COW DUNG AND RICE HUSK BIOCHAR TYPES AS PHOSPHORUS SOURCES FOR COWPEA (*VIGNA UNGUICULATA L.*) PRODUCTION IN A CALCIUSTERT.

BY

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DECLARATION

I hereby declare that the thesis herein presented for the award of Master of Philosophy in Soil Science is a result of my investigation. All references to other authors' work as sources of information have been duly acknowledged.

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DEDICATION

This thesis is dedicated to the memory of my late father, Anthony Kofi Siakwah. You will forever be remembered in our prayers and may God have an everlasting mercy on you.

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ABSTRACT

Production of cowpea (*Vigna unguiculata L.*) in Ghana has relied heavily on inorganic sources of phosphorus. However, with dwindling sources of the apatite rock worldwide, the high cost and associated contamination of inorganic P fertilized soils, it has become necessary to explore more sustainable sources of P for cowpea production. Traditionally, most P fertilizer trials have been concentrated on soils with low activity clays with little work done with heavy soils. A study was therefore carried out to explore the potential of using cow dung and rice husk biochar types, as a sustainable P amendment for improved cowpea growth and yield in a Calciustert. The study evaluated the effects of cow dung biochar (CDB) and rice husk biochar (RHB) in comparison with triple superphosphate (TSP) on cowpea growth parameters and yield in Akuse Series. Twenty-four ridges were formed on the Akuse Series after determination of the soil's standard phosphorus requirement (SPR). The CDB and RHB prepared on site at the Soil and Irrigation Research Centre (SIREC) of the University of Ghana, Kpong was then applied to 16 of the ridges; four each at the full SPR of the soil and another four each at half the SPR. There were four ridges with no amendment and another four ridges with TSP application at the SPR of the soil. All the treatments were in a randomized complete block design. The cowpea variety California Black Eye was sown on the 24 ridges at a spacing of 60 cm x 40 cm. Two weeks after sowing, the TSP at the full SPR treatment was imposed. Cultural practices were undertaken and data including average plant height to maturity, days to 50% flowering, number and weight of nodules, number of pods per plant, 100 seed weight and yield per hectare, biomass per plant at harvest, root length and mass, root and shoot P and N uptake, were taken. The experiment was repeated for another season to validate the results of the first. Cowpea plants grown in soil amended with CDB at the

full SPR had the highest yield of 2.75 and 2.14 tons/ha for the two seasons compared to 2.1 and 1.86 tons/ha for the TSP fertilized crops. All the crop parameters determined were generally higher in the CDB amended ridges at the SPR of the soil than from the other treatments. Crop parameters including yield of cowpea in the other amended ridges did not significantly differ from those in the un-amended ridges. The study concludes that biochar produced from cow dung has the potential of improving growth and yield of cowpea grown on ridges in a Calciustert at SIREC when applied at the SPR of the soil. It also concludes that the soils at SIREC should not be fertilized with TSP for cowpea production as there will be no response. Further research is recommended to determine the profitability or otherwise of using CDB applied at the SPR of the soil in growing cowpea for increased yield on the Calciustert at SIREC.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Cowpea, a warm-season legume (*Vigna unguiculata* L.), thrives well in Ghana. This versatile pulse is not just a crop; it is a main protein source in Ghanaian diet, especially in the north where its leaves are also consumed. Cowpea production stretches across the country, flourishing in the central and northern regions of Ghana. Ghana is ranked the fifth-highest producer of cowpea in Africa, with an average annual production of 143,000 MT on 156,000 hectares (Haruna et al., 2018). In Africa, Ghana boasts the crop's fastest-growing production. According to estimates made by Ghana's Ministry of Food and Agriculture (MoFA) (2010), cowpea production rose at 11.1% between 2010 and 2020. By fixing atmospheric nitrogen, cowpea can improve soil fertility (Chatterjee and Bandyopadhyay, 2017).

According to the Statistics, Research and Information unit (SRID) of MOFA (2021), cowpea grain production increased from 237,000 MT in 2018 to 257,000 MT in 2020. To meet the national demand, Ghana imports almost 10,000 MT of cowpea from Burkina Faso, Mali, and Niger. In 2020, Ghana's cowpea cultivation increased from 156,000 hectares to 169,000 hectares, showcasing the crop's importance to the nation's food security.

The crop is frequently grown because it can withstand challenging environmental conditions. Cowpea is currently regarded as a food security crop because of its tolerance to drought conditions and adaptation to low rainfall in arid and semi-arid regions (Carvalho et al., 2019).

Cowpea cultivation is mostly concentrated in the Guinea Savannah and Forest Transition Zones, notably in the Northern region and some parts of Brong Ahafo Region of Ghana (Quaye et al., 2009). Cowpea cultivation is not very common in the southern part of Ghana, and particularly the Coastal Savanna Zone. A study at the Soil and Irrigation Research Center (SIREC), in the Coastal Savvana Zone showed an average cowpea yield of 0.33 ton/ha (330 kg/ha), under rainfed conditions and 0.40 ton/ha (400 kg/ha) with supplementary irrigation. Maximum yields on tilled plots under irrigation reached 0.66 ton/ha (660 kg/ha) (Yangyuoru et al., 2003).

The soils in the Coastal Savanna Zone are dominated by those with vertic properties and Vertisols. The Vertisols in Ghana cover a total area of about 1,820 km^2 (Asiedu et al., 2001) with 90% (1,630 km^2) located within the Coastal Savanna zone of Ghana. The Vertisols swell on wetting (40%-50% swelling) and stick to farm implements during farm operations. They have poor soil structure, low hydraulic conductivity, develop deep cracks when dry, and become sticky when wet (Brierley et al., 2011). The Vertisols, however, have high montmorillonitic clay content which make them very fertile as they have the ability of storing large amount of cationic nutrients such as the basic cations Ca^{2+}, Mg^{2+}, K^+ and NH_4^+. The Vertisols' extreme swelling and shrinking properties have made them very difficult for use in cultivating upland crops including cowpea. The key challenge in cultivating Vertisols for large-scale upland crop production is mitigating their severe shrink-swell behaviour. Researchers have emphasized that addressing this physical constraint is essential for sustainable agriculture on Vertisols (Zong et al., 2014).

For the effective growth of cowpea, phosphorus (P), a key nutrient, is required in significant amounts. According to Schulze et al. (2006) and Maholtra et al. (2018), P is key in controlling enzymatic activity and energy conversion. According to Zhang et al. (2014), P is needed for metabolic processes such as respiration, photosynthesis, glucose metabolism, the production of nucleic acids, enzyme activation, and signalling. In P-deficient soils, crop development is, therefore, hindered (Zhang et al., 2014). The distribution of carbon among above- and below-ground plant components, as well as its absorption, can be severely impacted by an inadequate P supply (Zhang et al., 2014).

Numerous studies have shown that P is one of the nutrients that are most essential for producing legumes in various tropical soils. Many authors have documented increases in legume yield using phosphorus fertilizers (Uzoma and Osunde, 2006; Yakubu et al., 2010). Studies have shown how P functions in legumes, promoting root development, and root nodulation, and boosting grain production (Uchida, 2000; Tang et al., 2001; Maholtra et al., 2018; Nartey et al., 2023). The energy-intensive nature of symbiotic nitrogen fixation implies the use of significant amounts of phosphorus for energy-generating P (Schulze et al., 2006). Phosphorus fertilization can help increase legume yields in sub-Saharan Africa (Nkaa et al., 2014). However, due to their high surface and reactive aluminum and sesquioxide contents, which result in a high affinity for applied phosphorus and a low agronomic phosphorus use efficiency, many tropical soils are P-deficient (IUSS Working Group, 2006). Vertisols in the coastal savanna zone of Ghana have been reported to have total P ranging from 150-298 mg kg^{-1} but available P content from 0.1-3.5 mg kg^{-1} (Acquaye et al., 1989). Similarly, studies in India have shown available phosphorus content in Vertisols ranging from 11.09 to 16.24 kg ha^{-1} (Jayshive Patidar et al., 2019) or even 16.9 kg ha^{-1} (Tirunima Patle et al., 2019).

Under these circumstances, combining the application of phosphorus with biochar may be an effective corrective approach to improve crop nutrient uptake and agronomic use efficiency (Nartey et al., 2023). According to studies by Herath et al. (2013) and Mia et al. (2014), biochar has the potential to enhance crop performance by boosting soil biological processes and edaphic qualities.

1.2 Problem statements

Cowpea is a leguminous plant that fixes nitrogen in the soil. However, low soil phosphorus concentrations can interfere with the nitrogen fixation of cowpea thereby reducing productivity (Adusei et al., 2017; Nartey et al., 2023). Phosphorus is the least abundant phytonutrient for cowpea production in most tropical soils, especially forest transition and savanna regions of Ghana (Nartey et al., 2023).

Vertisols are soils characterized by high contents of 2:1 expanding clays. Although they are rich in nutrients, they are very difficult to manipulate, due to their poor physical features including their shrink-swell nature. They swell on wetting (40%-50% swelling) and stick to farm implements during farm operations. They also develop deep cracks when dry (Brierley et al., 2011).

The low availability of natural soil phosphorus required for plant growth is a limiting factor in achieving plant productivity gains (Lynch and Brown, 2008; Kahn and Jorgensen, 2009; Malik et al., 2012; Johnston et al., 2014). The Vertisols in the Accra plains have been reported to have low available P contents of 5.43 mg/kg (MacCarthy et al., 2020). These levels may not sustain the demand for high yield of cowpea. Natural P is unavailable due to precipitation and sorption activities that occur on soil colloidal surfaces (Alam and Ladha, 2004; Brady et al., 2008; Kahn and Jorgensen, 2009). For the very low efficiency of applied P (Syers et al., 2008), sufficient P fertilizers are required to increase P concentration in soil solutions for plant absorption and effectiveness (Zhang et al., 2010; Shen et al., 2011; Bai et al., 2013, Sulemana et al., 2021). Application of inorganic P fertilizers has become the main source of phosphorus for cowpea production. However, inorganic P fertilizers are not readily available in Ghana. They are also relatively expensive in Ghana. This has contributed to the low yield of cowpea in Ghana as smallholder farmers hardly fertilize their cowpea crops. The main P sources for crop production in Ghana are the SSP, TSP and the compound fertilizer NPK. These P sources are manufactured from the phosphate rock. The apatite from which these fertilizers are produced is a non-renewable natural resource which is declining rapidly. Reliance mainly on inorganic P sources is not a healthy strategy for sustainable farming (Cordell et al., 2009).

Scientists have worked on reliable alternatives like the use of plant and animal remains. The relatively lower concentration of P in these remains means large quantities ought to be applied for such P needed by crops which is a disincentive to farmers in sub-Saharan Africa.

Rice husk and cow dung as amendments play vital roles in soils. Their role in soil fertility remains short-lived due to fast mineralization and leaching of the nutrient (Shakya and Agarwal, 2017) especially in the Vertisols with high CEC under tropical environments. Conversion of rice husk and cow dung into a more stable amendment such as biochar will impart recalcitrance and lower mineralization rate and thus make P more available (Subedi et al., 2016; Nartey et al. 2023) for use as P sources. This is due to the soluble P in the carbonized feedstocks being up to 2.5 times greater than in the uncharred feedstock (Chan et al., 2008; Steiner et al., 2010; Nartey et al., 2023). Biochar is a fluffy bulking agent which will improve the overall physiochemical properties of Vertisols (Adiku et al., 2015).

The Vertisols in the Accra plains used for arable crop production are Calciustert. They abound in calcium carbonates nodules which may fix phosphorus when the nutrient is applied to the soil. However, very little data exists in literature on the standard phosphorus requirement (SPR) of the soil which will help in determining the P application rate to enhance crop yields. Most of the works done on biochar amendment to the Vertisols have focused on the plant-based with little data on animal-based biochar used as a phosphorus source for cowpea growth and development. The biochar type and the application rate that will improve P availability and hence yield of cowpea in the Calciustert is yet to be ascertained in Ghana.

1.3 Justification

The Vertisols cover about 1830 km^2 total area in Ghana (Asiedu et al., 2021; Nyasapoh et al., 2022) and have been used mainly for the cultivation of lowland crops such as rice and sugar cane. Bringing vertisols to upland crop production requires appropriate landforms (Yangyuoru et al., 2012). Cowpea production on these Vertisols has not gained much attention since there is scanty information as to the agronomy of the crop on Vertisols. The high cost of inorganic P fertilizers for cowpea production has called for cheaper alternatives of locally available organic resources as a source of phosphorus for cowpea production. Rice husk and cow dung biochar are rich P sources (Sulemana et al., 2021; Nartey et al., 2023). Rice husk and cow dung are readily available organic feedstocks in the Accra plains where the vertisols exist. Biochar produced from these feedstocks, is however, hardly used as P sources for cowpea production on the Vertisols in Ghana.

Biochar as a soil amendment has been used for enhanced P availability on upland crops like maize and cowpea in Alfisols and Ultisols in Ghana (Sulemana et al., 2021, Nartey et al., 2023). The amendments integrated effect with inorganic fertilizers on irrigated rice has also been investigated on Vertisols (MacCarty et al., 2020). However, the effect of biochar as a P source on the growth and development of cowpea in Vertisols has received very little attention.

The Vertisols in the Accra plains contain calcium carbonates which are likely to precipitate any added phosphorus thus decreasing P availability. For cowpea production on these soils therefore, it is thus imperative for the SPR of the soils to be ascertained. Knowledge of the SPR of the soils will help to ascertain the phosphorus application rates for enhanced P availability and cowpea production.

This knowledge gap in P application rates for enhanced cowpea production on vertisols must be bridged.

1.4 Research hypothesis

It is hypothesized that:

H_O: The right amounts of cow dung and rice husk biochar will not improve phosphorus availability, cowpea growth, and yield on Calciustert.

H_A: The right amounts of cow dung and rice husk biochar will improve phosphorus availability, cowpea growth, and yield on Calciustert.

1.5 Objective

The main objective is to determine the effect of rice husk and cow dung biochar as a source of phosphorus for cowpea nodulation, growth, and performance in a Calciustert.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Vertisols in Ghana

Vertisols form a group of clayey soils high in fertility but very poor in physical conditions. In Ghana, the Vertisols cover a total land area of 1,830 km^2, of which 1,630 km^2 (90%) is in the Coastal Savannah (Asiedu et al., 2001). Vertisols have high cation exchange capacity (CEC) often greater than 29.00 $cmol_c kg^{-1}$ (Coulombe et al., 1996; Asiedu et al., 2001; McCarthy et al., 2020). This is because they are inherently dominated by 2:1 clay minerals, mainly smectites. The pH of Vertisols ranges from 6.2 to 7.9 which is ideal for most crop growth. Despite the high fertility status of Vertisols, they have physical limitation attributed to their clay mineralogy. Vertisols have between 40-50% swelling clay content. Consequently, they are very sticky and clogs agricultural equipment during physical manipulation (Coulombe et al., 1996; Yangyuoru et al., 2012). Large soil pores formed during swelling close to prevent further intrusion promoting flooding conditions. However, in dry conditions, Vertisol shrinks, hardens, and develops deep cracks (Brierley et al., 2011; Zong et al., 2014). In general, the peculiar wet and dry condition hinder their cultivation (Thakur et al., 2016), especially in upland crop production. In Ghana, agricultural uses of Vertisol are mostly limited to large-scale irrigated rice cultivation during the rainy season and for dry season livestock grazing (Ahmad and Mermut, 1996; Asiedu et al., 2001). The major task of bringing Vertisols to optimum production is to reduce the shrink-swell properties (Nyasapoh et al., 2022).

2.2 Soil Phosphorus

Total phosphorus content varies in soils. The concentration of the nutrient is higher in young pristine soils, usually with low rainfall patterns, and lower in uncultivated acidic soils in moist areas of Ghana (Owusu-Bennoah et al., 1989). Phosphorus in soil can generally be grouped into organic and inorganic fractions. Organophosphorus components are found in organic matter. Owing to the accumulation of organic matter in the top soil, mineral top soils typically have higher surface organophosphorus concentrations than subsoils. Organophosphates normally occur in soil in three major forms: phospholipids, nucleic acids, and inositol phosphates (Tisdale et al., 1999). Soils contain a significant proportion of organophosphorus, which over time mineralizes into orthophosphate ions, $H_2PO_4^-$ and HPO_4^{2-} to soil solution (Leal et al., 2014). Inorganic phosphorus originates from the mineral apatite $Ca_5(PO_4)_3$ F, commonly known as fluoro apatite (Tisdale et al., 1999). Inorganic phosphorus distribution in soil profiles varies and depends on several factors such as pH, concentrations of Al, Fe, Ca, and Mg, soil clay content and surface area and CEC. The maximum availability of phosphorus for most crops is in the pH range of between 6.5 to and 7.2 (Tisdale et al., 1999).

2.2.1 Phosphorus role as a plant nutrient

After nitrogen, phosphorus is regarded as the second most important macro nutrient, accounting for approximately 0.2% of the dry weight of plants (Sharma et al., 2013). It has been noted to further boost cowpea development and is a crucial part of compounds including ATP, phospholipids, and nucleic acids (Souleymane, 2019).

Phosphorus is crucial in the early stage of crop plants as it enhances shoot and root tips development (Grant et al., 2005). Phosphorus supports root and flower initiation, fruit development, and seed formation of crop plants (Souleymane, 2019).

2.2.2 Phosphorus transport in soil

Phosphorus movement and form in soil is a highly dynamic process controlled by a set of biological and abiotic factors (Sulemana et al., 2021). Immobilization and mineralization processes control the transition between organic and inorganic forms of phosphorus in soils. Precipitation-dissolution and adsorption-desorption are mechanisms that control the exchange of phosphorus between the solid phase and the soil solution (Frossard et al., 2000; Gérard, 2016). According to Eriksson et al. (2015) and Gerard (2016), the type and concentration of Al and Fe oxides, the quantity and type of silicate clays, the amount of $CaCO_3$, concentration of competing anions, the ionic strength and pH control availability of phosphorus in soil.

According to Schumanns and Chardon (2015), the adsorption of Fe and Al in solution and ligand exchange reactions by sesquioxides control the movement of phosphorus in acidic soils. In alkaline and calcareous soils, the formation of calcium-phosphorus and magnesium-phosphorus compounds and adsorption and precipitation of phosphorus by $CaCO_3$ predominates (Eriksson et al., 2015). Therefore, the high level of phosphorus fixation in these soils severely limits the amount of phosphorus available to plants.

2.2.3 Cowpea response to phosphorus

Nitrogen and phosphorus are particularly deficient in tropical soils (Haruna et al., 2011). Phosphorus promotes growth, initiates nodulation, and affects the effectiveness of the symbiotic relationship between rhizobia and legumes (Haruna and Aliyu, 2011). Phosphorus is essential for the growth of immature cells, such as sprouts and root tips, where there is active metabolism and cell division is rapid. It also promotes the growth of flowers, seeds, and fruits (Ndakemi and Dakora, 2007). However, phosphorus deficiency is common in tropical soils and can be so severe in some soils of the West African Savannah that it can halt plant growth (Osodeke, 2005; Mokwunye and Bationo, 2002). Soil phosphorus deficiency is mainly caused by either the inherently low phosphorus content of the soil or phosphorus depletion due to cultivation.

2.3 Biochar

Biochar is a carbon-rich by-product of biomass pyrolysis. It is is a carbonaceous material formed by the thermochemical breakdown of organic material at temperatures between 300°C and 700°C (Schmidt et al., 2015). Biochar contains nitrogen and sulfur in addition to the primary components of carbon, hydrogen, and oxygen (Laird et al., 2010). It is primarily used to improve availability of soil nutrients such as P (Sulemana et al., 2021; Nartey et al., 2023) and sequester carbon from the soil environment (Lehmann 2009). The porous nature of biochar makes it a better alternative as a soil amendment. It also improves the soil's water-holding capacity (Srinivasarao et al., 2013).

The two meters depth of soil throughout the Amazon basin are the regions of *terra preta* (Nerves et al., 2004). The soil in this region is dark in colour due to the presence of **Terra Preta**, also known as "Amazonian Dark Earths" (ADE) or "Indian Black Earth". These are microscopic charcoal particles responsible for the soil's fertility and has been supporting the agricultural needs of the region for centuries. Biomass products, including plants and animals, can be pyrolyzed to produce biochar. The type of material and the thermochemical processes, rate of heating, duration of storage, and temperature affect the physicochemical characteristics of biochar (Spokas et al., 2012). As the pyrolysis temperature increases beyond 300 °C to 700 °C, there is a simultaneous rise in the carbon content and a decrease in the amounts of N, O, and H. Most studies have shown that biochar addition has significantly improved soil fertility and resulted in higher crop yields (Lehmann, 2006, Spokas et al., 2012). According to scientific research, the amendment of soil using biochar makes nutrients more available in soil solution (Sohi et al., 2010). Biochar is employed in energy production, waste-water treatment, and climate change mitigation in addition to enhancing soil fertility and productivity (Hassan et al., 2012).

2.3.1 Feedstocks for biochar production in Ghana

The volume of agricultural residues generated worldwide annually is estimated to be 500 million metric tons Duku et al. (2011). Yeboah et al. (2017) estimated production of 177,424,904 Mt of agricultural waste in Ghana that could be harnessed to supplement the generation and supply of electricity. Biomass generated in Ghana has been categorized into crop leftovers, forest residues, and animal remains (Duku et al., 2011). The underlying principle for use of organic waste in biochar production is to minimize deforestation. Consequently, use of tree species is discouraged to minimize logging. Only tree wastes such as saw dust are used. Organic waste used for biochar production in Ghana should also have limited competing use to increase availability and drive cost down. Charring of waste has also been used as a tool to manage organic waste in Ghana (Nartey et al., 2023).

Most of the plant waste types used for biochar production in Ghana have included cocoa pod husk, rice husk, maize cob groundnut husk and saws dust (Sam et al., 2017, Frimpong-Manso et al., 2019; Sulemana et al., 2021). The animal wastes have included poultry manure and cow dung (Nartey et al., 2023). Due to their abundance and low cost, these residues continue to be used as feedstock for biochar production. Converting these residues to biochar makes agricultural and forestry waste easier to manage and reduces the cost of waste disposal. Depending on the kind of biomass, there may be variations in their cellulose, hemicellulose, lignin and carbon contents which will ultimately determine the quality of biochar produced in relation to their recalcitrance.

2.3.2 Techniques for biochar production

According to Kapoor et al. (2020), pyrolysis is a thermochemical process that uses oxygen-restricted conditions to transform biomass into more carbonaceous material like biochar. Lipids, starches, and lignin are examples of long-chain polymers that break down during pyrolysis to generate gases including CO_2, CO, CH_4, and H_2.

Some molecules assemble to create condensable gases, liquid fuel, and aromatic compounds that polymerize or aromatize to produce char. Biochar's absence of cellular structure and presence of aromatic framework makes it resistant to decay. The soils' porous structure keeps biochar stable and recalcitrant for more than 100 years upon amendment (Lehmann et al., 2006; Zimmerman and Gao, 2011; Purakayastha et al., 2019).

There are three fundamental types of pyrolysis technologies. These according to Kan et al. (2016) are slow pyrolysis, flash pyrolysis, and fast pyrolysis. Slow pyrolysis steadily raises the biomass temperature to above 350 °C in a batch reactor or continuous system. It is the most often used pyrolysis system due to its simplicity. About 35% charcoal, 30% bio-oil, and 35% gas are produced by this process. For slow pyrolysis, less controlled kilns are utilized, and the gas and bio-oil are not separated. El-Naggar et al. (2019) claim that as a result, the biochar yield in slow pyrolysis can range from 25 to 60%. In flash pyrolysis, charring of biomass is carried out in batches under moderate to high pressure. It is designed specifically to increase the output of bio-oil to yields of 55% oil, 40% gas, and 5% charcoal. The technique can produce a mixture of 5–15% biochar and traces of bio-oil (tar) if it is improved. In a short amount of time, a rapid pyrolysis process boosts the temperature to 700 °C, producing more gases while giving less carbon. The products consist of 10–30% biochar, 15-20% gas, and 50–70% bio-oil. According to Nartey et al. (2014), the degree of pyrolysis temperature and residence pressure, biomass size, and kiln residence period all have an impact on the properties of biochar.

2.3.3 Biochar stability in soil

According to Glaser et al. (2001), the creation of polyaromatic carbon structures accounts for biochar resilience to abiotic and biotic degradation in soil. This demonstrates that biochar may withstand degradation of more than 1500 years in tropical and temperate soils (Eduah et al., 2019). Increased biochar stability and carbon sequestration potential can be achieved by using higher pyrolysis temperatures, which also result in higher carbon content and aromaticity (Novak et al., 2010). According to Glaser et al. (2001), biochar made from biomass with a high lignin content contains a larger proportion of aromatic carbon and decomposes more slowly. The oxygen-to-carbon ratio of biochar can be used to assess the strength of biochar based on its duration. Studies have shown that as pyrolysis temperature increases, the O:C ratio decreases and is inversely connected with biochar stability (Spokas, 2010). The half-life of biochar is typically 1000 years when the O:C ratio is 0.2, but it can reduce to 100 years when the O:C ratio is over 0.6 (Spokas, 2010).

Masek et al. (2011) observed an increase in oxidation of the biochar along with an increase in acidic functional groups that induce further negative charges after incubation for one year. Microbes are primarily responsible for biochar decomposition with erosion being the main cause of biochar loss from soil (Masek et al., 2011; Major et al., 2010).

2.3.4 Properties of biomasses and their biochar derivatives

Biochar is a complex material with a variety of stable and unstable components. Biochar, a carbon-rich material, is primarily composed of carbon, volatile substances, ash, and moisture. The specific proportions of these components significantly impact biochar's physical and chemical properties, ultimately determining its behaviour in the environment and its suitability for various applications.

Biochar is a carbon-rich material with a strong aromatic structure that is produced from various biomass materials under a variety of carbonization conditions (Sohi et al., 2009). The physicochemical properties of biochar are primarily influenced by the pyrolysis temperature and the feedstocks used in its production (Downie et al., 2009; Laird et al., 2009). For example, wood feedstocks have significantly higher cellulose, hemicellulose, and lignin contents than herbaceous feedstocks (Amonette and Joseph, 2009).

According to Demirbas (2004), the high carbon content and subsequently higher rate of biochar synthesis of the biomass used for production is due to the biomass' high lignin content. The lower volatilization and higher biochar yield have been attributed to the high amount of hemicellulose and lignin in the feedstock. Biomass that has a lot of lignin produces high yields of biochar (Amonette and Joseph, 2009).

Biochar EC values have been found to correlate more strongly with feedstock type than with pyrolysis temperature (Rajkovich et al., 2011 Brantley, 2014). Biochar produced from woody biomass has a lower salinity compared to biochar produced chicken manure and cow dung (Carrier et al., 2012 Chowdhury et al., 2016). The high amounts of Na+, K^+, Mg^{2+}, SO_4^{2-}, and PO_4^{3-}, which are essential nutrients for plant growth, account for the high electrical conductivity of biochar generated from biomass grown on soils amended with inorganic fertilizers. According to Hossain et al. (2011) and Yong et al. (2015), the concentrations of salt in biochar increases with increasing pyrolysis temperature up to 500 °C beyond which it decreases. In general, non-woody biomass feedstocks have higher quantities of hydroxyl and carboxyl groups than woody biomass (Ding et al., 2011; Harvey et al., 2011). According to Shin et al. (2010), manure-based biochar (cow dung and chicken manure) have greater CEC values and exchangeable cations than biochar from plant based feedstock. Woody biochar typically contains 1% less ash than non-woody biochar, which typically contains 24% more ash (Joseph et al., 2009).

2.3.5 Effect of pyrolysis temperature on biochar properties

Research has indicated that the temperature of the pyrolysis process affects the physicochemical characteristics of biochar. Pyrolysis temperature has a significant impact on biochar yield (Uchimiya et al., 2011) and is a primary cause of carbon loss during the production of biochar (Shaaban et al., 2018). When the temperature rises above 400 °C, a highly organized aromatic structure develops in the biochar, which has varying degrees of carbonization (Kim et al., 2012). The pyrolysis temperature can also alter the micromorphology, porous structure, and surface roughness of biochar (Gupta et al., 2019; Wang et al., 2019). Electrical conductivities (EC), pH, P, and N are all variable for biochar that has undergone various pyrolysis temperatures (Chan et al., 2008; Meier et al., 2017).

High pyrolysis temperatures cause high molecular weight hydrocarbon molecules to break down thermochemically, producing more syngas and less biochar. Increasing the pyrolysis temperature of hazelnut shells from 400 °C to 700 °C decreased biochar yield by 10% and sesame stem yield by 17% (Downie et al., 2009). Studies have also shown that biochar ash content increases at the expense of carbon content with increasing pyrolysis temperature (Gaskin et al., 2008). Biochar ash is composed of inorganic elements such as calcium, magnesium, sodium, potassium, and inorganic carbonates (Joseph et al., 2009).

The pH of biochar is affected by the pyrolysis temperature. Biochar can be acidic or alkaline, depending on the feedstock, but it is often alkaline (Ahmad et al., 2014). Some studies have shown that biochar pH increases with pyrolysis temperature. The release of alkali and alkaline earth metals from the feedstock during pyrolysis is the primary cause of high pH, according to Ahmad et al. (2014). Studies using Boehm titration have shown that total acidity decreases, and total alkalinity increases with increasing pyrolysis temperature, which is consistent with the pH trends of different biochar types produced at different pyrolysis temperatures (Zhang et al., 2015). For example, oak biochar produced at 200 °C had a pH of 4.60 and biochar produced at 400 °C and 600 °C were neutral and alkaline (6.6-7 and 7.5-10.5), respectively (Zhang et al., 2015a). At low pyrolysis temperatures (200-400 °C), maize straw and millet straw biochar had an acidic pH range of 4.87 to 6.11 (Nguyen et al., 2010; Hossain et al., 2011; Zhang et al., 2015b). Other types of biochar, such as wheat, and conocarpus waste have also been shown to have acidic pH at low pyrolysis temperatures (Nguyen et al., 2010; Hossain et al., 2011; Chen et al., 2014; Jin et al., 2016; Wang et al., 2015a; Zhang et al., 2015b; Subedi et al., 2015a, 2016; Al-Wabel et al., 2013). Biochar ash content increases with pyrolysis temperature and is positively correlated with biochar pH, suggesting that ash may contribute to biochar high pH (Yuan et al., 2011).

The loss of acidic functional groups, such as phenolic and carboxyl groups, at high pyrolysis temperatures may also contribute to high pH. For example, a study by Al-Wabel et al. (2013) found that the basic functional groups on the surface of biochar produced from organic waste increased from 1.15 to 4.55 mmol g^{-1}, while the acidic functional groups decreased from 5.17 to 1.22 mmol g^{-1} from 200 to 800 °C.

Biochar nitrogen content decreases with increasing pyrolysis temperature. Both woody and non-woody biochar types begin to lose nitrogen at 400 °C, with about 50% of the nitrogen lost via volatilization at 700 °C (Knicker, 2007). Nitrogen starts to volatilize at temperatures as low as 200 °C because it is primarily bound to organic molecules (DeLuca et al., 2009). At high temperatures (>550 °C), nitrogen is converted into a pyridine-like structure (DeLuca et al., 2009).

2.3.6 Impact of biochar on soil characteristics

Biochar, a carbon-rich material produced from the pyrolysis of biomass, has the potential to significantly improve soil properties, particularly in tropical and temperate regions. By increasing soil surface area, biochar enhances nutrient retention, water-holding capacity, and aeration, which can lead to improved plant growth and yield.

Studies have demonstrated that biochar can increase soil surface area by several-fold, creating more sites for nutrient adsorption and microbial activity. This increased surface area can also improve soil structure, leading to better water infiltration and retention. Additionally, biochar can reduce soil bulk density, allowing for greater root penetration and water storage.

The combination of increased surface area and reduced bulk density results in improved water-holding capacity, which is crucial for plant growth, especially during dry periods. By enhancing soil moisture retention, biochar can help mitigate the effects of drought stress and optimize plant water uptake.

Different soils respond differently to biochar depending on their structural class (Glaser et al., 2002). For example, adding 10% biochar to sandy soil increased its water content by 18%, but loamy and clay soils had less of an increase. Other studies have shown that sandy soils can hold more water than usual after biochar application (Gaskin et al., 2008). Several authors have attributed the increased soil moisture to the high surface area of biochar (Gaskin et al., 2008; Glaser et al., 2002).

Applying biochar, especially to tropical acidic soils, can increase the availability of nutrients in soil solutions. Most biochar types are alkaline, so they are used as liming agents (Glaser, 2002). The carbonates, bicarbonates, and silicates in biochar can raise the pH of neutral or acidic soils (Nguyen et al., 2010). The increase in soil pH after biochar application is caused by a reaction between hydrogen ions in the soil solution and acidic functional groups such as carboxyl groups in biochar (Lehmann et al., 2003). In a short-term cultivation experiment, Uzoma et al. (2011) found that biochar application increased soil pH from 4.5 to 6.3. Similarly, Yuan et al. (2011) showed that applying 1% of various types of biochar to several tropical soils increased pH by 0.59 to 1.05 units after 60 days.

In an incubation trial, Yuan et al. (2012) found that rice straw biochar increased CEC of Alfisols from 4.3% to 18%. Jien and Wang (2013) found that *Leucaena leucocephala* biochar improved CEC in severely weathered tropical soils by 6.4 cmolc kg^{-1}. However, it is important to note that the effect of biochar on CEC is not always consistent. Some studies have shown that biochar can increase CEC in soils with low initial CEC, but not in soils with high initial CEC (Peng et al., 2011).

Biochar can increase soil fertility by releasing basic cations directly into the soil solution. This is because of the material's wide surface area and abundance of acidic functional groups (Cheng et al., 2006). When biochar is added to soil, it is often found that exchangeable plant nutrients such as Mg^{2+}, Ca^{2+}, and K^{+} increase in the soil solution. In soils treated with biochar, the abundance of these exchangeable cations has been observed to increase by more than 60% (Wang et al., 2014). For example, the concentrations of Mg^{2+} and K^{+} increased from 26 to 235 mg kg^{-1} and from 18 to 163 mg kg^{-1}, respectively, in soils with maize cob biochar (Wang et al., 2014).

Biochar can improve soil fertility by increasing base saturation, reducing nitrous oxide (N_2O) emissions, and reducing nitrogen leaching.

Biochar can also reduce N_2O emissions by adsorbing N_2O molecules. Biochar can reduce nitrogen leaching by increasing retention of NH_4^+ through increased CEC of the soil. A study by Cheng et al. (2006) found that biochar application increased base saturation in soil from 5.4% to 22%. A study by Stewart et al. (2013) found that biochar applications reduced N_2O emissions by 21% to 92% depending on factors like application rates from soils with different physicochemical properties. A study by Wang et al. (2013) found that using soybean biochar could reduce N_2O emissions by 50% and 80%, respectively. However, some studies have found that biochar application has no effect on N_2O emissions in both template and tropical soils (Clough et al. 2010). Biochar produced at relatively moderate pyrolysis temperatures (300-400 °C) is more effective at reducing N_2O emissions than biochar produced at higher temperatures. This is because biochar produced at moderate temperatures contains more carboxylic and phenolic groups, which can adsorb N_2O molecules. Studies by Lehmann et al. (2003) and Major et al. (2009) found that nitrogen leaching in pot studies was reduced by roughly 70% after biochar application. Steiner et al. (2008) found that biochar can be a useful soil amendment in severely weathered soils to lower nitrogen leaching and boost nitrogen use efficiency.

2.3.7 Biochar impact on soil bioavailability of phosphorus

The effects of biochar on soil phosphorus availability are complex and have not been consistently described in the literature. Some studies have shown that biochar addition can increase phosphorus availability, while others have found that it can decrease phosphorus availability. For example, Lehmann et al. (2006) found that biochar-rich soils had increased phosphorus availability. However, Novak et al. (2010) found that soil column studies using biochar made from different sources reduced the available phosphorus content. On the other hand, it has been found that adding biochar to neutral and alkaline soils decreases the bioavailability of phosphorus because it increases phosphorus sorption to produce Ca-P and Mg-P compounds (Chintala et al., 2013). Biochar has a high natural phosphorus content. Consequently, it increases availability of the nutrient in soil solutions for plant absorption (Chan et al., 2007, Sulemana et al., 2021). According to Stevenson and Cole (1999), biochar affects soil phosphorus dynamics by chelating organic compounds like adsorbed phenolic acids and amino acids.

Xu et al. (2014) found that organic molecules adsorbed on the surface of biochar can reduce the ability of Al^{3+}, Fe^{3+}, and Ca^{2+} to precipitate phosphorus in soil. Cheng et al. (2008) found that biochar can alter the ion exchange characteristics of soil, which can, in turn, affect phosphorus bioavailability. Newly incorporated biochar frequently has a high anion exchange capacity due to its propensity to compete for P adsorption with both amorphous and crystalline Al and Fe oxides (Hunt et al. 2007).

Point of Zero Charge decreased and the negative surface charge potential increased when different types of biochar were added to soils (Hunt et al., 2007). Adding biochar to soil can increase soil cation exchange capacity (CEC) while increasing phosphorus availability due to repulsion between the negatively charged soil surface and phosphorus ($H_2PO_4^-$ or HPO_4^{2-}) (Nartey et al., 2023).

According to (Sohi et al., 2010), humic acid extracted from maize straw biochar, has increased the availability of phosphorus by a factor of two over humic acid from soil. Bohme et al. (2005) found that soil microbes and enzymes play a major role in phosphorus mineralization and that adding biochar to soil increases phosphorus mineralization and microbial activity. Alkaline phosphatase activity increases with soil pH, which has a significant impact on phosphorus (P) breakdown (Eduah, 2019).

2.4 Standard Phosphorus Requirement

Fox and Kamprath (1970) used a graph called "phosphorus sorption isotherm" to predict the amount of phosphorus required to be added to the soil to reach a specific level of phosphorus in the soil solution. This level is called the "equilibrium phosphate concentration" and was set at 0.2 milligrams per litre. The amount of phosphorus needed is called the "standard phosphorus requirement" (SPR). They found that the SPR calculated using this method often matches the amount of phosphorus needed in real-world farming situations. The behaviour of phosphorus in Vertisols is complex and influenced by various factors, including soil properties, microbial activity, and management practices. Understanding these behaviours is crucial for developing sustainable agricultural practices in regions dominated by Vertisols.

Table 2. 1 Classifying the standard P requirement (mg P kg^{-1}) according to how soil minerals affect it.

Standard P requirement at 0.2 mg L^{-1} soil	Scale	Usual mineralogy encountered
< 10	Very low	Quartz, organic minerals
10 - 100	Low	2:1 clays, quartz, and 1:1 clays
100 - 500	Medium	Fe and Al oxides in 1:1 clays
500 – 1000	High	moderately weathered ash, oxides
> 1000	Very highly	Desilicated amorphous substances

Juo and Fox, 1977

2.5 Phosphorus availability in Ghanaian soils

The vertisols also known as "Black Earth", is classified as Calcic Vertisols (FAO/UNESCO, 1990). Despite their potential for productivity, they pose challenges due to difficult tillage, nutrient deficiencies, and inadequate water management technologies. The Vertisols are derived from hornblende gneiss, have low inherent fertility, with a total phosphorus of 150-298 mg kg^{-1} and available phosphorus of 0.1-3.5 mg kg^{-1} (Acquaye and Owusu Bennoah, 1989). Vertisols are naturally low in fertility due to several factors. They have low organic matter content, typically between 1-2%, which is insufficient to support healthy plant growth and soil microbial activity. Additionally, the region's lower rainfall compared to forested areas limits plant growth and organic matter decomposition. Annual bush fires further exacerbate the issue by destroying vegetation and reducing organic matter input. Organic matter plays a crucial role in improving soil fertility by increasing nitrogen content and enhancing soil structure.

Acquaye (1986) found a strong link between soil fertility and organic matter (OM) content. Savanna soils had significantly lower OM levels (1-2%) compared to forest soils (4.5-6%). This difference was attributed to fewer bush fires and greater plant growth in the forest zone.

The high clay content in Vertisols can reduce phosphorus availability by forming tight bonds with clay particles. Soil pH also affects phosphorus availability. In acidic soils, phosphorus can be bound by iron and aluminium, while in alkaline soils, it can be precipitated by calcium.

Phosphorus is often a limiting factor for plant in many soils as well as Vertisols, despite the presence of substantial amount of total P. This is due to low availability of

P in the soil solution, that is essential for plant uptake. This low tendency is a result of P binding to soil particles and form insoluble compounds (Lynch and Brown, 2008; Khan and Joergensen, 2009; Malik et al., 2012; Johnston et al., 2014).

Though Vertisols contain some amounts of total P, however soil solution P concentrations are basically low and thus a hindrance for sufficient plant P absorption (Hinsinger, 2001). As P is subjected to precipitation reactions and sorption reactions on the soil surface, a significant amount of phosphorus in both applied and natural soil is not available to the plant (Alam and Ladha, 2004; Brady and Weil, 2008; Khan and Joergensen, 2009). As a result to the low efficiency of applied P, large quantities of P fertilizers are needed to adequately increase soil solution P concentrations for uptake by plants to sustain crop productivity. Due to high cost of inorganic P fertilizers or either out of reach by the resource poor farmer, they rely on government subsidies for inorganic P fertilizers. Moreover, natural phosphorus resources are diminishing quickly, relying entirely on inorganic phosphorus fertilizers is not a good long-term plan (Cordell et al., 2009). It is therefore of high significance that alternate agricultural management strategies are employed that are less expensive, P efficient and sustainable (Harvey et al., 2009; Sánchez, 2010).

2.6 Literature Review Summary

Tropical soils are highly weathered and highly acidic, and have low levels of organic carbon and sesquioxides. Phosphorus altered from organic or inorganic sources, or applied to acidic soils, gradually reacts with iron and aluminium compounds. Using sorption isotherms to determine P requirements in agricultural soils is considered to be the best option for predicting soil testing and thereby improving soil fertility and crop production. It has been suggested that biochar soil amendment can help tropical acidic soils that are deficient in phosphorus. The kind of biomass (plant waste and animal dung) and pyrolysis temperature, however, have a significant impact. The carbonization of rice husk and animal manure, especially cow manure, has been shown to increase the phosphorus concentration. Therefore, the use of biochar may be a suitable alternative to mineral fertilizer P made from phosphate rock. Using biochar types obtained from rice husk and cow manure recycles phosphorus in agricultural waste, minimizes exploration and decomposition of non-renewable phosphate rocks, and minimizes environmental degradation.

3.0 CHAPTER THREE

MATERIALS AND METHODS

3.1 Physiography of study site

The study was carried out at the University of Ghana's Soil and Irrigation Research Centre, Kpong in the Eastern Region of Ghana. The Centre has a total land area of 1068 hectares and is located along latitude 6^0 09' N and longitude 00^0 04' E at an elevation of 22 m above sea level. The Centre experiences a bimodal rainfall and has an average temperature of 27.7°C with maximum and minimum temperatures of 33.30 °C and 22.1°C, respectively. The relative humidity at the study site ranges from 70 to 90%. The area has a gentle topography with vegetation consisting mainly of grassland and a few shrubs and trees such as mangoes (Yangyuoru et al., 2012).

3.2 Soil

According to Brammer (1955), the soil was formed from the breakdown of garnetiferous hornblende gneiss. It has been categorized as a Calcic Vertisol according to the FAO/UNESCO (1974) classification system, while the soil survey staff classifies it as a Typicl Calciustert (Avornyo 2014). It is Tropical Black Clay and belongs to the Akuse Series (Adu, 1985; Amatekpor and Dowuona, 1995). Due to the high montmorillonitic clay content of between 30 and 55%, internal drainage is poor, and the land is regularly flooded during heavy rains especially on flat and bottom slopes. Being a 2:1 clayey soil, it is subjected to changes in volume with variation in soil moisture content, resulting in deep cracks when dry and becoming sticky and expanding when wet (Soil Survey Staff, 1996). It has calcium carbonate nodules in the subsoil (Dowuona, 1995).

3.3 Biochar Preparation

Rice husk RH) and cow dung (CD) were used as feedstocks for biochar preparation. These feedstocks were obtained from the Soil and Irrigation Research Center, University of Ghana. They were air-dried and pyrolyzed using a Kuntan kiln. The Kuntan kiln is made up of a female base with louver like slits which allowed for exchange of gases. It also has a male chimney mount as shown in Figure 3.1. Dry twigs from the surroundings were placed on a cemented platform and lit with a match and the female was placed over the fire. The fire served as the energy source for pyrolysis. The temperature of the base was ascertained after five minutes with a Extech 42570 dual laser Infrared Thermometer V1.6 (IR) short gun digital thermometer. When the temperature of the base was about 300^{o}C, the male chimney was inserted into the female base and the feedstock heaped around the base. To ensure complete charring, the feedstock was turned every five minutes whilst being heated by the metal base. Syngas from the charring material passed through the louvre slits to refuel the fire. Thus, the system was self-sustaining. The feedstock was turned intermittently with the use of a shovel to ensure uniform charring and to minimise the material catching fire. When the last particle was fully charred, there was no production of syngas and hence the fire could not be sustained and extinguished gradually. The pyrolysis temperature was determined at five-minute interval and the average over the charring period used as the charring temperature.

After the charring process was complete, the charred material was pushed aside using the shovel and doused with water. The wet biochar was spread out in a thin, even layer on a clean, dry surface. The spreading improved air circulation within the biochar mass and promoted water evaporation. The air drying continued till 10% moisture content was attained. The biochar was then bagged for use. Part of the bagged biochar was passed through a 2-mm sieve and stored for chemical characterization. The two biochar types vis rice husk biochar and cow dung biochar are herein after referred to as RHB and CDB, respectively.

Figure 3. 1 'Eve' of Kuntan kiln

Figure 3. 2 'Adam' of Kuntan kiln

Figure 3.3 Heaped rice husk around **Kutan kiln**

Figure 3.4 Biochar being ready

Figure 3.5 Cow dung being charred.

Figure 3.6 Cow dung biochar being ready

3.4 Soil Sampling

Samples of soil were taken at plough depths of 0 to 20 cm at ten different areas at the selected site were bulked and mixed to form a homogenized and composite sample. These were quickly put in a deep freezer to facilitate freeze drying and pulverization because of their shrink-swell properties. The pulverized soil was then screened through a 2 mm sieve to obtain the fine earth fraction which was subsequently used for some physicochemical analytical determinations. Undisturbed samples were taken at five different sites for bulk density determination

3.5 Physical Characterization

The soil sample was subjected to bulk density and particle size distribution determinations using the clods from the undisturbed soil and the fine earth fractions, respectively.

3.5.1 Bulk density (Clod Method)

The clod method was used to determine bulk density of the soil. Selected clods were oven-dried at 105 °C until constant weights were attained. A 100 ml measuring cylinder was filled with previously oven dried fine sand to a 30 ml mark. The oven dried clod which had hardened was then gently pushed into the cylinder with the aid of a spatula until it was completely covered by the sand in the cylinder. This caused the volume of sand to rise above the initial volume of 30 ml. The difference in volume was then taken as the volume of the air-dried clod. The bulk density was then calculated using the formula below:

$$BD\ (g/cm^3) = \frac{oven{-}dry\ mass\ of\ clod}{volume\ of\ clod}, \qquad \text{Eqn.3.1}$$

where BD is the bulk density.

3.5.2 Particle size distribution

The particle size distribution of the soils was ascertained using Day's (1965) modified Bouyoucos hydrometer method. In a 250 ml beaker, 40 grams (40 g) of the fine earth fraction were weighed. To the 40 g soil, 6% HCl was added to remove any carbonates which may be present in the form of $CaCO_3$ after which 10 ml of hydrogen peroxide (H_2O_2) was added to destroy organic matter in the soil. Then, a suspension of 100 ml of sodium hexametaphosphate (Calgon)) at 5% was added. A reciprocating shaker was used to shake the suspension for an hour, allowing the sand, silt, and clay particles to separate into their respective fractions. The soil suspensions were then poured into 1 L graduated sedimentation cylinders and filled with distilled water until they reached the 1000 ml mark. The suspension was fully mixed by repeatedly moving the plunger up and down inside the cylinder. A hydrometer was inserted after five minutes and the reading of the suspension was taken to represent the density of silt and clay. Thereafter the sample was allowed to stand, and a second reading was taken after five hours to represent the density of clay alone. The temperature of the suspension was taken with a thermometer each time the hydrometer reading was taken. The suspension was poured into a 47-µm sieve after the second and washed thoroughly with tap water until the water became very clear to collect the sand fraction. The sand fraction was oven-dried to a constant weight and the weight noted. There were three replications of the process. The relationship offered by Day (1965) was used to account for temperature impacts on density viz., for every degree above

19.5 degrees Celsius, the density of suspensions of clay and silt rises by 0.3. The distribution of particle sizes in the soil sample was calculated using the equation 3.2, 3.3 and 3.4 below.

$$\% \text{ clay} = \frac{hydromeretr\ reading\ at\ 5\,hrs}{40\ g} \text{ x } 100 \qquad \text{Eqn...........3.2}$$

$$\% \text{ silt} = \frac{hydrometer\ reading\ at\ 5\,min - hydrometer\ reading\ at\ 5\,hours}{40\ g} \text{ x } 100, \qquad \text{Eqn...3.3}$$

$$\% \text{ Sand} = \frac{weight\ of\ oven{-}dried\ sample}{40\ g} \text{ x } 100 \qquad \text{Eqn..........3.4}$$

Where 40 g is the weight of the fine earth fraction.

Texture classes were determined with the help of the USDA textural triangle.

3.6 Chemical Characterization of soil and biochar

The pH, EC, total carbon and nitrogen, total and available phosphorus, cation exchange capacity (CEC) and exchangeable base contents of both soils and the two feedstocks i.e. rice husk and cow dung, and their biochar derivatives were determined. The chemical characterization was done using the less than 2-mm fractions of the samples.

3.6.1 pH

A 1:2 (soil : water ratio) suspension of soil and water was made by the addition of 40 mL of deionized H_2O to 20 g of fine earth fraction of the soil into a 100 ml beaker. For the two biochar types and their respective feedstocks (rice husk, cow dung), a 1:5

sample to water ratio was used. All the samples were in triplicate. The suspensions were stirred for 30 minutes using a stirring rod, and the suspension was left to settle for an hour and equilibrate with the temperature of the room in which the pH meter was housed. The Oakton Pc 2700 electrometric pH meter was used to read the pH values of the suspensions after the pH meter had been standardized with respective appropriate buffered solutions at pHs of 4.0, 7.0 and 9.2.

3.6.2 Electrical Conductivity

The soil, feed stock and biochar suspensions used for the pH determination were also used for EC determination. The EC of the suspension was read on a mV-Temp PL-700PVEC meter after standardization with KCl solutions.

3.6.3 Determination of total carbon and nitrogen

The total carbon and nitrogen contents were determined using the < 2-mm fractions of soil, feedstock and the biochar types using the Leco Trumac Carbon, Nitrogen, and Sulfur version 1.3 Analyzer. A platinum crucible containing 500 g of comcat was filled with a 0.20 g of each of the samples i.e. soil, feedstock and the two biochar types. The crucible was then placed in the analyzer's furnace. After the samples had been combusted for six minutes, the amounts of C and N were measured.

3.6.4 Determination of Total Phosphorus

A 0.2 g of the < 2 mm fraction of each of the samples was weighed into 100 ml digest tubes in triplicates. The samples in the test tubes were then mixed with a digestion solution consisting of 25 ml of HNO_3 and 60% $HClO_4$ in a 2:3 ratio and heated for about 24 hours on a digestion rack until contents turned grey signifying complete digestion. A 100 ml volumetric flask was filled with the digested samples after it had been cooled, diluted with deionized water, and filtered with Whatman No. 42 filter paper. Deionized water was used to make up the volume to 100 ml.

The ascorbic acid method, as reported by Murphy and Riley (1962), was used for blue colour development and the various P concentrations of each of the samples measured at a wavelength of 712 nm using a Cole Parmer UV 8620 spectrophotometer. The P contents in each of the samples were calculated using equation 3.6.

$$\text{Total P } (mg/kg) = \frac{spectrometer\ reading \times volumme\ of\ extract\ x\ 100}{Aliquot\ x\ Weight\ of\ sample\ x\ 1000000} \qquad \text{Eqn.3.5}$$

3.6.5 Determination of Available phosphorus

The available phosphorus was determined using the Olsen method of 1965. A one (1) g each of the samples was weighed into a 200 ml plastic container and 100 ml of $NaHCO_3$ of pH 8.5 was added. The samples were covered, shaken on a reciprocating shaker for 30 minutes. The extracts were then filtered through Whatman's No. 42 filter paper. A 1 ml 1.5 M H_2SO_4 was added drop-wise to a 10 ml aliquot to decolorize the solution by settling the organic debris in it. Subsequently, the extracts were put in a refrigerator to cool. The extracts were then gently decanted to develop blue colour using the Murphy and Riley method (1962) by adding a drop of P-nitrophenol and a drop of ammonium hydroxide to a 2 ml aliquot of the sample solution in a 50 ml volumetric flask. After adding distilled water to fill the container to the 50 ml level, the phosphorus concentration was measured using a Cole Parmer

UV spectrophotometer at a wavelength of 712 nm. The available phosphorus content of the samples was then estimated as in equation 3.6.

$$P\ (mg/kg) = \frac{spectrometer\ reading \times volume\ of\ extract}{Aliquot\ x\ Weight\ of\ sample}, \qquad \text{Eqn...3.6}$$

3.6.6 Exchangeable bases

The exchangeable base cations (Ca^{2+}, Na^{+}, K^{+}, Mg^{2+}) were extracted with NH_4-acetate buffered at pH 7 and were read using Atomic Absorption Spectroscopy using the modified method of Hendershort et al. (2007). Five (5) g soil was weighed into a 50 mL plastic bottle and 20 ml 1 M NH_4-acetate added. The suspension was agitated for two hours on a reciprocating shaker after which it was filtered through a Whatman's No. 42 filter paper into a flask. The extract was finally transferred into a 200 ml volumetric flask, and filled to the mark with 1 M NH_4-acetate. The Perkin Elmer Atomic absorption spectrometer was calibrated with the appropriate standards for Ca, Mg, K and Na and the concentration of the aforementioned elements in the extracts were read.

The exchangeable bases of the biochar derivatives were also determined. Firstly 5 g of the biochar samples were put in funnels lined with filter papers and leached with 200 ml of deionized water to get rid of soluble bases. This was done by subsequent leaching four times with 50 ml of de-ionised water. Thereafter, the procedure employed for exchangeable bases as described for the soil was used.

Exchangeable bases in each of the samples were calculated as:

$$\text{Ex. bases } (cmol_c kg^{-1}) = \frac{R \text{ x vol. of extract x } 10^3 \text{ g x } 10^2 \text{ (cmol) x E,}}{\text{Wt. of soil x } 10^6 \text{ (}\mu g\text{) x atomic mass of element}} \qquad \text{Eqn. 3.7}$$

Where:

Ex. Bases = Exchangeable bases

R = AAS reading in mg L^{-1}

E = charge of the element.

3.6.7 Determination of CEC

Ten grams of the < 2 mm sieved soil sample was weighed into an extraction container with 100 ml of 1M NH_4OAc solution buffered to pH 7.0. The mixture was shaken for 30 minutes and then filtered using No. 42 Whatman filter paper. The samples were leached four times with 50 ml of ethanol to remove un-adsorbed ammonium, then four times with 50 ml of acidified KCl. Five ml of the leachate was pipetted into a Kjeldahl flask and 10 ml of 40% NaOH and 100 ml of distilled water added. This solution was distilled into boric acid to which three drops of methyl red methylene blue mixture were added to form ammonium borate. The ammonium borate was then titrated with 0.01M HCl back to boric acid and the number of moles of HCL consumed in the titration used to determine the concentration of ammonium. The concentration of ammonium (cmol/kg) was then used as the CEC of the soil. The same procedure was used for determining the CEC for two biochar types.

3.7 Phosphorus Sorption Study

Phosphorus sorption studies were carried out to determine the standard P requirement (SPR) of the soil according to the method of Fox and Kamprath (1970). An orthophosphate stock solution containing 50 mg P L^{-1} was prepared from KH_2PO_4 salt of Analar grade. Thirty millilitres of 0 (blank), 5, 10, 15, 20, 25, and 30 mg P L^{-1} in a background solution of 0.01M $CaCl_2$ solution were added to centrifuge tubes containing 3 g of the soil in triplicate. These gave solutions of the P concentrations with ionic strengths of 10 mM. Three drops of toluene were added to each centrifuge tube to prevent microbial activity. The suspensions were shaken on an end-to-end shaker for 30 minutes, twice daily, for six days. The suspensions were then centrifuged at 10000 rpm for 15 minutes. The liquid portion (supernatant) was filtered using a Whatman No. 42 filter paper. The filtered liquid was then analyzed to determine its phosphorus (P) concentration. The analysis used a specific method described by Murphy and Riley (1962), which involves a colour development technique using molybdate and ascorbic acid.

To calculate the amount of P adsorbed by the soil, the initial P concentration was compared to the final P concentration after the adsorption process. The resulting data was then used to create a Langmuir adsorption isotherm model.

$$\frac{c}{x} = \frac{1}{kb} + \frac{c}{b} \qquad \text{Eqn. 3.8}$$

Where,

C (mg P L^{-1}) = P concentration in the equilibrium solution

x (mg P kg^{-1}) = P sorbed

k (L mg^{-1}) = affinity index or constant relating to binding energy.

The Standard Phosphorus Requirement (SPR) is the amount of P that must be added to the soil to attain soil solution concentration of 0.2 mg/L after equilibration. To obtain the SPR adsorbed P was regressed on equilibrium P concentration and the isothermal equation was used to predict the standard phosphorus requirement (SPR) of the soil by using the curvilinear form of the Langmuir equation. The isotherm equation was then used to predict the standard phosphorus requirement (SPR) of the soil by substituting 0.2 mg P L^{-1} for x in the isotherm equation.

3.8 Agronomic trial

A field experiment was conducted to evaluate the efficacy of rice husk and cow dung biochar types as P sources for cowpea production at the University of Ghana, Legon, Soil and Irrigation Research Center (SIREC). Inorganic P source, TSP was used as the farmers' practice and there was control treatment where no amendment was applied.

The design of the experiment used was a randomized complete block (RCB). The experiment was established using two application rates of P `viz. the standard phosphorus requirement of the soil (SPR) and half SPR for the biochar amendments. The CDB was applied at a rate of 6.67 kg/plot at the full SPR (T1) and 3.33 kg/plot at the half SPR (T2). The RHB was applied at 16.67 kg/plot for the full SPR (T3) and 8.33 kg/plot for the half SPR (T4). The inorganic amendment, TSP, was applied at only the SPR rate of 0.012 kg/plot (T5). There was a treatment where there was no amendment i.e. zero P application which served as the control (T0); These were replicated four times. Thus, with two organic amendments at two P rates, and one inorganic amendment at one rate and a control with no amendment at 4 replications, there were six x four (24) experimental units. Each of these treatments was randomized on a plot of size 27 m x 43.8 m. The treatments and the amount of specific amendment applied are shown in Table 3.1.

The plot was demarcated into six blocks with each block having all the six treatments. Each of the four blocks were separated by a 3 m distance. Each of the treatments was imposed on 3 m x 3.8 m plots with 3 m distances between two treatments as shown in Plate 1. The 27 m x 43.8 m plot was ploughed and ridges of length 3 m and 0.6 m at the base, 0.4 m at the crest and a 0.2 m height were formed using a hoe. The inter ridge space was 0.2 m. Therefore, there were five ridges per 3 m x 3.8 m plot. Twenty-four ridges as per the experimental units were formed and randomized within the 27 m x 43.8 m area of land. The biochar types at their respective aforementioned rates were incorporated into the appropriate ridges with the use of a hoe and allowed to equilibrate for two weeks.

The black-eyed cowpea (*Vigna unguiculata* L. Walp), variety of 90% germination was used for the experiment. It has a determinate growth habit with erect stem.

The variety was acquired from the CSIR-Crop Research Institute, Kumasi, and has a maturity period of 60 days. Three seeds were sown per hole at an intra spacing of 60 cm ridges and 40 cm within plants. Thus, the planting distance was 60 cm x 40 cm. The seedlings were thinned to two plants per stand, eight days after planting. Triple superphosphate was applied 14 days after planting (DAP) to the plots requiring that treatment. All cultural practices pertaining to cowpea cultivation such as weeding, insect pest and disease control were undertaken. The experiment was rain-fed and the first efficacy trial was done between 10th June and 15th August 2023. The second trial was between 20th July and 10th September 2023.

Table 3. 1 Treatments and their respective amendment application rates*

Treatment	Amount of amendment (tons/ha)
T0	0.0
T1	6.67
T2	3.33
T3	16.67
T4	8.33
T5	8.33 kg

T0 = No amendments

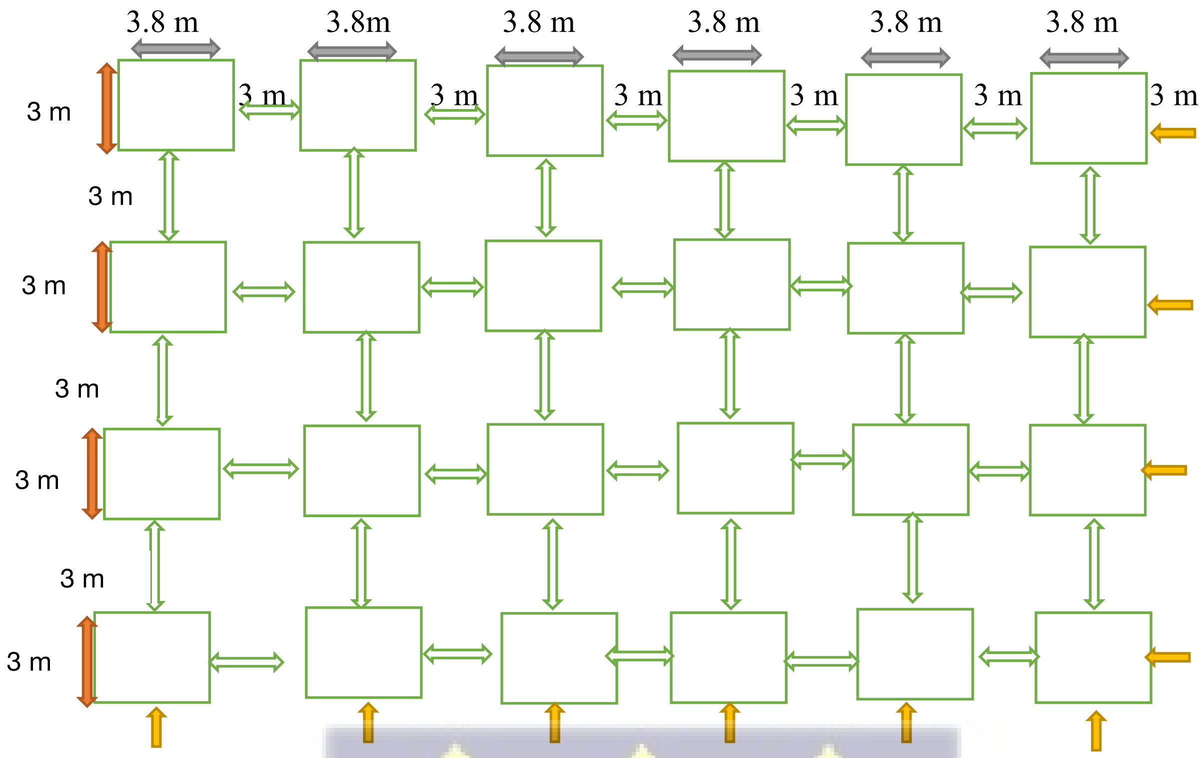
T1 = Cow dung biochar at full SPR

T2 = Cow dung biochar at 1/2 SPR

T3 = Rice husk biochar at full SPR

T4 = Rice husk biochar at 1/2 SPR

T5 = Triple Superphosphate at full SPR



Legends

width = 3 m

Length = 3.8 m

Alleys = 3 m

Borders = 3 m

Borders = 3 m

Plate 1. Scheme of the experimental layout of plots

3.9 Agronomic data taken and Analysis

Plant height was measured weekly using a meter rule from 7 to 35 days after germination (DAG). These measurements were then averaged for each treatment. Additionally, the number of days it took for the first flower to appear, the average number of days for 50% of the plants to flower, and the average number of days for 50% of the plants to reach maturity were all recorded.

At 70% maturity, pods were harvested and counted per plot. Five pods were chosen per plot, their length measured with a meter rule and recorded. Five dry, normal pods were used to determine the number of seeds per pod. Seeds were dried to 10% moisture content, then weighed individually. Two plants per plot were carefully uprooted and extraneous soil was carefully removed from the roots. Roots were separated from the stems and placed in labeled envelopes. These were oven-dried at 70°C until constant weight was reached, providing the shoot dry weight. The water displacement method was used to determine root volume. The severed roots were kept in labeled envelopes and oven-dried at 70°C until constant weight was attained. The dried harvested cowpea was threshed manually. The grains were subsequently weighed using the weighing balance to get the grain weight for determination of the yield.

3.10 Determination of plant phosphorus uptake

The dried roots, shoot and cowpea seeds were milled and the concentration of P in the various plant parts and the grain were determined. A 0.1 g of the milled roots, shoot and the seed was weighed into digestion tubes and digested with 5 ml of concentrated sulphuric acid on a digestion rack. Drops of hydrogen peroxide were added till clear solution was obtained. The content of the digest after cooling was transferred into 100 mL volumetric flask and distilled water was used to make up to the mark. The method of Murphy and Riley (1962) was used for colour development as described in the previous section.

The concentration of P in the roots, shoot and seeds determined using equation below;

$$\text{P uptake by plant (g P/plant)} = \frac{P\ concentration\ x\ dry\ matter\ yield}{100} \qquad \text{Eqn.3.9}$$

3.11 Residual Analysis

The soils on each of the ridges for the various treatment were taken, air dried, pulverized and passed through a 2-mm sieve to obtain the fine earth fraction. These samples were then used to determine the residual pH, EC, total carbon, total nitrogen, total and available P and exchangeable bases.

3.11.1 pH and EC

The pH and the EC of the soil was determined as outlined in sections 3.6.1 and 3.6.2, respectively.

3.11.2 Total and Available P

Available and total P of the residual soil were determined per the process described in sections 3.6.4 and 3.6.5.

3.11.3 Total carbon

The wet combustion method of Walkley and Black (1934) was used to estimate the total carbon content in the soil. A 0.5 g of the less than 0.5 mm fraction of the residual soil was weighed into 500 ml conical flask and 10 ml of 0.167 M $K_2Cr_2O_7$ solution and 20 ml of concentrated H_2SO_4 was added and was allowed to stand for 30 minutes. A 200 ml of distilled water was added, mixed and cool for 30 minutes, after which 10 ml of 85% orthophosphoric acid was added. The amount of the potassium dichromate remaining after digestion was titrated against 0.5 M Ammonium Ferrous Sulphate using barium diphenylamine sulphonate as an indicator. The same procedure was used for the blank as the check.

The percentage organic carbon was estimated as follows;

Organic carbon (%) $= \frac{(10-T\,N)x\,0.3x\,0.133}{W}$, Eqn............... 3.11

Where T = titre value (ml);

N = molarity of $(Fe(NH_4)_2(SO_4)_{2;}$

W = weight of soil sample taken

0.3 = milliequivalent of carbon

1.33 = standard convection factor used in the Walkely and Black method for incomplete oxidation of organic carbon C (assuming an average 77% recovery of organic carbon to convert Walkely and Black C to total organic carbon).

3.11.4 Exchangeable bases

The exchangeable bases were determined as outlined in the section 3.6.7 above.

3.11.5 Total nitrogen

The total nitrogen of soil was determined using the macro Kjeldahl procedure involving digestion and distillation as outlined by Soil Laboratory Staff (1984).

A 0.5 g air dried soil sample was weighed into a Kjeldahl digestion flask and 10 ml of concentrated sulphuric acid was added to it. A catalyst mixture was added, mixed carefully and digested, drop of H_2O_2 was added until a clear and colourless digest was obtained. The digest was allowed to cool and then decanted into a 100 ml volumetric flask and made up to mark with distilled water. A 5 ml aliquot of the digest was transferred to the Kjeldahl distillation apparatus and 5 ml of 40% NaOH solution was added and followed by distillation. The distillate was collected in 5 ml of 4% boric acid. Using bromocresol green and methyl red as indicator, the distillate was titrated with 0.01 *N* HCl till blue colour changes to grey and then suddenly flashes to pink. A blank distillation and titration was also carried out to take care of traces of nitrogen in the reagents as well as the water used.

$$\%N = \frac{\text{Titre value} \times M \times \text{Vol. of digest} \times 14 \times 10^2}{s \times t \times 10^3} \qquad \text{Eqn 3.12}$$

Where:

M = Molarity of HCl used in titration (0.01 M)

(14 = atomic weight of nitrogen)

V = total volume to digest

s = weight of air dry soil sample (0. 5 g)

t = volume of aliquot taken for distillation (5 ml)

3.12 Data Analyses

Data was subjected to analysis of variance (ANOVA) using the Genstat Discovery 12th Edition to establish if any, significant treatment effects at $p < 0.05$. Mean separations were down using LSD (0.05) and Tukey multiple means separation.

CHAPTER FOUR

4.0 RESULTS

4.1 Soil Characterization

The physico-chemical properties of the plough (0-20 cm) layer of the soil used for the study are detailed in Table 4.1. The soil exhibited a medium bulk density of 1.46 Mg/m^3. Almost half (48.8%) of the mineral fraction of the Akuse Series used for the study is clay making the soil have a textural classification of clay as per the USDA system (2003).

The pH of the soil measured in water (6.8) was neutral making it suitable for cowpea production. The electrical conductivity (EC) was 0.6 dS/m, indicating a low salinity level. The soil has a total phosphorus (P) content of 220.4 mg/kg of which 91.2% was in the readily available P form of (201.1 mg/kg). Consequently, the soil has a low standard P requirement of 2 mg/kg. The total carbon content was 11.55 g/kg of which 18% was total nitrogen (N). The soil has moderate levels of available calcium (Ca^{2+}) and magnesium (Mg^{2+}) with concentrations of 2.45 cmol/kg and 0.5 cmol/kg, respectively. The potassium (K^+) content is very low (0.04 cmol/kg), while the sodium (Na^+) content is slightly higher (0.3 cmol/kg). The soil has a high CEC of 31.4 cmol/kg, typical of a Vertisol.

4.2 Chemical characterization of feedstock and biochar

Some chemical characteristics of both cow dung (CD) and rice husk (RH), along with their corresponding biochar products, cow dung biochar (CDB) and rice husk biochar (RHB), obtained through pyrolysis at 480 °C, are outlined in Tables 4.2. The pH of cow dung was 7.99 and slightly alkaline.

Table 4. 1 Physicochemical properties of the soil used*

Soil Property	Concentration
Bulk density (Mg/m^3)	1.46
Sand (%)	42.0
Silt (%)	9.2
Clay (%)	48.8
Textural class	Clay
pH (H_2O)	6.8
EC (dS/m)	0.60
Total P (mg/kg)	220.43
Available P (mg/kg)	201.12
Total C (g/kg)	11.55
Total N (g/kg)	2.08
C/N Ratio	5.54
Ca^{2+} (cmol/kg)	2.45
Mg^{2+} (cmol/kg)	0.50
K^{+} (cmol/kg)	0.04
Na^{+}(cmol/kg)	0.30
CEC (cmol/kg)	38.4
SPR (mg/kg)	2.0

Table 4. 2 Chemical properties of feedstock and their biochar derivatives*

Feedstock/ Biochar	pH (1:1 H_2O)	EC (dS/m)	Total C	Total N	C:N	Total P	Av P
			---------(g/kg)------			-----(mg/kg)------	
CD	7.99	4.29	137.65	21.20	6.49	4882.5	-
RH	5.99	1.04	293.28	4.79	61.23	544	-
CDB	8.25	10.97	224.34	12.89	17.40	5712.5	947.25
RHB	7.87	1.39	423.81	8.99	47.14	2022.75	283.25

*CD=cow dung, RH=rice husk, CDB=cow dung biochar, RHB=rice husk biochar

This increased by 0.26 units to 8.25 after charring to the biochar (CDB). The rice husk which was slightly acidic in water (5.99) increased by 1.88 pH units to 7.87 making it slightly alkaline. This shift from slightly alkaline to strongly alkaline in the case of the cow dung and its biochar derivative, and from slightly acidic to strongly alkaline of the rice husk and its biochar agrees with Verheijen *et al.* (2010), and Nartey *et al.* (2023) who asserted that anaerobic pyrolysis of feedstock leads to biochar of pH between neutral to strongly alkaline. Electrical conductivity (EC) of the rice husk and cow dung feedstocks were 1.04 and 4.29 dS/m, respectively. The EC in the cow dung biochar increased astronomically to 10.97 after the pyrolysis process while the RHB demonstrated a marginal increase of 1.39 after pyrolysis of the original feedstock (Table 4.2).

The cow dung had a total C content of 137.65 g/kg which increased 1.63-fold when it was pyrolysed. The rice husk had a higher total carbon content of 293.28 g/kg which increased to 423.81 g/kg upon charring (Table 4.2). The cow dung had a total nitrogen content of 21.20 g/kg, 4.43 times higher than the content in the the rice husk (4.79 g/kg). Upon charring however, the total nitrogen in cow dung decreases by 60.8% to 12.89 g/kg whilst the content in the rice husk more than doubled to 8.99 g/kg. Consequently, the C:N ratio which was 6.49 in the cow dung increased to 17.40 in the biochar derivative, CDB while that in the RH decreased from 61.23 to 47.14 in RHB

The total P concentration in the CD was 4882.5 mg/kg, 8.98 times higher than content in the RH (544 mg/kg). The total P after charring of the CD increased 1.2-fold to 5712.50 mg/kg with the RH increasing by 3.7-fold to 2022.75 mg/kg. The available P content of the CDB was 16% of its total P and 3.34 times more than the available P in the RHB. Available P in the RHB was 14% the content in the total P fraction.

Table 4.3 illustrates the available bases in the two biochar types used as amendments for cowpea cultivation. The cow dung biochar had higher bases than the rice husk biochar. Calcium and Magnesium which are the major liming materials were 0.12 and 0.08 cmol/kg, respectively in the CDB as opposed to 0.02 in the RHB. Available K and Na were generally higher in the two biochar types than Ca and Mg. Cation exchange capacity in the CDB, 26.9 cmol/kg was 7.9 cmol/kg higher than in the RHB.

4.3 Effects of amendment on some phenological properties of cowpea

The various amendment may have had varying effects on some phenological properties of the cowpea. This section looks at effects of the amendments and their varying P rates on some key component of the plant that are controlled by P. These include plant height, days to 50% flowering, nodule numbers and weight, 100 seed weight, yield, root volume and mass at harvest and root and shoot P accumulation.

4.3.1 Effects of amendments on some growth parameters of cowpea grown in the first season

Table 4.4 presents the effects of different amendments on some cowpea growth parameters in the first season. The average plant height of cowpea grown on the un-amended soil was 44.1 cm which did not vary statistically from ridges T2, T3, T4 and T5 amendments. Plants from ridges that had been amended with cow dung biochar at the full SPR (T1) were tallest reaching heights of 50.52 cm, 10 cm more than counterparts from the un-amended ridges.

Table 4. 3 Chemical characteristics of the two biochar types*

Biochar type	Ca	Mg	K	Na	CEC
	---------------------------		-cmol/kg-		---------------------------
CDB	0.12	0.08	0.38	0.31	26.9
RHB	0.02	0.02	0.32	0.31	19.0

* CDB = cow dung biochar; RHB = Rice husk biochar.

Table 4. 4 Effects of amendments and application rates on some growth parameters of cowpea in season 1*

Treatments	Amount of Amendment (tons P/ha)	Average Plant height (cm)	Average Days to 50% flowering	Average Nodule Number	Average Nodule wt (g)	Average No. Pod per plant	Average No. of seed/pod	Average 100 seed wt/plant (g)	Yield (tons/ha)
T0	0	44.10 a	38.25 c	75.2 a	0.35 a	17.90 a	13.20 a	21.97 a	1.77 ab
T1	6.67	50.52 b	35.00 a	150.5 b	0.83 b	21.83 a	13.55 a	25.02 b	2.75 c
T2	3.33	42.77 a	38.00 c	77.0 a	0.43 a	18.08 a	12.68 a	21.02 a	1.65 a
T3	16.67	46.37 a	37.75 bc	134.8 b	0.35 a	19.45 a	12.83 a	22.42 a	1.82 ab
T4	8.33	44.05 a	37.25 bc	75.0 a	0.60 ab	19.00 a	12.78 a	20.52 a	1.68 ab
T5	0.01	44.15 a	36.25 ab	106.8 ab	0.45 a	18.83 a	13.78 a	23.20 ab	2.10 b

* Means with the same letters are not significantly different.

T0=No amendment, T1= cow dung biochar at full SPR, T2= cow dung biochar at half SPR, T3= rice husk biochar at full SPR, T4= rice husk biochar at half SPR, T5= Triple superphosphate at full SPR.

It took on the average 38.3 days for 50% of the cowpea plants grown on the un-amended ridges to flower. This number of days to flower was similar to that of plants grown on ridges amended with T2, T3 and T4.

Plants from the biochar at full SPR (T1) and the TSP amended ridges (T5) flowered 3 and 2 days earlier, respectively, with the days to flower for plants from T1 and T5 being statistically the same in the first season. Number of nodules on roots of cowpea grown in the un-amended ridges were 75 and statistically the same as those from the ridges amended with CDB at half SPR (T2), those from ridges amended with half RHB at half SPR (T4) and plants from the inorganically amended (T5). Cowpea plants from the CDB (T1) and RHB (T3) amended at the full SPR rate significantly had the highest number of nodules of 150 and 135, respectively. Despite the significantly similar nodule numbers on roots of cowpea plants from both T1 and T3 ridges, it was only nodules on plants from the CDB amended ridges at full SPR that were heaviest. These nodules were 2.37 and 1.84 times, respectively, heavier than their counterparts from the RHB ridges amended at full SPR (T3) and the inorganically amended ridges at full SPR (T5).

The average number of pods and number of seeds per pod were statistically the same for the cowpea plant grown on all the ridges, irrespective of whether they are amended or not or the rate at which the ridges were amended in season 1. Conspicuously, the 100 seed weight from plants grown in ridges fertilized with CDB at the full SPR (T1) were significantly the heaviest of 25.02 g with 100 seed weights from plants on the other five ridges being lighter and between 21 and 23 g.

The heavier seeds on plants from the T1 ridges translated into superior yields of 2.75 tons/ha, 0.65 tons more than yields from the inorganically amended ridges and 0.93 ton/ha more than yields from the RHB amended ridges.

4.3.2 Effects of amendments on the growth parameters of cowpea grown in the second season

The average cowpea plant height from the un-amended ridges was 43.1 cm (table 4.5), similar to what it was in the first season. The height of plants from the un-amended ridges was similar to those from T2, T3, T4 and T5 just as was observed in the first season. In the second season, it took on the average between 45 and 47 days for cowpea plants from the T0, T2, T3, T4 and T5 ridges for 50% of the plants to flower. Plants for the T1 ridges flowered earlier at 43 days. On the average, plants from the second season flowered 7 days later than those in the first season. The average number of nodules on roots of plants from the un-amended ridges were 73 similar to the 75 (Table 4.5) obtained in the first season. These nodule number was statistically similar to numbers from plant grown in the T2, T3 and T5 ridges just as was observed in the first season albeit higher numbers in the first season. The number of nodules in the second season was highest from plants grown in the T1 amended soil as was observed in the first season. In fact, number of nodules of plants from the T1 ridges in the second season was approximately thrice the number in the T5 inorganically amended ridges. Nodule weights from plant from the T0, T2, T3 and T5 ridges were statistically similar just as their numbers (Table 4.5). The nodules were heaviest in cowpea plants from the T1 amended ridges as was observed in the first season. Nodules from the T1 amended ridges were on the average 4.26 times heavier than those from the T5 amended ridges (Table 4.5).

Table 4. 5 **Effects of different P source amendments on growth parameters of Cowpea grown on biochar amended Calciustert, (Season 2)***

Treatments	Amount of Amendment (tons P/ha)	Average Plant height (cm)	Average Days to 50% flowering	Average Nodule Number	Average Nodule wt (g)	Average No. Pod per plant	Average No. of seed/pod	Average 100 seed wt/plant (g)	Yield (tons/ha)
T0	0	43.10 a	45.75 b	73.0 ab	0.33 ab	12.05 a	12.80 a	22.03 a	1.54 a
T1	6.67	50.41 c	43.50 a	184.8 c	0.98 c	16.45 b	13.15 a	25.38 c	2.14 b
T2	3.33	44.57 ab	46.50 b	60.8 a	0.18 a	12.30 a	12.28 a	21.23 a	1.46 a
T3	16.67	47.37 bc	46.50 b	67.2 a	0.23 a	12.15 a	12.35 a	22.73 ab	1.62 a
T4	8.33	45.25 ab	47.00 b	169.5 bc	0.78 bc	12.40 a	12.38 a	20.55 a	1.40 a
T5	0.01	44.45 ab	46.25 b	61.2 a	0.23 a	12.75 a	13.65 a	23.10 ab	1.86 ab

* Means with the same letters are not significantly different

There were on the average 12 pods from plants grown in the T2, T3 and T4 amended ridges. In the second season, however, 16 pods per plant were observed on the T1 amended ridges, five less than what was observed on plants from the same treatment in the first season and four more than from counterparts grown in ridges amended with T3 and T5 in the second season (Table 4.5). There were no significant differences in number of seeds per pod among plants grown in the various ridges as they all had on the average between 12 and 14 seeds per pod. The number of seeds per pod from plants in the second season were far less than from the first season. For example, there were 13 seeds/per pod from the T1 amended ridges in season 2 as opposed to 21 in season 1.

The average weight of 100 seeds from plant grown in the un-amended ridges was 22 g in the second season (Table 4.5) similar to the 21.97 g from plants from the same ridges in the first season. The weight of 100 seeds of plants grown in the T2, T3, T4 and T5 amended ridges were statistically similar to their un-amended counterpart (Table 4.5) as was observed in season 1. One hundred seeds from plants grown in the CDB amended ridges at the SPR of the soil were significantly the heaviest (25.4 g) in season 2 similar to weights observed in season 1.

Yield of cowpea in season 2 was lower than that in season 1. Yields from T1 and T5 ridges were 2.14 and 1.86 tons/ha respectively in season two as opposed to 2.75 and 2.1 tons/ha, respectively for season one. There were statistically similar yields of between 1.54 tons/ha and 1.86 tons/ha of cowpea grown in T0, T2, T3, T4 and T5 amended ridges (Table 4.5). It was, strikingly, the T1 amended ridges just as was observed in the first season that gave the highest cowpea yield; 0.28 tons/ha more than yield from the inorganically amended T5 ridges and 0.52 ton/ha more than from the RHB amended ridges at full SPR of the soil of 2.14 tons/ha.

4.3.3 Effects of amendments on biomass, root length, root mass and root volume of cowpea grown during the first season

Phosphorus is the main nutrient that controls root formation and elongation. It was therefore imperative to ascertain the effect of the different sources and varying rates of P on length, mass and volume of roots of the cowpea plants length. The P accumulation in the shoot and the root will also help explain some reproductive properties of the cowpea plant.

The effect of the amendments and their varying rates of application on length, mass and volume of cowpea roots in the first season are shown in Table 4.6. From the table, the biomass of cowpea plant from the un-amended ridges was 120 g which was statistically similar to biomass of cowpea plants from the inorganically amended ridges (T5), and the amended T2, T3, and T4 ridges. The T1 ridges produced plants with the heaviest biomass of 51.8 g heavier than the counterparts from the T5 ridges. The roots of plants from all the ridges were similar ranging from 30 cm to 42.6 cm. Similarly, the mass of roots of plants grown on all the ridges were similar ranging between 4.9 g and 7 g. Root volumes of all the roots were also statistically similar (Table 4.6).

Just as was observed in season 1, the biomass of cowpea plants in season 2 were heaviest in the T1 ridges in season 2 (Table 4.7). These plants were 166.8 g and this was 4 g heavier than in season 1. Plants from the other ridges in season 2 were not significantly different from each other and similar to the biomass observed in season 1.

Table 4. 6 Effect of amendment on biomass, root length, mass and volume in season 1

Treatment	Average biomass (g)	root length (cm)	root mass (g)	root volume cm^3
T0	120.0 a	30.10 a	5.15 ab	12.75 a
T1	162.6 b	42.67 b	7.43 b	14.88 a
T2	112.5 a	29.10 a	4.73 a	11.95 a
T3	108.6 a	40.62 b	6.03 ab	12.25 a
T4	132.8 a	31.52 a	5.05 a	11.43 a
T5	110.8 a	32.92 a	4.98 a	13.00 a

* Means with the same letters are not significantly different.

Table 4. 7 Effect of amendment on biomass, root length, mass and volume in season 2

Treatment	Average biomass (g)	root length (cm)	root mass (g)	root volume cm^3
T0	125.3 a	30.90 a	6.03 ab	12.68 a
T1	166.8 b	43.30 b	7.83 b	14.73 a
T2	116.5 a	29.95 a	5.48 a	12.00 a
T3	112.7 a	40.92 b	6.90 ab	12.75 a
T4	136.8 a	31.77 a	5.85 ab	11.93
T5	115.2 a	33.50 a	5.73 ab	13.48 a

* Means with the same letters are not significantly different.

The roots of cowpea plants from the un-amended ridges were on the average 30.9 cm long and this was similar to length from the same ridges in season 1. Roots form the T2, T4 and T5 ridges had similar lengths as those from the un-amended ridges as was observed in season 1. The T1 ridges produced plants with the longest roots of 43.3 cm similar to roots of plants from T3 ridges in season 2. Root volume of cowpea roots was statistically similar when grown in all the ridges and ranged between 11.9 and 14.7 cm^3 (Table 4.7).

Generally, patterns of biomass, root length, mass and volume of cowpea plants grown in season 1 and 2 were similar.

4.3.4 Partitioning of P and N uptake in cowpea plant

P uptake in the root of cowpea plants from the un-amended ridges in season 1 was the least of 18.56 mg/plant similar to uptake in roots of plant from the T2 ridges (20.64 mg/plant) (Table 4.8). Uptake of P in roots of plants from the T1, T3, T4 and T5 plants increased significantly to between 29 and 36.7 mg/plant in season 1. Shoot P in plants from all the ridges were statistically similar ranging between 447 g/plant and 581.6 g/plant except for plants grown in the T1 amended ridges which had the highest P uptake of 792.5 g/plant. Seed P uptake was in the order of T1 > T3 > T5 >T2 = T4 > T0. Infact seed P uptake in plants from the T1 ridges was 1.89 and 1.3 time higher than seeds from un-amended ridges and T5 amended ridges, respectively. Root N uptake was significantly the highest in plants from the T1 and T3 amended ridges.

The shoot N of 4.10 g/plant was significantly the highest in the plants from the T1 amended ridges. This shoot N uptake was 1.4 g higher than uptake from plants grown in the T5 amended ridges in season 1. (Table 4.8)

In season 2, root P uptake in plants grown in the un-amended ridges was 19.02, similar to uptake in the first season (Table 4.9). Root P uptake was highest in plants from the T1 and T3 amended ridges with uptake of P in roots of plants from the other ridges being statistically similar to those from the un-amended ridges. Shoot P of 955 g/plant was again highest in plants from the T1 ridges. Shoot P uptake in plants from the T1 ridges was more than twice the uptake in the un-amended ridges. Shoot P uptake as was observed in the first season was similar in plants from T2, T3, T4 and T5 amended ridges. Seed P uptake in the second season was statistically similar in plants from the T1, T3 and T5 amended ridges albeit higher than from plants grown in the T2 ridges. In general, level of seed P uptake in the second season were similar to uptake in the first season.

Root N uptake just as was observed in season one was the least in plants from T0, T2 and T4. The highest root N uptake was observed in plants grown in the T1 amended ridges with uptake levels more than twice the levels in plants from the T0, T2 and T4 ridges. Root N uptake of 2.9 mg/plant was the second highest in plants from the T3 ridges with plants from the T5 ridges being the third highest in root N uptake. Shoot N of 3.49 g/plant was again the highest in plants grown in the T1 amended ridges. The shoot N uptake of plants from the other ridges were statistically the same, ranging between 1.94 g/plant in the T0 ridge to 2.48 g/plant in the T4 ridge.

4.3.5 Effect of amendments on residual soil properties

Table 4.10 shows the effects of the amendments on residual soil properties after harvesting mature cowpea plants. The pH in water of the soil at the beginning of the experiment was 6.8 which did not change in the un-amended (T0) and the inorganically amended ridges (T5) as these two ridges recorded residual pHs of 7.0 and 7.1, respectively in season 1. The pHs of soils of the ridges amended with T1 and T3 increased significantly to 7.55 and 7.36, respectively. The residual pHs of the half dose of T1 and T3 which were applied to ridges T2 andT4 did not have any significant increase as they were 7.25 and 7.12.

The EC of the ridges after cultivation were decreased marginally from that at the onset of the experiment (0.6 dS/m) to between 0.34 and 0.45 dS/m. Total carbon which was 11.55 g/kg did not change after the first season trial in the un-amended ridges and the ridges amended with T5 as the concentration was 12.55 g/kg and 13.42 g/kg, respectively (Table 4.10). Residual total C in the T1 ridges increased to 54.4 g/kg and 58.4 g/kg, respectively in the T1 and T3 amended ridges. The T2 and T5 organically amended ridges also had residual carbon contents increasing to 35.38 and 41.73 g/kg, respectively. Residual total N contents in the un-amended (2.8 g/kg), T4 (2.94 g/kg) and T5 ridges (2.82 g/kg) were similar to that at the onset of the experiment (Table 4.10). Residual total N in the T1 and T3 amended ridges were respectively 1.48 and 1.4 times the contents in the un-amended ridges.

Strikingly, total P which was 220.43 mg/kg of which 91% was in the available form at the onset of the experiment decreased sharply to a total P content of 59.0 mg/kg and an available P of a paltry 34.61 mg/kg. Total P of the ridges amended inorganically with TSP decreased from that of the original soil to 73.2 mg/kg of which approximately half was in available form at the end of the first season trial. Total P decreased from that at the onset of the first season trial after amendment of T1 to a residual total P content of 165.2mg/kg of which 23.6% was in the available form. The residual; total and available P in the RHB amended ridges was 129.7 mg/kg and 39.61 mg/kg respectively.

In general, residual total P was in the order of T1 >T3 + T2 > T5 >T0 > T4 with residual available P being in the order of T1 > T3 > T2 > T5 >T0 > T4.

In season 2. The residual pH of the un-amended ridge (T1) and the inorganically amended ridge (T5) was 7.11 and 7.15, respectively and similar to pHs recorded for the same ridges in season 1 (Table 4.11). The T1 and T3 organically amended ridges had the highest pHs of 7.45 and 7.49, respectively.

The T2 and T4 organically amended ridges had residual pHs not significantly higher than the original soil and those of T0 and T5. The residual ECs of soils from all the ridges were low and similar to those of season 1 (Table 4.11) .

Total carbon contents of the residual soils from ridges T0 and T5 were approximately 12.7 g/kg and similar to the contents at the beginning of the trail and those of residual soils from the same treatments in season 1. The highest total carbon content was observed in the soils in ridges T3 and this was 10.38 g/kg higher than the contents in ridges T1. The residual C contents in T2 and T4 were 53.5% and 58% the respective contents in T1 and T3. Residual total N in the un-amended ridges and the inorganically amended T5 were between 2.37 and 2.7 g/kg and similar to residual contents the same ridges in season 1. The T1 amended ridge just as was observed in season 1 had the highest total N content of 4.21 g/kg and similar to content recorded in season 1. The T2, T3 and T4 residual soils had similar total N contents of between 3.19 and 3.49 g/kg.

The residual total P in the un-amended soil was 66.6 mg/kg of which more than 53% was in the available form. The highest residual total P contents of 177.1 mg/kg was observed in the T1 ridges just as was observed in season 1. The residual total P contents in the soils of T3 amended ridges were 161.4 mg/kg, 70 mg/kg more than total P in the T5 amended ridges. The residual total P in the T4 amended ridges were

Table 4. 8 Partitioning of N and P in shoot root and seed of cowpea for season 1

Treatment	Root P (mg/plant)	Shoot P (g/plant)	Seed P uptake (mg/plant)	Root N (mg/plant)	Shoot N (g/plant)
T0	18.56a	447.0a	0.264a	104.2a	2.68a
T1	33.19b	792.5b	0.498e	161.8c	4.10b
T2	20.64a	507.0a	0.332b	94.6a	2.75a
T3	36.71b	486.2a	0.460d	139.3bc	2.58a
T4	29.32b	581.6a	0.312b	107.6ab	3.04ab
T5	31.31b	470.1a	0.381c	118.0ab	2.73a

* Means with the same letters are not significantly different.

Table 4. 9 Partitioning of N and P in shoot root and seed of cowpea for season 2

Treatment	Root P (mg/plant)	Shoot P (g/plant)	Seed P uptake (mg/plant)	Root N (mg/plant)	Shoot N (g/plant)
T0	19.02a	459.2a	0.275a	118.5a	1.94a
T1	33.00c	955.6c	0.465d	262.4d	3.49b
T2	20.90a	569.9ab	0.341b	116.8a	2.29a
T3	28.79bc	524.6ab	0.440cd	209.1c	2.30a
T4	22.62a	603.0ab	0.407c	123.2a	2.48a
T5	23.19ab	689.4b	0.433cd	177.0b	2.42a

* Means with the same letters are not significantly different.

Table 4. 10 Effect of amendments on residual soil properties in season 1*

Treatment	P rate tons P/ha	pH (H_2O)	EC dS/m	TC g/kg	TP mg/kg	Available P mg/kg	TN g/kg
T0	0	7.01	0.42	12.55 a	59.0 a	34.61 a	2.80 a
T1	6.67	7.55	0.45	54.4 d	165.2 d	39.06 b	4.13 c
T2	3.33	7.46	0.44	35.38 b	127.4 c	35.27 a	3.60 b
T3	16.67	7.36	0.39	58.40 e	129.7 c	39.61 b	3.92 b
T4	8.33	7.12	0.37	41.73 c	58.5 a	33.41 a	2.94 a
T5	0.01	7.12	0.34	13.42 a	73.2 b	35.21 a	2.82 a

*EC= electrical conductivity, TC= total carbon, TP= total phosphorus, AV= available summary of results
The legends are the same as described in Table 4.13; means with the same letters are not significantly different.

Table 4. 11 Effect of amendments on residual soil properties in season 2*

Treatment	P rate tons P/ha	pH (H_2O)	EC dS/m	TC g/kg	TP ......mg/kg......	Available P ......mg/kg......	TN g/kg
T0	0	7.11	0.39	12.68 a	66.6 a	35.40 a	2.69 a
T1	6.67	7.45	0.51	46.62 d	177.1 f	38.50 b	4.21 c
T2	3.33	7.24	0.44	24.96 b	135.2 d	36.31 b	3.39 b
T3	16.67	7.49	0.43	57.00 e	161.4 e	38.68 b	3.49 b
T4	8.33	7.19	0.38	33.20 c	72.4 b	35.40 b	3.19 b
T5	0.01	7.15	0.39	12.73 a	91.6 c	34.40 b	2.37 a

*EC= electrical conductivity, TC= total carbon, TP= total phosphorus, AV= available phosphorus, TN=total nitrogen.
The legends are the same as described in Table 4.13; means with the same letters are not significantly different.

almost 45% the contents in the T3 amended ridges. In season 2, the residual available P contents in soils of all the ridges were statistically the same and ranged between 34 and 38 mg/kg (Table 4.11).

4.4 Summary of results

From the two seasons of cowpea cultivation in all the amended soils, it is clear that the cow dung biochar amended ridges especially at the SPR of the soil produced superior plants with better growth parameters and higher yield. It is also clear from the two-season data that the first season produced plants with shorter days to flowering, higher number of nodules, heavier seeds and consequently higher yield than the second season. However, the pattern of the growth parameters were similar in the two seasons Thus, the season 2 efficacy trial validated that of season 1.

CHAPTER FIVE

5.0 DISCUSSION

5.1 Soil characterization

The clay textural classification of the soil indicates a high water-holding capacity soil which with the montmorillonitic nature will hold water for rice production and explains why the Akuse-Asutuare enclave is noted for rice production. The soil will also be sticky when wet, making it difficult for root formation, elongation and proliferation. It therefore, needs amendment to make it more friable. The high clay content also explains the high CEC of 31 cmol/kg and indeed confirms the soil's status as a Vertisol. The medium bulk density of 1.46 Mg/m^3 which falls within the typical range for agricultural soils (Davenport & DeMoranville, 1993) indicates a good balance between soil porosity and compaction. Amendment with biochar will, however, increase soil volume to decrease bulk density and invariably increase porosity for improved upland crop growth especially in the rainy season

The neutral pH of the soil (6.8) would generally make many nutrients readily available in the soil, explaining its very high fertility status. The neutral pH in water of 6.8 is just 0.4 pH units lower than the pKa of orthophosphoric acid (Tan, 1998). At this pH, most of the orthophosphate anions in soil solution will be present as $H_2PO_4^-$ and HPO_4^{2-}, the readily available forms of P. With the high CEC of the soil, it implies that there will be great repulsion of the permanent negative charges of the clay and the orthophosphate ions. This may account for the high availability P (201 mg/kg) in the soil.

The expansive nature of the clay in the soil will also minimize adsorption. Neutral pH will also decrease solubility of Al and Fe and Ca; three cations which precipitate P in most soils. Any added P is not likely to be prone to adsorption through precipitation nor onto clay surfaces. It, therefore, stands to reason that almost 91% of 220 mg/kg total P in the soil was in the available form. The high repulsion and low adsorption of P in the soils also corroborates the very low standard phosphorus requirement of 2 mg/kg.

The neutral pH will make the soil conducive for habitation by microbes to facilitate organic matter decomposition. This may, in part, account for the generally higher total carbon content of the soil than most Ghanaian soils which are generally less than 10 g/kg (Wang et al., 2014). The neutral pH and the high availability of P should promote nodulation of legumes, should the soil be manipulated to have good tilth. It was for this reason that ridges were used as landforms for the trial. It also explains why biochar amended ridges especially those at the full SPR of the soil especially T1 produced cowpea plants with the heaviest and highest number of nodules in the two-season trial. The ridges shed off water to minimize expansion. Addition of CDB at the SPR of the soil coupled with ridging increased soil volume culminating in reduced bulk density. This increased porosity to minimize soil strength. Roots of cowpea plant proliferated as evident in the longer roots of plants from T1 ridges with a consequential increased root P uptake, higher nodule number and weight with a concomitant superior root and shoot N. These eventually translated to taller plants, shorter days to flower, heavier seeds and eventually the highest yields for plants from the T1 ridges.

The low EC of the soil is an indication of minimal salinity and no threat of salt injury to plants. This allows plants to access water and nutrients efficiently, enhancing healthy growth and development. The low EC of the soils despite continuous flooding could be due to the fact that the salts are shed through the landforms used for cultivation in the area. Most upland crops are grown on camber beds at SIREC. The salts may have also been leached out of the soil.

The moderate total N content (2.08 g/kg) is sufficient for legumes, but additional N fertilization might be needed for high N-demanding crops (Havlin et al., 2014). Legumes need an initial amount of available N from the soil (17-34 kg/ha) before BNF kicks in effectively. The N level was enough of cowpea production and explains the rationale for not applying basal N in the experiment. The low C:N ratio implies that immobilization of N will be hindered and added organic matter is likely to decompose very fast affirming the high fertility status of the soil.

5.2 Feedstock and Biochar Characterization

The difference in pH of the rice husk and cow dung could be as a result of the differences in the composition of the feedstocks. The cow dung is the digestive product of mainly forage while the rice husk is a component of a seed with high Si content. The cow dung has higher EC of 3.25 dS/m more than the rice husk implying that there are more cations and anions in the former than the latter. Perhaps, the higher liberated basic cations in the cow dung than the rice husk might have given the former, its higher pH. With fermentation in the gut leading to methane production, the digestive product, cow dung, must have liberated Ca from the cell wall of the forage (Owens et al., 2016). The rumination process and further digestion of plant material by the cow might have given the feedstock the initial slightly alkaline pH of 7.99.

This methane production through rumination may, in part, also explain the 155 g/kg more C in the rice husk than the cow dung. There was loss of C through methane production during the dung production in the gut of the cow. With CH_4 production and a concomitant loss of C from cow dung, N and P concentration per unit mass would increase. This resulted in a lower C:N ratio of the final product as was exhibited by the 6.49 value of the cow dung. It also explains the higher C but lower N in the rice husk with a higher C:N ratio of 61.2 This may also account for the 8.9 times more total P content in the cow dung than its rice husk feedstock counterpart Getabalew et al., (2019).

Charring the cow dung to the biochar did not significantly alter pH as change in pH was below 0.5 pH units (Nartey et al., 2000). However, charring the rice husk significantly increased pH by 1.88 pH units. This increase in pH might be due to breakdown at high pyrolysis temperature of acid functional groups such as carboxylic acids (COOH) and phenolic groups (Kim et al., 2011; Ahmad et al., 2014; Nartey et al., 2023). This aligns with existing research suggesting that the breakdown of acidic groups, increases availability of exchangeable cations like Ca and Mg. The potential release of alkaline salts during pyrolysis also contribute to the observed increase in biochar pH (Eduah et al., 2019; Frimpong-Mano 2019). This is further corroborated by the basic cations persistent in the biochar derivatives of cow dung and rice husk. With rumination and fermentation, some of these groups might have already been lost in the cow dung, hence the non-significant change in pH after charring.

These two biochar types with their slightly alkaline pH and low available basic cations may not be effective as liming material. Large amounts may have to be applied to raise the pH of acidic soils. They may however, be conducive for use in neutral soils as P sources with no adverse change in pH and EC as relatively low amounts per/ha would be applied as evident in this study.

The higher carbon content of the RHB than the CDB was due to the higher contents of C in the rice husk feedstock than the cow dung feedstock. The high temperature (480°C) used during charring caused a significant portion of the unstable nitrogen (due to digestion) in the feedstock to be vaporized and lost. This accounted for the decreased N in the cow dung biochar (CDB). With elevated C and decreased N, during charring, it stands to reason that the CDB had an increase in C:N ratio from 6.49 to 17.4. The rice husk had a more stable N because, the feedstock prior to charring, had not been modified. Consequently, it was converted to the more heterocyclic pyridine to increase its concentration during charring (Tomczyk et al., 2020). The increase in C content of rice husk after charring was not commensurate with the almost doubling of its N content. Thus, the C:N ratio reduced from 61.23 in the feedstock to 47.14 after charring of rice husk.

The high C:N ratio of rice husk biochar compared to cow dung biochar from Table 4.2, indicates the slow availability of nitrogen in RHB. This may explain the general higher uptake of N in the cowpea shoots and roots from T1 ridges than T3 ridges in the two-season trial. While not ideal for immediate plant growth (Lehmann and Joseph, 2015), RHB may be suitable in the long term for carbon sequestration.

The increase in both total phosphorus and available P in the biochar compared to their original feedstock could have resulted from the concentration effect caused by the volatilization of oxygen, hydrogen, and nitrogen during pyrolysis (Lehmann and Joseph, 2015). As these elements volatilize, the phosphorus becomes more concentrated in the remaining biochar material. The higher 16% availability of CDB's total P compared to RHB's 14% of total P coupled with the 3.34 times more available P in CDB than RHB suggest that CDB could be a better alternative for readily available phosphorus for plants. This is corroborated by the fact that at the SPR of the soil, CDB amended ridges produced cowpea plants with better phenological properties and superior yield in the two seasons. It is, however, imperative to undertake a cost benefit analysis as to ascertain the profitability or otherwise of using CDB as a P source at the SPR of the soil.

5.3 Effects of amendments on cowpea growth and development of cowpea

The results from the study showed that the CDB amendment at the SPR of the soil amendment significantly improved the growth parameters of cowpea in both first and second seasons over the un-amended and TSP amended ridges. The results also showed that the pattern of growth and development of cowpea in the two seasons had similar patterns and thus the second seasons results validated that of the first season.

Phosphorus is the main nutrient that controls root formation. Thus, treatments with more available P, are likely to influence cowpea growth better. The residual pHs of all the amendments were neutral implying that P availability would be optimum with respect to soil reaction. This is corroborated by the high Olsen available P (> 30 mg/kg) in the soils after harvest. The fact that for the two seasons, T1 showed consistently the highest residual available P after harvest, highest root P uptake, longest roots, tallest plants, highest shoot N uptake, shortest days to flower and highest yield go to show that T1 was superior to all the other amendments for cowpea production in the Akuse Series. The highest available P in the T1 amended ridges indicates that during the growing period, P was the most readily available. Amending the soil with 6.67 tons/ha of CDB to attain the SPR of the Akuse Series might have reduced bulk density to increase porosity. With the highest available P in the T1, amended ridges, root initiation was fastest leading to longest roots and mass encouraging better root P and N uptake. The highest root uptake and length of roots translated to better shoot P and N uptake. Plants from the T1 plants, therefore, became the tallest and had better interception of light. This translated to better shoot and N uptake and consequently the heaviest biomass. With better assimilation of nutrients, especially the major N and P, days to flowering was shorter by 2.5 days compared to the inorganically amended ridges which is the farmer's practice. Yield was subsequently highest in the T1 amended ridges. Yield from the T1 amended ridges was on average 0.48 tons/ha per season more than from the inorganically amended ridges. It also explains why yields from the T1 ridges were 0.98 and 0.6 higher in the two seasons over those from the un-amended ridges.

In general, there were taller cowpea plants on all the ridges and shorter days to flower in addition to higher yields in the first season than in the second season. This is because the first season trial was in the period between 10th June 2023 and 8th August 2023, coinciding with the peak of the rainy season at Akuse. The second season started on 7th July and stretched to 9th September 2023. Majority of the days for the season 2 trial were in late July and the whole of August which coincided with a dry spell. The higher and better distribution of rainfall during the first season trial (Appendix B) might have accounted for the superior growth parameters of the cowpea plant, irrespective of treatment.

The T1, T3 and T5 amended ridges were all amended to the standard P requirement of the soil implying that they all had equal amounts of available P in solution at the time of sowing. There were generally similar residual available P levels in these ridges after harvest especially in the first season. The fact that the cowpea plants exhibited better growth parameter in the two seasons in T1 than plants from the T3 and T5 ridges implies that there was better uptake of nutrients by plants from the T1 plants. This is corroborated by higher root and shoot P and shoot N in plants from T1 than those from T3 and T5. This is also evident in the superior nodule numbers and mass in plants from T1 over the two seasons than in the plants from T3 and T5.

The lower C:N ratio of the CDB coupled with a much higher residual total N in the T1 ridges than the T3 and T5 suggest a much higher availability of N in the T1 mended ridges. This reflected in higher N uptake in shoots and ultimately heavier biomass of plants in the T1 ridges than in the T3 and T5 ridges. The significantly highest number of nodules which were heaviest even though they were not incised to test for presence of leg-haemoglobin may also account for more N uptake in shoot of plants from the T1 ridges than their counterpart from T3 and T5. The higher availability of P in the T1 ridges which led to the highest root uptake of P may have contributed to better nodule formation and weights.

Seed quality in terms of uptake being best in the T1 plants in the first season and among the best three with plants from T3 and T5 ridges in the second season is also a reflection of better root and shoot P uptake. With superior root and consequently, shoot uptake, it stands to reason that more P would be portioned into the seed.

The fact that there were generally no significant differences in yield of cowpea from the T2, T3, T4 and T5 amended ridges over the un-amended ridges suggests that there was no response to fertilization. It is, therefore, not advisable to amend the ridges with RHB at both half and full SPR, and at half SPR with CDB. It is also not prudent to fertilize cowpea grown in the Akuse Series with TSP at SPR. This is to save cost as yield increases will not be commensurate with cost of fertilization (Tisdale et al., 2013).

5.4 Effects of amendments on some soil residual properties

There was no significant change in pH of the inorganically amended and the un-amended residual ridges compared to the original soil mainly because the T0 and T5 ridges did not contribute to production of either H^+ or OH^-; ions which alter pH. The marginal 0.3 pH units increase could be due to non-significant ammonification reactions in the original soil as in equation 5.1 which did not lead to a 0.5-unit change in pH (Nartey et al., 2000).

$$R\text{-}NH_2 + 2H_2O \rightarrow OH^- + R\text{-}OH + NH_4^+ \qquad [5.1]$$

The T1 and T3 ridges were amended with 6.67 and 16.67 tons/ha of CDB and RHB, respectively. These added appreciable amounts of available bases contributed significantly to the > 0.5 unit in increase in pH of the residual soils from 6.8 of the original soil. The slightly alkaline pH of 8.25 of CDB and 7.87 of the RHB might have; in part, also contributed to the change in pH considering the tonnage of the biochar types applied. The fact that residual T2 and T4 ridges did not record significant changes in pH implies that the respective 3.33 and 8.33 tons/ha of CDB and RHB applied was not enough to alter pH.

According to the U.S. Salinity Laboratory Staff (1954), a soil with EC of the saturated paste extract of more than 4 dS/m is considered saline The EC of all the remedial soils were very low and less than 0.7 dS/m even for the organically amended ridges indicating that there will be no salt injury nor salinity threat to subsequent crops grown on the residual ridges. It is, however, necessary to monitor the EC of the

T1 ridges after each season in view of the high EC of the CDB. This is to avoid salinization of the soil.

To attain the SPR of the soil, 10 tons/ha more of RHB than CDB was applied even though the former had 199.47 g/kg total C more than CDB. The higher amount of RHB coupled with its higher total C concentration contributed to the highest accumulation of total C in the residual soil. For carbon sequestration, therefore, it is better to use RHB than CDB. This is further supported by the higher C:N ratio of 47.14 compared to the 17.4 of CDB. Higher C:N ratio will confer better stability of C. Total P which was 220.43 mg/kg of which 91% was in the available form, decreased sharply to 59 and 66.6 mg/kg in season one and season two, respectively due to uptake by plants grown in the T0 ridges. This is corroborated by substantial P uptake in roots shoot and seeds from plants grown in the un-amended ridges. The high Olsen available P in the residual T0 ridges of over 30 mg/kg is far higher than available P in most Ghanaian soils. This further confirms the high availability of P in the original soil and explains the non-responsiveness of the TSP fertilization (Abekoe et al., 2011). All P amendments except rice husk biochar at half rate (T4) significantly increased total soil phosphorus (TP) compared to the control (T0). However, the highest increase was observed in cow dung biochar at full rate (T1). This suggests that biochar amendments, particularly at a full rate, can be effective in raising total soil phosphorus levels. The high residual available P of about 35 mg/kg is high enough to sustain non legume crop production. For legume production, especially for N fixation, there must be external application of P, AHDB (2023).

The higher total P fractions, especially in the T1 and T3 amended ridges than the T5 amended ridges even though they were all applied to meet the SPR of the soils shows that the T1 and T3 ridges have better P reserves which can mineralize later for subsequent crop production. The slightly higher residual available P in the T1 and T3 ridges over the T5 ridges especially in season 1, goes to show that the organic amendments, particularly the CDB is superior to the inorganic P fertilizer, TSP when applied to the Akuse Series.

The superior total N contents in the residual T1, T2 and T3 ridges than the T0 and T5 counterparts in both seasons is likely due to the inherent total N from the CDB and RHB added to the ridges indirectly through P application. The CDB and RHB contain total N unlike the TSP. The similar residual TN contents of the T0 and T5 ridges which were marginally higher than contents at the onset of the trials suggest that these two treatments had similar total N addition to the soil which could not have been through external application.

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The study clearly indicated that cow dung and rice husk when pyrolyzed can produce amendments with high available P concentration. The study has shown that amending cow dung biochar to ridges of Akuse Series at the standard phosphorus requirement of the soil produces cowpea with better growth parameters and higher yield than when the crop is amended with triple super phosphate at the SPR of the soil.

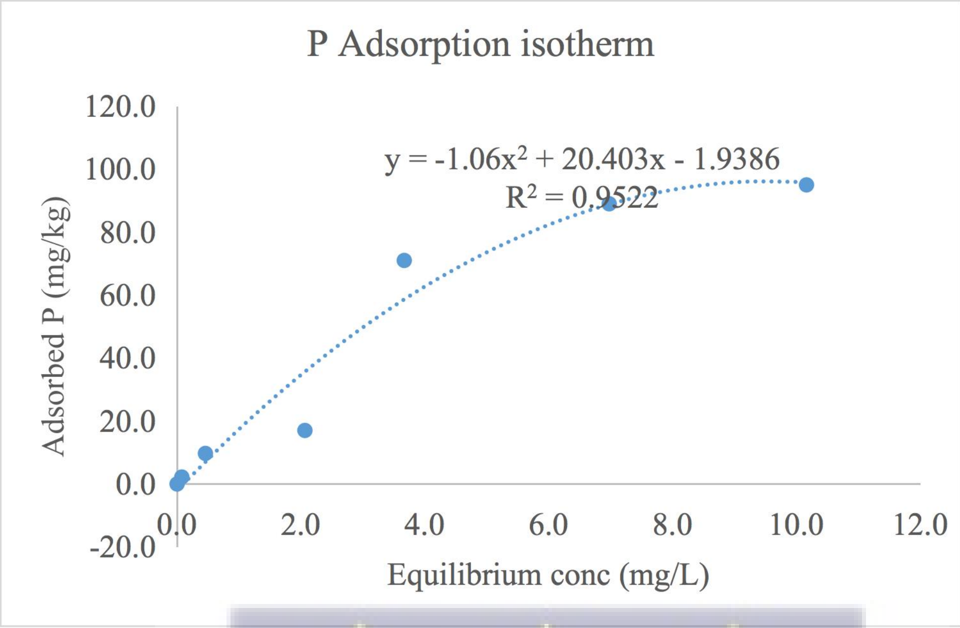
The study demonstrated that the rice husk biochar applied at half and the full SPR of the soil in addition to the cow dung biochar applied at half the SPR and TSP at the SPR of the soil did not increase the yield of cowpea over that of the un-amended soil.

Amendment of the Akuse Series with cow dung biochar and rice husk biochar at both half SPR and full SPR of the soils allowed the soil to remain neutral in reaction with no threat to salt injury to crops

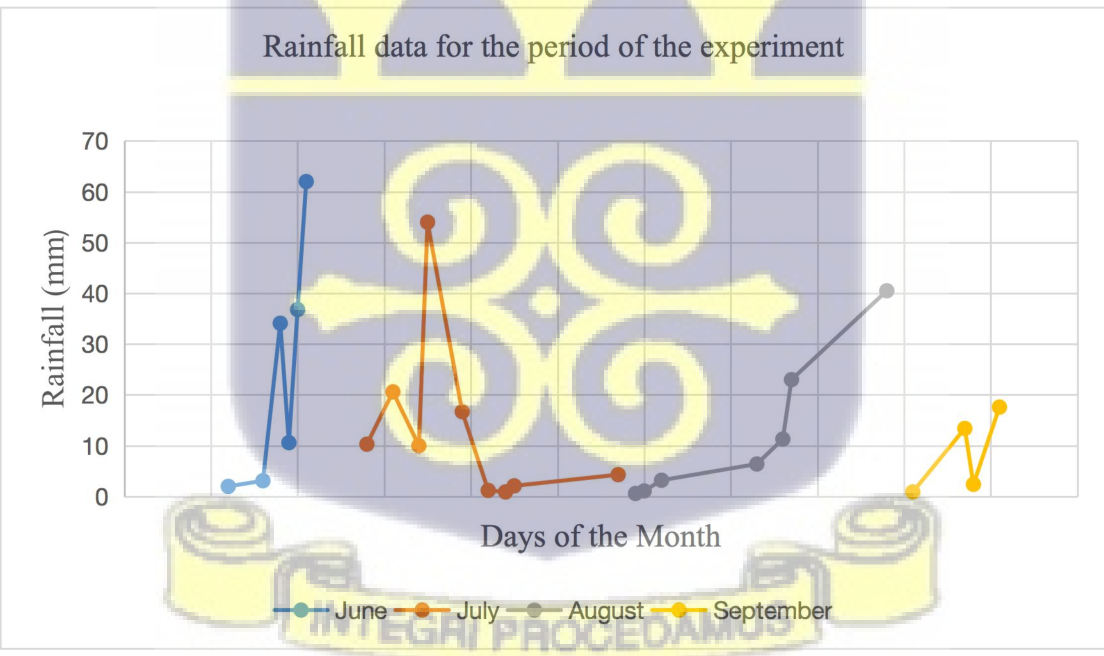
6.2 Recommendations

- It is recommended for farmers cultivating cowpea on ridges on Akuse Series with high inherent P to amend the soil with cow dung biochar at 6.67 tons/ha at the SPR of the soil for increased yield.
- It is not advisable for farmers to grow cowpea on the Akuse Series inherently high in P to fertilize the soil with triple super phosphate
- Further research might be needed to ascertain the residual effect of total and available P after CDB application at the SPR of the soil on subsequent cowpea cultivation.
- A cost benefit analysis must be carried out to ascertain if amending the soil with cow dung biochar at the SPR of the soil is profitable in view of the drudgery and cost involved in the charring and application.

APPENDIX



Appendix A: Relationship between equilibrium P concentration and P adsorbed



Appendix B: Amount and distribution of rainfall over the two seasons

REFERENCES

Abekoe, B. A., & Agorhoro, J. A. (2011). Evaluation of Low Phosphorus Tolerance of Rice Varieties in Northern Ghana. Ghana Journal of Agricultural Science, 44(2), 79-88.

Acquaye & Owusu-Bennoah, 1989 (Cited in: Amankwa, B. T., & Kwakye, P. K. (2007). Fertilizer Phosphorus Fractions and their Availability to Maize on different Landforms on a Vertisol in the Coastal Savanna Zone of Ghana. West African Journal of Applied Ecology, *11*(1).

Acquaye D. K. (1986). Agricultural sector rehabilitation credit. Fertilizer imports study. University of Ghana, Legon.

Acquaye D.K. and Owusu-Bennoah E. (1989). Chemical characterization of some Vertisols in Ghana. In vertisols Management in Africa. Proceedings of a Workshop held at Harare, Zimbabwe 16-21 January 1989.

Acquaye, D. K., & Owusu-Bennoah, E. (1989). Fertilizer Phosphorus Fractions and their Availability to Maize on different Landforms on a Vertisol in the Coastal Savanna Zone of Ghana. African Journals Online, 11(2).

Acquaye, D.K., & Owusu-Bennoah, E. (1989). Phosphorus in Soils of Ghana. Technical Report, CSIR-Soil Research Institute, Kwadaso, Kumasi, Ghana.

Adiku, S., Nartey, E., Tsatsu, D., Koomson, E., Marschner, B., Peassah, S., Lawson, I., (2015). Preliminary Studies of Biochar Effects on the ShrinkSwell Properties of a Typic Calcic Ustert (Vertisols) in Ghana. “Unpublished Result.” Summer School 2015, Bochum, Germany.

Adusei, B., Buah, S. S., Offei, S. K., & Agyeman, K. O. (2017). Phosphorus fertilizer application and inoculation with Bradyrhizobium sp. influence nodulation, growth, and yield of cowpea in a sandy loam soil. African Journal of Agricultural Research, 12(27), 2233-2240.

Adusei, E. K., Addai, K., Ofori, P., & Quaye, W. (2017). Phosphorus sorption and desorption characteristics of some selected soils in Ghana. Agricultural and Food Science, 26(3), 185-191. Agr Ecosyst Environ. 191: 83–91.

AHDB. (2023, July 12). Identification of critical soil phosphate (P) levels for cereal and oilseed rape crops on a range of soil types. Retrieved from https://ahdb.org.uk/identification-of-critical-soil-phosphate-p-levels-for-cereal-and-oilseed-rape-crops-on-a-range-of-soil-types

Ahmad, M., Usman, M., Zheng, H.,的地方性知识 (Local Knowledge), & Liu, Y. (2014). Physico-chemical characteristics of biochar produced from mature sugarcane bagasse under different pyrolytic conditions. Journal of Analytical and Applied Pyrolysis, 109, 179-186.

Ahmad, N., & Mermut, A. R. (1996). Vertisols of Ghana: Their characterization, classification, and management. Geoderma, 72(1-2), 115-131.

Alam, M. M., and Ladha, J. K. (2004). Optimizing phosphorus fertilization in an intensive vegetable–rice cropping system. Biol. Fertil. Soils 40, 277–283.

Alam, M., & Ladha, J. K. (2004). Biofertilizers: A sustainable way to increase crop production. Current Science, 86(12), 1503-1509.

Al-Wabel, M. I., Al-Omran, A., El-naggar, A. H., Nadeem, M., & Usman, A. R. A. A. (2013). Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. Bioresource Technol-ogy, 131, 374–379.

Amonette JE, Joseph S (2009) Charecteristics of biochar: microchemical properties. In: Lehmann J, Joseph S (eds) Biochar for environmental management science and technology. Earthscan, London.

Asiedu, K. A., Owusu-Bennoah, E., Ofori-Frimpong, K., & Tetteh, F. M. (2001). Characterization of Vertisols in the Coastal Savanna Zone of Ghana. Communications in Soil Science and Plant Analysis, 32(5-6), 811-821.

Asiedu, K. O., Adjei, K. S., & Opoku, A. (2021). Distribution of soil types in the coastal savannah zone of Ghana. Journal of the Ghana Science Association, 23(1), 1-10.

Avornyo, V.K. Adjadeh, T.A. and Amatekpor, J.K. 2013. Morphological, Chemical and Physical properties of two pan soils in the Lower Volta Basin of Ghana. West African Journal of Applied Ecology. 21 (2) 63-77.

Bai, Z., Li, H., Yang, X., Zhou, B., Shi, X., Wang, B., et al. (2013). The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. Plant Soil 372, 27–37.

Bai, Z., Li, X., Yang, X., & Zhang, J. (2013). Phosphorus availability and maize yield in response to long-term application of organic and inorganic fertilizers on a calcareous soil. Field Crops Research, 154, 13-21.

Bohme, L., Lehmann, J., Nguyen, B. T., & Joseph, S. (2005). Black carbon effects on soil properties and nutrient uptake from compost. Soil Science Society of America Journal, 69(6), 1684-1692.

Brady, N. C., and Weil, R. R. (2008). The Nature and Properties of Soils, 4th Edn. Upper Saddle River, NJ: Prentice Hall.

Brady, N. C., Weil, R. R., & Brady, N. C. (2008). The nature and properties of soils (14th ed.). Pearson Education.

Brantley, S. L. (2014). Biochar: A sustainable solution to climate change and soil degradation? Science, 345(6197), 519-522.

Brierley, G., Fryirs, K., Mtakwa, P., & Ng'ang'a, F. (2011). Understanding the spatial and temporal variability of soil erosion in the East African Rift Valley using remotely sensed imagery. Remote Sensing of Environment, 115(11), 2939-2950.

Brierley, J.A., H.B. Stonehouse, and A.R. Mermut. 2011. Vertisolic soils of Canada: Genesis, distribution, and classification. Can. J. Soil Sci. 91:903-916.

Carrier, M., Ramier, D., Bohrer, V., Chou, N., & Nguyen, C. (2012). Biochar influence on water quality in agricultural fields: A review. Water Research, 46(20), 6438-6453.

Carvalho M, Castro I, Moutinho-Pereira J, Correia C, Egea-Cortines M, Matos M, Rosa E, Carnide V, Lino-Neto T, 2019. Evaluating stress responses in cowpea under drought stress. J. Plant Physiol. 153001.

Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., & Joseph, S. (2008). Agronomic values of greenwaste biochar as a soil amendment. Australian Journal of Soil Research, 46(5), 439-449.

Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., & Joseph, S. (2007). Agronomic values of greenwaste biochar as a soil amendment. Australian Journal of Soil Research, 45(8), 629-634.

Chatterjee R, Bandyopadhyay S, 2017. Effect of boron, molybdenum and biofertilizers on growth and yield of cowpea (Vigna unguiculata L. Walp.) in acid soil of eastern Himalayan region. J. Saudi Soc. Agric. Sci. 16:332-6.

Chen, T., Zhang, Y.X., Wang, H.T., Lu, W.J., Zhou, Z.Y., Zhang, Y.C. & Ren, L.L., (2014). Influence of pyrolysis temperature on characteristics and heavy metal adsorptive performance of biochar derived from municipal sewage sludge. Bioresource Technology. 164, 47-54

Chen, Y., Li, L., Lehmann, J., Joseph, S., Crowley, D., & Huang, Z. (2011). Biochar soil amendment increases maize nutrient availability, retention and yields in field trials. Nutrient cycling in agroecosystems, 91(1), 141-155.

Cheng, C. H., Lehmann, J., & Engelhard, M. H. (2006). Oxidation of black carbon by manganese oxides in alkaline soils. Geochemical Transactions, 7(1), 1-13.

Cheng, C. H., Lehmann, J., & Engelhard, M. H. (2008). Oxidation of black carbon by manganese oxides in alkaline soils. Geochemical Transactions, 7(1), 1-13.

Chintala, R., Schumacher, T. E., & Malo, D. D. (2013). Phosphorus sorption characteristics of biochars produced from dairy manure and crop residues. Journal of Environmental Quality, 42(6), 1726-1733.

Chowdhury, R., Dick, W. A., & Schmidt-Rohr, K. (2016). Nitrogen and phosphorus transformations in biochar amended soil during four-year field trial. Soil Biology and Biochemistry, 99, 201-212.

Clough, T. J., Lehmann, J., & Gaunt, J. (2010). Long-term and residual effects of biochar on nitrous oxide emissions from a tropical soil. Environmental Science & Technology, 44(20), 7984-7989.

Cordell, D., Drangert, J. O., & White, S. (2009). The story of phosphorus: Global phosphorus scarcity and the need for a new paradigm. Ambio, 38(2), 93-98.

Coulombe, C. E., Chanasyk, D. S., Zentner, R. P., & Curtin, D. (1996). Influence of cropping system on physical properties of a Vertisol. Canadian Journal of Soil Science, 76(2), 259-267.

Davenport, J.R., & DeMoranville, C.J. (1993). A survey of several soil physical characteristics of cultivated cranberry bog soils in North America. Communications in Soil Science and Plant Analysis, 24(13-14), 1769-1773.

DeLuca, T.H., MacKenzie, M.D. & Gundale, M.J. (2009). 'Biochar effects on soil nutrient transformations', in Lehmann, J. and Joseph, S. Biochar for environmental management: science and technology, Earthscan, United Kingdom: 251–70.

Demirbas A (2004) Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues. J Anal Appl Pyrol 72:243–248

Ding, Y., Liu, Y. C., Wu, W., Shi, D. Z., Yang, M., & Zhong, Z. K. (2011). Evolution of biochar properties and its impact on adsorption of ammonium and nitrate from aqueous solution. Environmental Pollution, 159(8), 2020-2027.

Downie, A., Carswell, A., Mackowiak, C., Crossley, P., & Sohi, S. (2009). Biochar as a soil amendment: A review of its effects on soil properties and plant growth. GCB Bioenergy, 1(1), 266-276.

Downie, A., Evans, K., Biochar Research Network, & Biochar Research Network. (2009). Biochar for environmental management: Science, technology and implementation (2nd ed.). Routledge, London, UK.

Duku, M. H., Gu, S., & Ben Hagan, E. (2011). A comprehensive review of biomass resources and biofuels potential in Ghana. Renewable and Sustainable Energy Reviews, 15(4), 404-415.

Duku, M. H., Gu, S., & Ben Hagan, E. (2011). Biochar production potential in Ghana-A review. Renewable and Sustainable Energy Reviews, 15(9), 3539-3551.

Duku, M. H., Owusu-Bennoah, E., & Quansah, G. W. (2011). Biochar production, potential benefits and challenges in Ghana. Agriculture and Biology Journal of North America, 2(4), 692-701.

Eduah, J. O. (2019). Phosphorus availability and uptake by plants in acidic soils: A review. Journal of Soil Science and Environmental Management, 10(8), 190-202.

Eduah, J. O., Olayinka, K. O., Alo, M. N., & Olayiwola, M. O. (2019). Biochar: A sustainable soil amendment for carbon sequestration. Agronomy, 9(8), 472.

El-Naggar, A. A., El-Naggar, M. A., & Abdel-Aal, E. S. (2019). Biochar as a soil amendment for improving crop production and soil properties: A review. Journal of Soil Science and Agricultural Engineering, 10(10), 1-11.

Eriksson, J., Ehlert, P., & Hultgren, J. (2015). Phosphorus transport in agricultural soils—Modelling approaches and importance of different pathways for surface and subsurface losses. Geoderma, 237-238, 34-46.

FAO/UNESCO (1990). Soil Map of the world, revised legend. World Soils Resource Report 60. FAO, Rome. 41 pp.

Fox, R. L., & Kamprath, E. J. (1970). Phosphate Sorption Isotherms for Evaluating the Phosphate Requirements of Soils1. Soil Science Society of America Journal, 34(6), 902.

Frimpong-Manso, E., Adjadeh, T. A., & Darko, D. A. (2019). Use of Corn Cob and Rice Husk Biochar as Liming Materials in Acid Soils. 27(2), 32–50.

Frossard, E., Bühler, S., Morel, C., & Stauffacher, W. (2000). Phosphorus in agricultural soils: A review of phosphate desorption and its implications for phosphorus availability to plants. Plant and Soil, 221(1), 1-15.

Gérard, F. (2016). Phosphorus dynamics in soil: a review. Agronomie, 36(1), 1-15.

Gaskin, J. W., Steiner, C., Harris, K., Das, K. C., Bibens, B., & Lehmann, J. (2008). Effect of low-temperature pyrolysis biochar on soil nutrient retention and availability. Communications in Soil Science and Plant Analysis, 39(15-16), 2235-2250.

Getabalew, M., Alemneh, T. and Akeberegn, D. (2019) Methane Production in Ruminant Animals: Implication for Their Impact on Climate Change. Concepts of Dairy & Veterinary Sciences, 2, 204-211.

Glaser, B. (2002). Charcoal and soil fertility: Black carbon and its influence on the properties and functions of soils. In J. Lehmann, D. C. Kern, B. Glaser, & W. Zech (Eds.), Amazonian dark earths: Origin, properties, management (pp. 267-279).

Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001). The "terra preta" phenomenon: A model for sustainable agriculture in the humid tropics. Naturwissenschaften, 88(1), 37-41.

Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—A review. Biology and Fertility of Soils, 35(4), 219-230.

Grant, C. A., Flatman, P., & Clarkson, D. T. (2005). The regulation of root hair development in Arabidopsis thaliana by phosphate availability. Plant, Cell & Environment, 28(2), 451-461.

Gupta, S., Gupta, G.K., Mondal, M.K., 2019. Slow pyrolysis of chemically treated walnut shell for valuable products: effect of process parameters and in-depth product analysis. Energy 181, 665–676.

Haruna , A.T. Asare, E.A. Bediako, and F. Kusi, (2018). Farmers and Agricultural Extension Officers Perception of Striga gesnerioides (Willd.) Vatke Parasitism on Cowpea in the Upper East Region of Ghana

Haruna, I. M., & Aliyu, M. B. (2011). Phosphorus status of soils of the semi-arid tropics of Nigeria and its implications for cowpea (Vigna unguiculata L.) production. African Journal of Plant Science, 5(4), 224-229.

Haruna, I. M., Aliyu, M. B., & Itodo, G. A. (2011). Effect of phosphorus fertilizer application on nodulation, growth, and yield of cowpea (Vigna unguiculata L.) in a sandy loam soil of the semi-arid tropics of Nigeria. African Journal of Agricultural Research, 6(5), 1102-1107.

Harvey, O. R., Herbert, B. E., Kuo, L. J., Louchouarn, P., Amonette, J. E., & Chang, C. C. (2011). Role of biochar in climate change mitigation and adaptation. In: Biochar for environmental management: Science, technology and implementation (J. Lehmann & S. Joseph, eds.), 2nd ed., Routledge, London, UK, pp. 43-73.

Harvey, O.R., Herbert, B.E., Rhue, R.D., Kuo, L.J., (2011). Metal interactions at the biochar-water interface: energetics and structure-sorption relationships elucidated by flow adsorption microcalorimetry. Environmental Science and Technology. 45, 5550-5556

Harvey, P. R., Warren, R. A., and Wakelin, S. (2009). Potential to improve root access to phosphorus: the role of non-symbiotic microbial inoculants in the rhizosphere. Crop Pasture Sci. 60, 144–151.

Hassan, M., Ahmed, A., & Khattak, S. G. (2012). Biochar and its potential applications in agriculture and environment: A review. Journal of the Saudi Society of Agricultural Sciences, 11(1), 23-31.

Havlin, J. L., Beaton, J. D., Tisdale, S. L., & Nelson, W. L. (2014). Soil fertility and fertilizers: An introduction to nutrient management (6th ed.). Pearson Education Limited.

Herath, H. M. V. U., Camps-Arbestain, M., Hedley, M. J., Singh, B. K., & Murrell, T. G. (2013). Effect of biochar on phosphorus availability and ryegrass growth in a phosphorus-fixing soil. Nutrient Cycling in Agroecosystems, 96(2-3), 263-274.

Hinsinger, P. (2001). Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. Plant Soil 237, 173–195.

Hossain, M. K., Strezov, V., Yin, H., & Chen, P. (2011). Pyrolysis characteristics and basic properties of biochar produced from different biomass wastes. Bioresource Technology, 102(15), 7385-7391.

Hunt, J. A., Bird, M. I., De la Rosa, D. J., & Jones, R. J. (2007). The influence of biochar additions on nitrogen availability and leaching in a sandy soil. Soil Science, 172(7), 527-536.

IUSS Working Group. (2006). World reference base for soil resources 2006: A framework for international classification, correlation and communication and is the fifth edition of the FAO Legend. World Soil Resources Reports No. 103. FAO, Rome.

Jien, H. L., & Wang, S. L. (2013). Effects of biochar on soil properties and crop productivity in a coastal saline soil. Soil Science and Plant Nutrition, 59(1), 104-111.

Jin, Y., Liang, X., He, M., Liu, Y., Tian, G., & Shi, J., (2016). Manure biochar influence upon soil properties, phosphorus distribution and phosphatase activities: a microcosm incubation study. Chemosphere. 142, 128-135.

Johnston, A. E., Poulton, P. R., & Coleman, K. (2014). Phosphorus: Global issues, sustainable management and closing the cycle. CABI.

Johnston, A. E., Poulton, P. R., Fixen, P. E., and Curtin, D. (2014). Phosphorus: its efficient use in agriculture. Adv. Agron. 123, 177–228.

Joseph, S., Peacocke, C., Lehmann, J. & Munroe, P. (2009). Developing a biochar classification and test methods. In: Biochar for environmental management: science and technology (eds J. Lehmann & S. Joseph), pp. 107–126. Earthscan, London; Sterling, VA.

Kahn, J. R., & Jorgensen, J. H. (2009). Phosphorus availability in the rhizosphere: Implications for plant nutrition and mycorrhizal symbioses. Plant Physiology, 151(3), 550-559.

Kan, T., Van Zwieten, L., Lehmann, J., Joseph, S., Masiello, C. A., Camps-Arbestain, M., ... & Paz-Ferreiro, J. (2016). Biochar: A negative emission pathway and soil amendment. Nature Climate Change, 6(4), 500-506.

Kapoor, V., Kumar, A., & Singh, B. (2020). Pyrolysis: A thermochemical conversion technique for biochar production and its applications. Bioresource Technology, 305, 123134.

Khan, K. S., and Joergensen, R. G. (2009). Changes in microbial biomass and P fractions in biogenic household waste compost amended with inorganic P fertilizers. Biores. Technol. 100, 303–309.

Kim, K.H., Kim, J., Cho, T., Choi, J.W., 2012. Influence of pyrolysis temperature on physicochemical properties of biochar obtained from the fast pyrolysis of pitch pine (Pinus rigida). Bioresour. Technol. 118, 158–162.

Kim, W.-S., Jung, S.-H., Lee, M.-W., & Park, Y.-K. (2011). Influence of pyrolysis temperature on physicochemical properties and heavy metal immobilization of biochar from rice straw. Science of the Total Environment, 409(11), 2287-2295.

Knicker, H. (2007). How does fire affect the nature and stability of soil organic nitrogen and carbon? A review on Biogeochemistry. 85, 91–118.

Laird, D. A., Anderson, R. C., Donne, D. C., Morris, P., Reeburgh, W. S., Tiemann, L. K., & Lehmann, J. (2010). Guidelines for biochar use as a soil amendment. USDA Natural Resources Conservation Service.

Laird, D. A., Brown, R. C., Amonette, J. E., & Lehmann, J. (2009). Review of the pyrolysis platform for coproducing bio-oil and biochar. Biofuels, Bioproduct and Biorefining. 3, 547-562

Leal, I. R., van Groenigen, J. W., de Deyn, G. B., & Cardoso, E. J. B. N. (2014). Soil organic matter contributes to phosphorus availability in tropical rainforests. Biogeochemistry, 119(1-3), 339-353.

Lehmann, J. (2006). Biochar soil management on highly weathered soils in the tropics. In Biochar for environmental management (pp. 105-124). Springer.

Lehmann, J. (2009). Bio-energy in the black. Frontiers in Ecology and the Environment, 7(6), 389-395.

Lehmann, J., & Joseph, S. (2015). Biochar for environmental management: Science and technology.

Lehmann, J., Kern, D.C., Glaser, B., and Woods, W.I. 2003. Amazonian Dark Earths: Origin, Properties and Management. Kluwer Academic Publishers, The Netherlands.

Lehmann, J., Pereira da Silva, Jr., J., Steiner, C., Nehls, T., Zech, W., & Glaser, B. (2006). Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil, 249(2), 343-357.

Lynch, J. P., and Brown, K. M. (2008). “Root strategies for phosphorus acquisition,” in The Ecophysiology of Plant-Phosphorus Interactions. eds P. J. White and J. P. Hammond (Dordrecht: Springer),

MacCarthy, D.S., Darko, E., Nartey, E.K., Adiku, S.G.K., Tettey, A., (2020). Integrating biochar and inorganic fertilizer improves productivity and profitability of irrigated rice in Ghana, West Africa. Agronomy 10, 1–23.

Major J, Steiner C, Downie A, Lehmann J., 2009. Biochar effects on nutrient leaching. In Lehmann J, Joseph S, editors. Biochar for environmental management: Science and Technology. pp. 271–287.

Major, J., Lehmann, J., Rondon,M., Goodale, C., 2010. Fate of soil-applied black carbon: downward migration, leaching and soil respiration. Glob. Chang. Biol. 16, 1366–1379.

Malhotra, H., Vandana, S. Sharma and R. Pandey (2018). Phosphorus nutrition: Plant growth in response to deficiency and excess. In: Plant nutrients and abiotic stress tolerance (M. Hasanuzzaman et al. eds.).

Malik, M. A., Marschner, P., and Khan, K. S. (2012). Addition of organic and inorganic P sources to soil- effects on P pools and microorganisms. Soil Biol. Biochem. 49, 106–113.

Masek, O., Brownsort, P., Cross, A., Sohi, S., & Snape, C. E. (2011). The role of pH and oxygen on the aging of biochar in soil. Environmental Science & Technology, 45(17), 7755-7761.

McCarthy, J. F., Naidu, R., Alburquerque, J. A., Arnold, J., Bachmann, R., Bailey, L., … & Buss, S. (2020). Soil amendments for the remediation of metal-contaminated soils: A review. Environmental Pollution, 261, 114255.

Meier, S., Curaqueo, G., Khan, N., Bolan, N., Cea, M., Eugenia, G.M., Cornejo, P., Ok, Y.S., Borie, F., 2017. Chicken-manure-derived biochar reduced bioavailability of copper in a contaminated soil. J. Soil Sediment 17, 741–750.

Mia, S., J.W. van Groenigen, T.F.J. van de Voorde, T.M. N.J. Oram, T.M. Bezemer, L. Mommer and S. Jeffery (2014). Biochar application rate affects biological nitrogen fixation in red clover conditional on potassium availability.

MoFA. (2010). The Study on Upper West Integrated Agricultural Development in the Republic of Ghana (Issue March).

Mokwunye, A. U., & Bationo, A. (2002). Management of phosphorus in West African soils: A review. Nutrient Cycling in Agroecosystems, 62(1), 7-24.

Murphy, J. A. M. E. S. and Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta, 27, 31-36.

Nartey, E. K., Sulemana, N., Razak, A., Adjadeh, T. A., Akumah, A. M., Amoatey, C., & Abekoe, M. K. (2023). Poultry litter and cow dung biochar as P sources for cowpea cultivation in two Ghanaian soils. Frontiers in Agronomy, 5, 1233255.

Nartey, E., Matsue, N. and Henns, T. (2000). Adsorptive mechanisms of orthosilicic acid on neoball allophane. Clay Science 11, 125-136.

Nartey, O. D., Agblevor, F. A., & Dodoo-Arhin, D. (2014). Biochar production from cassava peelings and its potential application in improving soil fertility. Waste Management, 34(12), 2356-2361.

Nartey, O. O., Blay, D. G., & Asiamah, R. D. (1997). Factors influencing phosphorus sorption and desorption in some Ghanaian soils. Ghana Journal of Agricultural Science, 30(1), 11-18.

Ndakemi, P. A., & Dakora, F. D. (2007). Symbiotic nitrogen fixation and phosphorus acquisition in cowpea (Vigna unguiculata L.) in response to phosphorus fertilization. Journal of Plant Nutrition and Soil Science, 170(2), 284-291.

Nerves, J. (2004). Biochar: a new frontier in soil science. Terra preta. Nova Delhi, India: Oxford University Press.

Nguyen, B. T., Lehmann, J., Kinyangi, J., Niyogi, B., Lam, N. Q., Joseph, S., & Hossain, M. B. (2010). Biochar improves soil properties and crop production in a highly weathered tropical soil. Soil Science Society of America Journal, 74(4), 949-960.

Nguyen, B.T., Lehmann, J., Hockaday, W.C., Joseph, S. & Masiello, C.A. (2010). Temperature sensitivity of black carbon decomposition and oxidation. Environmental Science and Technology. 44, 3324-3331.

Nkaa, F.A., O.W. Nwokeocha and O. Ihuoma (2014). Effect of phosphorus fertilizer on growth and yield of cowpea (Vigna unguiculata). IOSR J Pharm Biol Sci. 9: 74-82.

Novak, J. M., Busscher, W. J., Laird, D. A., Ahmedna, M., Watts, D. W., & Niandou, M. (2010). Impact of biochar amendment on fertility of a southeastern coastal plain soil. Soil Science, 175(1), 105-112.

Nyasapoh, G. Y., Afuakwah, S. O., Owusu-Bennoah, E., Agyeman, F. K., & Ntiamoah, F. (2022). Biochar application as a sustainable approach to improving the productivity of Vertisols in the coastal savannah zone of Ghana. Journal of Soil and Water Conservation, 77(2), 127-135.

Caddel, J., Redfearn, D., Zhang, H., Edwards, J., & Deng, S. (2011). Forage legumes and nitrogen production.

Osodeke, V. E. (2005). Phosphorus availability and response of cowpea (Vigna unguiculata L. Walp.) to phosphorus fertilization on some Nigerian soils. Journal of Tropical Agriculture, 43(1-2), 11-15.

Owens, F.N. and Basalan, M., 2016. Ruminal fermentation. Rumenolog*y, pp.63-102.*

Owusu-Bennoah, E. & Acquaye, D.K. (1989) Phosphate sorption characteristics of selected major Ghanaian soils. Soil Sci. 148, 114-123.

Peng, X., Ye, L., Wang, C., Zhou, H., Sun, B., & Huang, W. (2011). Effects of biochar amendment on soil properties and nutrient uptake by rice plants in a field trial. Catena, 85(1-2), 23-30.

Purakayastha, T. J., Sarmah, A. K., Baruah, L., & Gogoi, N. (2019). Biochar production, characterization and applications in soil fertility and water conservation. In Biochar for sustainable soil management (pp. 1-14). Springer.

Quaye, W., Adofo, K., Madode, Y., Abizari, A.R., 2009. Exploratory and multidisciplinary survey of the cowpea network in the Tolon Kumbungu district of Ghana: a food sovereignty perspective. Afr. J. Agric. Res. 4 (4), 311–320.

Rajkovich, S., Enders, A., Hanley, K., Lehmann, J., Joseph, S., & Biochar Research Network. (2011). Biochar properties and effects on soil physical properties. In: Biochar for environmental management: Science, technology and implementation (J. Lehmann & S. Joseph, eds.), 2nd ed., Routledge, London, UK, pp. 165-192.

Sánchez, P. A. (2010). Tripling crop yields in tropical Africa. Nat. Geosci. 3, 299–300.

Schmidt, M. W., Pyrogenic carbon: a review of the literature on its nature, production, application, and environmental fate. Journal of Environmental Engineering, 2015, 141(10), 04014101.

Schulze, J., G. Temple, S.J. Temple, H. Beschow andC.P. Vance (2006). Nitrogen fixation by white lupin under phosphorus deficiency. Ann. Bot. 98(4): 731-740.

Schumanns, J., & Chardon, W. J. (2015). Phosphorus dynamics in acidic soils: A review. European Journal of Soil Science, 66(4), 494-504.

Shaaban, M., Van Zwieten, L., Bashir, S., Younas, A., Núñez-Delgado, A., Chhajro, M.A., Kubar, K.A., Ali, U., Rana, M.S., Mehmood, M.A., Hu, R., 2018. A concise review of biochar application to agricultural soils to improve soil conditions and fight pollution. J. Environ. Manage. 228, 429–440.

Shakya A, Agarwal T (2017) Poultry litter biochar: an approach towards poultry litter management—a review. Int J Curr Microbiol App Sci 6:2657–2668

Sharma, S. K., Sharma, P. C., & Sharma, R. P. (2013). Phosphorus availability in soil: A review. Journal of the Indian Society of Soil Science, 61(4), 269-281.

Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., et al. (2011). Phosphorus dynamics: from soil to plant. Plant Physiol. 156, 997–1005.

Shin, Y., Lehmann, J., Joseph, S., Nizamuddin, S., & Bachmann, R. T. (2010). Nutrient availability from biochar depends on its chemical properties. Plant and Soil, 334(1-2), 175-186.

Sohi, S. P., Lehmann, J., Krull, E., Bol, R., & Amonette, J. E. (2010). Biochar influence on soil physical properties. Soil Science, 175(7), 348-358.

Sohi, S., Loez-Capel, S.E., Krull, E. & Bol, R. (2009). Biochar's roles in soil and climate change: a review of research needs. CSIRO, land and water science report 05/09, February; 64 pp.

Soil laboratory Staff (1984). Analytical methods of the service laboratory for soil, plant and water analysis. Part 1: Methods for soil analysis. Royal Tropical Institute. Amsterdam.

Souleymane, A. (2019). The importance of phosphorus in the nutrition of plants. In Phosphorus: Properties, recovery, and utilization (pp. 65-78). Springer Nature.

Spokas, K. A. (2010). Review of the stability of biochar in soils: predictability of biochar carbon recalcitrance and impacts on soil fertility. Plant and Soil, 337(1-2), 1-28.

Spokas, K. A., Cantrell, K. B., Novak, J. M., Archer, D. W., Ippolito, J. A., Collins, H. P., & Boateng, A. A. (2012). Biochar: a synthesis of its effects on soil properties and plant growth. Agronomy Journal, 104(6), 1039-1050.

SRID, MOFA. 2021. Facts and Figures: Agriculture in Ghana, 2020.

Srinivasarao, C., Gollakota, A. R., Naidu, R., & Kumar, S. N. (2013). Biochar amendments in agriculture and environment: A review. Bioresource technology, 138, 752-769.

Steiner, C., Das, K. C., Melear, N., and Lakly, D. (2010). Reducing nitrogen loss during poultry litter composting using biochar. J. Environ. Qual. 39 (4), 1236–1242.

Steiner, C., Glaser, B., Lehmann, J., & Teixeira, W. G. (2008). Nitrogen retention in a severely weathered soil amended with biochar and organic fertilizer. Plant and Soil, 303(1), 279-292.

Stevenson, F. J., & Cole, M. A. (1999). Cycles of soil: Carbon, nitrogen, phosphorus, sulfur, micronutrients. John Wiley & Sons.

Stewart, C. E., Paustian, K., Carlton, G. C., & Reay, D. S. (2012). Biochar priming of nitrogen pools and losses in a Colombian savanna soil. Geoderma, 173, 262-270.

Subedi, R., Taupe, N., Pelissetti, S., Petruzzelli, L., Bertora, C., Leahy, J., Grignani, C., (2016). Greenhouse gas emissions and soil properties following amendment with manure-derived biochars: influence of pyrolysis temperature and feedstock type. Journal of Environmental Management. 166, 73-83.

Sulemana, E.K. Nartey, M.K. Abekoe, (2021). Use of Biochar-Compost for Phosphorus Availability to Maize in a Concretionary Ferric Lixisol in Northern Ghana Agronomy 2021, 11, 359.

Syers, J. K., Johnston, A. E., and Curtin, D. (2008). Efficiency of Soil and Fertilizer Phosphorus Use: Reconciling Changing Concepts of Soil Phosphorus Behaviour with Agronomic Information. Rome: FAO.

Tan, K. H (1998). Principles of Soil Chemistry. CRC Press Amazon, 369.

Thakur, P.B., Bhattacharyya, T., Ray, S.K., Chandran, P., Pal, D.K., Telpande, B.A., (2016). Research shrink-swell measurement and relationship with soil properties of black clayey tropical vertisols. Clay Research 35, 37–54.

Tisdale, S.L., Havlin, J.L., Beaton, J.D. & Nelson. W.L. (1999). Soil fertility and fertilizers: An introduction to nutrient management. 6499 pp.

Tomczyk, A., Sokołowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Reviews in Environmental Science and Biotechnology, 19(1), 191–215.

Uchida, R. (2000). Essential nutrients for plant growth: Nutrient functions and deficiency symptoms. Plant Nutrient Management in Hawaii's Soils: 4: 31-55.

Uchimiya, M., Wartelle, L.H., Klasson, K.T., Fortier, C.A., Lima, I.M., 2011. Influence of pyrolysis temperature on biochar property and function as a heavy metal sorbent in soil. J. Agr. Food Chem. 59, 2501–2510.

US. Salinity Laboratory Staff. (1954). Diagnosis and Improvement of Saline and Alkali Soils. USDA Agriculture Handbook No. 60.

Uzoma, A.O., Osunde, A.O. and Bala, A., (2006). Effect of phosphorus and Rhizobium inoculation on the yield and yield components of cowpea breeding in Minna. In Proceedings of 31st Annual Conference of Soil Science Society of Nigeria. 13th-17th November, 2006, ABU, Zaria.

Uzoma, K. C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., Nishihara, E., & Sakurai, T. (2011). Effect of biochar amendment on soil fertility and crop productivity under field conditions. Soil Science and Plant Nutrition, 57(3), 331-344.

Van Reeuwijk, P. 2002. Procedures for soil analysis. International Soil Reference and Information Centre (ISRIC), Wageningen, The Netherlands.

Verheijen, F., Jeffery, S., Bastos, A. C., Van der Velde, M., and Diafas, I. 2010. Biochar application to soils. A critical scientific review of effects on soil properties, processes, and functions. EUR, 24099: 162.

Wang, J., Xiong, Z., Zhang, C., Sun, X., Dong, W., & He, Y. (2013). Effects of biochar application on nitrous oxide and methane emissions from a paddy field during rice growth period. Environmental Science & Pollution Research, 20(12), 8655-8666.

Wang, Z., Wang, J., Xie, L., Zhu, H., Shu, X., 2019. Influence of the addition of cotton stalk during co-pyrolysis with sewage sludge on the properties, surface characteristics, and ecological risks of biochars. J. Therm. Sci. 28, 755–762.

Wang, Z., Zheng, H., Zhang, Z., Guo, H., Zhang, J., & Wang, H. (2014). Effects of biochar on release of nutrients from maize straw and crop growth in a sandy loam soil. Environmental Science and Pollution Research, 21(1), 399-408.

Weil, R. R. (2017). The Soil Habitat. CRC Press. (https://www.amazon.com/Nature-Properties-Soils-Global/dp/1292162236) establishes the critical C:N ratio of 20 for rapid nutrient release.

Xu, X., Cao, X., Liu, F., Xu, H., Lu, K., Wang, J., & Li, Y. (2014). Effects of biochar amendment on the availability of soil phosphorus and crop yields in a field trial. PLoS One, 9(6), e99023.

Yakubu, H., Kwari, J. D. and Sandabe M.K. (2010). Effect of Phosphorus Fertilizer on Nitrogen Fixation by Some Grain Legume Varieties in Sudano–Sahelian Zone of North Eastern Nigeria. Nigerian Journal of Basic and Applied Science 18(1): 19-26.

Yangyuoru, S.G.K. Adiku and K.B. Laryea (2012). Changes in Shape and Water Shedding Potential of Three Landforms on a Vertisol in Ghana. Journal of Ghana Science Association, 14 (1).

Yeboah, V., Asibey, M. O., & Abdulai, A.-S. J. (2017). Palm biomass waste as supplementary source of electricity generation in Ghana: Case of the Juaben Oil Mills. Journal of Renewable Energy, 2017, Article ID 3218804.

Yong, Y., Chen, B., Zhang, G., Wu, C., Liu, Y., & Ye, Y. (2015). Biochar amendment to a degraded soil: Effects on soil properties, crop yields and greenhouse gas emissions. Journal of Soils and Sediments, 15(5), 1081-1090.

Yuan, J. H., Xu, R. K., Wang, H., Zhang, B., & Leng, Y. J. (2011). The effects of biochar amendment on soil properties and crop productivity under field conditions. Journal of Soil Science and Plant Nutrition, 11(4), 239-252.

Yuan, J. H., Xu, R. K., Wang, H., Zhang, B., & Leng, Y. J. (2012). The effects of biochar amendment on soil properties and crop productivity under field conditions. Journal of Soil Science and Plant Nutrition, 11(4), 239-252.

Zhang, F., Shen, J., Zhang, J., Zuo, Y., Li, L., and Chen, X. (2010). Chaptervone-rhizosphere processes and management for improving nutrient use efficiency and crop productivity: implications for China. Adv. Agron. 107, 1–32.

Zhang, H., Voroney, R.P., Price, G.W., (2015a). Effects of temperature and processing conditions on biochar chemical properties and their influence on soil C and N transformations. Soil Biology and Biochemstry. 83, 19-28

Zhang, J., Liu, J., Liu, R.L., (2015b). Effects of pyrolysis temperature and heating time on biochar obtained from the pyrolysis of straw and lignosulfonate. Bioresource Technology. 176, 288-291.

Zhang, M., and Ok, Y.S. 2014. Biochar soil amendment for sustainable agriculture with carbon and contaminant sequestration. Carbon Management. 5(3): 255-257.

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nature 528 (7580), 51–59.

Zimmerman, A. R., & Gao, B. (2011). Positive and negative carbon mineralization priming effects induced by biochar and their implications for offsetting global warming. Global Change Biology, 17(11), 2201-2211.

Zong, Y., Chen, D., Lu, S., (2014). Impact of biochar on swell-shrinkage behaviour, mechanical strength, and surface cracking of clayey soil. Journal of Plant Nutrition and Soil Science 177, 920–926.