab}
CA+PP	1.85 ± 0.17 ^{ab}
C+PP	1.76 ± 0.127 ^b

Different letters indicate significance difference at $P < 0.05$, and same letters indicate no significance $P > 0.05$.

(a i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	0.2702	0.09003	2.965	0.0748
Residuals	12	0.3643	0.03036		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(b) Grain yield in the second growing season of pigeon pea.

Treatments	Yield (tons/ha)
CA+BC+BC+PP	1.37 ± 0.29 ^a
CA+BC+PP	1.36 ± 0.24 ^a
CA+PP	1.29 ± 0.45 ^a
C+PP	1.04 ± 0.35 ^a

Same letters indicate no significance $P > 0.05$.

(b i)

	DF	SS	MS	F.Value	Pr (>F)
Treatment	3	0.291	0.097	0.843	0.496
Residuals	12	1.380	0.115		

Appendix 9: Analysis of soil organic carbon



Appendix 10: Readily oxidizable carbon analysis using Bio spectrometer



Appendix 11: Closed chamber gas collection at research site in Unyama



Appendix 12: Weighing of below and above ground biomass.



Appendix 13: GUREC Approval

GULU UNIVERSITY

P.O. Box 168, Gulu (U) Website: www.guluc.ac.ug Email: gurec@guluc.ac.ug
Tel: +256 471 432 096 Fax: +256 471 432 913 Mob: +256 772 964 491 +256 776 812 147
RESEARCH ETHICS COMMITTEE

28/04/2025

To: CINDERELLA ABER

0

Type: Initial Review

Re: GURICU-2025-1178: EFFECT OF CLIMATE SMART AGRICULTURAL PRACTICES ON SOIL ORGANIC CARBON AND YIELD OF PIGEON PEA IN NORTHERN UGANDA

I am pleased to inform you that at the 123rd convened meeting on 20/02/2025, the Gulu University REC meeting voted to approve the above referenced application.

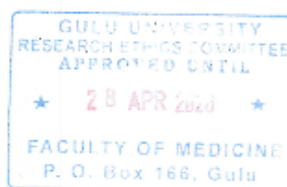
Approval of the research is for the period of 28/04/2025 to 28/04/2026.

As Principal Investigator of the research, you are responsible for fulfilling the following requirements of approval:

1. All co-investigators must be kept informed of the status of the research.
2. Changes, amendments, and addenda to the protocol or the consent form must be submitted to the REC for re-review and approval **prior** to the activation of the changes.
3. Reports of unanticipated problems involving risks to participants or any new information which could change the risk/benefit ratio must be submitted to the REC.
4. Only approved consent forms are to be used in the enrollment of participants. All consent forms signed by participants and/or witnesses should be retained on file. The REC may conduct audits of all study records, and consent documentation may be part of such audits.
5. Continuing review application must be submitted to the REC **eight weeks** prior to the expiration date of 28/04/2026 in order to continue the study beyond the approved period. Failure to submit a continuing review application in a timely fashion may result in suspension or termination of the study.
6. The REC application number assigned to the research should be cited in any correspondence with the REC for proof of record.
7. You are required to register the research protocol with the Uganda National Council for Science and Arts Technology (UNCST) for final clearance to undertake the study in Uganda.

The following is the list of all documents approved in this application by Gulu University REC.

1. Protocol	2. Consent Form	3. Certificate of Approval
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No.	Document Title	Language	Version Number	Version Date
1	Application for waiver of informed consent	English	Version 2	2025-04-23
2	Protocol	English	Version 2	2025-04-23
3	Community Engagement Plan	English	Version 2	2025-04-23
4	Data collection tools	English	Version 2	2025-04-22
5	COVID-19 & EBOLA risk management plan	English	version 2	2025-02-06

Yours Sincerely

Julaina A. Obika

Julaina A. Obika (PhD)
For: Gulu University REC

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5	COVID-19 & EBOLA risk management plan	English	version 2	2025-02-06



Appendix 14: Plagiarism Check Report

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