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EFFECTS OF BIOCHAR APPLICATION RATES ON GROWTH OF TERMINALIA SUPERBA SEEDLINGS, SOIL CHEMICAL PROPERTIES AND SOIL ORGANIC CARBON UNDER NURSERY CONDITIONS

BY

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SEPTEMBER, 2025

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THESIS SUBMITTED TO THE DEPARTMENT OF ATMOSPHERIC AND CLIMATE SCIENCE, SCHOOL OF GEOSCIENCES OF THE UNIVERSITY OF ENERGY AND NATURAL RESOURCES SUNYANI GHANA, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF PHILOSOPHY DEGREE IN CLIMATE CHANGE

SEPTEMBER, 2025

DECLARATION AND CERTIFICATION

Student Declaration

I Benjamin Yamba Abonkra (UEMP1601223), hereby declare that this thesis is the result of my own original work and that no part or whole has been submitted for another degree in this University or any other educational institution. References made to the work of other authors in the thesis have been duly acknowledged.

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ABSTRACT

Producing high quality seedlings is essential for successful plantation establishment and the choice of growing medium plays a critical role. This study determined the effects of biochar application rates by volume (v) on the growth of *Terminalia superba* seedlings and on key soil chemical properties under nursery conditions. Biochar was amended to sandy loam soil at different rates in two nursery experiments conducted. Experiment one constituted 10% (v), 25% (v) and 50% (v) biochar amendment rate and control (unamended topsoil), each replicated six times. Experiment two constituted 2% (v), 5% (v) and 10% (v) and each replicated three times. Biochar treatments in both experiments were arranged in a Randomized Complete Block Design (RCBD). In both experiments, seedling growth parameters (seedling height, root collar diameter and number of leaves) and soil chemical properties (pH, nitrogen, phosphorus, potassium and soil organic carbon) were observed. The results showed that biochar amendment significantly influenced seedling growth parameters and soil chemical properties. In experiment one, the 10% (v) biochar treatment significantly increased seedling growth parameters compared to the control, while the highest rate biochar amendment 50% (v) suppressed seedling growth parameters. Similarly, in experiment two, low biochar amendment rates 2% (v) and 5% (v) enhanced seedling growth parameters. In both experiments, biochar consistently improved soil chemical properties. In experiment one, pH increased significantly by 0.92 units, N by 164%, P by 51%, K by 68% and SOC by 114% relative to the control. In experiment two, N increased significantly by 189%, P by 61%, K by 48% and SOC by 146% compared to the control. Higher biochar amendment rates (v) significantly increased pH, N, K and SOC, while P significantly increased mainly at low to moderate rates (v). The study concludes that low biochar amendment rates (v) are optimal for raising *Terminalia superba* seedlings, whereas higher rates (v) are more suitable for enhancing soil carbon sequestration and long-term soil fertility.

DEDICATION

I dedicate this thesis to my Wife, Ursula Awewura Banki and my Children Miracle Welaga Boateng Abonkra and Hugh Bennett Boateng Abonkra.

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I am grateful to God for seeing me through the successful completion of this thesis, glory be to his name. I am grateful to my supervisors Dr. Naomi Kumi and Dr. Nana Agyemang Prempeh of the Department of Atmospheric and Climate Science for their mentorship, scholarly comments and constructive criticisms from the start of this study to the end of the thesis. My appreciation goes to Dr. Kwabena Attakora, Senior Lecturer at the Department of Horticulture and Crop Production of the University of Energy and Natural Resources and Dr. Hamza Issifu, Senior Lecturer at the Department of Forestry and Forest Resources Management of the University for Development Studies for their guidance during the start of the experiments. I am again grateful to Greater Rural Opportunities for Women (GROW2) Project, located in Upper West Region of Ghana for providing the biochar used in this study. I am also grateful to management and staff of Forest Services Division, in the Sunyani Municipality of the Bono

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

In West Africa, the degradation of tropical forests is a major environmental issue that is made worse by unsustainable management practices and increasing demand for agricultural land and firewood (Laïla and Bah, 2024). These land use changes lead to a significant biodiversity loss and a reduction in ecosystem services, indicating the need of reforestation in restoring landscapes and preventing soil erosion (Laïla and Bah, 2024). Biochar is being utilized most as soil amendment in reforestation projects which is made by pyrolyzing organic materials (Laïla and Bah, 2024). Biochar utilization may be an effective means to aid in the development of young plants in nurseries in West Africa, where soils are frequently deficient in nutrients and susceptible to erosion. The application of biochar in nurseries may boost plant biomass, growth and germination rates, leading to more resilient and robust output against environmental stressors (Laïla and Bah, 2024). In the past ten (10) years, biochar's ability to improve soil fertility, plant growth and water retention in poor soils while simultaneously enabling carbon sequestration has drawn attention (Danish *et al.*, 2024). Among other benefits, biochar enhances nutritional content and the ability of soil to retain water. According to Danish *et al.* (2024), this is due to biochar's porous nature and cation exchange capacity, both of which are important for fostering plant growth and development.

Biochar is rich in carbon (65%-90%) that is produced by the thermal breakdown of biomass at high temperatures usually less than 700^0 C in full or partial anaerobic conditions (Yang *et al.*, 2024). The production of biochar uses the following primary sources of raw materials (feedstock); animal manure, municipal solid waste, forestry residue, agricultural residue and waste from wood processing (Yadav *et al.*, 2024). Biochar's high stability can remain in all kinds of soils for decades to thousands of years (Zulkifli and Md Nor, 2024). Commonly known as "black gold" (Aluthge *et al*., 2025), biochar's inorganic component differs depending on the feedstock type and is mainly made up of nutrients including carbonate ions, calcium, magnesium and potassium. The organic component is composed of high carbon content (Aluthge *et al*., 2025). Biochar has proven to enhance the physical and chemical properties of soil, including bulk density, permeability, water-holding capacity, nutrient availability and retention (Aluthge *et al*., 2025). According to Hossain *et al*., 2020, biochar natural feedstock can supply nitrogen, phosphorus, potassium and other trace elements. Biochar is mostly used as soil amendment to increase plant growth, nutrient retention, soil structure and soil organic carbon content (Schaffert *et al*., 2022).

The application of biochar to forest trees have proven to either increase or decrease their growth (Parvin *et al*., 2019). Despite increase in research on this subject, few studies have reported on biochar as soil amendment for the growth and development of woody vegetation and trees (Opoku *et al*., 2022). In boreal and sub-boreal ecosystems, numerous research have documented the beneficial effects of biochar on tree growth; however, in tropical and temperate climates, these studies are limited (Parvin *et al*., 2019). Carbon (C) storage, timber production, local climate regulation, and other cultural functions related to human recreational activities are only a few of the vital ecosystem services that forests are essential for preserving and providing protection to keep the forest from destruction (Akowuah *et al*., 2025). However, the combined consequences of forest degradation and deforestation pose a major threat to forests' ability to continue providing these vital functions (Akowuah *et al*., 2025). In Ghana, logging, mining, forest fires, agricultural expansion, and the unsustainable extraction of non-timber forest products are the main drivers of forest loss (Akowuah *et al*., 2025). Nonetheless, forest plantations provide a sustainable resource base that will meet the need for industrial timber in the future and improve environmental quality, which helps to reduce pressure on natural forests and increase forest cover (Akowuah *et al*., 2025).

In accordance with this, the government of Ghana is committed to plantation development (Adane et al., 2016). The Ghana Forest and Wildlife Policy of 2012 states that the government is committed to restoring degraded landscapes through extensive plantation development projects (Adane et al., 2016). After many years of anthropogenic and non-anthropogenic disturbances, plantation forestry can be utilized as a strategy to both stop forest degradation and to promote the restoration of significant native forest flora (Baatuuwie et al., 2011). Producing high quality, commercially viable tropical timber seedlings that can survive in the field during the early planting stages is crucial in plantation forestry (Gyimah and Nakao, 2007). One of Ghana's primary indigenous species for afforestation and reforestation initiatives is *Terminalia superba* (Gyimah and Nakao, 2007). *Terminalia superba* is of the *Combretaceae* family *(*Amponsah et al., 2018). In Ghana, it is locally known as Ofram, a deciduous forest tall tree. *Terminalia superba*, loses its leaves during the dry season. Simple, alternating leaves form clumps at the tips of branches and, when dropped, leave noticeable markings. It possesses the quality of deep roots (Orwa et al., 2009).

1.2 Problem Statement

Ghana has one of the highest rates of deforestation in West Africa; over-harvesting for timber, forest fires, and farming have left many of the forest reserves in a degraded state (Apetorgbor and Siaw, 2013). Establishing plantations has become an important panacea to decrease the pressure on Ghana's depleting forest resources (Apetorgbor and Siaw, 2013). The 2012 Forest and Wildlife Policy of Ghana placed a strong emphasis on reforestation initiatives in an effort to restore a significant portion of the country's original forest cover. In line with this, the Forestry Commission Forest Services Division (FSD) is committed to restoring degraded landscapes by establishing smallholder and commercial forest plantations, enrichment planting of degraded forests, and supporting the integration of trees into farming systems (Brown et al., 2016). However, forest restoration programs have a high failure rate (Simiele et al., 2022). Low seedling quality, transplant shock, competing vegetation and poor soils are frequently linked to poor performance of planted seedlings (Tsakaldimi et al., 2013). Poor quality seedlings at the juvenile stage may result in the poor establishment of seedlings on the field, slow growth, and reduced survival percentage (Akpalu et al., 2021).

These factors have made it more crucial than ever to create techniques that could improve the vigor, development, and survival of seedlings. The use of nursery produced seedlings is the most popular technique in forest restoration programmes and it is important to make sure that planted seedlings have excellent survival rates and good growth (Simiele et al., 2022). Traditionally, Ghana Forestry Commission nurseries raise seedlings, typically on soils without the need of additional fertilizer (Gyimah and Nakao, 2007). Soils in Ghana's degraded semideciduous forests are naturally low in fertility (Gyimah and Nakao, 2007), since many tropical soils experience frequent nutrient depletion biochar is mostly advocated as a soil amendment for the regeneration of forests (Opoku *et al.*, 2022). In Ghana, key soil related constraints to plant productivity include deficiencies in soil organic carbon (SOC), soil texture, pH, cation ex-change capacity (CEC), nitrogen (N), phosphorus (P), and potassium (K) (Simperegui et al., 2025). Above all, most of the soils are developed on thoroughly weathered parent materials, they are old and have been leached over a long period of time and are therefore, of low inherent fertility (Logah et al., 2010). It is therefore, obvious that soil fertility decline in Ghana would be on the increase if pragmatic measures are not taken to curtail the situation. One way of addressing this problem is the study of biochar as soil amendment.

1.3 Justification of the Study

Nursery treatments can increase field establishment by ensuring high quality seedlings, which promotes seedling development and survival (Tsakaldimi et al., 2013). The survival of seedlings at transplanting is partly dependent on the medium from which seedlings are transplanted (Akpalu et al., 2021). Seedling field performance is affected by seedling quality (Grossnickle and MacDonald, 2018) and the use of high quality seedlings is the basis for tree planting success (Riikonen and Luoranen, 2018). Quality seedlings are those that when transplanted, will meet the required level of growth and survival at an affordable cost (Davis and Jacobs, 2005). Quality nursery produced seedlings grow larger and better, with higher survival and greater competitive ability in the field after transplanting (Al Pavel et al., 2024). Successful forest restoration requires planting quality seedlings with optimal growth potential, thus, nurseries need to produce seedlings with plant attributes that favor the best chance of successful establishment once they are field planted (Grossnickle and MacDonald, 2018). However, it is acknowledged that producing high quality planting stock is a crucial initial step in the establishment of a successful plantation (Hamza *et al.*, 2016). Majority of studies on biochar has been in the agricultural field, but very few studies exist on biochar as soil amendments for raising tree seedlings (Lefebvre *et al.*, 2019). Among the various soil amendments, biochar provides an affordable way to increase soil fertility (Mwadalu *et al.*, 2020). Biochar used for soil amendment has drawn attention as a sustainable method of environmental rehabilitation (Tamang *et al.*, 2021). The use of biochar as soil amendments in degraded tropical soils has resulted in positive effects on plant growth and soil fertility (Laïla and Bah, 2024). Despite the large number of studies on biochar, there is a dearth of information on biochar soil plant interactions. This study will guide nursery management practices and sustainable soil improvement strategies in the transitional zone of Ghana.

1.4 Aim and Objective of the Study

1.4.1 Aim of the Study

The aim of the study was to determine the effects of biochar application rates on growth of *Terminalia superba* seedlings, soil chemical properties and soil organic carbon under nursery conditions.

1.4.2 Specific Objectives

The specific objectives of the study were to:

1. determine the effects of biochar application rates on the growth of *Terminalia superba* seedlings.
2. examine the effects of biochar application rates on soil chemical properties (soil pH, nitrogen, phosphorus and potassium).
3. assess the effects of biochar application rates on soil organic carbon.

1.5 Research Questions

The research seeks to answer the following questions:

1. What are the effects of biochar application rates on the growth of *Terminalia superba* seedlings?
2. What are the effects of biochar application rates on soil chemical properties (soil pH, nitrogen, phosphorus and potassium)?
3. What are the effects of biochar application rates on soil organic carbon?

1.6 Organization of the Thesis

This study is organized under five chapters. Chapter one gives an introduction and background of the study, statement of the problem, justification of the study, aim and objectives of the study and research questions. Chapter two which is the literature review, situates the study in the body of existing knowledge. Chapter three entails a description of the methodology used to address the set objectives. Chapter four then deals with the results and discussions while Chapter five outlines the conclusions and recommendations of the study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background and Properties of Biochar

Biochar is generally defined by the International Biochar Initiative (IBI) as a solid material that is produced by thermochemically converting biomass in an oxygen-limited environment (Hossain *et al*., 2020). According to the UK Biochar Research Center, biochar is a porous carbonaceous solid that is produced when organic materials are thermochemically converted in an oxygen depleted atmosphere. Its physiochemical properties make it appropriate for the long-term, safe storage of carbon in the environment as well as possibly improving soil (Ebeheakey, 2013). The concept of biochar is gaining more and more attention in the academic and political arenas; research centers for biochar have been established in a number of nations (including the United States, New Zealand, and the United Kingdom), and it is frequently promoted as a miracle treatment in the media (Ebeheakey, 2013). According to Neves *et al*. (2004), the concept of "biochar" has ancient roots, yet the name was just recently created. In the Amazon Basin, there are areas of terra preta that are up to two meters deep. The Amazonians have relied on this extremely fertile, dark-colored soil for centuries to meet their agricultural demands.

High levels of charcoal and organic materials, including plant and animal remains (fish, bones, and manure), have been found in analyses of the dark soils. Terra preta is productive in regions where soils are often acidic because it retains nutrients well and has a neutral pH (Lehmann 2007). It is interesting to note that terra preta can only be found in inhabited places, indicating that humans created it. The process by which terra preta was formed so many years ago has not been confirmed. There are many of theories available. One of the most popular theories is that the dark earth was caused by ancient slash-and-char methods. Slash-and-char methods are similar to slash-and-burn methods in that they entail removing vegetation from a small plot and setting it on fire, but only letting the waste smoulder rather than burn. The smoldering char eventually turns into terra preta when it is buried beneath a layer of dirt and combined with other biomass. These hypotheses of early slash-and-char techniques are the basis for the techniques that modern scientists have developed to produce biochar (Talberg, 2009). Egyir (2016) stated that biochar did not get the recognition it deserved until the publication of the article "Putting the carbon back; Black is the new green" in Nature.

According to Piash *et al.* (2021), the feedstock, production temperature, and the physicochemical properties of the soil itself are some of the factors which influence biochar's capacity to supply nutrients. Soil nutrients can be affected by biochar in a number of ways; as a source of nutrients for soil microorganisms and plants (Li *et al.* 2017b), as a nutrient sink, influencing the minerals' bioavailability and mobility (Gul and Whalen 2016), and as a soil conditioner, modifying soil properties that influence nutrient cycling and reactions (Lusiba *et al.*, 2017). Purakayastha *et al.* (2019) reported that as a source, biochar can supply nutrients including nitrogen, phosphorus, potassium and other trace elements naturally present in the feedstock used in the production of biochar. The increase in pyrolytic temperature increases the phosphorus and potassium contents as the amount of ash increases but a decrease in nitrogen content by gaseous emission. (Hossain *et al.*, 2020). Piash *et al.* (2021) noted that high temperature produces high levels of phosphorus and potassium but low temperature produces high nitrogen levels. As a nutrient sink, biochar could retain nutrients, lower their losses through gaseous emission and leaching. The application of biochar reduces the loss of nitrogen through nitrous oxide emission and phosphorus and potassium through leaching (Hossain *et al.*, 2020).

2.2 Biochar Production Techniques and Methods

Yadav *et al*. (2017) reported that biochar is a byproduct of pyrolysis, which is the thermal breakdown of organic materials without oxygen. It differs from charcoal by its use as soil amendment**.** Purakayastha *et al*. (2015) explained that biochar is a highly carbonaceous, finegrained byproduct of biomass that has been pyrolysed at low temperatures. The stability of biochar in soil is highly influenced by the pyrolysis temperature; the higher the temperature, the more stable the biochar will be. Biochar is a charred organic product composed of carbon that is biologically resistant and difficult for soil microbes to mineralize (Chan and Xu, 2012). The carbon in biochar is in an aromatic form, which gives it more stability and resistance to decomposition, making it a crucial tool for sequestering carbon (Yadav *et al*., 2017). Carbon rich charcoal like material known as biochar is produced by thermally breaking down biomass (organic matter) under low oxygen levels and relatively moderate temperatures (less than 700°C), a process called pyrolysis (Yadav *et al*., 2017). Carbon is nearly half of the dry biomass weight. Almost all of the carbon in biomass is released into the environment within a few years of being allowed to decompose in the atmosphere (Yadav *et al*., 2017). About half of the carbon in biomass is converted into biochar during pyrolysis. Approximately two-thirds of the remaining 50% can be released as useful energy. For example, 1 MT of dry biomass locks away 0.3 MT of carbon equivalent to 1.2 MT CO_2.Therefore, biochar may be a valuable tool for removing carbon from the atmosphere (Yadav *et al*., 2017).

According to Humnessa et. al. (2023) the source of biomass used and the pyrolysis temperature determine how biochar affects soil fertility. Bakshi et. al. (2016) explained that the primary factor influencing the properties of biochar is its biomass. Biochar can be produced from a variety of biomass sizes and types, each of which has a unique chemical, physical, and structural composition. It is proposed that almost any kind of biomass can be used to produce biochar. According to scientific literature, there are several different types of biomass feedstocks used to produce biochar. This includes biomass derived from plant growth, such as any kind of crop used for agriculture, aquatic, energy or forests. Biomass produced as a result of processing, and or transformation of other biomass kinds, such as sawdust, husks, hulls, and shells. Municipal solid waste, paper sludge, manures, and sewage sludge are examples of biomass derived from organic wastes. Bakshi et. al. (2016) further explained that the primary thermochemical process used to produce biochar is pyrolysis. There are three different kinds of pyrolysis systems: gasification, fast, and slow. In slow pyrolysis, biomass is heated utilizing slow heating rates and extended residence durations to temperatures between 350^0C and 600^0C without the presence of oxygen. Fast pyrolysis is a high temperature method that quickly (seconds) heats up small biomass particles without the presence of oxygen. One unique method of pyrolysis and combustion that uses little oxygen and necessitates a high temperature of between 8000 and 10,000 degrees Celsius is gasification. Humnessa et. al. (2023) reported that biochar produced at low temperatures (less than 550°C) favors more soil nutrients, increases soil fertility responsiveness, and improves soil fertility compared to biochar produced by pyrolysis at a higher temperature. For agro-environmental uses, biochar produced by pyrolysis at temperatures between 350 and 700 degrees Celsius is preferable (Saffari *et al*., 2020).

2.3 Effect of Biochar Application Rates on Soil Chemical Properties (Nitrogen, Phosphorus, Potassium and Soil pH)

According to Antonangelo *et al*. (2025), the biological, chemical and the physical properties of soil that enable it to promote plant growth, nutrient cycling, biodiversity, and overall environmental sustainability is known as soil health. Antonangelo *et al*. (2025) explained that using biochar as a soil amendment is one method of maintaining soil health, which enhances environmental health and long-term productivity. As soon as biochar is added to the soil, it begins to interact with the soil chemistry by first dissolving (less than a month), then developing reactive surfaces (1-6 months) and lastly degrading or aging (more than 6 months) (Nepal et al., 2023). Biochar provides macronutrients thus nitrogen, phosphorus and potassium necessary for effective agriculture Yadav *et al*. (2025). Sharma *et al*. (2023) noted that the application of biochar directly results in different types of nitrogen which are mainly categorized as either inorganic or organic nitrogen. Sharma *et al*. (2023) further noted that the application of biochar to agricultural soils has beneficial effects on soil phosphorus levels. The type of biomass used in the production of biochar has effect on the phosphorus levels, therefore it is important to choose the right feedstock to produce phosphorus enriched biochar Hossain *et al*. (2020). Biochar with a high ash content has high phosphorus levels (Laghari *et al*., 2016). The feedstock type and pyrolysis temperature also determine the levels of potassium in biochar (Hossain *et al*., 2020).

Soil acidity is a barrier in tropical Africa. To mitigate soil acidity, liming could offer the traditional solution but peasant farmers rarely have access to lime due to its high cost and limited availability, therefore its patronage is low (Agyei *et al*., 2021). Agyei *et al*. (2021) stated that adding biochar to soil has a liming effect that can promote the release of nutrients from natural soil nutrient pools. However, different types of soil and biochar have different soil liming potentials (Hossain *et al*., 2020). Hossain *et al*. (2020) explained that for instance, in a three-month incubation research, applying biochar at 1% and 2% rates made from different types of crop straws resulted in a pH value of 7.69 to 10.26, which gradually lowered the pH of an acidic Ultisol (pH 4.31). However, in field research, applying biochar made from paddy straw (whose pH was 10.50) to sandy soil (whose pH was 5.24), increased the soil's pH by 4.5 units in comparison to the control. According to Schaffert *et al*. (2022) although biochar is often alkaline, its addition to soil typically results in less than noticeable changes in pH due to the soil's natural buffering capacity. Hossain *et al*. (2020) reported that alkaline biochar application tends to increase the pH of neutral and acidic soils. The ideal pH range of biochar is 6.52-12.64 which is positively correlated with the feedstock type and pyrolytic temperature.

The application of biochar that contains ash with basic metallic ions can effectively decrease soil acidity and enhance growth especially in low fertile soils (Agyei *et al*., 2021). Biochar as soil amendment increases the pH of the soil, enhances its health and promotes plant growth by increasing nutrient availability Bahrun *et al*. (2018).

2.4 Effect of Biochar Application Rates on Soil Organic Carbon (SOC)

Soil Organic Carbon (SOC) is an important indicator for soil fertility and soil health in tropical soils (Adekiya *et al*., 2024). Apart from being an important measure of soil fertility, Soil Organic Carbon (SOC) also plays a vital role in the global carbon cycle (Ding et al., 2024). It is essential for nutrient cycling, water retention and general ecosystem services (Adekiya *et al*., 2024). SOC is crucial for regulating the chemical and physical properties of soil and addressing soil fertility challenges (Jiang *et al*., 2021). Sustainable agriculture in the tropics has major setbacks which include low nutrients, rapid decomposition in hot and humid environments, lack of SOC and the consistent use of synthetic fertilizers that degrade the soil structure (Chen *et al*., 2024). Biochar increased the stable organic matter or soil organic carbon which will help mitigate the effects of climate change (Haider *et al*., 2014). Biochar as soil amendment is a unique method to provide a long-term CO_2 storage sink without returning to the atmosphere (Jiang *et al*., 2021). Biochar as soil amendment expands the carbon pool (Chen *et al*., 2024). Biochar used as soil amendment does not only increase the organic carbon of the soil but also enhances the development of soil macroaggregates, which makes the soil organic carbon more stable (Chen *et al*., 2024). Sharma *et al*. (2023) reported a recent comprehensive meta-analysis, the rate at which biochar was amended had the highest effect on the total carbon content, by increasing the biochar, the effects of other factors were outweighed and the total carbon content of the soil increased significantly from 28.9% to 140%. Syahrinudin *et al*. (2021) found that rice and cottonseed husks were used to produce biochar at varying application rates, and as the application rate increased so did the SOC content, this increase was mainly caused by the direct contribution of stable carbon sources in biochar. Yadav *et al.* (2017) reported that biochar is more resistant to soil microbial decomposition, it is a stable product that may be added to soil and remain in it for centuries, safely storing carbon for long-term sequestration.

2.5 Biochar Application Rates

According to Hanyabui (2020), applying biochar at the minimal or ideal rate is preferable because it can increase soil fertility using too much biochar is not cost effective. Rondon et al. (2004) noted that crop yields decreased when biochar was applied at a high rate to poor soil. Winsly (2007) observed that if biochar is applied at even small rates and contains sufficient nutrients that the soil lacks, it can significantly increase crop output. Chan et al. (2007) also noted that applying large amounts of biochar to soil can boost the carbon credit value, but it may not support crop yield in low nitrogen soils since a high C/N ratio result in limited nitrogen availability. Taisa *et al.* (2019) reported that research on a number of plants has shown that applying biochar at a rate of 5% to 20% of the total soil volume improves crop yields. Furthermore, a number of findings have demonstrated that applying small amounts of biochar can clearly increase the development of some plants. According to Schaffert *et al.* (2022), although application rates should be taken into account for each type of biochar feedstock, most studies that show benefits from the use of biochar often end up with application rates ranging from 4% to 10% by volume enhance the health conditions of the soil or plants. Several experiments conducted in urban environments revealed that applying wood chip biochar at 5% to 10% by volume improved moisture of soil or tree growth parameters in sandy soils. Schaffert *et al.* (2022) reported that practically, the weight of biochar can differ significantly based on the feedstock. So, a percentage by volume is a better way to make sure the right amount is applied for surface area contact. Schaffert *et al.* (2022) suggested applying 5% by volume to rhizosphere soil at a rate of no more than 10%, since treatments over 25% have had negative effects, such as decreased plant productivity and the occurrence of phytotoxicity. Schaffert *et al*. (2022) stated that a reduction in soil pH at higher biochar application rates (25%-50% by volume) decreased the photosynthetic rate in conifers and essentially made the soil unsuitable for conifer seedling growth, underscoring the necessity of designing suitable rates for applying biochar amendments to soil.

2.6 Effect of Biochar Application Rates on Growth of Seedlings

Nurseries may vary in quality and quantity of planting stocks produced, however, it's primarily aim is to produce quantity and quality seedlings to satisfy the needs of seedling use (Humnessa et. al., 2023). Reasons to raise seedlings in nursery rather than sowing directly to the field include; Majority of tree plantations need to be established using seedlings grown in nurseries, some species do not seed every year, so it needs to be raised annually in nursery, slowly growing species need to be raised in nursery since they simply swamped by weeds and plantation on poor and barren sites needs vigorous seedlings raised in nursery (Humnessa et. al., 2023). Access to quality seedlings is essential component for successfulness of tree planting programs. However, growing media is the main factor that affects the production of seedlings in nursery and its survival after field plantation. Thus, balanced growing media is needed in order to supply functional requirements for seedlings and provide good physical, biological and chemical soil properties to enhance growth of plants (Humnessa et. al., 2023).

Biochar has been shown to improve soil health in forestry systems in a number of studies. For instance, *Tilia europaea* trees cultivated on soils amended with biochar showed a 22% increase in total biomass when compared to control trees, demonstrating the function of biochar in promoting tree vigor and overall productivity in urban areas (Antonangelo et al., 2025).

Antonangelo *et al*. (2025) further explained that using biochar as a growth medium for tree seedlings in nurseries can improve transplant survival and root development. According to Martínez-Gómez *et al*. (2022), biochar derived from a variety of sources, including forestry and agricultural residue, animal and human waste has been demonstrated to be beneficial in enhancing plant growth or production. Syahrinudin *et al*. (2019) found that applying 10% by volume biochar increased the seedlings growth rate by 253% as compared to the control. By enriching the biochar, the effect of applying 25% by volume biochar amendment rate on the height growth rate of seedlings increased to 386% as compared to the control. However, Syahrinudin *et al*. (2019) observed that *Anthocepalus cadamba* seedlings height growth rate decreased at higher biochar application rates (i.e., 25% by volume and 100% by volume), which could be related to microorganisms immobilizing nutrients by consuming the volatile matter in biochar. Thomas and Gale (2015) also reported that there is compelling evidence that adding biochar to woody plants has a favorable impact on their growth, with responses generally seeming to be higher than those observed in agricultural crops. Antonangelo *et al*. (2025) reported that in *Tilia europaea* trees cultivated on soils amended with biochar showed a 22% increase in total biomass when compared to control trees, demonstrating the function of biochar in promoting tree vigor and overall productivity in urban areas. They further explained that using biochar as a growth medium for tree seedlings in nurseries can improve transplant survival and root development.

2.7 Background of *Terminalia superba*

Terminalia superba, locally known as Ofram, is an African pioneer tree that is a member of the *Combretaceae* family. It is typical of tropical secondary semi-deciduous forests with an average annual rainfall of more than 1500 mm and a dry season lasting fewer than four months (Orwa *et al*., 2009). *Terminalia superba* has been planted in Africa, America and Asia due to its rapid plantation development for economic purposes. The tree grows tall reaching a height of 50 meters and a diameter of 150 cm and mostly found in agricultural fields integrated with cocoa plantations (Demenou and Hardy 2018). It grows 0.7 cm per year and reaches sexual maturity when the diameter reaches 40 cm. The inflorescences, which are axillary spikes with greenish white flowers, measure 7 to 18 cm. The fruits have two rigid lateral wings and are small samaras (1.5-2.5 x 4-7 cm, including the wing) and are mostly dispersed by the wind. They grow during the rainy season and reach maturity during the leafless period at the beginning of the dry season; fruiting lasts ranging from six to nine months. When two dry seasons coincide, the lengthier one yields the most seeds. Dadzie *et al*. (2016) noted that in Ghana's natural forests, *Terminalia superba* is one of the commercial timber species most frequently used to produce lumber, plywood, furniture, and finger-jointed goods for both domestic and international markets.

Makouanzi *et. al*. (2023) also reported that a highly exploited timber species in Africa is *Terminalia superba* therefore plantations of this species have only helped to contain this condition to a certain extent.

CHAPTER THREE

METHODOLOGY

3.1 Study Area

The study was conducted in the nursery of the Forest Services Division, Sunyani District Office (Latitude North: 7° 20' 54", Longitude West: 2° 20' 40") within the Sunyani Municipality in the Bono Region which is in the Western part of Ghana (Figure 3.1). The total land area of Sunyani Municipality is 829.3 square kilometers, with the exception of the town center, Sunyani is a moderately forested city that borders the Sunyani West District to the north, the Dormaa East District to the west, the Asutifi District to the south, and the Tano North District to the east (Osei-gyabaah *et al*., 2023). The monthly temperature ranges from 23°C to 33°C, with August experiencing the lowest and March and April experiencing the highest. Rainfall averages 88.99mm. The major rainy season, which lasts from March to September, and the minor season, which lasts from October to December, are the two distinct rainfall patterns that define it. Vegetative development requires relative humidity that averages between 75% and 80% during the rainy seasons and less than 70% during the dry seasons. A significant portion of Sunyani Municipality is located in the Moist Semi-Deciduous Forest Vegetation Zone (Agyemang-badu *et al*., 2023).

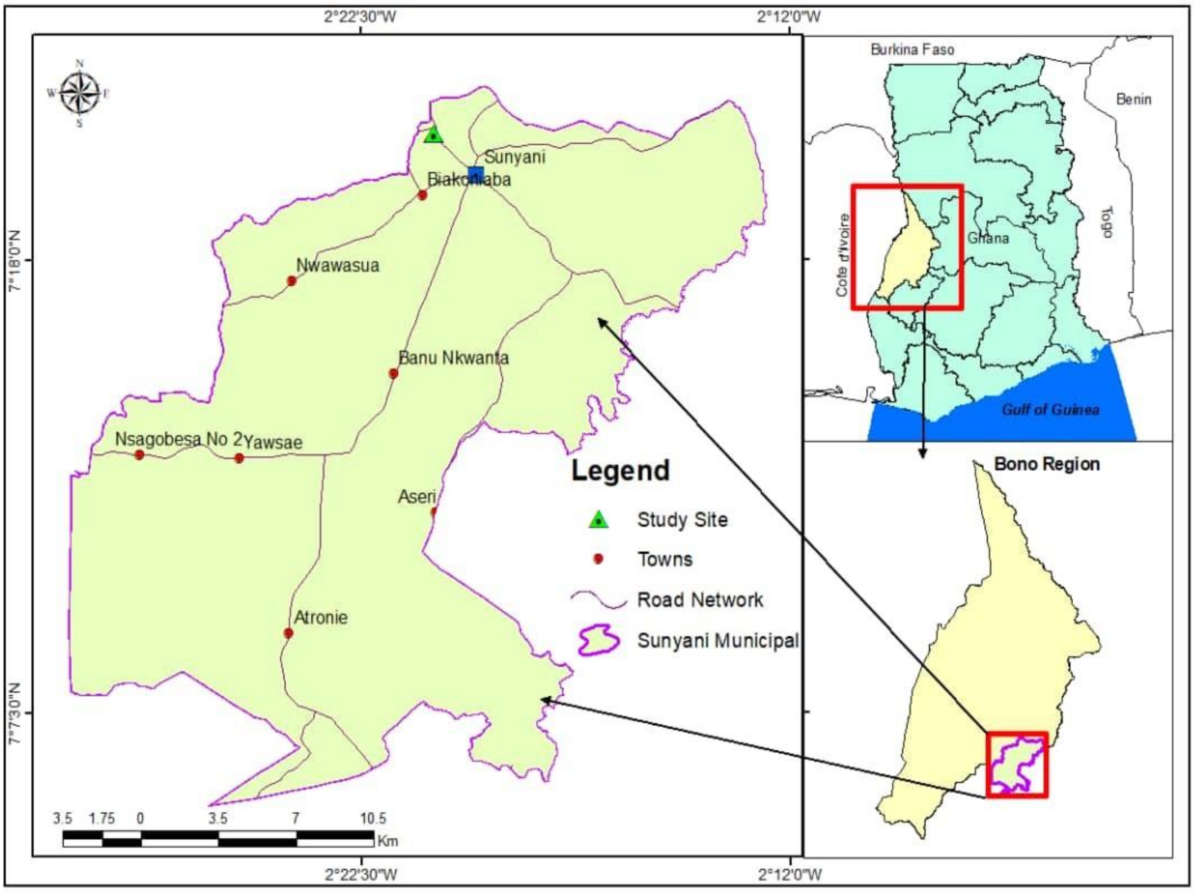

Figure 3.1: Map of the Study Area

3.2 Data

The data used in this study was taken from different sources;

3.2.1 Seed Source

Seeds used in the study were collected under healthy *Terminalia superba* trees in Opro Forest Reserve of Offinso Forest District of the Ashanti Region of Ghana.

3.2.2 Soil Type

The primary soil (topsoil 0-20 cm deep) used in the experiments were collected from Chiraa Kobedi in the Bono Region of Ghana and was analyzed at the University of Energy and Natural Resources Chemical Science Laboratory, the type of soil was sandy loam according to the USDA soil taxonomy.

3.2.3 Collection of Data

3.2.3.1 Seedling Height

Monthly measurements of seedling height were done during the three-month study period. A meter rule was used to measure the height of the seedlings from the soil surface to the tip of the apical leaf. In experiment one, seedling height of one hundred and sixty (160) healthy random seedlings were tagged and measured per block, making a total of nine hundred and sixty (960) seedlings height measured in the entire experiment per month. In experiment two, seedling height of forty (40) healthy random seedlings were tagged and measured per block, making a total of one hundred and twenty (120) seedlings height measured in the entire experiment per month.

3.2.3.2 Root Collar Diameter (RCD)

Monthly measurements of Root Collar Diameter were done in the second and third month in both experiments since seedlings were still delicate in the first month following seeding. An electronic digital caliper was used to measure the Root Collar Diameter of seedlings to the nearest millimetre. In experiment one, one hundred and sixty (160) healthy random seedlings were tagged and measured per block, making a total of nine hundred and sixty (960) seedlings Root Collar Diameter measured in the entire experiment per month. In experiment two, forty (40) healthy random seedlings were tagged and measured per block, making a total of one hundred and twenty (120) Root Collar Diameter measured in the entire experiment per month.

3.2.3.3 Number of Leaves

Number of leaves in both experiments were counted manually in each month. In experiment one, number of leaves of one hundred and sixty (160) healthy random seedlings were tagged and counted per block, making a total of nine hundred and sixty (960) seedlings number of leaves counted in the entire experiment per month. In experiment two, number of leaves of forty (40) healthy random seedlings were tagged and counted per block, making a total of one hundred and twenty (120) number of leaves counted in the entire experiment per month.

3.2.3.4 Soil Samples

Prior to biochar amendment, soil samples were taken. Following the experiment's conclusion, soil samples from each biochar treatment replicate were taken. Samples of soil taken before and after the end of the experiments were taken to the University of Energy and Natural Resources Chemical Science Laboratory for soil analysis.

3.3 Material

3.3.1 Biochar Source

The biochar used in the experiment was obtained from Greater Rural Opportunities for Women (GROW2) Project, located in Upper West Region of Ghana.

3.4 Methodology

Two (2) nursery experiments were conducted for this study, namely; experiment one and experiment two. The experiments were conducted for three months.

3.4.1 Biochar Characteristics

Corn cob, groundnut husk, soybean husk and millet stalk were used as the feedstock for the biochar, which was produced by pyrolysis at 150^0 C- 300^0 C for one (1) hour in a locally open pit. Before the amendment, a laboratory analysis of the biochar was conducted to ascertain its nutritional value. The study used biochar with the following fundamental physicochemical properties: pH (9.69), Organic Carbon (19.16%), Nitrogen (0.87 mg/kg), Phosphorus (36.85 mg/kg) and Potassium (305 mg/kg).

3.4.2 The Set-up of Experiment One

A 50m^2 (10m x 5m) plot was laid. The plot was divided into six (6) blocks. Biochar was sieved to a particle size 2 mm for the amendment to guarantee a uniform distribution of the biochar. Biochar was amended to sandy loam soil (topsoil) by the following treatments; Treatment 1 (T1): 10% by volume biochar and 90% by volume topsoil, Treatment 2 (T2): 25% by volume biochar and 75% by volume topsoil, Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil, control (unamended topsoil). The three (3) biochar treatments, including the control, were replicated six (6) times each, making a total of twenty-four (24) replications. Each replicate was filled into black polypots measuring 10cm by 8cm with drainage holes at the bottom. Treatments were arranged in a Randomized Complete Block Design (RCBD), with each biochar treatment including the control represented in each block. 240 healthy *Terminalia superba* seeds were sown per block, making a total of 1,440 (240 x 6) seeds sown in the entire experiment. A black polythene bag was used to cover the treatments to promote germination. At 14 days (2 weeks) after sowing, germination was recorded in all biochar treatments including the control. For two months, the experiment received two daily waterings (morning and evening) on need bases. During the third month, seedlings were rainfed to mimic nature but they were watered once a day on need bases when it did not rain. Regular hand removal of weeds was done to avoid competition.

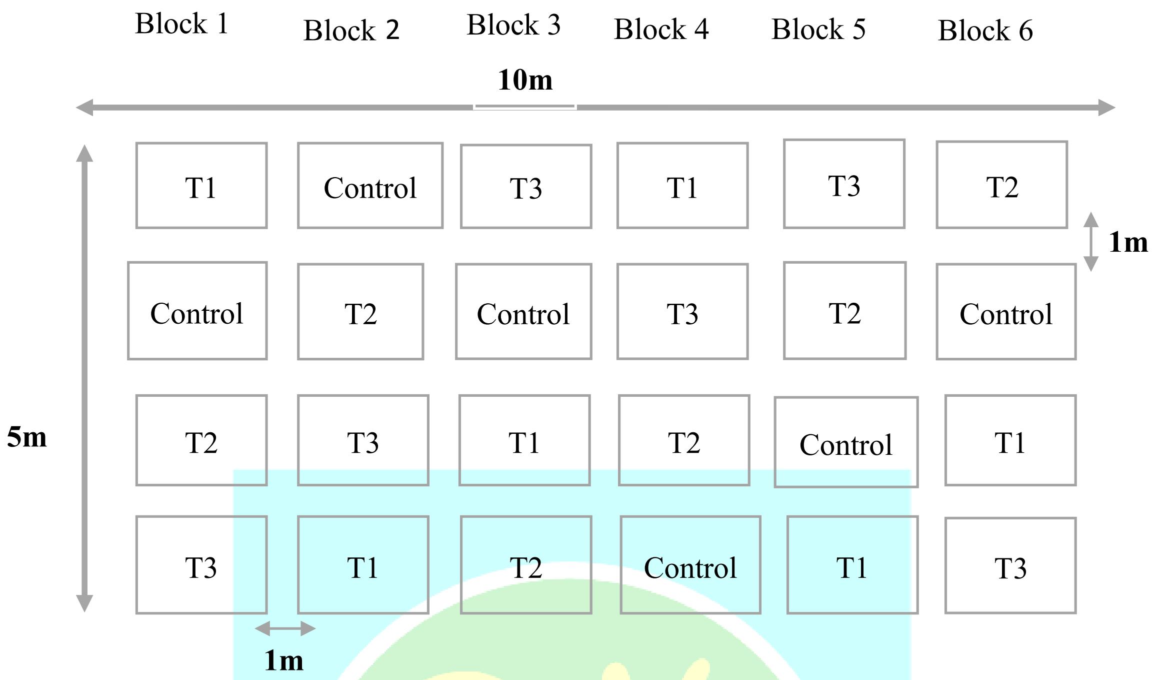

Figure 3.2: Plot Layout for Experiment One

3.4.3 The Set-up of Experiment Two

A plot measuring 4m x 3m ($12m^2$) was laid. The plot was divided into three (3) blocks. Before the amendment, biochar was sieved to a particle size 2 mm in order to ensure a uniform distribution of biochar. It was then amended to sandy loam soil (topsoil) by the following treatments; Treatment 1 (T1): 2% by volume biochar and 10% by volume topsoil, Treatment 2 (T2): 5% by volume biochar and 10% by volume topsoil, Treatment 3 (T3):10% by volume biochar and 10% by volume topsoil and control (unamended topsoil). Each of the three (3) biochar treatments including the control were replicated three (3) times, for a total of twelve (12) replications. Each of these replicates was put into a 10cm by 8cm black polypot with drainage holes on the bottom. Treatments were arranged in a Randomized Complete Block Design (RCBD) making sure that each treatment is represented in each block. Fifteen (15) healthy *Terminalia superba* seedlings at the two (2) leaf stage were transplanted in each biochar treatment including the control, making a total of sixty (60) seedlings transplanted per block.

In all one hundred and eighty (180) seedlings were transplanted in the entire experiment. For the first two months of the experiment, the seedlings were watered twice a day (morning and evening) on need bases. In the third month, they were rainfed to mimic nature, although they were only watered once a day on need bases when it did not rain. Regular hand removal of weeds was done to avoid competition.

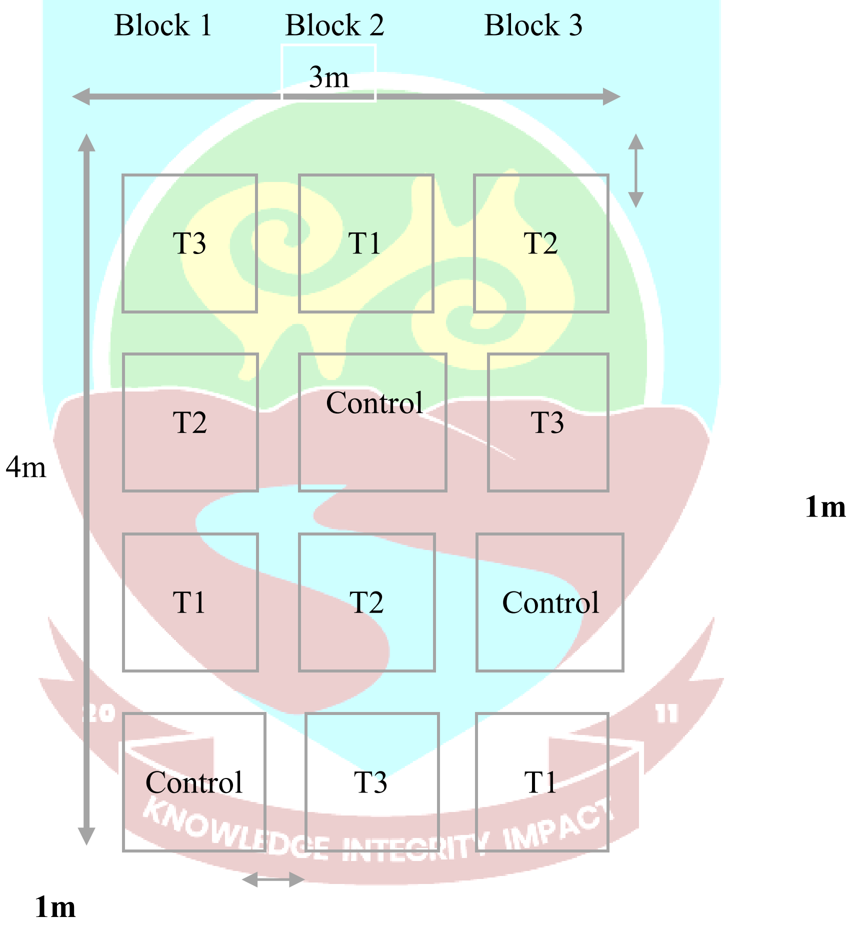

Figure 3.3: Plot Layout for Experiment Two

3.4.4 Soil Analysis

Soil samples were crushed and sieved using a 2 mm mesh sieve after being oven dried for eight (8) hours at 105°C to determine the pH, nitrogen, phosphorus, potassium concentrations and organic carbon content.

3.4.4.1 Soil pH Determination

The pH measuring device was calibrated in accordance with the manufacturer's standard operating procedures before use. The pH of the samples was determined using a pH meter (PHS-3C). Thirty (30) milliliters of deionized water were added to 10 grams of the sieved soil, which had been weighed and put in a glass beaker. To guarantee even mixing, the soil-water mixture was thoroughly stirred for approximately five minutes using a stirring rod. The mixture was then left undisturbed for half an hour to allow the soil particles to settle. Each sample’s pH values were obtained by immersing the probe in the supernatant (the bulb was lowered to the proper depth as recommended by the manufacturer) and waiting for a stable reading. To avoid sample cross-contamination, deionized water was used to rinse the probe after every measurement (FAO, 2021).

3.4.4.2 Soil Texture

The Jar Test (Sedimentation Method) was used (Clemson, 2023). The soil sample was put in a transparent jar until it was about one-third full. Water was then added until the jar was almost full, leaving a small amount of space at the top to aid in the separation of the soil particles. After that, the jar was tightly closed and shaken vigorously for two to three minutes to make sure the soil was thoroughly mixed and there were no remaining clumps. After the jar was shaken and set on a flat surface, the soil particles were allowed to settle at different rates for 72 hours. A meter rule was used to measure the thickness of each layer once they had settled completely. After taking note the height of the layers of sand, silt and clay, the following formula was used to determine the percentage of each component (Clemson, 2023);

Percentage of Sand = (Sand layer height ÷ Total soil height) × 100

Percentage of Silt = (Silt layer height ÷ Total soil height) × 100

Percentage of Clay = (Clay layer height ÷ Total soil height) × 100

Based on the calculated percentages, the soil texture was determined using a soil texture triangle.

3.4.4.3 Soil Organic Carbon (Walkley and Black Method)

Using this method, one gram of oven-dried finely ground soil was accurately weighed into a 250 mL Erlenmeyer flask. This was mixed with 10mL of a 0.167M potassium dichromate ($K_2Cr_2O_7$) solution. Twenty (20) mL of concentrated sulfuric acid (H_2SO_4) was carefully added and the mixture immediately swirled to ensure it was thoroughly mixed. To ensure that all of the organic materials had completely oxidized, the reaction was left undisturbed for 30 minutes. 100 mL of distilled water was added to the flask after the reaction period to dilute the solution. Four drops of ferroin indicator were then added. A solution of 0.5M ferrous ammonium sulphate (Fe (NH4)2 (SO4)2.6H2O) was then used to titrate the excess dichromate. A noticeable change in color from blue-green to reddish-brown indicated the endpoint. To determine the total amount of dichromate initially present, a blank determination was also carried out in the same conditions but without soil. The amount of organic carbon (%) in the soil was calculated using the formula (Shamrikova et al., 2023);

Organic Carbon (%) = $(B-S) \times M \times 0.003 \times f \times 100/W$

Where:

B = Volume (mL) of Fe $(NH_4)_2(SO_4)_2.6H_2O$ used in the blank

S = Volume (mL) of Fe $(NH_4)_2(SO_4)_2.6H_2O$ used in the sample

M = Molarity of Fe $(NH_4)_2(SO_4)_2.6H_2O$ solution

W = Weight of soil sample in grams

0.003 = Amount of carbon oxidized by 1 mL of 1N $K_2Cr_2O_7$ f = Correction factor for incomplete oxidation, 1.33 (assumes 77% efficiency)

3.4.4.4 Potassium (Flame Photometry)

Sample of the sieved soil was weighed and put into a 100 mL beaker. Twenty-five (25) mL of a 1M ammonium acetate solution was added to the sample in order to extract potassium ions. To guarantee adequate extraction, the mixture was subsequently shaken for half an hour using a mechanical shaker. A 50 mL volumetric flask was filled with the solution after it had been shaken and filtered through filter paper. Standard potassium solutions were then prepared with known concentrations to serve as calibration reference points. After turning it on, the flame photometer was left to warm up for 15 to 30 minutes in order to stabilize. The appropriate filter was selected. Prior to calibration, ammonium acetate was used as a blank to zero the instrument. A calibration curve was then produced by passing the prepared standard solutions (0, 5, 10, 15, 20, 25, 30, and 40 ppm) through the flame photometer. The standards for the calibration were prepared below;

Table 3.1: Standard for the Calibration (Dilutions from 100-ppm stock $C_1V_1 = C_2V_2$)

Final concentration (ppm)	**Volume of 100-ppm stock (mL)**	**Volume of Diluted added (mL)**	**Total volume (mL)**
5 ppm	5 mL	95	100 mL
10 ppm	10 mL	90	100 mL
15 ppm	15 mL	85	100 mL
20 ppm	20 mL	80	100 mL
25 ppm	25 mL	75	100 mL
30 ppm	30 mL	70	100 mL

40 ppm	40 mL	60	100 mL
0 ppm (blank)	0 mL	100	100 mL water

Following calibration, the soil extract was aspirated into the flame photometer, and the potassium emission intensities were recorded. The obtained readings were then compared with the calibration curve to determine the concentrations of these elements in the soil sample (Bazargan et al., 2022).

3.4.4.5 Phosphorus (ascorbic acid-molybdate blue method)

The Mehlich-1 extraction method and colorimetric analysis based on the ascorbic acidmolybdate blue method were used to determine the amount of phosphorus that was available in the soil. Mehlich-1, being more acidic is more effective at releasing phosphorus bound to iron or aluminium, and also Mehlich-1 is a ‘double - acid’ extractant, giving a better estimation of plant available phosphorus in strongly phosphorus fixing soils whiles Bray-1 also works for acidic soils but becomes unreliable when free aluminium or iron oxides are very high. A 5gram sample of soil that had been sieved and oven-dried was weighed and put in a clean extraction bottle. Twenty-five milliliters of Mehlich-1 extractant, which comprised 0.0125 M sulfuric acid and 0.05 M hydrochloric acid, were added to this. A 0.5M sodium bicarbonate solution with a pH of 8.5 was used to extract the biochar. The mixture was filtered through Whatman No. 42 filter paper after being shaken for five minutes with a mechanical shaker. A sample of the clear filtrate was taken for analysis. Three milliliters of the soil extract or the reference solution were pipetted into a test tube in order to develop color. Three milliliters of freshly prepared reagent in an equal volume were added (the reagent was prepared by mixing 200 milliliters of deionized, 50 milliliters of 4 M sulfuric acid, 15 milliliters of ammonium molybdate solution, 30 milliliters of ascorbic acid solution, and 5 milliliters of potassium antimony tartrate solution). After carefully mixing the mixture, it was left to stand for half an hour to fully develop its color. The UV-1800 spectrophotometer (manufacturer- Shimadzu Corporation, Country of origin- Japan) was used to measure the absorbance at 880 nanometers. Standard phosphate solutions (KH2PO4) with concentrations of 0.0, 0.4, 0.8, 1.2, 1.6, and 2.0 mg/L were used to produce a calibration curve. The absorbance values of the soil samples were compared to the standard curve in order to determine the phosphorus concentration in the soil samples. Results were expressed in milligrams of phosphorus per kilogram of soil (Silva et al., 2024).

3.4.4.6 Nitrogen (Vanadium (III) Chloride Reduction and Griess Colorimetric Method)

First, 5g of oven-dried, sieved soil was extracted with 25 mL of 2 M KCl by shaking for 30 minutes. The mixture was filtered using Whatman number 1 filter paper (11 µm pore size), and the sample for analysis was the clear filtrate. Sodium nitrate was used to produce standards at concentrations of 0, 0.01, 0.05, 0.10, 0.20, and 0.50 mg/L. A reagent flask was filled with exactly 5 mL of the standard or filtered water sample. 0.256 milliliters of vanadium chloride reagent and 0.250 milliliters of Griess reagent (1% sulfanilamide solution and 0.1% N-(1naphthyl)-ethylenediamine dihydrochloride) were added and the mixture was heated in a 60 °C water bath for 30 minutes. After the incubation, the sample was cooled to room temperature.

A UV-1800 spectrophotometer was used to measure the absorbance of the resultant solution at 540 nm following the incubation period. The absorbance value was compared to the standard nitrate calibration curve to measure the nitrate concentration in the sample. The nitrate content was then computed and expressed as mg NO_3^-–N per kilogram of soil (Doane and Horwáth, 2003).

3.4.5 Data Analysis

All of the data obtained was entered and categorized using Microsoft Office Excel. The R Statistical Package, version 4.5.1 (The R Foundation for Statistical Computing Platform) was used to analyze the data using one-way analysis of variance (ANOVA). Tukey's Honestly Significant Difference (HSD) test was then used to evaluate significant ANOVA's and the significance level for each statistical test was set at 0.05. Bargraphs and boxplots were used to show the results. Details of the analysis of variance are showed in Appendices.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Physicochemical Properties of Sandy loam Soil and Biochar used in the Study.

Physicochemical properties of the biochar and sandy loam soil used in the study are shown in Table 4.1. The pH of the sandy loam soil was 6.26 which is slightly acidic, while the pH of the biochar was 9.69, which indicates that it is alkaline. Biochar had slightly high nitrogen concentrations of 0.87 mg/kg than sandy loam soil nitrogen concentration of 0.78 mg/kg, but it had significantly higher phosphorus concentration of 36.85 mg/kg and potassium concentration of 305 mg/kg than sandy loam soil phosphorus concentration of 10.75 mg/kg and potassium concentration of 112 mg/kg. Biochar had a higher organic carbon content (19.16%) than the sandy loam soil (2.37%), indicating that biochar used in the study contained a lot of carbon. The physicochemical properties of the sandy loam soil used in the study are low compared to the biochar.

Table 4.1: Physicochemical Properties of Sandy Loam Soil and Biochar used in the Study.

Parameter	**Sandy Loam Soil (Mean ± SD)**	**Biochar (Mean ± SD)**
pH	6.26 ± 0.015	9.69 ± 0.02
Nitrogen (mg/kg)	0.78 ± 0.000	0.87 ± 0.00
Phosphorus (mg/kg)	10.75 ± 0.000	36.85 ± 0.00
Potassium (mg/kg)	112 ± 2.65	305 ± 5.00
Organic Carbon (%)	2.37 ± 0.087	19.16 ± 1.01

4.2 Effects of Biochar Application Rates on Growth of *Terminalia superba* seedlings.

The results showed that the various biochar treatments significantly ($p < 0.001$) affected seedling height in experiment one. Seedlings of Treatment 1 (T1): 10% by volume biochar and 90% by volume topsoil significantly attained the highest mean seedling height of 33.50 cm over the control with a mean seedling height of 26 cm. Seedlings of Treatment 2 (T2): 25% by volume biochar and 75% by volume topsoil had a mean seedling height of 29.50 cm over the control. However, seedlings of control performed better than Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil with a mean seedling height of 24 cm (Figure 4.1).

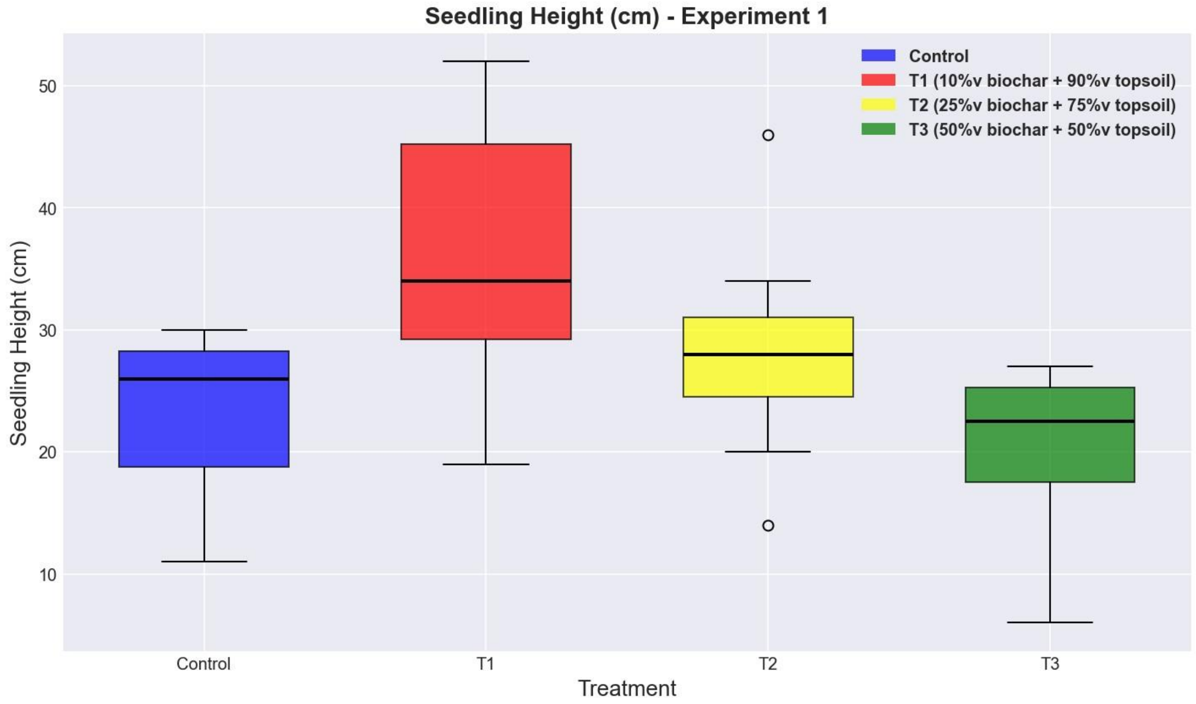

Figure 4.1: Effect of Biochar Application Rates on Seedling Height

In the first month of experiment one, there was no significant ($p = 0.067$) difference in seedling height between treatments, indicating that the rates at which biochar was amended had no effect on seedling height in the first month. However, the second and third months showed the onset of biochar treatment effects, with significant ($p < 0.001$) differences. The highest height was consistently attained by seedlings of Treatment 1 (T1): 10% by volume biochar and 90% by volume topsoil in the second and third months. These were followed by seedlings of Treatment 2 (T2): 25% by volume biochar and 75% by volume topsoil. Control and Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil, however, had comparatively lower height increments (Figure 4.2).

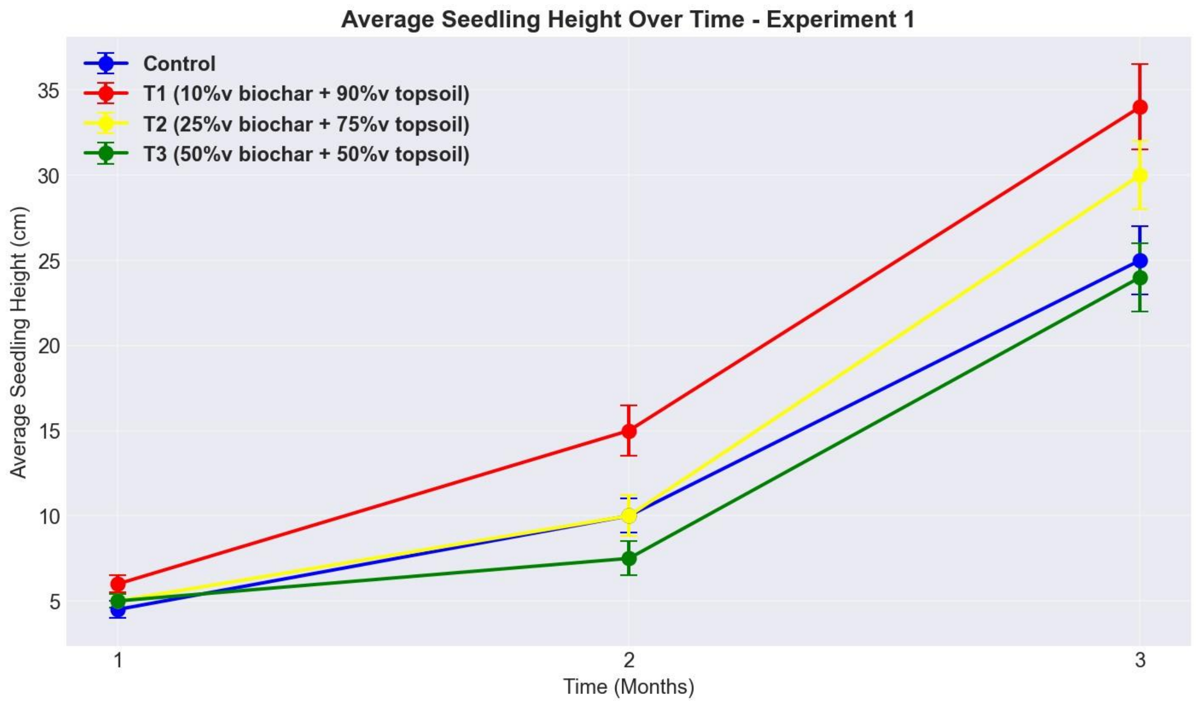

Figure 4.2: Monthly Growth Trends on Seedling Height in Experiment One

A highly significant ($p < 0.001$) effect was observed between biochar treatments on seedling height in experiment two. Seedlings of Treatment 1 (T1): 2% by volume biochar and 10% by volume topsoil had the highest mean seedling height of 25.80 cm compared to the control mean seedling height of 15 cm. Seedlings of Treatment 2 (T2): 5% by volume biochar and 10% by volume topsoil had a mean seedling height of 23.50 cm over the control. Treatment 3 (T3): 10% by volume biochar and 10% by volume topsoil recorded a mean seedling height of 13 cm lower than the control (Figure 4.3).

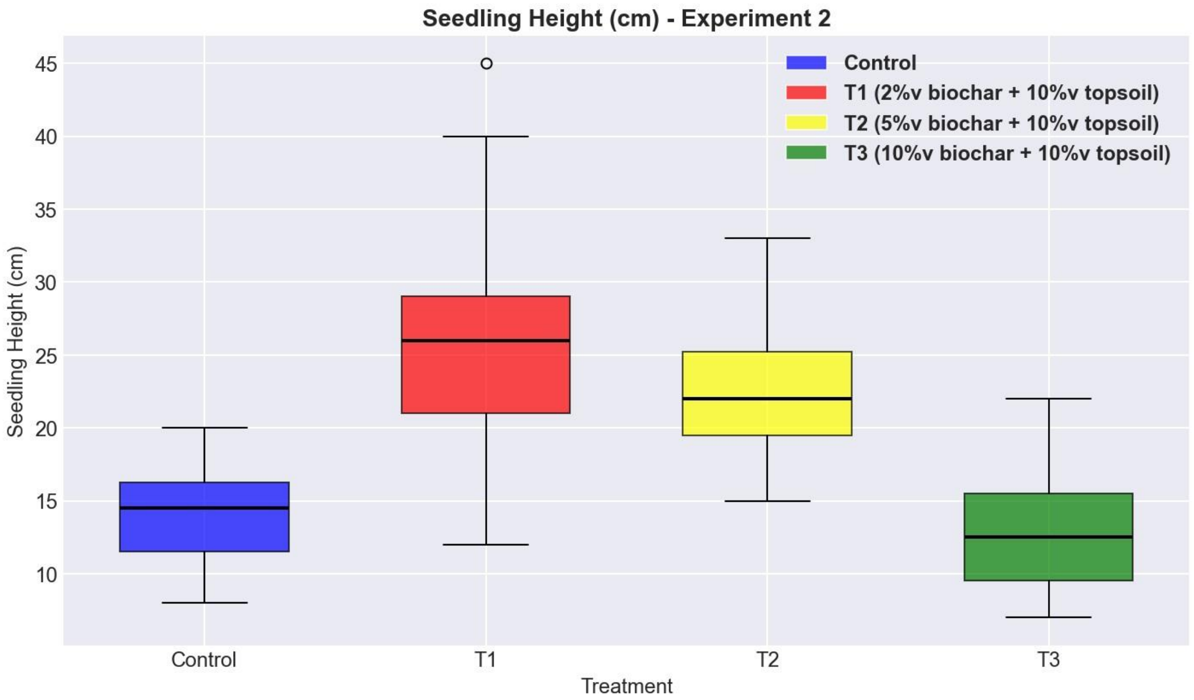

Figure 4.3: Effect of Biochar Application Rates on Seedling Height

In experiment two, seedling height was significantly ($p < 0.001$) influenced by the rates at which biochar was amended. The highest height was continuously observed in Treatment 1 (T1): 2% by volume biochar and 10% by volume topsoil followed by Treatment 2 (T2): 5% by volume biochar and 10% by volume topsoil. Monthly height increments were relatively lower in Treatment 3 (T3): 10% by volume biochar and 10% by volume topsoil and control (Figure 4.4).

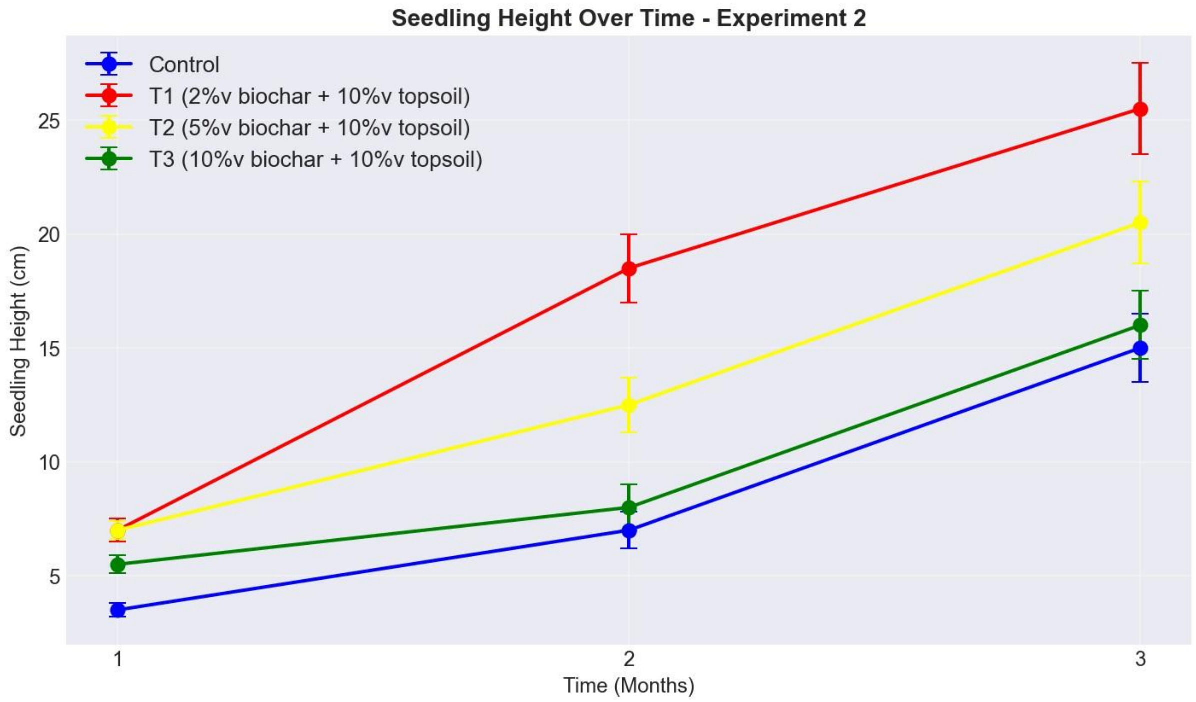

Figure 4.4: Monthly Growth Trends on Seedling Height in Experiment Two

The findings from this study consistently demonstrated that higher biochar application rates resulted in decreased seedling height, whereas low to moderate biochar application rates improved early seedling height. Low and moderate biochar rates 10% by volume biochar with a mean seedling height of 33.50 cm and 25% by volume biochar with a mean seedling height of 29.50 cm in experiment one, 2% by volume biochar and 5% by volume biochar in experiment two with a mean seedling height of 25.80 cm and 23.50 cm respectively were shown to produce the highest seedlings in both experiments. This demonstrated that soil conditions for early seedling height can be significantly improved with minimal amendment. A similar finding was made by Winsly (2007), who reported that biochar can boost plant output if it is applied at even modest rates and contains enough nutrients that the soil lacks. These findings also align with Gebisa and Regasa's (2024), who reported that the use of biochar as an amendment at lower rates improves coffee seedlings nutrient uptake, providing alternative media options for coffee seedling development. However, at high amendment rates biochar may have a negative impact on seedling development.

Similar findings were reported by Syahrinudin et al. (2019), who found that adding 10% by volume biochar to *Anthocepalus cadamba* seedlings enhanced the seedlings growth rate by 253% in comparison to the control. The observed reduction in height at higher rates (50% by volume biochar and 50% by volume topsoil in experiment one and 10% by volume biochar and 10% by volume topsoil in experiment two) is in line with Tamang et al. (2021) findings who found no beneficial effects from increasing the percentage of biochar in the growing medium for kiwifruit seedlings. Similar findings were reported by Solis et al. (2021), who found that applying 25 and 50 tons/ha of biochar made from *Tectona grandis* wood to *Cedrela odorata* seedlings significantly increased their diameter, height and number of leaves in the nursery. However, when applying the biochar at the highest rate (75 tons/ha), stunted growth of *Cedrela odorata* seedlings was observed. Syahrinudin et al. (2019) found that the height growth rate of *Anthocepalus cadamba* seedlings decreased at higher rates of biochar application.

A statistically significant ($p < 0.001$) effect was observed on Root Collar Diameter (RCD) by the various biochar treatments in experiment one. Seedlings of Treatment 1 (T1): 10% by volume biochar and 90% by volume topsoil had the highest RCD mean of 4.60 mm relative to the control RCD mean of 2.70 mm. Seedlings of Treatment 2 (T2): 25% by volume biochar and 75% by volume topsoil recorded RCD mean of 3.40 mm over the control. The lower RCD mean was observed in seedlings of Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil with a RCD mean of 2.20 mm (Figure 4.5).

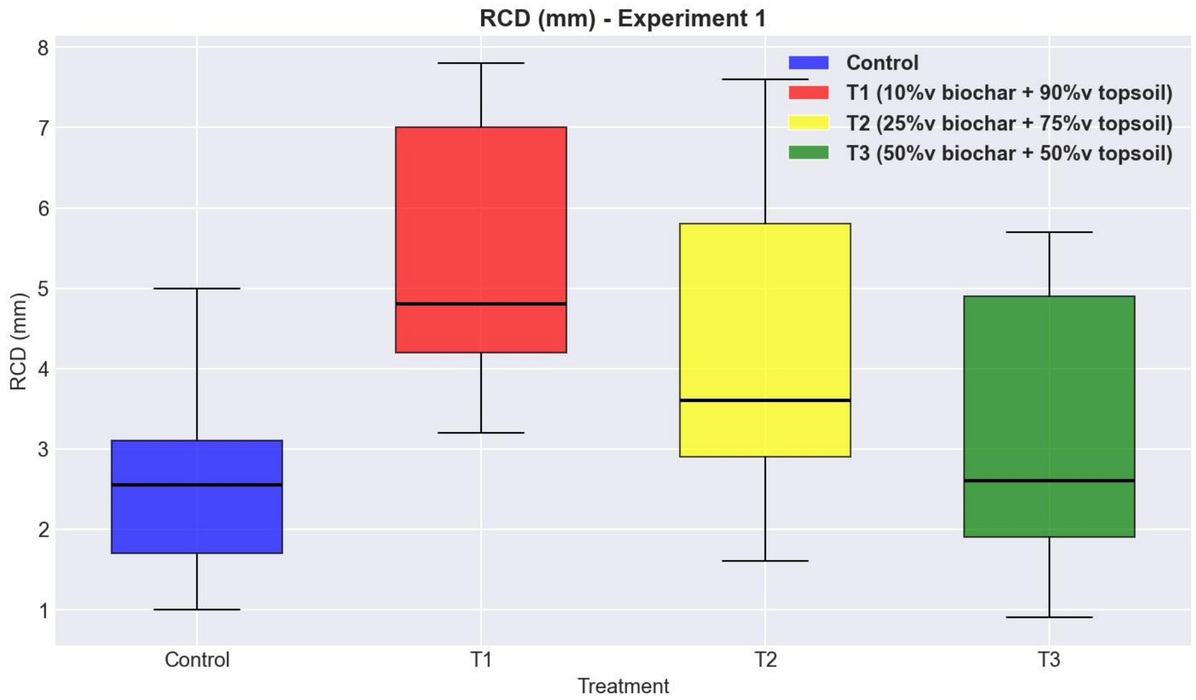

Figure 4.5: Effect of Biochar Application Rates on Root Collar Diameter (RCD)

In the second and third months of experiment one, there was a significant ($p < 0.001$) difference in Root Collar Diameter (RCD) across biochar treatments. In each month, RCD gradually increased for all biochar treatments. The highest RCD was consistently recorded in seedlings of Treatment 1 (T1): 10% by volume biochar and 90% by volume topsoil. Lower RCD increment was observed in Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil and control (Figure 4.6).

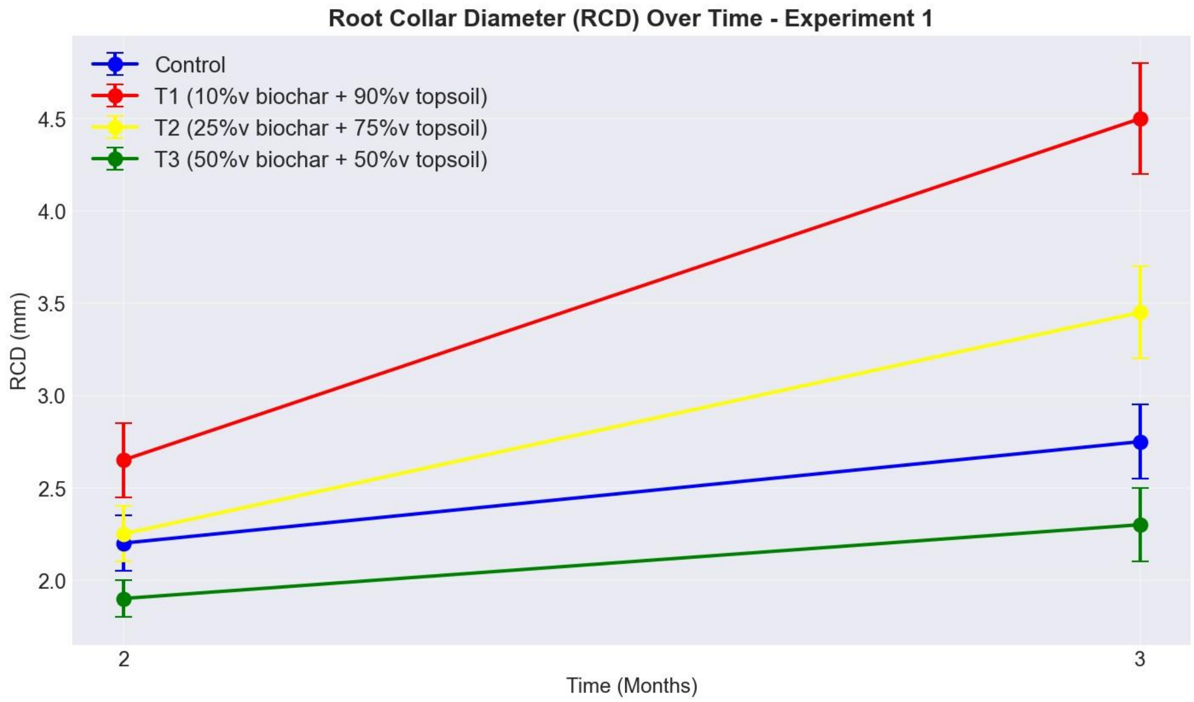

Figure 4.6: Monthly Growth Trends on Root Collar Diameter (RCD) in Experiment One

The result showed a significant ($p < 0.001$) effect of biochar amendment rates on Root Collar Diameter (RCD) in experiment two. Seedlings of Treatment 2 (T2): 5% by volume biochar and 10% by volume topsoil attained the highest RCD mean of 4.20 mm when compared to the control which recorded RCD mean of 3.25 mm. Seedlings of Treatment 1 (T1): 2% by volume biochar and 10% by volume topsoil recorded RCD mean of 4.15 mm over the control. Seedlings of Treatment 3 (T3): 10% by volume biochar and 10% by volume topsoil recorded the least RCD mean of 2.80 mm (Figure 4.7).

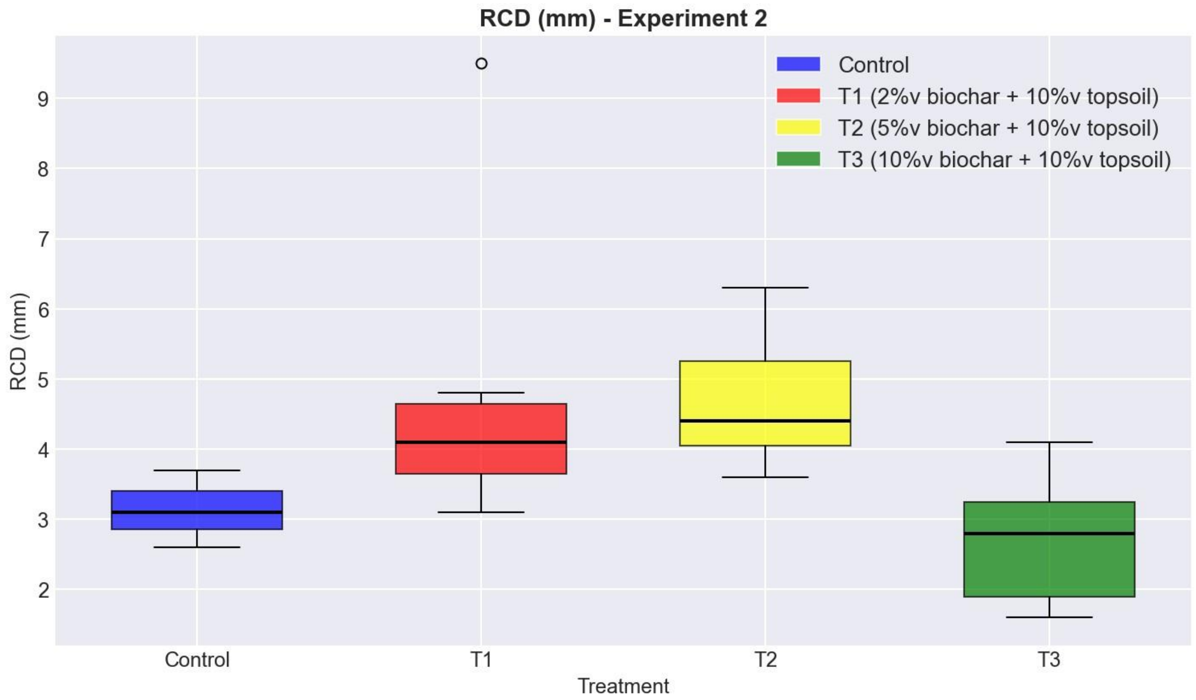

Figure 4.7: Effect of Biochar Application Rates on Root Collar Diameter (RCD)

Root Collar Diameter (RCD) increased significantly ($p < 0.001$) in all biochar treatments during the second and third months in experiment two. The highest RCD at the end of the experiment was observed in Treatment 2 (T2): 5% by volume biochar and 10% by volume topsoil followed closely by Treatment 1 (T1): 2% by volume biochar and 10% by volume topsoil. Treatment 3 (T3): 10% by volume biochar and 10% by volume topsoil and control consistently recorded the least RCD (Figure 4.8).

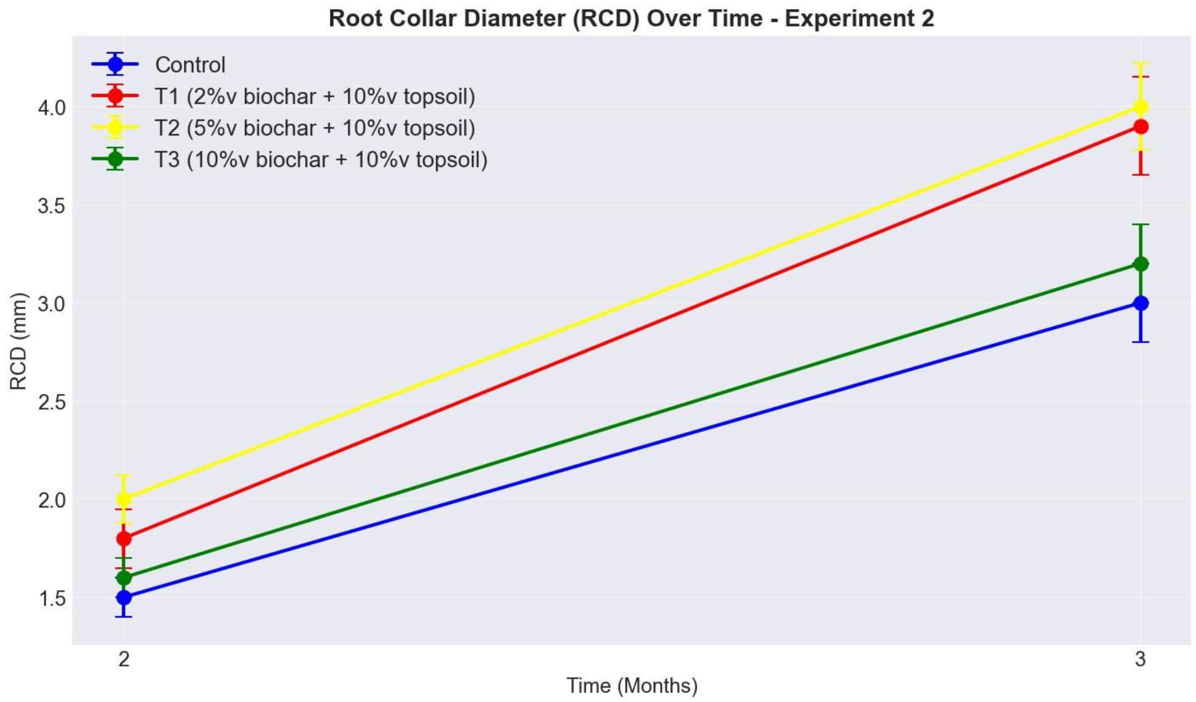

Figure 4.8: Monthly Growth Trends on Root Collar Diameter (RCD) in Experiment Two

A reliable indicator of seedling vigor and field survival is Root Collar Diameter (RCD) (Grossnickle, 2012). Low and moderate biochar rates improved Root Collar Diameter (RCD) more than either high rates or unamended soils (control). In experiment one, the highest RCD mean of 4.60 mm was obtained by 10% by volume biochar. In experiment two, the highest RCD mean of 4.15 mm and 4.20 mm was obtained by 2% and 5% by volume biochar respectively. Higher biochar application rates result in a decrease in RCD, which validates the seedling height findings. The control occasionally performed better than the highest rate of biochar amendment (50% by volume biochar and 50% by volume topsoil in experiment one, 10% by volume biochar and 10% by volume topsoil in experiment two), which is interesting because it indicates that too much amendment might be worse than none at all. These findings align with Warnock et al. (2007), who cautioned that in some situations, the capacity of biochar to absorb nutrients may limit their availability to plants due to higher pH effects that may lead to nutrient unavailability or higher exchange capacity. Similar findings were reported by

Humnessa et. al. (2023) who reported excellent growth of root collar diameter in seedlings raised in potting media with biochar at low amendment rate.

Result of this study showed that the various rates of biochar significantly ($p < 0.0001$) influenced the number of leaves per plant in experiment one. Seedlings of Treatment 1 (T1): 10% by volume biochar and 90% by volume topsoil number of leaves per plant recorded a significant high mean of 14 over the control which had a mean of 10 number of leaves. Seedlings of Treatment 2 (T2): 25% by volume biochar and 75% by volume topsoil recorded a mean of 13 number of leaves per plant over the control. Seedlings of Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil had a mean of 9 number of leaves lower than the control (Figure 4.9).

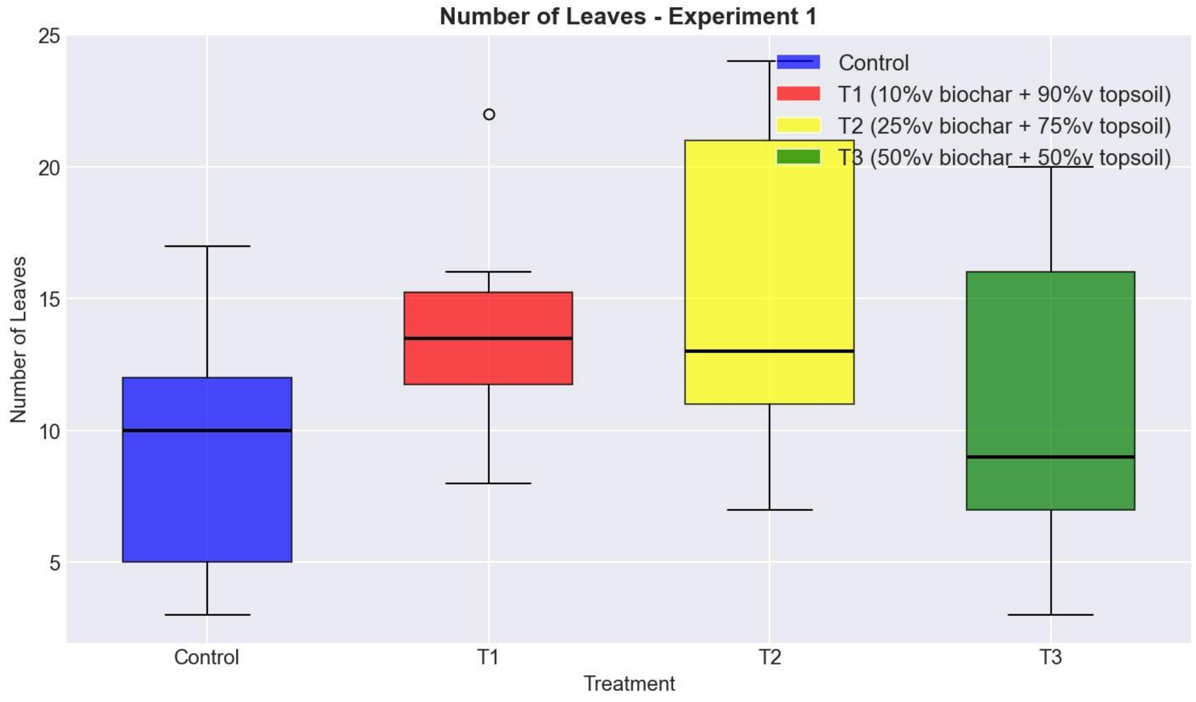

Figure 4.9: Effect of Biochar Application Rates on Number of Leaves

During the three months of experiment one, an increase in the number of leaves per plant was observed for all biochar treatments. There is a significant ($p < 0.001$) difference in the number of leaves per plant of seedlings in the first, second and third months between biochar treatments. The biochar treatment that produced the most leaves per plant each month was Treatment 1 (T1): 10% by volume biochar and 90% by volume topsoil. A similar lower pattern was observed in Treatment 2 (T2): 25% by volume biochar and 75% by volume topsoil. The number of leaves per plant was lower in the control and Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil in the early stages but both showed improvement by the third month. (Figure 4.10).

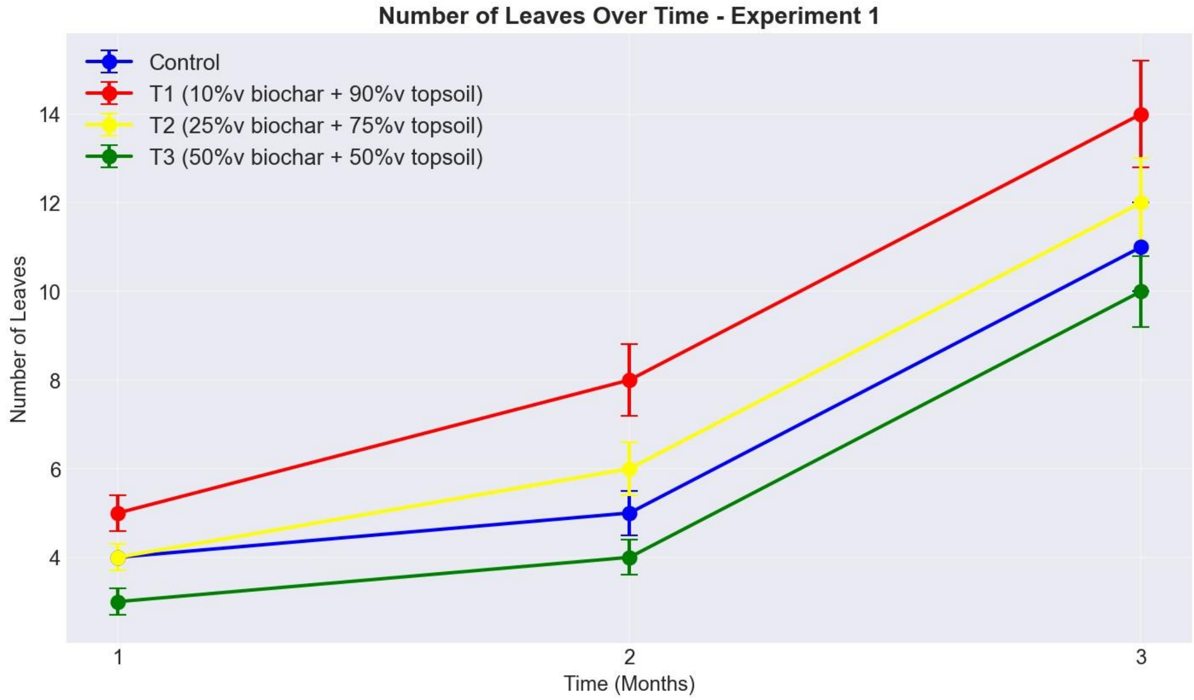

Figure 4.10: Monthly Growth Trends on Number of Leaves in Experiment One

Biochar application rates had a significant ($p < 0.001$) effect on number of leaves per plant of seedlings in experiment two. Seedlings of Treatment 1 (T1): 2% by volume biochar and 10% by volume topsoil recorded the highest number of leaves per plant with a mean of 16 compared to the control which had mean number of leaves of 11. Seedlings of Treatment 2 (T2): 5% by volume biochar and 10% by volume topsoil attained a mean of 14 number of leaves per plant over the control (Figure 4.11).

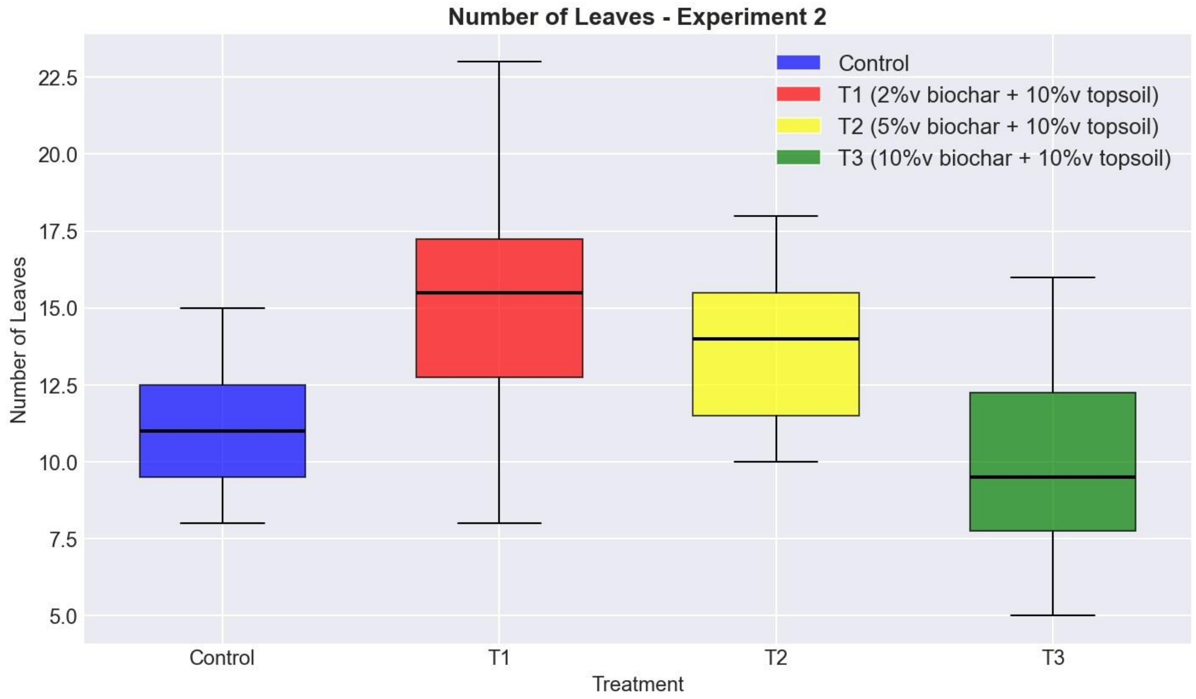

Figure 4.11: Effect of Biochar Application Rates on Number of Leaves.

The number of leaves per plant of seedlings increased significantly ($p < 0.001$) among biochar treatments in all the months in experiment two. Seedlings of Treatment 1 (T1): 2% by volume biochar and 10% by volume topsoil recorded the highest number of leaves per plant in each month followed by seedlings of Treatment 2 (T2): 5% by volume biochar and 10% by volume. Seedlings of Treatment 3 (T3): 10% by volume biochar and 10% by volume topsoil and control showed comparatively lower number of leaves per plant of seedlings (Figure 4.12).

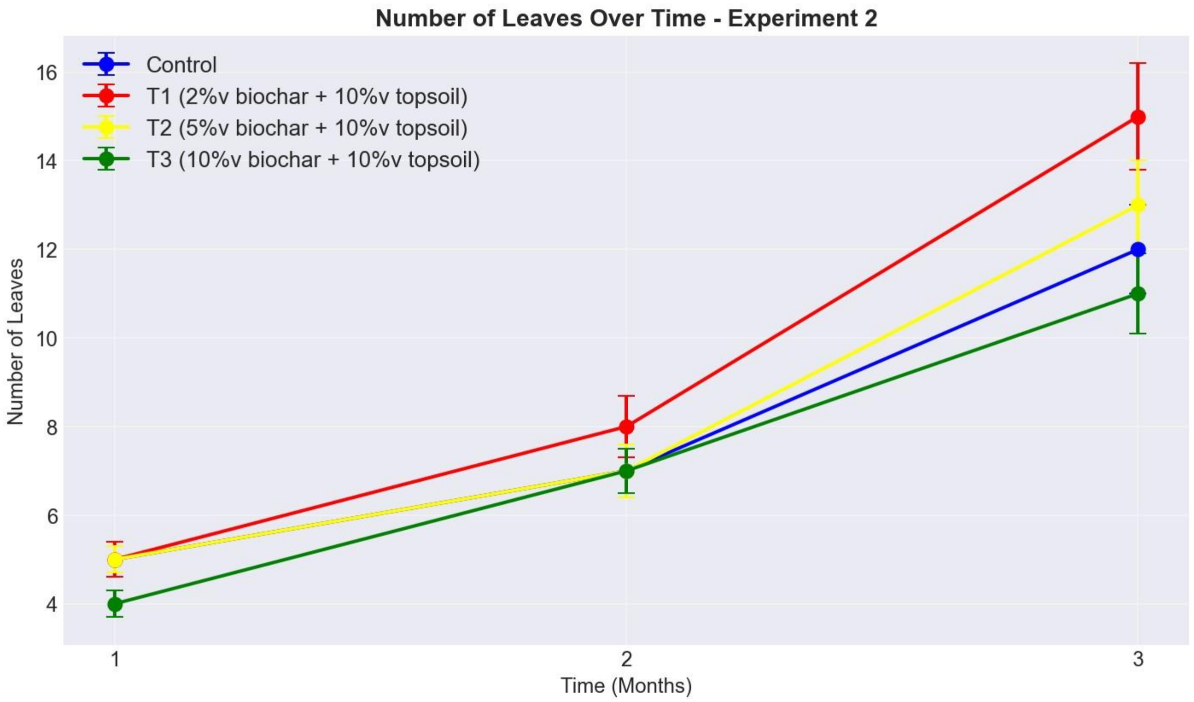

Figure 4.12: Monthly Growth Trends on Number of Leaves in Experiment Two

The number of leaves on a seedling further confirmed the beneficial effects of low and moderate rates of biochar treatment on seedling growth. The lowest amendment rates produced the highest mean number leaves in both experiments, while higher rates resulted in a decline. In experiment one, 10% by volume biochar and 90% by volume topsoil produced the highest mean number of leaves of 14 whereas 50% by volume biochar and 50% by volume topsoil produced the lowest mean number of leaves of 9. Similar observation was made in experiment two, 2% by volume biochar and 10% by volume topsoil obtained the highest mean number of leaves of 16 whereas 10% by volume biochar and 10% by volume topsoil recorded the lowest mean number of leaves of 10. This pattern indicates that while excessive application may result in nutrient imbalances that limit leaf production, modest increases in soil fertility at low and moderate biochar rates promote photosynthetic capability and canopy development (Glaser et al., 2002). These findings agree with Schaffert et al. (2022), who reported that rhizosphere soils perform best when amendments are applied at 5% - 10% by volume, while rates above 25% can reduce plant productivity and cause phytotoxicity.

Similar findings were made by Taisa et al. (2019) who reported that studies on various plants have shown that the application of biochar at a rate of 5% to 20% of the total soil volume increases plant growth. The monthly growth trends for every parameter that was measured showed that after the first month, differences between treatments were increasingly noticeable. With the influence of soil amendments becoming evident as root systems became more established, this delayed divergence indicate that initial development was primarily supported by seed reserves and natural seedling vigor. Similar findings were made by Yamato et al. (2006), who found that the effects of biochar are cumulative rather than immediate in *Acacia mangium* and Eucalyptus species treated with biochar amendment.

4.3 Effects of Biochar Application Rates on Soil Chemical Properties (Soil pH, nitrogen, phosphorus, potassium).

Result showed a significant (p = 0.001) effect between biochar treatments in experiment one. The pH of Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil was significantly increased by the biochar amendment with a pH of 6.82 over the control. The pH of Treatments 2 (T2): 25% by volume biochar and 75% by volume topsoil increased slightly compared to the control (Figure 4.13).

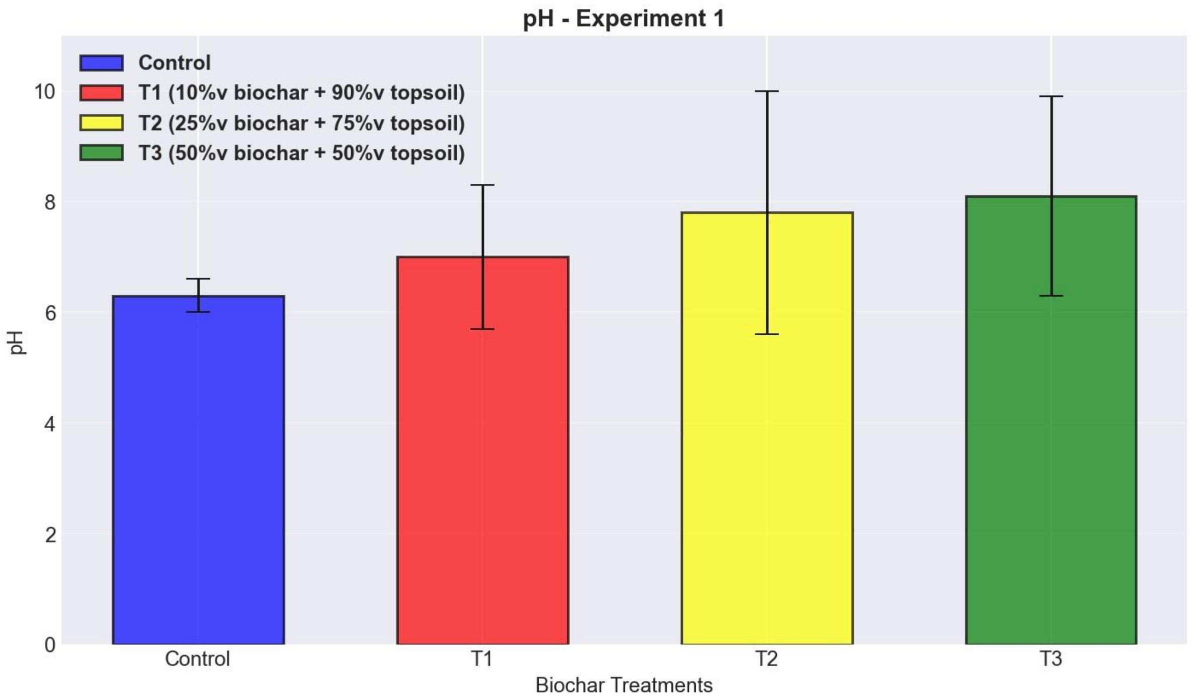

Figure 4.13: Effects of Biochar Application Rates on Soil pH

Error Bars Represent Mean ± Standard Deviation

Soil pH varied significantly (p = 0.003) among the biochar treatments in experiment two. Treatment 3 (T3): 10% by volume biochar and 10% by volume topsoil resulted in a slight increase in pH (6.36) over the control. However, the pH of Treatment 1 (T1): 2% by volume biochar and 10% by volume topsoil decreased to 6.18 compared to the control (Figure 4.14).

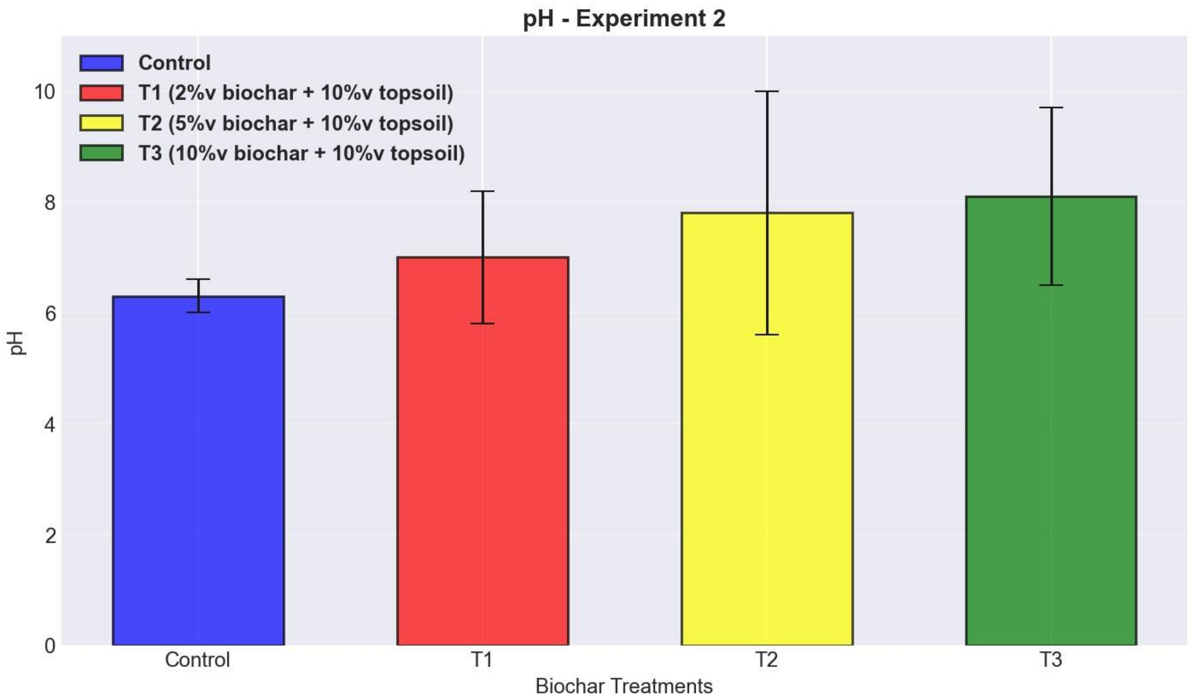

Figure 4.14: Effects of Biochar Application Rates on Soil pH

Error Bars Represent Mean ± Standard Deviation

Compared to the control pH of 6.26, the application rates of Treatment 2 (T2): 25% by volume biochar and 75% by volume topsoil, Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil increased the pH of the soil by 6.43 and 6.82 respectively, in experiment one. In experiment two, the application rate of Treatment 3 (T3): 10% by volume biochar and 10% by volume topsoil, slightly increased the pH of the soil to 6.36 from the control pH of 6.26. These results align with the findings of Agyei et al. (2021), who found that the addition of biochar increased the pH of the soil. As the rate of biochar amendment increases, the pH of amended treatments also increases showing a positive correlation between biochar amendment rate and pH. This finding is in line with Abukari (2014), who reported that high biochar application rates led to a noticeable increase in pH. Similar findings were made by Zhu et al. (2025), who found that biochar increased the pH of amended soils significantly and the pH increased as the application rate increased. From the findings, the pH increased without going beyond the ideal range of pH for most plants which is consistent with Parikh and James (2012) findings. At the highest rate of amendment, the pH remains between 6.36 and 6.82 in both experiments. The pH of the biochar used in the study was 9.69 which is in line with the findings of Abukari et al. (2022), who reported that the pH range of biochar is 4-12 and its alkaline nature affects the pH of amended soils. Their findings stated that increasing the rate of biochar amendment increases the pH of amended soils.

Similar findings were made by Schaffert et al. (2022), who reported that biochar amended soils leads to low noticeable pH changes although the biochar is alkaline, this is due to the soil natural buffering capacity. Bahrun et al. (2018), concluded in their findings that biochar amended soils increases pH, improves soil health and promotes plant growth by releasing nutrients. However, the decrease in pH by 6.18 and 6.23 in both experiments are consistent with the findings of Lehmann et al. (2011) who reported that the application of biochar may increase or decrease the pH of amended soils depending on the pH and liming value of the biochar. Similar findings were reported by Piash et al. (2021), who found that biochar amended soils decreased the pH of the soil. Their findings explained that the high amount of decomposable volatile matter could result in the decrease in soil pH, microorganisms can decrease the pH by breaking down small organic molecules and producing CO_2, organic acids and ammonium ions. From the finding's biochar amended soils increased the pH which has proven to be an important tool for addressing soil acidity. Similar findings were made by Tao et al. (2024), who found that the application of biochar to acidic soil can effectively reduce its acidity and increase its capacity to neutralize acids.

A significant (p = 0.002) effect in nitrogen concentration was observed between treatments in experiment one. Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil nitrogen concentration increased significantly to 2.06 mg/kg relative to the control. Treatment 2 (T2): 25% by volume biochar and 75% by volume topsoil nitrogen concentration increased to 1.34 mg/kg when compared to the control nitrogen concentration of 0.78 mg/kg (Figure 4.15).

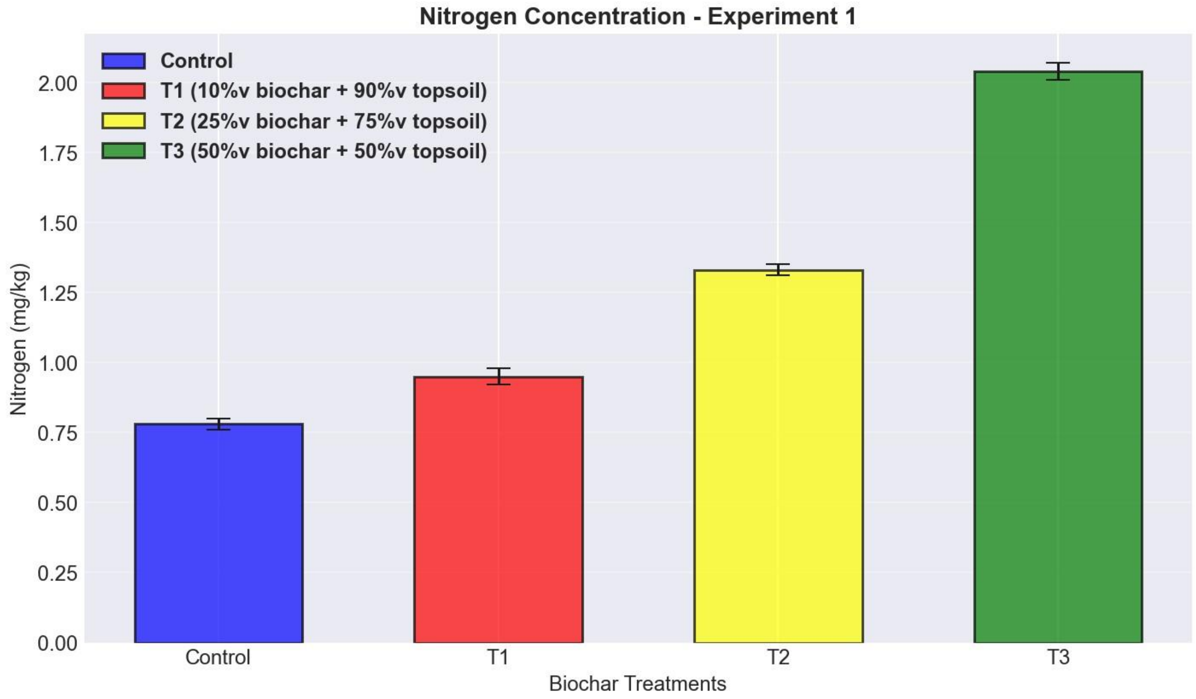

Figure 4.15: Effects of Biochar Application Rates on Nitrogen Concentration in Soil Error Bars Represent Mean ± Standard Deviation

There was a significant (p = 0.003) effect in nitrogen concentration between the biochar treatments in experiment two. The nitrogen concentration continuously increases from control to Treatment 1, Treatment 2, and Treatment 3 indicating a positive correlation between nitrogen concentration and the rate at which biochar was amended. The nitrogen concentration in Treatment 3 (T3): 10% by volume biochar and 10% by volume topsoil, increased significantly to 2.25 mg/kg over the control (Figure 4.16).

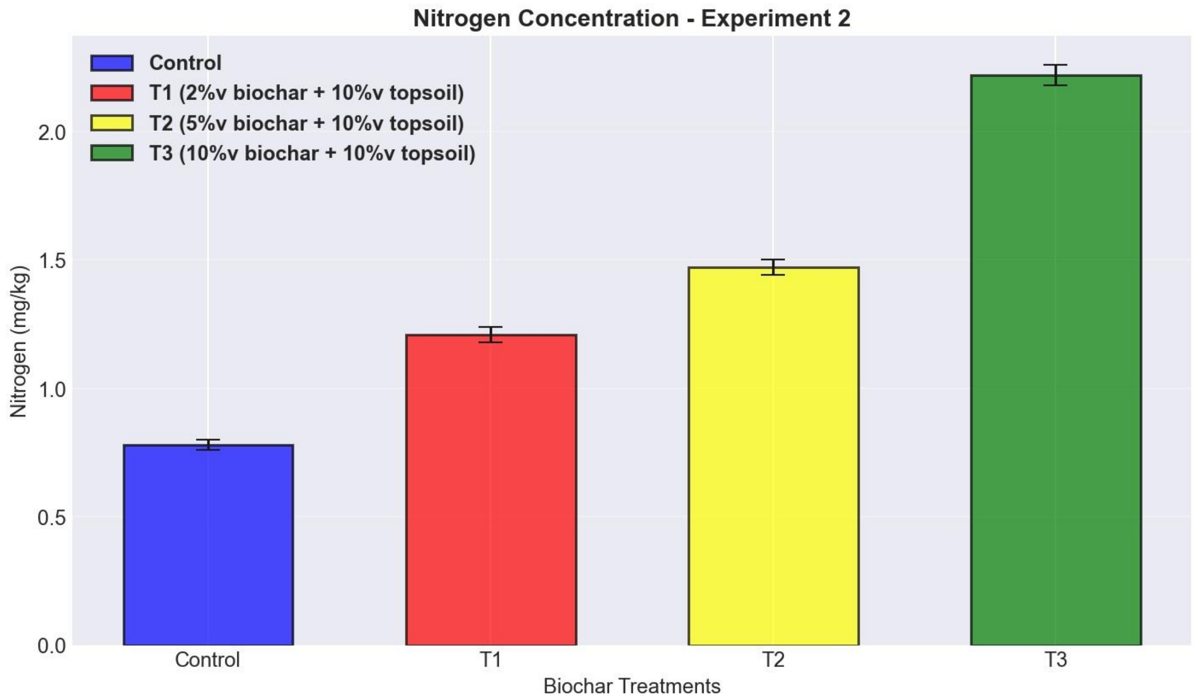

Figure 4.16: Effects of Biochar Application Rates on Nitrogen Concentration in Soil Error Bars Represent Mean ± Standard Deviation

Nitrogen concentration increased significantly ($p \leq 0.003$) in all biochar treatments compared to the control in both experiments. In both experiments, it was found that the concentration of nitrogen in the soil increases as the application rates increased. The nitrogen concentration of the biochar used in the study was low, at 0.78 mg/kg in both experiments. This indicates that adding soil amendments particularly at higher rates with biochar can improve nitrogen availability or retention more effectively. From the findings applying biochar can significantly increase soil nitrogen levels, especially at higher rates. The synergistic interaction of biochar as soil amendment increases the nitrogen availability beyond the natural nitrogen content of the biochar that makes the biochar a useful amendment for nitrogen deficient soils. These findings are consistent with Chan et al. (2008) who reported that biochar's high surface area and cation exchange capacity enhances nitrogen retention. Similar findings were made by Yao et al. (2021) who found that higher total nitrogen content in the soil was positively correlated with the amount of biochar added. They stated in their findings that biochar amended soils enhances the soil capacity to retain nutrients especially when the biochar is amended at higher rates. The findings are also in agreement with Abukari et al. (2022) who reported that biochar amended soils changes the flow, storage and conversion of nitrogen, reducing nitrogen leaching and increasing nitrogen availability. Similar findings were made by Sharma et al. (2023) who found that biochar amended soils increases the levels of various nitrogen types most of which are categorized as either organic or inorganic nitrogen. Parker et al. (2021) made a similar observation, stating that the application of biochar increased the percentage of total nitrogen in all biochar treatments above the control.

Phosphorus concentration showed a statistically significant ($p < 0.001$) effect among the biochar treatments in experiment one. The amendment of 25% by volume biochar and 75% by volume topsoil in Treatment 2 (T2) increased phosphorus concentration to 16.25 mg/kg, which was significantly higher than the control, which had a phosphorus concentration of 10.75 mg/kg (Figure 4.17).

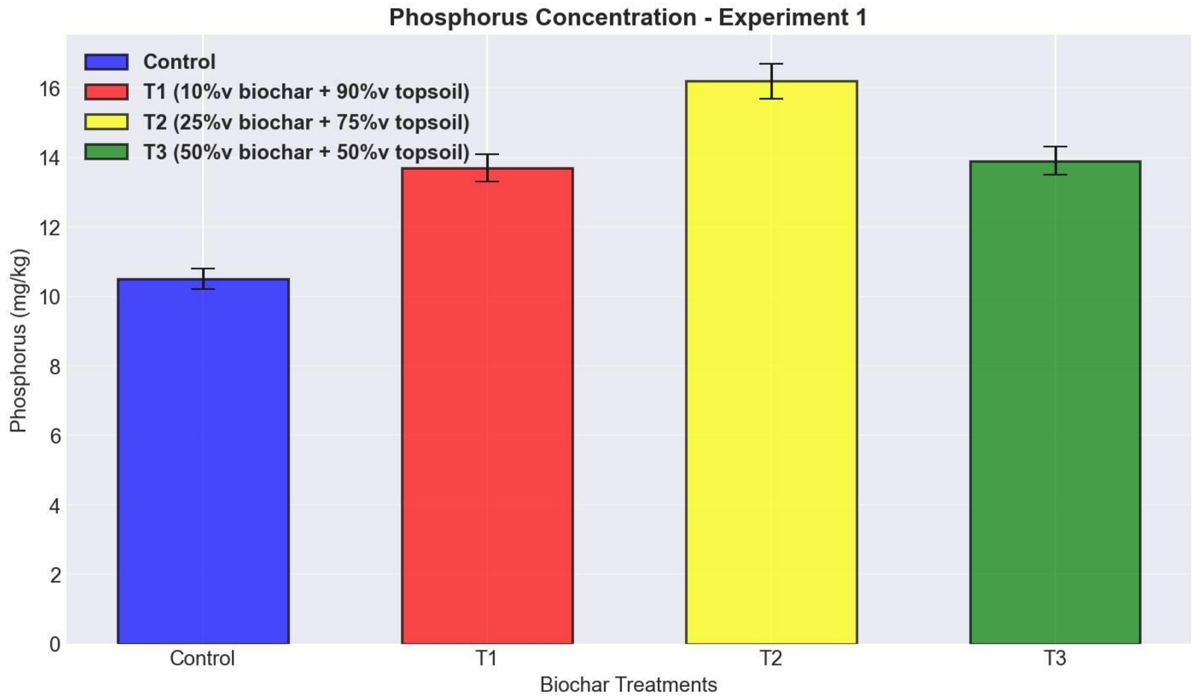

Figure 4.17: Effects of Biochar Application Rates on Phosphorus Concentration in Soil

Error Bars Represent Mean ± Standard Deviation

Phosphorus concentration varied significantly ($p < 0.001$) among the biochar treatments in experiment two. In all biochar treatments, the amendment of biochar increased the phosphorus concentration. However, phosphorus concentration in Treatment 1 (T1): 2% by volume biochar and 10% by volume topsoil increased significantly to 17.30 mg/kg when compared to the control (Figure 4.18).

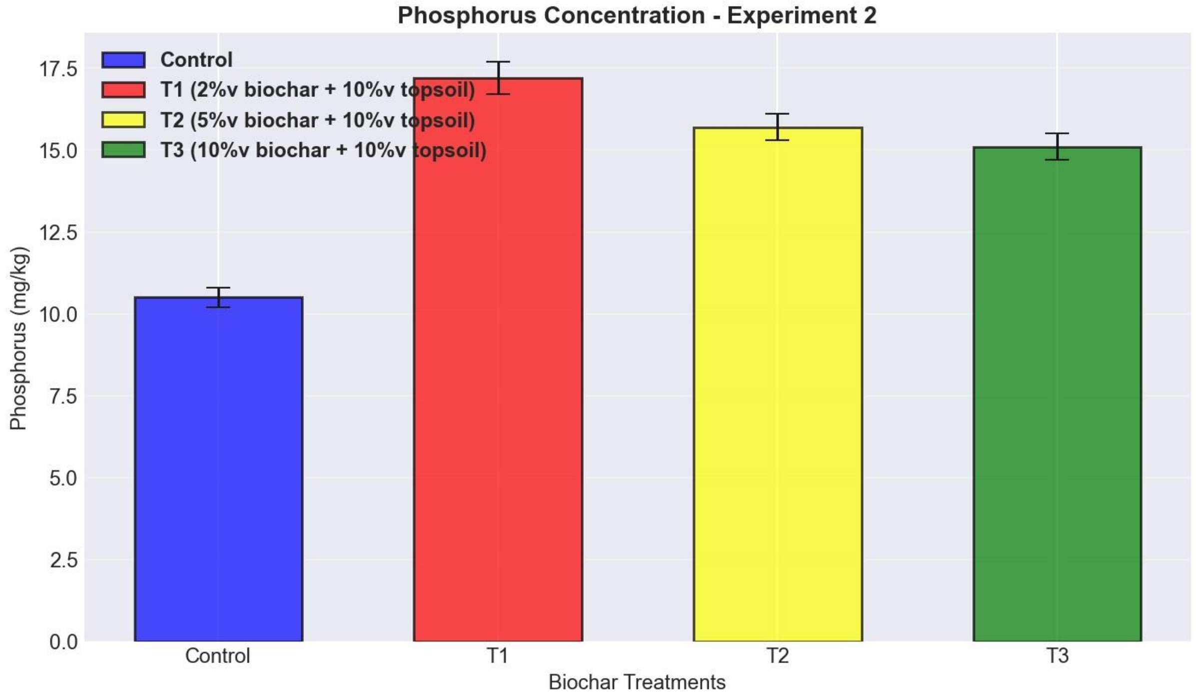

Figure 4.18: Effects of Biochar Application Rates on Phosphorus Concentration in Soil Error Bars Represent Mean ± Standard Deviation

In both experiments, the concentration of phosphorus was significantly high in all biochar amended treatments than in the control. The highest phosphorus concentration in experiment one was 16.25 mg/kg for Treatment 2 (T2): 25% by volume biochar and 75% by volume topsoil while the highest phosphorus concentration in experiment two was 17.30 mg/kg for Treatment 1 (T1): 2% by volume biochar and 10% by volume topsoil. As observed in pH and nitrogen, the increase in phosphorus concentration did not correspond with the trend of increasing biochar application rate. This demonstrated that the ideal rates for releasing phosphorus are low to moderate since high amounts pose the risk of being fixed by iron and aluminum oxides, which are prevalent in Ghanaian soils (Amoah et al., 2012). These findings are consistent with those of Tanzito et al. (2020), who found that biochar enhanced the amount of phosphorus available in the soil. Similar findings were made by Gao et al. (2019) who reported an increase in soil phosphorus after the amendment of biochar. Agyei et al. (2025) findings noted that biochar's ability to decrease phosphorus fixation in soils and potentially release phosphorus from its ash content is responsible for the increase in available phosphorus. The findings also align with Apori (2021), who reported that corncob biochar amendment alone increased the amount of phosphorus available in the soil when compared to the control. Similar findings were made by Gezahegn et al. (2024), who reported that the increase in availability of phosphorus is associated to biochar high phosphorus content, enhanced soil pH and high biochar amendment. The findings also align with Tazebew et al. (2024) who found that organic amendments have high levels of available phosphorus which are responsible for the increase in available phosphorus with biochar amendments.

There was a statistically significant ($p < 0.001$) effect in potassium concentration among biochar treatments in experiment one. In all biochar amendments there was an increase in potassium concentration. The potassium concentration in Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil increased significantly to 188 mg/kg compared to the control potassium concentration of 112 mg/kg (Figure 4.19).

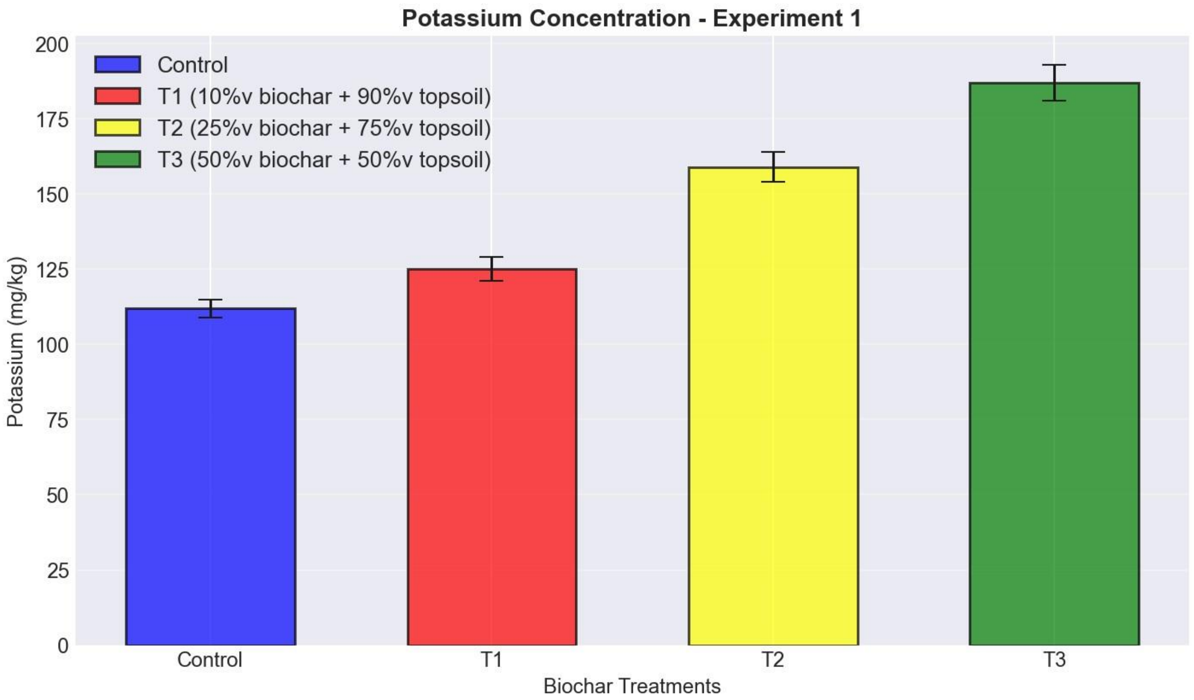

Figure 4.19: Effects of Biochar Application Rates on Potassium Concentration in Soil Error Bars Represent Mean ± Standard Deviation

Biochar amendment rates significantly (p = 0.003) influenced potassium concentration among the various treatments in experiment two. Biochar amendment had a major effect on Treatment 3 (T3): 10% by volume biochar and 10% by volume topsoil, potassium concentration was found to be 166 mg/kg significantly higher than control which recorded a lower potassium concentration of 112 mg/kg (Figure 4.20).

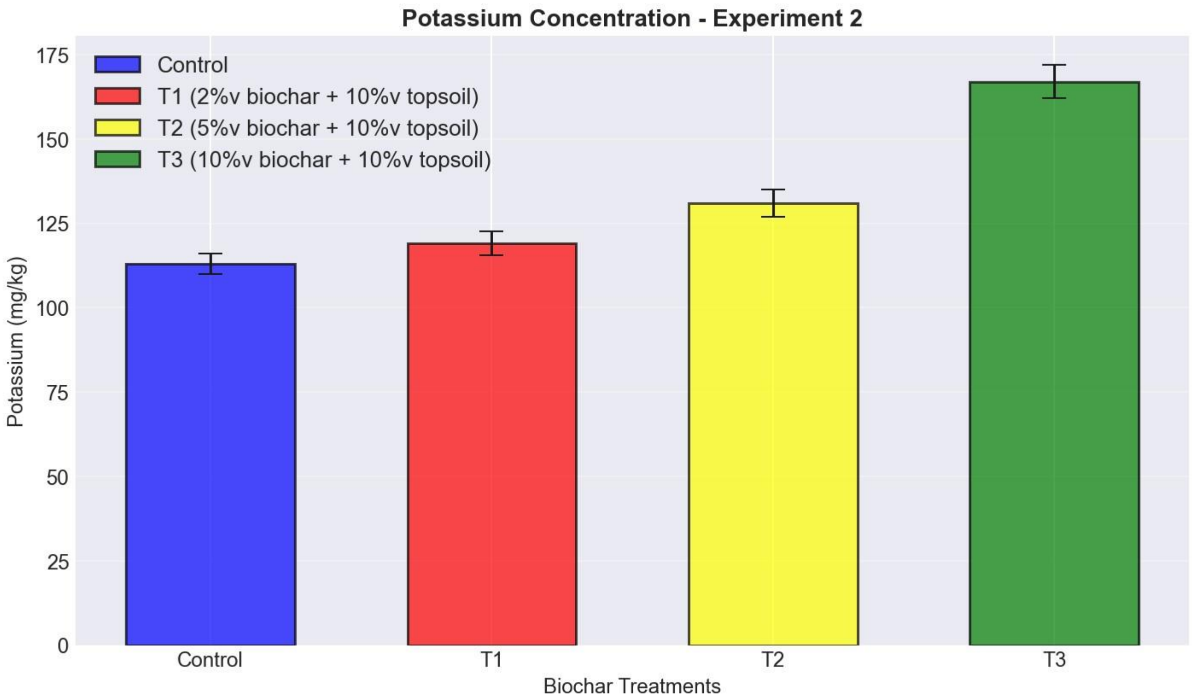

Figure 4.20: Effects of Biochar Application Rates on Potassium Concentration in Soil

Error Bars Represent Mean ± Standard Deviation

The findings showed that, in both experiments, the potassium concentration was high in all biochar amended treatments than in the control. In both experiments, the concentration of potassium increase as the rates at which biochar was applied increased. The highest rates of biochar amendment in both experiments showed the highest potassium concentration. This effect can be attributed by the 305 mg/kg of potassium in biochar, this observation aligns with the findings of Chen et al. (2024), who stated that the significant potassium content of the biochar itself is most likely the cause of this outcome, directly benefiting the soil. The findings are consistent with Doulgeris et al. (2023), who found that there is a significant effect on potassium release when the rate of biochar application increases. Similar findings were reported by Kononchuk et al. (2022), who found that the addition of biochar at concentrations of 3% and 5% increased the potassium content of the control soil which was previously low. They attributed the increase to biochar's high potassium concentration. The findings are in line with Entio et al. (2024), who found that applying biochar changed potassium levels, increasing them by 174% to 425% in sandy loam soil. Similar findings were made by Liang et al. (2024), who noted that when the pH is low potassium elements in acidic soil are easily fixed but difficult for plants to absorb and utilize, however, when the pH is increased by biochar amendments, it enhances the release of potassium elements and makes it easier for plants to absorb. From the findings of this study, biochar amendments in sandy loam soil resulted in a significant increase in the concentration of nitrogen, phosphorus and potassium. High biochar amendments showed a significant increase in soil nutrients, with the exception of phosphorus which is in line with the findings of Zhou et al. (2024), who reported that high biochar amendments increased soil available nutrients.

4.4 Effects of Biochar Application Rates on Soil Organic Carbon (SOC).

A statistically significant ($p = 0.002$) effect on soil organic carbon was observed among the biochar treatments in experiment one. In comparison to the control, which recorded 2.37% soil organic carbon, the biochar amended treatment increased significantly the amount of soil organic carbon in Treatment 3 (T3): 50% by volume biochar and 50% by volume topsoil, which recorded 5.07% soil organic carbon (Figure 4.21).

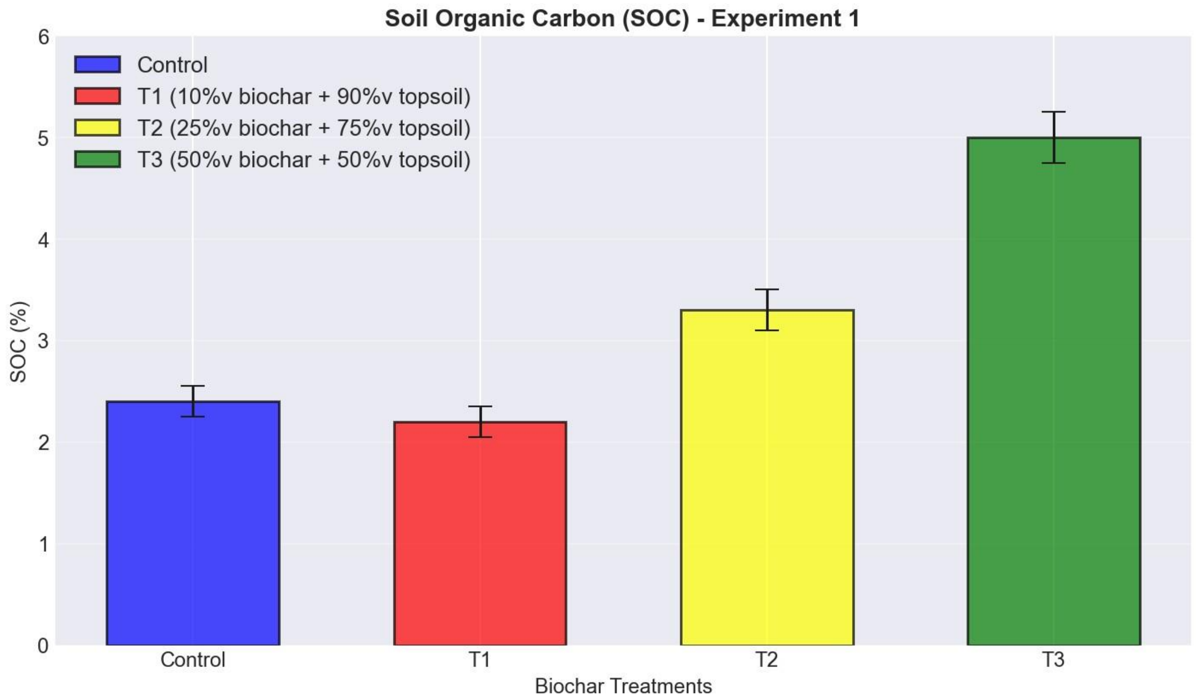

Figure 4.21: Effects of Biochar Application Rates on Soil Organic Carbon (SOC) Error Bars Represent Mean ± Standard Deviation

A highly significant ($p < 0.001$) effect was observed between biochar treatments on soil organic carbon in experiment two. Biochar amendment in Treatment 3 (T3): 10% by volume biochar and 10% by volume topsoil significantly increased soil organic carbon to 5.83% relative to the control soil organic carbon of 2.37% (Figure 4.22).

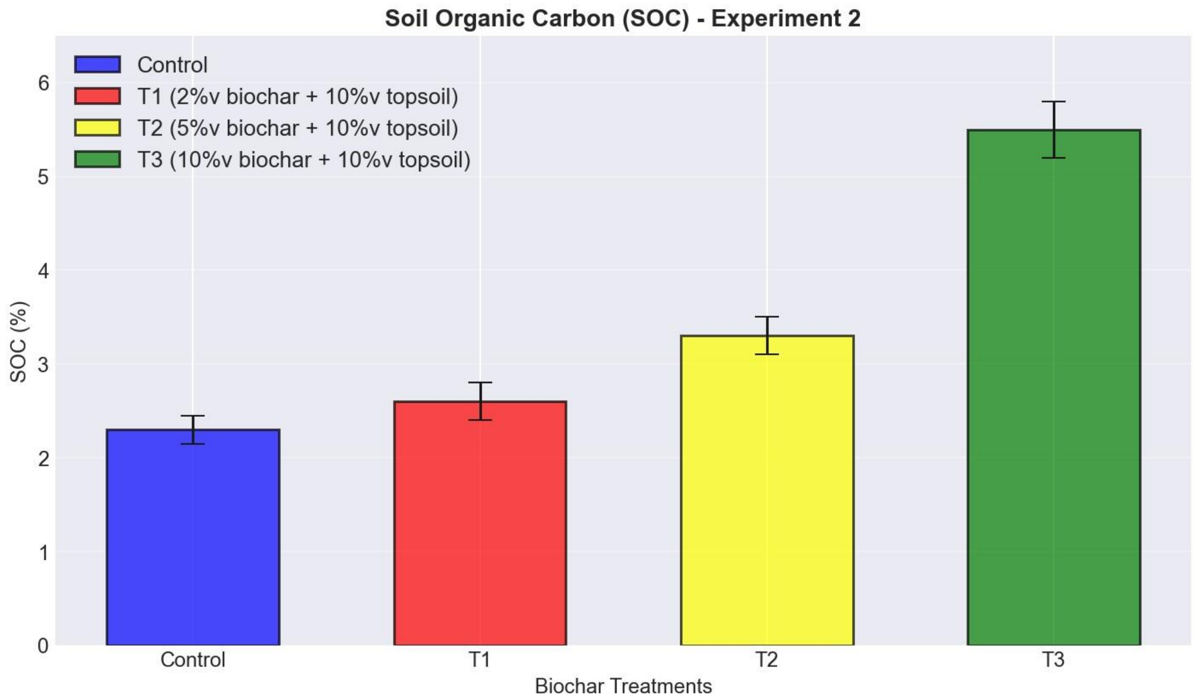

Figure 4.22: Effects of Biochar Application Rates on Soil Organic Carbon (SOC) Error Bars Represent Mean ± Standard Deviation

All biochar amended treatments showed a significant increase in soil organic carbon compared to the control in both experiments. As the rates of biochar application increased in both experiments, so did the amount of soil organic carbon. In both experiments, the highest rates of biochar amendment resulted in the highest levels of soil organic carbon. Biochar application significantly improved the soil organic carbon content and this can be attributed to the high percentage of stable carbon in biochar which is the highest among all the mineral elements found in the ash (Ofori et al., 2021). The carbon content of the biochar used in this study was 19.16%, combined with the capacity of biochar to resist decomposition contributed significantly to the soil organic carbon content increase. This finding is in line with Sharma et al. (2023), who found that the rate at which biochar is amended to soil has the highest effect on the soil general carbon content. In their findings they stated that biochar amendments increased significantly the total soil carbon content from 28.9% to 140%.

The findings of this study are consistent with the findings reported by (Jiang et al., 2021; Chen et al., 2024; Agyei et al., 2025; Parker et al., 2021; Syahrinudin et al., 2021 and Manka'abusi et al.,2024), who collectively demonstrated that total organic carbon (TOC) increases progressively with higher rates of biochar amendment. Across these studies, biochar application was shown to enrich soil carbon pools due to its high carbon stability, slow decomposition rate, and strong resistance to microbial mineralization. As the proportion of biochar incorporated into the soil increased, total organic carbon levels increased correspondingly, indicating a direct and positive relationship between amendment rate and soil carbon accumulation. These authors further noted that the highest biochar amendment rates produced the highest improvements in total organic carbon, confirming the capacity of biochar to act as a long-term carbon reservoir in soil. This trend aligns with the findings of this study, where increasing the amendment rate resulted in a consistent increase of organic carbon content. Such effects can be attributed to the inherently carbon-rich structure of biochar, which remains stable in soil and contributes significantly to total carbon content. Additionally, biochar's porous nature can promote the retention of organic matter and enhance the protection of carbon from decomposition, further supporting sustained increases in total organic carbon. Overall, the convergence of evidence suggests that biochar amendments play a central role in enhancing soil organic carbon, with higher application rates producing proportionately higher increases. The persistent maintenance of increased carbon levels observed in both the present study and previous studies emphasizes the potential of biochar as an effective strategy for improving soil carbon status and supporting long-term soil quality.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Poor quality seedlings raised at the nursery has led to the failure of many plantation restoration programmes. The success of plantation restoration programmes depends on growing medium for raising quality nursery seedlings which is capable of surviving field conditions at the early stage. Biochar is advocated as the affordable growing medium for soil amendment. This study however, examined the effects of biochar amendment on the growth of *Terminalia superba* seedlings, soil chemical properties and soil organic carbon which will help in policy making on the appropriate biochar amendment to improve soil conditions for raising quality nursery seedlings in the transitional zone of Ghana. The findings from this study reveals that low biochar application rates, 10% by volume biochar amendment in experiment one and 2% - 5% by volume biochar amendment in experiment two consistently increased significantly the growth parameters when compared to the control. The growth performance was, however, decreased by higher biochar application rates (50% by volume biochar and 50% by volume topsoil, 10% by volume biochar and 10% by volume topsoil), which in certain instances performed worse than the control. This showed that higher biochar application rates can have detrimental effects on soil chemical properties resulting in nutritional imbalances that hinder the growth of early seedlings.

Biochar amendments increased the soil chemical properties (pH, nitrogen, phosphorus and potassium) relative to the control. The concentration of nitrogen and potassium were positively correlated with the rates at which biochar was amended, indicating that the biochar directly enriched the nutrients and enhanced their retention. However, low and moderate application rates were found to optimize the phosphorus concentration, while excessive amendment resulted in decreased release. In order to mitigate soil acidity without causing alkalinity, the biochar amendment increased the pH of the soil while maintaining it within the ideal range for plant growth. Higher rates of biochar amendments were found to significantly increase soil organic carbon. Soil organic carbon content was consistently higher in biochar treatments with the highest biochar rate. This showed the potential of biochar as a long-term carbon sink and a means to enhance soil carbon sequestration. The study findings demonstrate that biochar is a useful soil amendment for improving seedling growth and soil fertility but its effects vary depending on the rate at which it is amended; a low rate of biochar amendment promotes growth, while a higher rate, though advantageous for soil organic carbon sequestration and soil fertility, will hinder plant development during the nursery stage.

5.2 Recommendation

The following recommendations are made from the findings of this study;

1. Low biochar application rates (2% by volume biochar and 10% by volume topsoil or 5% by volume biochar and 10 % by volume topsoil or 10% by volume biochar and 90% by volume topsoil) are recommended. Without inducing nutritional imbalances, these levels improve seedling height, Root Collar Diameter (RCD) and number of leaves. During the early stages of seedling establishment, it is important to avoid applying rates than this quantity.
2. Higher application rates can be suitable as long as they are balanced with the needs of plant growth if soil carbon sequestration and soil improvement are the main objectives of reforestation or soil rehabilitation projects beyond nursery conditions.
3. Long-term research should be done to assess how the biochar-amended nursery of *Terminalia superba* seedlings affects their survival and establishment in the field.

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APPENDICES

Appendix 1: Seedling Height Tukey HSD Test

Group 1	Group 2	Mean diff	P-Adj	Lower	Upper	Reject
Control	T1	11.1133	0	7.5145	14.7121	True
Control	T2	9.2867	0	5.6879	12.8855	True
Control	T3	-0.36	0.9938	-3.9588	3.2388	False
T1	T2	-1.8267	0.5502	-5.4255	1.7721	False
T1	T3	-11.4733	0	-15.0721	-7.8745	True

Appendix 2: Seedling Height ANOVA Table

Experiment	Time	Metric	F-statistic	p-value
Experiment 1	One Month	Height (cm)	42.9194	0
Experiment 1	Two Month	Height (cm)	321.9467	0
Experiment 1	Three Month	Height (cm)	135.8125	0
Experiment 2	One Month	Height (cm)	17.5393	0
Experiment 2	Two Month	Height (cm)	20.1709	0
Experiment 2	Three Month	Height (cm)	38.2905	0

Appendix 3: Number of leaves Tukey HSD Test

Group 1	Group 2	Mean diff	P-Adj	Lower	Upper	Reject

Control	T1	3.7667	0	1.7589	5.7745	True
Control	T2	2.3333	0.0158	0.3255	4.3411	True
Control	T3	-1.7	0.1274	-3.7078	0.3078	False
T1	T2	-1.4333	0.2507	-3.4411	0.5745	False
T1	T3	-5.4667	0	-7.4745	-3.4589	True

Appendix 4: Number of leaves ANOVA Table

Experiment	Time	Metric	F-statistic	p-value
Experiment 1	One Month	No. of Leaves	66.1917	0
Experiment 1	Two Month	No. of Leaves	758.8619	0
Experiment 1	Three Month	No. of Leaves	198.1929	0
Experiment 2	One Month	No. of Leaves	10.376	0
Experiment 2	Two Month	No. of Leaves	18.6384	0
Experiment 2	Three Month	No. of Leaves	19.8689	0

Appendix 5: Root Collar Diameter Tukey HSD Test

Group 1	Group 2	Mean diff	P-Adj	Lower	Upper	Reject
Control	T1	1.38	0	0.8464	1.9136	True

Control	T2	1.3733	0	0.8397	1.907	True
Control	T3	-0.0567	0.9926	-0.5903	0.477	False
T1	T2	-0.0067	1	-0.5403	0.527	False
T1	T3	-1.4367	0	-1.9703	-0.903	True

Appendix 6: Root Collar Diamter ANOVA Table

Experiment	Time	Metric	F-statistic	p-value
Experiment 1	Two Month	RCD (mm)	172.9906	0
Experiment 1	Three Month	RCD (mm)	346.3367	0
Experiment 2	Two Month	RCD (mm)	30.161	0
Experiment 2	Three Month	RCD (mm)	31.4285	0

Appendix 7: Effect of Biochar Application Rates on Soil Chemical Properties ANOVA Table

Experiment	**Parameter**	**F-value**	**Significant ($p < 0.05$)**
Experiment 1	pH Value	31483.42	0.0012
Experiment 1	Soil Organic Carbon (SOC)	759.9441	0.0022
Experiment 1	Potassium Concentration	2328.883	0.0002

Experiment 1	Phosphorus Concentration	459142.7	0.0001
Experiment 1	Nitrogen Concentration	693075.5	0.0022
Experiment 2	pH Value	24509.92	0.0025
Experiment 2	Soil Organic Carbon (SOC)	736.5719	0.0002
Experiment 2	Potassium Concentration	2458.686	0.003
Experiment 2	Phosphorus Concentration	4552143	0.0002
Experiment 2	Nitrogen Concentration	663075.5	0.0027

Appendix 8: Phosphorus (mg/kg) Tukey HSD Test

Group 1	Group 2	Mean diff	P-Adj	Lower	Upper	Reject
Control	T1	3.05	0	2.9776	3.1224	True
Control	T2	5.5	0	5.4276	5.5724	True

Control	T3	3.1567	0	3.0842	3.2291	True
T1	T2	2.45	0	2.3776	2.5224	True
T1	T3	0.1067	0.0047	0.0342	0.1791	True
T2	T3	-2.3433	0	-2.4158	-2.2709	True

Appendix 9: Potassium (mg/kg) Tukey HSD Test

Group 1	Group 2	Mean diff	P-Adj	Lower	Upper	Reject
Control	T1	13	0.0013	5.5596	20.4404	True
Control	T2	45.6667	0	38.2263	53.1071	True
Control	T3	76	0	68.5596	83.4404	True
T1	T2	32.6667	0	25.2263	40.1071	True
T1	T3	63	0	55.5596	70.4404	True
T2	T3	30.3333	0	22.8929	37.7737	True

Appendix 10: Nitrogen (mg/kg) Tukey HSD Test

Group 1	Group 2	Mean diff	P-Adj	Lower	Upper	Reject
Control	T1	0.44	0	0.44	0.44	True
Control	T2	0.7	0	0.7	0.7	True

Control	T3	1.47	0	1.47	1.47	True
T1	T2	0.26	0	0.26	0.26	True
T1	T3	1.03	0	1.03	1.03	True
T2	T3	0.77	0	0.77	0.77	True

Appendix 11: pH Tukey HSD Test

Group 1	Group 2	Mean diff	P-Adj	Lower	Upper	Reject
Control	T1	-0.0367	0.0648	-0.0753	0.002	False
Control	T2	0.17	0	0.1314	0.2086	True
Control	T3	0.5567	0	0.518	0.5953	True
T1	T2	0.2067	0	0.168	0.2453	True
T1	T3	0.5933	0	0.5547	0.632	True
T2	T3	0.3867	0	0.348	0.4253	True

Appendix 12: SOC (%) Tukey HSD Test

Group 1	Group 2	Mean diff	P-Adj	Lower	Upper	Reject
Control	T1	-0.08	0.9994	-1.2933	1.1333	False
Control	T2	1.0533	0.0976	-0.16	2.2666	False

Control	T3	2.6967	0.0002	1.4834	3.91	True
T1	T2	1.1333	0.07	-0.08	2.3466	False
T1	T3	2.7767	0.0002	1.5634	3.99	True
T2	T3	1.6433	0.0084	0.43	2.8566	True

Pictures from the Study Conducted