ASSESSING THE POTENTIAL OF BIOCHAR TO RESTORE DEGRADED LANDS

by

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Declaration

I hereby declare that the MSc research project entitled “Assessing the potential of biochar to restore degraded lands” is an original work carried out by me under the supervision of Professor EM Stam and Dr L Mugwedi at the University of Venda. All sources of information and data used in this project have been acknowledged and cited appropriately. I confirm that this project has not been submitted for the award of any other degree or diploma in any other institution of higher education and learning. Furthermore, I confirm that the work presented in this project is my own, and any contributions made by other individuals have been duly acknowledged. I also declare that the research conducted in this project observed the ethical principles and guidelines for this type of research. I acknowledge that any breach of the above declaration may result in the nullification of this project and may also have legal implications.

Student: Hazel Shirinda

Signature:

Signature: 03/07/2023

Dedication

I would like to dedicate this MSc research project to my supervisors, Prof EM Stam and Dr L Mugwedi, who have been a constant source of inspiration and motivation throughout my academic journey. Their unwavering support, encouragement, and belief in my abilities have been instrumental in shaping my academic and research pursuits. This project reflects their influence and impact on my life, and I am grateful for their firm support. I hope this project serves as a testament to their guidance and encouragement and that it inspires others to pursue their academic goals with determination and dedication.

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Abstract

Land degradation and climate change are interlinked processes that negatively impact sustainable development. Globally, they pose a risk to human livelihoods, but their effects are even more prominent in developing nations, especially in sub-Saharan Africa. Even with land degradation and climate change currently happening, communities, especially in developing countries, still need to adapt to the changes. This may be due to the high adaptation costs and the need for more knowledge. Biochar is the product of the thermochemical conversion of biomass through pyrolysis. Using biochar as a soil ameliorant has been increasingly advocated because of its effects on soil properties, crop productivity, and carbon sequestration. Biochar has been reported to improve soil quality, crop yield, and soil carbon sequestration potential. Despite this, little is known about the effects of biochar on soil physical properties, making it difficult to recommend biochar to improve soil quality in agriculture. Thus, this study aims to assess the potential of biochar to restore severely degraded land by improving soil properties and crop productivity and mitigating climate change through carbon sequestration at the Lapalala Wilderness Reserve, Waterberg District, Limpopo Province, South Africa. For this purpose, four treatments (biochar, biochar with fertilizer, biochar without fertilizer, and control) were applied to four plots, each replicated five times. A 14-species grass mixture was sown in each of the 20 plots. Soil physical and chemical properties, plant biomass, carbon stock, species richness, and species composition were then measured. None of the four treatments had a significant effect on soil bulk density while only biochar had a significant effect on soil chemical properties of soil Total C, Na and soil pH. No treatment had a significant effect on plant biomass. The analysis of similarity showed no significant difference in species composition for all treatments at month three and month six. The species composition for both treatments and sites for months three and six was mostly similar. The effects of biochar were not significant on soil chemical and physical properties as well as plant growth and biomass. Longer-term studies with higher rates of biochar application are required to confirm the effects of biochar on soil properties, plant growth, and species composition. The biochar feedstock (e.g., agricultural residues, forestry residues, and grassland cutting), biochar properties (such as porosity, bulk density, carbon content) and soil types need to be taken into consideration before application of biochar into the soil to enhance soil properties and plant growth.

Keywords: *Climate change, Soil degradation, Carbon offsets, Carbon sequestration, Ecosystem restoration, Biodiversity.*

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Acronyms

ADE : Amazon Dark Earths
ANOSIM : Analysis of similarity
CEC : Cation Exchange Capacity
IAPs : Invasive alien plants
IBI : International Biochar Initiative
IPBES : Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem services
IPCC : Intergovernmental Panel on Climate Change
IUCN : International Union for the Conservation of Nature
GHGs : Greenhouse gases
HTC : Hydrothermal carbonization
LDN : Land degradation neutrality
LULCC : Land use/ Land cover change
LWR : Lapalala Wilderness Reserve
NBS : Nature-based solutions
Pg : Petagrams
SDGs : Sustainable Development Goals
SOC : Soil organic carbon
SOM : Soil organic matter
SSA : Sub-Saharan Africa
VOCs : Volatile organic compounds
UNFCCC : United Nations Framework Convention on Climate Change
UNCCD : United Nations Convention to Combat Desertification
UNESCO : United Nations Educational, Scientific and Cultural Organization
UNGA : United Nations General Assembly
UNSDG : United Nation Sustainable Development Goals

CHAPTER 1: INTRODUCTION

1.1 Background

Climate change threatens ecosystems and human well-being, primarily through food insecurity. The geographical ranges of many species are likely to be altered by changes in precipitation and temperature conditions, and some may be driven to extinction (Sietz *et al*., 2011; Bradley *et al.*, 2012; Hurni *et al*., 2015; Pecl *et al*., 2017; Amoak *et al*., 2022). Understanding the impacts of climate change on natural and human systems and the risks involved is important for comprehending the state of climate emergency (Adger *et al*., 2003; Roberts, 2008; Panteli and Mancarella, 2015; Fawzy *et al*., 2020).

Due to their high vulnerability to extreme climatic events such as floods and droughts, developing countries have specific needs to adapt to climate change (Mertz *et al.*, 2009; Adedeji *et al*., 2014). Such adaptation involves changes in social-ecological systems in response to the impacts of climate change in the context of interacting non-climatic changes. The adaptation strategies range from short-term coping mechanisms to long-term, more profound, transformations (Moser and Ekstrom, 2010; Nalau *et al.*, 2015; Pandey and Bardsley, 2015; Dang *et al*., 2019; Adams, 2021; Bruley *et al*., 2021). Adaptation has thus established itself as an essential much-needed response to global climate change (Fussel, 2007; Hannah, 2010; Termeer *et al*., 2016; Conway *et al*., 2019), and has risen sharply as a topic of scientific inquiry in the first decade of the 21st century in both local and international policy, planning, media, and public awareness.

Land is essential for providing the principal basis for human livelihoods and well-being, including the supply of food, freshwater, and other essential ecosystem services (IPCC, 2019). Over 33% of global land resources are degraded (Abhilash, 2021). The impact of land degradation on world food security and environmental quality increases the importance of land degradation, among other global environmental issues (Imoke *et al.*, 2010). Land degradation and climate change are interlinked processes with biophysical and human drivers, impacts, and responses. Land degradation processes, including accelerated soil erosion, can be exacerbated by climate change effects, such as increased evapotranspiration rates, rainfall intensity, flooding, frequent and severe droughts, dry spells, heat waves, and storms (Gisladottir and Stocking, 2005; Webb *et al.*, 2017; IPCC, 2019). Land degradation and climate change are escalating challenges affecting biodiversity, ecosystem services, global agricultural production, and food security (Aggarwal *et al*., 2010; Tirado *et al*., 2010; Lu, *et al*., 2015; Gupta, 2019).

Sustainable Development Goal 15 aims to protect, restore, and promote the sustainable use of terrestrial ecosystems, sustainably manage ecosystems, combat desertification, stop and reverse land degradation and stop biodiversity losses (Akhtar-Schuster *et al*., 2011; Webb *et al*., 2017). Furthermore, SDG 15.3 specifically targets the need to combat desertification, drought, and floods and strives to achieve a neutral land degradation world by 2030 (UNGA, 2015).

The Earth System has been affected by the overuse of resources, poor land management and planning, poor land use, and impacted heavily by the adverse effects of climate change. Changes in natural Earth System cycles, such as the water, carbon, and nitrogen cycles, have resulted in land degradation and desertification in some parts of the world (Keestra *et al*., 2018).

Changes in land use are significant drivers of soil degradation. Soil degradation results in the loss of critical functions and ecosystem services that ensure sufficient food and water supply, acting as a buffer against extreme climatic events, supporting biodiversity, and providing a terrestrial store of carbon and nutrients (Karlen and Rice, 2015). In the carbon cycle, soil plays an important role and accounts for more than two-thirds of carbon stocks in terrestrial ecosystems. However, soil organic carbon stocks and soil fertility are rapidly diminishing (Burgeon, 2017). The overexploitation and inappropriate use of the earth has negatively impacted food production and this will continue unless it is addressed (Taraqqi-A-Kamal *et al*., 2021).

Ecological restoration is regarded as an effective strategy to restore/revive/rehabilitate ecosystem services and reverse local biodiversity loss. Martin (2017) defined ecological restoration as a process that aids the recovery of degraded or damaged ecosystem. Ecological restoration is essential in global environmental policy, because of its potential to improve human livelihoods and enhance biodiversity (Bullock *et al*., 2011). Many UN SDGs link to land and water management and call for sustainable use of resources, restoration of ecosystems and their services and biodiversity, carbon sequestration, and sustainable catchment management. A solution for most of these problems is restoring ecosystems. Most restoration projects focus on artificial and high-maintenance strategies, which are expensive and unproductive in the long-term (Keestra *et al.*, 2018).

Biochar is a solid material produced through the thermochemical decomposition of biomass. It can be used as a soil amendment due to its high mineral content and unique physicochemical structure (Uras *et al.*, 2012; Cha *et al.*, 2016). Other biochar applications include carbon sequestration and plant growth improvement (Chen *et al.*, 2018; Verheijen *et al.*, 2009). One of the critical properties of biochar for carbon sequestration is its stability (Uras *et al.*, 2012). Therefore, biochar has potential as a climate change mitigation tool that can sequester carbon for long periods while at the same time improving soil conditions; this being due to its recalcitrant chemical composition and high carbon content (Verheijen *et al.*, 2009).

1.2 Problem statement

Worldwide, land degradation remains one of the main threats to ecological functioning, ecosystem services provision, and development (Willemen *et al.*, 2018; UNCCD, 2015). Land degradation negatively impacts ecosystems and plays a significant role in biodiversity losses. Despite great effort to combat and prevent land degradation, the problem continues globally and is aggravated by climate change.

Climate change can accelerate the impacts of land degradation, and nearly all the drivers of land degradation are exacerbated by climate change. These include extreme weather events, increased risk of wildfires, the emergence of pests and diseases, and the distribution of alien invasive species (IPBES 2018). Climate change has impacted negatively on terrestrial ecosystems and food security worldwide and contributed to desertification and land degradation (IPCC, 2019).

Ecological restoration has become an effective strategy for increasing the provisioning of ecosystem services and reversing biodiversity loss (Bullock *et al.*, 2011). Rehabilitation and restoration measures, such as reforestation, can help address climate change and land degradation but may not be fully effective on their own due to their limited scale, competing land use demands, and inability to address greenhouse gas (GHG) emissions which requires a combination of strategies (UNEP 2011; IPBES 2018). Biochar may potentially restore degraded land by ameliorating degraded soils and improving vegetation growth which may help solve the problem of land degradation, especially in severely degraded land like the Lapalala old fields in the Waterberg District, Limpopo Province, South Africa (Ruwanza 2018), the Sneeuberg uplands in the eastern Karoo, South Africa (Boardman *et al*., 2017), and the Swartland in the Western Cape Province, South Africa (Meadows 2003). Biochar has been shown to amend degraded soil and sequester carbon and store it in the soil for long periods because of its recalcitrant nature (reference).

1.3 Aim and objectives

1.3.1 Aim

The aim is to determine biochar's usefulness in restoring degraded lands.

1.3.2 Specific objectives

- To determine the amount of carbon in the soil before and after applying biochar.
- To determine the potential of biochar to alleviate degraded soil and restore soil fertility in degraded lands.
- To assess temporal changes in soil properties after treatment with biochar.
- To determine the impact of biochar on the growth of selected grasses.

1.3 Significance of the study

This study views climate change and land degradation as interwoven processes and thus addresses them together. Due to their profound effects and the urgent need to address these challenges, this study investigates how biochar can be incorporated into the soil to improve soil properties and simultaneously offset carbon. There is a need for South Africa to adopt land management strategies that will enable improved productivity, especially in agricultural systems. Insights into how biochar can improve soil fertility provides useful knowledge for farmers, communities, authorities, and other stakeholders.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Land degradation is defined as "a process whereby land resources deteriorate or loss of the economic productivity of land over time as a result of land uses or human activities and or from one or more processes, including soil erosion, long term vegetation loss and deterioration of the physical, chemical, and biological properties of soil" (UNCCD 1994; Conacher and Conacher 1995; Webb *et al*., 2017). Land degradation and climate change are interlinked processes with biophysical and human drivers, impacts, and responses, presenting many challenges to global food security and development (Gisladottir and Stocking, 2015; Webb *et al*., 2017; Smith *et al*., 2019). Land degradation increases the vulnerability of systems to climate change, reducing the effectiveness of adaptation (Warner *et al*., 2009; Mbow *et al*., 2017). Climate change can increase land degradation through various means, including increased soil erosion, evapotranspiration rates, drought, and changes in biological diversity (Gisladottir and Stocking, 2005; Cowie *et al*., 2011; Webb *et al*., 2017). Land degradation may then further influence the extent and direction of the impacts of climatic changes on systems (Webb *et al*., 2017; IPCC, 2019). In the last century alone, the world has seen significant land degradation due to climate change, deforestation, and poor land use practices. It is estimated that about 23% of the global terrestrial land is already degraded (Albaladejo *et al*., 2021; IPBES, 2018).

It is important to address land degradation because land provides humans with many goods and services vital for sustaining life (Lynd *et al*., 2015; Cowie *et al*., 2018). Many regulating and supporting services on which the provisioning services depend, together with food and other materials, are provided by land (Joshi and Joshi, 2018; Kotsila *et al*., 2020). In addition to enhancing food security and sustainable living, land degradation management will have co-benefits for climate change mitigation, adaptation, and biodiversity conservation (Akhtar-Schuster *et al*., 2011; Cowie *et al*., 2018).

Land degradation has severe environmental consequences, including loss of soil, biodiversity, ecosystem services, the release of carbon dioxide (CO_2) into the atmosphere, and deteriorating water quality. The initial stage of land degradation is slow and barely noticeable, often leading the population and authorities to ignore it. Once initiated, land degradation develops into a torrent of undesirable environmental impacts (Pacheco *et al*., 2018).

2.2 Global and local extent of land degradation

Land degradation is a severe problem for many communities worldwide, especially tropical regions (Andersson *et al*., 2011). In sub-Saharan Africa, soil erosion is widely recognized as a severe environmental problem, contributing to food insecurity in the region (Kiage, 2013). In South Africa, land degradation, particularly soil erosion, is severe and widespread in large-scale commercial farms and former homelands (Critchley and Netshikovhela, 1998). Soil erosion threatens food and water security, economic development, and natural resource conservation (Bai *et al*., 2008). Historical and political situations, together with rainfall and geomorphological factors, are likely to make the communal areas of South Africa more susceptible to land degradation, specifically under the influence of climate change (Meadows and Hoffman, 2003). In essence, the climate of most of South Africa is semi-arid, and rainfall highly capricious. Soil erosion is a significant environmental problem because of rainfall seasonality across the country (Meadows and Hoffman, 2002).

2.3 Causes of land degradation

The causes of land degradation may be bio-geophysical, socio-economic, and institutional factors, such as insufficient land policy frameworks (Ezeaku and Davidson, 2008). Although the causes and consequences of land degradation differ from region to region, some similarities exist (Adewuyi and Baduku, 2012). Some significant causes of land degradation are human-induced climate change, land clearing, and deforestation. Overgrazing by livestock, incorrect irrigation methods, and urbanization can also lead to land degradation (Conacher, 2003; Barman *et al*., 2013). There are also other causes of land degradation. These include the introduction and spread of exotic species, animals, pests and diseases, fire, overexploitation of resources, people's attitudes, awareness, and knowledge, inaction by government agencies, and inappropriate government policies (Conacher, 2003; IPCC 2019).

In Africa, soil erosion is the most common cause of land degradation, followed by encroachment of unpalatable or low-quality plant species, depletion of nutrients, compaction, poor drainage, crusting and salinization, and soil contamination (Ezeaku and Davidson, 2008).

2.3.1 Climate change

Climate change is one of the world's most significant challenges, impacting natural and human systems (Zegeye, 2018). Variations in climate are a critical factor that contributes to land degradation. Climate change is associated with drought, floods, and forest fire intensification, which may lead to land degradation (Aggarwal *et al*., 2010). Due to climate change, drought, heat waves, and changes to seasonal precipitation patterns are expected to become more extreme and frequent. All these are physical drivers of land degradation. (Hermans and McLeman, 2021).

Climate change, directly and indirectly, impacts land degradation in forested and agricultural environments. These include a potential increase in heat stress on vegetation, changes in soil moisture availability, increased soil erosion by wind and rain, loss of soil nutrients, and an overall decline in vegetation and biomass. The above impacts can accelerate land degradation where it already occurs and initiate it in new areas. In turn, land degradation can contribute to climate change in regions affected by reducing carbon stocks in soils and vegetation through the release of CO_2. The exact impacts of climate change on land degradation processes are context-specific and depend on the physical characteristics of the exposed area and associated land-use systems (Antwi, 2013; Hermans and McLeman, 2021).

An important feedback loop occurs between climate change and land degradation, especially in drylands where climate warming and droughts may promote desertification, increase soil erosion, dust storms, and changes in albedo (McDonough *et al*., 2006). While climate change can exacerbate impacts on land degradation processes and reduce the viability of the available options to avoid, reduce, or reverse land degradation, land degradation can exacerbate climate change impacts and contribute to changes in the climate through a reduction in vegetation cover, increasing GHGs in the atmosphere (IPBES, 2018).

2.3.2 Land-use change

Amongst the significant causes of land degradation, land-use change has been shown to have the most critical environmental consequences through its impacts on soil and water quality, biodiversity, as well as ammonia (CH_4) and CO_2 emissions (Khresat *et al*., 2008). In the highlands of Ethiopia, changes in land-use, land cover, and inappropriate agricultural practices have resulted in severe land degradation, which led to loss of biological diversity (Alemu, 2015). In East Africa, land-use changes consist of transformation of land into farmlands, grazing lands, human settlements, and urban centres, all at the expense of natural vegetation. These changes are associated with deforestation, land degradation, and biodiversity loss (Maitima *et al*., 2009).

2.3.3 Land management

Land management maintains and improves land productivity for agriculture, forestry, and wildlife habitat. Land management encompasses all activities associated with managing land and natural resources required to achieve sustainable development (Enemark, 2006). Poor land management practices such as overgrazing, destructive farming practices such as deforestation, the overuse of inorganic fertilizers and pesticides, deep ploughing and tilling, monoculture, and leaving the land bare during rainy seasons can negatively impact the land and its productivity. As a result, poor land management practices can lead to land degradation. Therefore, sustainable land management practices, such as cover cropping, crop rotations, intercropping, conservation agriculture, agroforestry systems and precision agricultural systems, must be adopted to prevent land degradation and promote long-term productivity and sustainability (Lal, 2001; Lal, 2005; Reynolds *et al*., 2007; Motavalli *et al*., 2013; Branca *et al*., 2013).

2.4 Consequences of land degradation

Human activities and related land-use change are the primary cause of accelerated soil erosion, which has substantial implications for nutrient and carbon cycling, land productivity, and worldwide socio-economic conditions (Borrelli *et al*., 2017). Land-use change, e.g., from pasture to arable land, leads to new landscape structures (e.g., hedgerows, and paths) and a modified competence of a site or landscape to perform ecosystem services. It causes changes in factors, processes, and their interrelationships (Baude *et al*., 2019).

2.4.1 Impacts on soil

Soil is a dynamic living natural body important for well-functioning terrestrial ecosystems (Lehman *et al*., 2015; Okpara *et al*., 2018). Since the beginning of agriculture around 10 000 years ago, farmers have recognized the importance of healthy soils, using qualitative terms such as colour, taste, and smell to refer to soil conditions and performance for crop production (Lehman *et al*., 2015).

While soils are the central compartment of terrestrial ecosystems, they are prone to degradation, especially in semi-arid and arid regions of the globe. Irreversible impacts have been imposed on soils since the beginning of human activities, which enable, cause, and accelerate soil degradation (Emadodin and Bork, 2012; Mbaabu *et al*., 2020). Soil is a non-renewable resource over the human time scale and the primary medium for food production (Lal *et al*., 1989). Overgrazing is considered the primary cause of land degradation in rangelands, leading to a decrease in the number of edible species, bush encroachment of unwanted shrubs and forbs, and a decline in water infiltration rates and soil organic matter content (Khresat *et al*., 1998; Rowntree *et al*., 2004; Oluwole and Sikhalazo, 2008; Niu *et al*., 2019).

Soils have a considerable carbon storage capacity, exceeding the biosphere and atmosphere. In the one metre deep profile, soils store about 1 500 Pg of soil organic carbon. About 50% of carbon is likely to be in the first 30 centimetres of the soil depth, and this is twice the amount of carbon found in the atmosphere and almost three times the amount of carbon stored in terrestrial vegetation. This makes soils the third-largest carbon reservoir after oceans which hold about 38 000 Pg carbon (Rillig *et al*., 2001; Malhi, 2002; Janzen, 2006; Powlson *et al*., 2011; Scharlemann *et al*., 2014; Amundson and Biardeau, 2018; Pravalie *et al*., 2021).

Pressures on soil are widespread and varied, and the challenges these demands create determine our continued ability to provide sufficient resources for the world's growing population. Some forms of soil degradation, like erosion, fertility loss, salinity, acidification, compaction, and soil carbon loss, are natural processes that can be accelerated by extreme land clearing and inappropriate farming practices. Although it is often too expensive, improving and changing land management practices can sometimes reverse land degradation (Koch *et al*., 2013; Gunal *et al*., 2015; Karlen and Rice, 2015; Tsegaye, 2019).

The key aim in securing soil is to maintain and improve its functionality: its structure and form, its diverse and complex ecosystems of soil biota, its nutrient cycling capacity, its roles as a substrate for growing plants, as a regulator, filter, and holder of fresh water, and as a potential mediator of climate change through the sequestration of atmospheric CO_2 (Zedler and Kercher, 2005; Creamer *et al*., 2016; Srivastava *et al*., 2021). Maintaining the innumerable interactions between these processes gives soil resilience, productivity, and efficiency. Permanent loss of soil natural capital through erosion, loss of structure, soil sealing, and other types of degradation severely impact the delivery of these ecosystem services (Haygarth and Ritz, 2009; Koch *et al*., 2013; Smith *et al*., 2015; Steinhoff-Knopp *et al*., 2021).

2.4.1.1 Chemical properties

The processes involved in chemical degradation include changes in the soil's chemical properties which are responsible for regulating nutrient cycling and maintaining a balance among the principal nutrient elements and accumulating substances to possibly toxic levels or concentrations (Sheoran *et al*., 2010; Cardoso *et al*., 2013). The inappropriate use of synthetic fertilizers and pesticides may cause chemical soil degradation. This can manifest as a slow accumulation of crop protection compounds that may hinder plant growth and development, deplete soil nutrients, and reduce agricultural production (Chalise *et al*., 2019).

2.4.1.2 Biological properties

Soil biological degradation is related to the improper use of chemical fertilizers, pesticides, and land-use practices, which reduces soil organic matter. The associated impacts include reduced soil organism diversity, soil-borne diseases, and decreased soil biota functions (Chalise *et al*., 2019).

2.4.1.3. Physical properties

Changing soil structure is a principal effect of physical degradation and may manifest as crusting, compaction, poor aeration and impeded drainage or high runoff, and even accelerated erosion (du Preez and van Huyssteen, 2020). Deforestation, intensive row-cropping and ploughing are significant factors responsible for the physical degradation of the soil (Lal *et al*., 1989). Soil structural deterioration with increased bulk density, a decrease in the effective soil pores, and increased runoff are forms of physical soil degradation. It includes soil compaction by heavy tillage implements such as tractors and harvesters (Sishekanu, 2006; Chalise *et al*., 2019).

2.4.2 Impacts on ecosystem services and biodiversity

Ecosystem services are benefits obtained from ecosystems, contributing significantly to human wellbeing and economic wealth. Land degradation presents a considerable threat to the provision of ecosystem services (Kertesz *et al*., 2019; Luo *et al*., 2019). Land degradation causes long-term losses in ecosystem function and the ability of ecosystems to provide valuable services such as clean water, food, nutrient cycling, and GHG absorption, among many others (Tarrason *et al*., 2016). Natural ecosystems' degradation negatively impacts the climate, producing large amounts of carbon emissions through degradation of carbon-rich soils (Nauman *et al*., 2014).

2.4.3 Impacts on food security

In 1996 in Rome, the World Food Summit stated that food security occurs when all people have physical and economic access to adequate, safe, and nutritious food to meet their dietary needs as well as food preferences to living an active and healthy life. Despite increasing efforts to ramp up food production to reduce food insecurity, the number of people without food continues to rise, especially in the sub-Saharan Africa and South Asia regions where population densities are high. Poverty is widespread, while agricultural productivity is low owing to the lack of resources and high climatic risks (Aggarwal *et al*., 2010).

In sub-Saharan Africa, food insecurity and hunger are widespread; primarily attributed to the rain-fed agriculture in the area. Availability, access, and utilization are the three components of food security, which are highly sensitive to changes in climate. Availability relates to food production and its physical presence in a particular region, and examples include crop production and food stocks. Access is characterized by the ability of an individual or individuals to obtain or access sufficient food, access to the market, employment, and wealth distribution. Utilization is characterized by the usage of the food that has been produced and accesses.

Few coordinated efforts exist that seek to address land degradation and food security in an integrated way, even though there are clear and common links between these challenges and the numerous agencies or institutions responsible for addressing them. Many environmental, political, economic, and social factors act as drivers and can, in turn, reduce the land's productive ability and obstruct food security. Thus, land degradation can generate or exacerbate food insecurity through various negative impacts (Stringer *et al*., 2011).

Land degradation, poverty, and food insecurity are ubiquitous and interconnected challenges. Stochastic rainfall causes severe droughts at irregular intervals, threatening the lives and livelihoods of millions worldwide. This calls for policies and technologies to increase food production and improve food security (Holden and Shiferaw, 2004).

Land degradation must be offset by restoration or rehabilitation of the land to achieve the UN's goals. In the future negative environmental impacts of land degradation will not be offset by assigning more land to agriculture. This presents challenges for agriculture in the twenty first century of having to provide enough food for the whole population while at the same time ensuring the safety of the environment (Agegnehu *et al*., 2017).

2.5 Introduction to biochar

The International Biochar Initiative (IBI) defined biochar as "a solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment" (IBI, 2012). The growing interest in biochar came from rediscovering *Terra Preta* (*de Indio*), a dark, rich, and highly productive soil in the Amazon Basin. The surrounding soils in the Amazon Basin are poor in nutrients and contain red clay known as Oxisol. According to locals, *Terra Preta* soils resulted from humans' adding the charred remains of organic matter (IBI, 2012; Jirka and Jeffrey, 2015; Tomlinson, 2015).

The use of pyrolysis, combined with biochar residue application on land, carbon sequestration, and renewable energy, are not alternatives but may become a joint strategy (Lehmann 2007a; Lehmann 2007b).

2.5.1 History of biochar: the Amazonian dark earth

The Amazonian dark earth (ADE) occurs as patches that are much darker than the surrounding and underlying soils. The dark coloration results from a high biochar content, with increased soil organic matter (SOM), pH, and nutrient levels. *Terra Preta* (black earth) and *Terra Mulata* (brown earth) are the two subdivisions of ADE (reference). It is generally accepted that these soils were formed by human beings, although, some studies suggest *Terra Preta* may have resulted from village waste and fire ash that slowly accrued around dwellings (reference). Others point out that South American pre-conquest farmers deliberately formed these soils to sustain their intensive farming over prolonged periods on poor soils (Jirka and Tomlinson, 2015; Aller, 2016; Tomczyk *et al*., 2020). Although familiar and widespread in the Amazon region, *Terra Preta* soils are not unique to the Amazon. They are found worldwide, including the tropics in Africa and Asia and some temperate regions of Europe and the United States grasslands (Aller, 2004, 2016; Sombroek *et al*., 2004; Jirka and Tomlinson, 2015; Tomczyk *et al*., 2020).

Having high organic matter content of 150 $g{\cdot}kg^{-1}$, these relict Anthrosols have persisted for centuries despite the prevailing humid tropical conditions and rapid mineralization rates. Farmers highly prefer these soils because of their high fertility and high productivity. The grounds are mainly distributed along waterways from Eastern Amazonia to the Central Amazon Basin and range in size from 1 ha to more than 100 ha (Lehmann *et al*., 2003; Diatta *et al*., 2020).

The ancient Japanese agricultural text also mentions biochar, called *Miyazaki*, which translates to fire manure (Lehman and Joseph, 2009). Furthermore, there are written records of biochar used in agricultural and horticultural books dating back to the nineteenth century (Lehman and Joseph, 2009). Biochar was highly recommended for improving soils (i.e., conserving nutrients), increasing the growth of seedlings, plant substrate, and water retention (Lehmann and Joseph, 2009; Aller, 2016).

At the beginning of the 21st century, more detailed studies about carbon contents and characteristics of *Terra Preta* soils were published, sparking new interest in applying biochar to the soil. Biochar production programs have increased in popularity, especially in developing countries (Aller, 2016).

2.5.2 Production, feedstock, and properties

Pyrolysis is the primary thermochemical treatment used to produce biochar (Lehmann, 2007a; Woolf *et al*., 2010; Aller, 2016). Sustainably acquired biomass is pyrolyzed using modern technology to produce bio-oil, syngas, process heat, and biochar. Owing to pyrolysis, the rapid decay of these biomass inputs is evaded. The pyrolysis process (Fig. 1) products provide energy, avoid GHG emissions (CH_4 and N_2O), and improves agricultural soils. Bioenergy is used to offset the emission of fossil fuels while returning about half the carbon fixed by photosynthesis to the atmosphere (Lehmann, 2007a; Woolf *et al*., 2010; Amin *et al*., 2016).

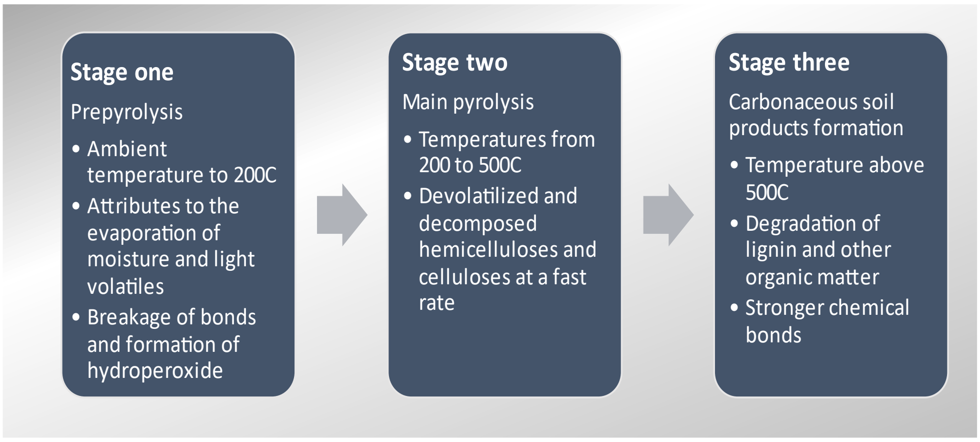


Figure 1: The three stages of pyrolysis (Lehmann, 2007a; Amin et al., 2016; Cha et al., 2016)

During pyrolysis, thermochemical conversion alters the principal carbon compounds to yield materials depleted of hydrogen (H) and oxygen (O). It holds a higher percentage of aromatic carbon than the biomass feedstock (Fig. 2). These materials offer greater chemical recalcitrance and resistance to biological decomposition, thus ensuring the fortitude of any biochar beneficial effects (Enders *et al*., 2012).

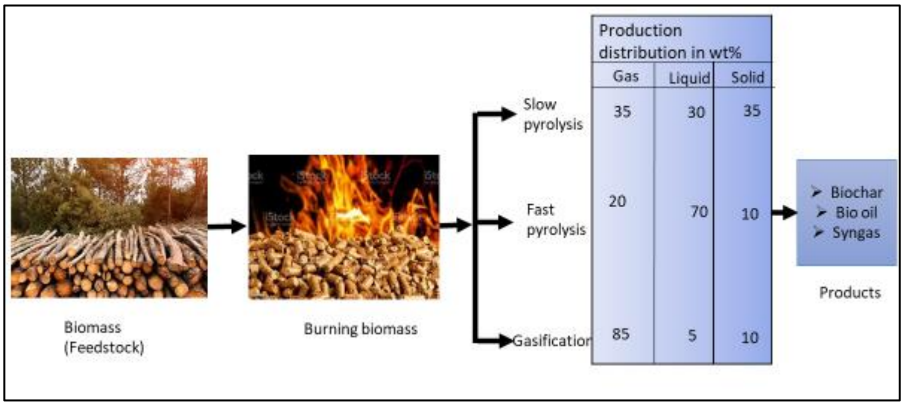


Figure 2: A product distribution of pyrolysis and biomass gasification (adapted from Cha et al., 2016)

2.5.2.1 Biochar production methods

Slow pyrolysis

Slow pyrolysis is also called conventional carbonization and has been used for thousands of years to produce charcoal. During slow pyrolysis, biomass is heated without O at temperatures between 400 and 600 °C using slow heating rates (0.1 to1 °C/s) for a longer residence time (five to 30 minutes). It takes several hours to complete the process, and a significant product of biochar is produced (35-45%), along with other products such as bio-oil (25-35%), and syngas (20-30%) (Lehmann 2007a; Ahmed *et al.*, 2016; Aller, 2016; Tripathi *et al.*, 2016; Gabhane *et al.*, 2020).

Generally, a continuous auger/screw pyrolizer reactor is used in slow pyrolysis. Secondary reactions have enough time to occur due to the extended vapour residence and lower heating rates. The long vapour residence time allows for the complete removal of vapours that are produced during the secondary reaction, ultimately resulting in the formation of solid carbonaceous biochar (Lehmann 2007a; Ahmed *et al.*, 2016; Aller, 2016; Tripathi *et al.*, 2016; Gabhane *et al.*, 2020).

Fast pyrolysis

Fast pyrolysis is a high-temperature process in which small biomass particles are rapidly heated without O in seconds. Fast pyrolysis has a residence time of a few seconds and generates more bio-oil and less biochar than slow pyrolysis (Lehmann, 2007a; Woolf *et al.*, 2010; Aller, 2016).

High-temperature pyrolysis (>5508 °C) produces biochar that generally has high surface areas (>400 m^2 /g) and is highly aromatic at a heating rate of 10–200 °C for a short period (one and 10 seconds). The resulting biochar is recalcitrant to decomposition and a suitable adsorbent. However, low-temperature pyrolysis (<5508 °C) favours a more significant recovery of carbon and of several nutrients, such as N (nitrogen) and K (potassium,) that are increasingly lost at higher temperatures (Jeffrey *et al*., 2015; Tripathi *et al*., 2016; Gabhane *et al*., 2020; Akhil *et al*., 2021).

The advantages of fast pyrolysis include short retention time and high product recovery. However, the major products are bio-oil and syngas rather than biochar when subjected to the upgrading process to produce liquid transportation fuels or fuel additives. The product yield of fast pyrolysis is 60% bio-oil, 20% biochar, and 20% syngas (Tripathi *et al*., 2016; Gabhane *et al*., 2020; Akhil *et al*., 2021).

Low-temperature biochar, which has a less-condensed carbon structure, is expected to have a greater reactivity in soils than higher-temperature biochar. Low-temperature biochar also has a better influence on soil fertility. Pot and field trials have indicated shown that high mineral-ash biochar produced at temperatures <5008 °C have, in some cases, given higher crop yields than more recalcitrant biochar made at a higher temperature (Jeffrey *et al*., 2015; Tripathi *et al*., 2016).

Intermediate pyrolysis

Intermediate pyrolysis is generally used to balance liquid and solid products. Slow pyrolysis produces high char yields with relatively low liquid products, whereas fast pyrolysis produces high liquid results but with reduced char yield. In intermediate pyrolysis, the operating conditions are in between slow and fast pyrolysis. During the process, pressure usually remains at 0.1 MPa. The process operates between 500 and 650 °C, with heating rates between 0.1 and 10 °C min^{-1}, with a residence time of 300–1000 s. The formation of high molecular tars is inhibited due to the pyrolysis conditions. The main product is dry char, suitable for agriculture or energy production, and high-quality bio-oil. Typically, the product contains 40–60% liquid, 20–30% non-condensable gases, and 15–25% biochar. Intermediate pyrolysis does not have a high quantity of reactive tar and can be used directly in boilers and engines (Tripathi *et al*., 2016).

Flash pyrolysis

Flash pyrolysis is an improved and modified form of fast pyrolysis. In flash pyrolysis, biomass decomposes at higher temperatures (i.e., more than 1000 ℃) in less than a minute. Flash pyrolysis is operated at temperatures ranging from 900 to 1200 ℃, which can be attained within a second. Such a rapid heating rate with high temperatures and low vapour residence time leads to a high bio-oil yield, reducing the biochar yield in the process. Though flash pyrolysis is carried out in a fluidized bed reactor and twin-screw mixing reactor, its industrial applicability is minimal due to the requirement of the reactor having to operate at high temperatures with high heating rates. In the product distribution of flash pyrolysis, the transfer of heat and mass processes alongside the chemical kinetics of the reactions and phase transition behaviour of the biomass plays a critical role (Tripathi *et al*., 2016; Gabhane *et al*., 2020; Akhil *et al*., 2021).

The biggest challenge of using flash pyrolysis on an industrial scale is the reactor configuration in which the input biomass can reside briefly under extremely high heating rates. The problem in flash pyrolysis reactors is the stability and quality of the bio-oil, as it is strongly affected by the char/ash present in the product. The char in the bio-oil can also catalyze the polymerization reaction inside the liquid product, causing an increase in oil viscosity (Tripathi *et al*., 2016; Akhil *et al*., 2021).

Vacuum pyrolysis

Vacuum pyrolysis is a thermal degradation of biomass under low pressure in the absence of oxygen. Pressure and temperature range during vacuum pyrolysis are controlled between 0.05 and 0.20 MPa and 450-600 ℃, respectively. Like slow pyrolysis, the heating rate in vacuum pyrolysis is low. Though the heating condition and heating rate are identical to slow pyrolysis, the end products differ significantly. This is due to the effective removal of vapour during vacuum pyrolysis (Carrier *et al*., 2012; Tripathi *et al*., 2016; Gabhane *et al*., 2020). In vacuum pyrolysis, vacuum or low pressure is used to remove the vapor generated during pyrolysis, which shows a significantly good impact on product quality and yield due to the prevention of devolatilized inorganics. Vacuum pyrolysis is used to produce high-quality biochar, which offers high porosity and is thus highly useful in the adsorption of minerals and when applied as a soil amendment (Carrier *et al*., 2012; Tripathi *et al*., 2016; Bardestani and Kaliaguine, 2018; Gabhane *et al*., 2020; Ge *et al*., 2020; Santos *et al*., 2020).

The vapor residence time is significantly reduced by the rapid removal of organic vapours that are formed during primary pyrolysis, thereby reducing the secondary reactions and ensuring a high product yield of liquid (Carrier *et al*., 2012; Tripathi *et al*., 2016; Bardestani and Kaliaguine, 2018; Ge *et al*., 2020).

In addition to the improved yield of liquid products, it has also been observed that biomass vacuum treatment also enhances the biochar product's porosity and develops multiple microporous or macroporous structures. The porosity of the produced biochar varies with the feedstock's cellulose and lignin composition. Whereas plant biomass with high cellulose content produces biochar with a microporous structure, plant biomass with high lignin content produces biochar with a macroporous design (Tripathi *et al*., 2016; Ge *et al*., 2020; Santos *et al*., 2020; Akhil *et al*., 2021).

Hydropyrolysis

Hydropyrolysis is a relatively new technique used to convert biomass into high-quality bio-oil. The heating rate, residence time, and temperature are almost the same as for fast pyrolysis. Therefore, hydropyrolysis can be considered a quick process, but under high pressure and in the presence of hydrogen/hydrogen-based materials. Since hydrogen is a reducing agent, hydrogen at high pressure and high temperature reduces the oxygen content in the produced bio-oil and inhibits char production. Furthermore, once the biomass is devolatilized, hydropyrolysis adds some hydrogen to the liquid product (Tripathi *et al*., 2016; Akhil *et al*., 2021; Hu *et al*., 2021; Jaiswal *et al*., 2021; Tian *et al*., 2021).

Hydropyrolysis often involves using a catalyst to remove oxygen, water, and CO_2 from the liquid product. Employing a catalyst also ensures a reduction of depolymerization and coking reactions. An effect of removing oxygen and adding hydrogen is the reduction in the requirement of recirculation of solid heat carriers. In catalytic hydropyrolysis, both the pyrolysis and catalytic stages are exothermic, an advantage over other pyrolysis techniques. However, developing a catalyst for this purpose is still challenging for catalytic hydropyrolysis (Rombola *et al*., 2016; Tripathi *et al*., 2016; He *et al*., 2018; Hu *et al*., 2021; Jaiswal *et al*., 2021; Li *et al*., 2022).

Microwave pyrolysis

Biochar production through microwave heating is advantageous over conventional heating as microwave generates thermal energy through dielectric heating. The energy is introduced into the reactor remotely without contacting the energy source and the reaction mixture. It is more rapid and material-selective heating than the conventional techniques (Li *et al*., 2016; Tripathi *et al*., 2016; Kostas *et al*., 2020). Microwave technology has drawn attention in academic and industrial fields for its outstanding thermal characteristics due to fast and uniform heating while offering decreased sintering temperature that enhances steam gasification. Biochar produced through microwave heating has more advantages over conventional pyrolysis as it reduces the temperature requirement by 200 ℃ while achieving similar results (Foong *et al*., 2020; Gabhane *et al*., 2020; Kostas *et al*., 2020; Akhil *et al*., 2021).

Gasification

Gasification is a form of pyrolysis and combustion that uses limited oxygen and higher temperatures (Lehmann, 2007a; Woolf *et al*., 2010; Aller, 2016). The gasification process occurs at a temperature range of 600 to 1200 °C, with a heating rate of 50-100 °C min^{-1} and a vapor residence time of 10-20 s. Unlike pyrolysis, gasification is carried out in the presence of O_2 (including O_2, air, steam, CO_2. or a mixture of the gases). It is primarily used for syngas production (i.e., CO, CO_2, CH_4, and H_2) instead of biochar. Due to this, the biochar yield is minimized (<10 wt. %). Research on the feasibility of biochar from the gasification process, especially for soil amendment purposes, is not very advanced (Wu *et al*., 2009; Yao *et al*., 2016; You *et al*., 2017; Abdelhafez and Abbas, 2020; Nidheesh *et al*., 2021).

Torrefaction

Known as mild pyrolysis, torrefaction is a thermochemical process that occurs at temperatures of 200-300 ℃ at atmospheric pressure and inert atmosphere, with heating rates of ≤50 ℃ min^{-1} and a residence time of 30 min to 2 hours. Nevertheless, torrefaction is not a process technique for biochar production, regardless of a higher product yield (70-80 wt. %), since the torrefied biomass still contains a significant fraction of volatile components from the raw biomass, and the physicochemical properties are in between raw biomass and biochar. Therefore, torrefaction is often applied as a pre-treatment process for moisture removal, biomass densification, and improving biomass properties. While the torrefaction process alone cannot be used for biochar production, a combination of torrefaction pre-treatment and pyrolysis is feasible for exceptional biochar production (in terms of yield) with good physicochemical characteristics (e.g., surface area) (Gan *et al.*, 2018; Zhang *et al.*, 2019; Abdelhafez and Abbas, 2020; Chen *et al.*, 2021; Kwoczynski and Čmelík, 2021; Yek *et al.*, 2021).

Hydrothermal carbonization (HTC)

Hydrothermal carbonization, also known as wet pyrolysis, is another process used to produce biochar (Aller, 2016). Unlike pyrolysis and torrefaction, typically carried out under a dry atmosphere, HTC is performed in a biomass-water solution at temperatures of 180-250°C at high pressure for several hours (Fig. 3). Like pyrolysis, HTC produces 50-80 wt. % solid char (termed hydrochar), bio-oil and water mixture (5-20 wt. %), and synthetic gas that is mainly CO_2 (2-5 wt. %). The advantage of hydrothermal technology is that it can avoid the preliminary energy-intensive drying process usually required for conventional pyrolysis, thus minimizing operational costs.

Biochar made through HTC has different properties than traditional char, although it is less frequently reported in the scientific literature, mainly because HTC is a more modern process (Lehmann, 2007a; Woolf *et al.*, 2010; Regmi *et al.*, 2012; Liu *et al.*, 2013; Oliveira *et al.*, 2013; Aller, 2016; Abdelhafez and Abbas, 2020).

Electro-modified biochar

The adsorption capacity of biochar helps remove pollutants from soil, water, and air. It is also helpful in the absorption of nutrients (Nartey and Zhao, 2014; Kumar *et al.*, 2022). The biochar modification should be done to adsorb a particular group of compounds while efficiently removing undesired moiety from a specific environment (Gabhane *et al.*, 2020; Mian and Liu, 2020). Such biochar modification is carried out by chemical treatment, and the resultant biochar is termed modified biochar. The chemical treatment includes mixing biochar in Fe, Mg, or Al for 2-12 hours in the presence of an electric current that might alter the functional groups on the surface of the pores and ultimately improves specific adsorption (Jung *et al.*, 2015; Gabhane *et al.*, 2020; Anto *et al.*, 2021).

Magnetic biochar

Enhanced adsorption capacity with complete recovery of adsorbent material has attracted research attention worldwide, which can intensify research toward novel adsorbents. Magnetic biochar shows very high adsorption capacity with complete separation and recovery from water or pollutants site (Tang *et al.*, 2018; Zhou *et al.*, 2018; Qu *et al.*, 2020; Ye *et al.*, 2020; Zhou *et al.*, 2020). Magnetic biochar is prepared by adding Fe ions to the surface of biochar with the help of a binding agent (Li *et al.*, 2016b; Kumar *et al.*, 2017; Gabhane *et al.*, 2020; Zhou *et al.*, 2020; Shin *et al.*, 2021).

2.5.2.2 Feedstock

Feedstock is the raw material used to prepare biochar and provides the required biomass for biochar production. Biochar yield depends on the feedstock's cellulose, hemicellulose, lignin, and moisture content. It is essential to select an appropriate method for the preparation of biochar depending on the feedstock (wet or dry biomass). Wet biomass (>30% moisture content) is freshly harvested from sludge waste, vegetable waste, algae, and animal waste, and dry biomass can be obtained from agricultural residues and wood waste (<30% moisture content) (Fig. 4) (Zhao *et al.*, 2013; Ahmed *et al.*, 2016; Gabhane *et al.*, 2020; Tomczyk *et al.*, 2020; Nidheesh *et al.*, 2021).

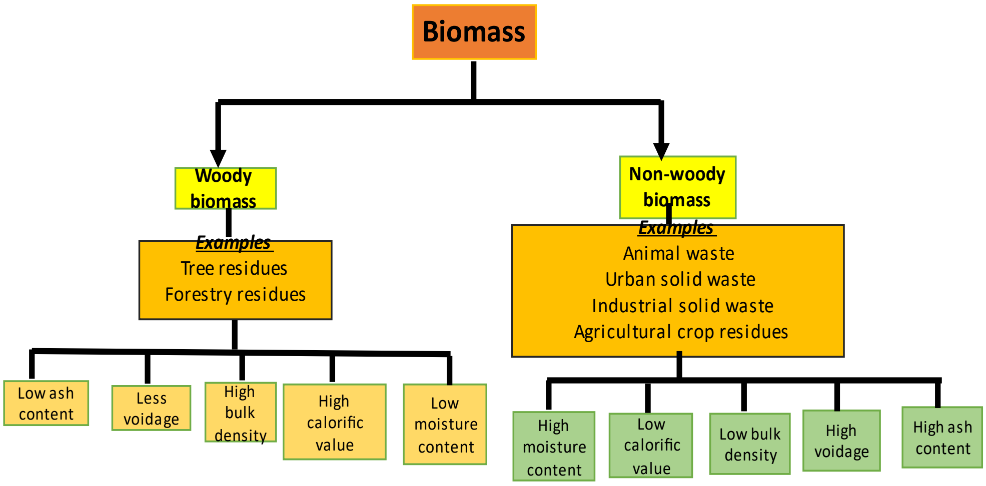


Figure 3: Different biomass used for biochar production and their products (adapted from Jeffrey et al., 2015; Ahmed et al., 2016; Gabhane et al., 2020; Tomczyk et al., 2020)

Specific guidelines must be followed for a feedstock to qualify for biochar production. For example, the feedstock must combine biomass and diluents but not contain more than 2% dry-weight contaminants (IBI, 2012; Jeffrey *et al.*, 2015).

Processed and unprocessed feedstocks are the two types with different requirements for sampling and analysing potential toxic substances. Suitable feedstocks include agriculture, food, and forestry residue, which may also have some minimum quantity of contaminants as part of the feedstock (Fig. 3) (IBI, 2012; Mukome *et al.*, 2013; Zhao *et al.*, 2013; Jeffrey *et al.*, 2015; Tomczyk *et al.*, 2020).

2.5.2.3 Biochar properties

The physical and chemical properties of biochar contribute to its function as a tool for environmental management. The physical and chemical characteristics of biochar can be directly and indirectly linked to how it affects soil systems. Depending on the nature of minerals and organic matter, their relative amounts, and how they are associated, each soil type has its distinct physical and chemical properties (Amin *et al.*, 2016; Lehmann and Joseph, 2009). The physical and chemical properties that determine the functions of biochar are surface area, total porosity, density, mechanical strength, elemental or nutrient content, and biological properties related to microorganisms' habitat (Berek, 2014).

2.5.2.3.1 Physical properties of biochar

The physical properties of biochars contribute to their function as a tool for environmental management. Their physical characteristics can be directly and indirectly related to how they affect soil systems.

Surface area and porosity

Surface area and porosity determine biochar's water retention capacity, surface chemistry or reactivity, absorption capacity, and related biological properties (Berek, 2014; Igalavithana *et al.*, 2017). The surface area of biochar is usually less than 10 $m^2 \cdot g^{-1}$ at low treatment temperatures (450 °C) and increases to 400 $m^2 \cdot g^{-1}$ at higher temperatures (600-750 °C) (Berek, 2014). During pyrolysis, high temperatures force volatile substances out of the char, resulting in pore formation and increased surface area (Igalavithana *et al*., 2017; Pandey *et al*., 2020).

Pore size distribution

Pore size distribution of biochar refers to the size range of the pores within the biochar material. These pores can range from <2 nm to >50 nm in size, and their distribution is essential in determining the suitability of biochar for specific applications. Various techniques, including mercury porosimetry, N adsorption-desorption isotherms, and scanning electron microscopy, can be used to determine the pore size distribution of biochar. These techniques allow the pore size distribution, surface area, and total pore volume to be quantified. Numerous studies have examined the pore size distribution of biochar produced from different feedstock under different pyrolysis conditions. For example, Mukherjee *et al.* (2020) showed that biochar produced at lower pyrolysis temperatures had more micropores, while that produced at higher temperatures had more macropores. Moreover, feedstock type was shown to impact pore size distribution of the resulting biochar (Lehmann and Joseph, 2009; Rajapaksha *et al*., 2016).

Biochar density

Biochar has two densities: bulk density and solid density. Solid density is density on a molecular level and is related to the packing degrees of the carbon structure. Bulk density is the density of the material consisting of multiple particles and includes the macroporosity within each particle void (Downie *et al*., 2009).

A decrease in bulk density often accompanies an increase in solid density as porosity develops during pyrolysis. The feedstock and pyrolysis process determines the density of biochar. An increase in process temperature and heating residence time causes an increase in biochar's solid density by converting low-density disordered carbon to higher density turbostratic carbon. Bulk density is an essential property of biochar. The bulk densities of biochar made from wood processed in different types of traditional kilns usually range from 0.30g cm^{-3} to 0.43g cm^{-3} (Downie *et al*., 2009; Lehmann and Joseph, 2009).

2.5.2.3.2 Chemical properties of biochar

Carbon content

The composition of biochar can be divided into recalcitrant carbon, labile or leachable carbon, and ash. A significant chemical difference between biochar and other organic matter is the proportion of aromatic carbon and the occurrence of fused aromatic carbon structures in contrast to other aromatic forms of soil organic matter, such as lignin (Lehmann *et al*., 2011). The fused aromatic structure of biochar can have different forms, including amorphous carbon, which is dominant at lower pyrolysis temperatures, and turbostratic carbon, which forms at higher pyrolysis temperatures (Lehmann *et al*., 2011). Biochar produced at temperatures below 550 ℃ has surface and internal properties that result in complex interactions with soil components, specifically soils with high ash content. Low-temperature biochar has a largely unstructured carbon structure with lower aromaticity than biochar produced at high temperatures (Joseph *et al*., 2010; Amin *et al*., 2016).

pH

Biochar's pH and electrical conductivity depend on the content and composition of the mineral fraction (also referred to as the ash fraction), which in turn depend on the type of feedstock used and the process conditions under which the biochar is produced. The nutrient content of biochar is also influenced by the feedstock and pyrolysis conditions. In contrast, the availability of nutrients in biochar is related to the bonds associated with the elements involved. Phosphorus is mainly found in the ash fraction, with pH-dependent reactions and chelating substances controlling its solubility (Joseph *et al*., 2010; Amin *et al*., 2016).

The pH value is an essential characteristic of biochar and is used to classify biochar as acidic or basic. The pH of biochar increases with an increasing temperature of pyrolysis, which is due to volatilization. Pyrolysis at 600 °C yields biochar pH 9.0, indicating the alkaline nature of the biochar surface at high temperatures (Berek, 2014; Akhil *et al*., 2021).

Nutrient content

Adsorption of minerals and organic matter retains nutrients in the soil and ensures their availability to plants. Cation exchange capacity (CEC) is the ability of soils to retain cations in an exchangeable and plant-available form, typically increasing in proportion to the quantity of SOM. Due to its larger surface area, greater negative surface charge, and greater charge density, biochar has a larger ability to adsorb cations per carbon unit than other SOM. Although the mechanism is unclear, biochar also adsorbs phosphate strongly (despite being an anion) compared to other SOM, making biochar an ideal substance to retain exchangeable cations and hence plant-available nutrients in the soil, improve crop yields, while lessening environmental pollution by nutrients. Applying biochar to soils can reduce nutrient leaching which can exhaust soil fertility, speed up the acidification of soil, increase the cost of fertilizers for farmers, reduce crop yield, and, threaten environmental health (Agegnehu *et al*., 2017).

Stability

The stability of biochar is due to the ability of biochar to resist biochemical degradation. It is an important property that determines how long biochar, as a black carbon, is sequestered when applied to the soil and how long it will continue to benefit the soil. Biochar comprises more than 80% organic carbon of aromatic compounds, which is similar in soil or other environments. Biochar's efficiency in sequestering carbon results from its recalcitrance in the soil, accounting for hundreds to thousands of years compared to organic matter (humus), which only has decades for its resident time in soil (Lehmann *et al*., 2006; Berek 2014; Akhil *et al*., 2021).

The degree of aromatic condensation is the principal factor that contributes to the stability of biochar, aside from feedstock composition and pyrolysis process conditions. Biochar produced under high pyrolysis temperature has higher thermal stability, because the aromatic carbon content of biochar increases prominently with increasing pyrolysis temperature (Lehmann *et al*., 2006; Pandey *et al*., 2020).

2.6 Biochar applications

Unlike charcoal, biochar can also be used as a soil amendment to improve soil fertility and sequester carbon to mitigate climate change (Fig. 4) (Lehmann *et al*., 2011; Vijayaraghavan, 2021). According to Lehmann *et al.* (2006), biochar has the potential to act as a soil conditioner and enhance the growth of plants through the supply and retention of nutrients and provision of other essential services, such as improving the physical and biological properties of the soil (Lehmann, 2007b; Vijayaraghavan, 2021). Carbon sequestration, soil fertility enhancement, biofuel/bioenergy production, immobilization of pollutants, and waste disposal are the claimed benefits of biochar (Jeffrey *et al*., 2015; Yaashikaa *et al*., 2020).

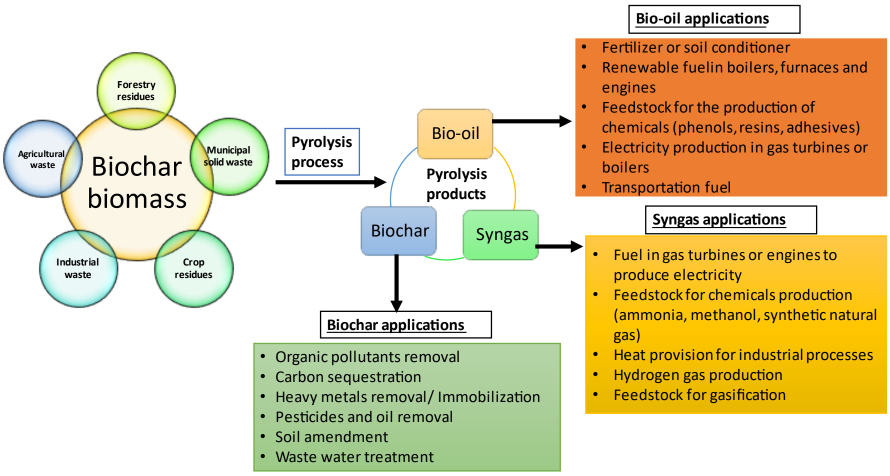


Figure 4: Biomass used for biochar production and applications of the various products (Lehmann et al., 2011; Jeffrey et al., 2015; Vijayaraghavan, 2021)

2.6.1 Soil amelioration

In many world regions, and especially in sub-Saharan Africa and South Asia, soil improvement is necessary, given the lack of food security (Lehmann and Joseph, 2009). The use of biochar as a soil amendment is advocated for reasons related to sustainability. Using biochar to ameliorate degraded soil is a win-win strategy (Jeffrey *et al*., 2015).

When used as a soil ameliorant, biochar can alter the surface area, pore distribution, bulk density, water-holding capacity, and soil penetration resistance. Multiple studies suggest that biochar has an agronomic value by improving soil composition, water retention, and increased nutrient uptake and crop yield. Biochar can contain the fertilizing elements N, P, and K, depending on the chemical composition of the feedstock used and the pyrolysis conditions under which it was produced. This is especially true for biochar produced from manure or sludge feedstock. Even though biochar cannot be used as a fertilizer that can be applied yearly, it aids as a slow-releasing reservoir of soil nutrients (Ameloot *et al*., 2013; Brassard *et al*., 2016; Agegnehu *et al*., 2017). Besides soil amendment and climate change mitigation, biochar has potential co-benefits; it is a source of renewable bioenergy, it reduces nutrient loss and the runoff of agricultural chemicals, it can improve the soil's water-holding capacity, and it can be produced from biomass waste (Woolf *et al*., 2010; Ameloot *et al*., 2013).

Soil chemical properties

Recent studies show significant changes in soil quality, including increased pH levels, organic carbon, exchangeable cations, nitrogen fertilizer use efficiency, and reduced tensile strength at higher biochar rates (>50 t ha^{-1}). For example, the application of biochar made from a paper mill at a rate of 10 t ha^{-1} in a Ferrosol, increased the pH, CEC, exchangeable Ca and total carbon, as well as reduced Al availability, while in a Calcarosol, it increased carbon and exchangeable K (Agegnehu *et al*., 2017; Li *et al*., 2018; Huang and Gu, 2019).

Applying biochar to soil may improve the supply of nutrients to plants. An essential characteristic of soils in terms of nutrient availability and plant growth is soil reaction, with most plants having an ideal pH range where maximum growth and production can be achieved. Depending on the source of the fertilizer, the differential uptake and distribution of positively and negatively charged ions, plant growth, application of fertilizer, and harvesting of crops can acidify the soil. Adding agricultural lime to raise the pH allows plants to grow when other requirements, such as water and nutrient availability, are met, which is a usual practice to amend acidic soils. Previous studies have shown that high pH biochar elevates pH at about one-third of the rate of lime, increasing Ca levels and reducing Al toxicity on red ferralitic soils (Agegnehu *et al*., 2017; Rawat *et al*., 2019).

Soil physical properties

The contribution of biochar to the physical nature of the system may be significant when biochar is added to the soil mixture, influencing the soil's depth, texture, structure, porosity, and consistency by changing surface area, pore size distribution, particle-size distribution, density, and packing. The effects of biochar on soil physical properties may therefore have a direct impact on the growth of plants because the penetration depth and availability of air and water within the root zone are determined mainly by the physical makeup of soil horizons (Lehmann and Joseph 2009; Agegnehu *et al*., 2017; Blanco-Canqui 2017; Yadav *et al*., 2018).

Bulk density is a ratio of the mass of oven-dry soil volume (volume of soil particles + volume of pore spaces) and measures how tightly pressed the soil particles are. Soil bulk density has a significant effect on soil properties and plant growth. For example, soil with high bulk density has less capacity to absorb water and presents penetration resistance to plant roots, ultimately affecting plant growth. Biochar application reportedly decreases soil bulk density due to its highly porous structure, which increases the pore volume of soil (Mukherjee and Lal., 2013; Aslam *et al*., 2017; Blanco-Canqui *et al*., 2017; Huang and Gu, 2019).

The soil water retention capacity refers to the maximum amount of water that soil can retain. Soils storing large amounts of water decrease the need for frequent irrigation. Applying biochar to the soil increases the availability of water in the soil by up to 97% (Aslam *et al*., 2017). According to Herath *et al.* (2013), after treatment with biochar, there is a significant increase in soil water retention capacity in sandy soils, however, little to no increase in clay and loam soils. After applying biochar into the soil, biochar increases the soil's water retention capacity due to the increased soil porosity and biochar's adsorptive nature (Aslam *et al*., 2017).

Soil aggregation refers to the process whereby soil particles bind together to form clumps of soil. Well aggregated soils have suitable structures and provide an excellent medium for nutrients and water movement into the soil and uptake by plants. Applying biochar into the soil provides a refuge for microorganisms which also protects the microorganisms from desiccation and predators; in turn, these microorganisms secrete polysaccharides which increase soil aggregation (Aslam *et al*., 2017; Blanco-Canqui, 2017; Juriga and Simansky, 2018; Baiamonte *et al*., 2019). By affecting these physical characteristics, the presence of biochar directly affects the soil's response to water, its aggregation and workability during soil preparation, swelling–shrinking dynamics, permeability, its capacity to retain cations, and its response to changes in ambient temperature. (Lehmann and Joseph, 2009; Rawat *et al*., 2019).

Physical soil conditions directly influence soil's ability to produce crops through water holding capacity, aeration, and soil strength limitations for root activity. Soils with a good structure provide a suitable medium for the growth and benefit of microorganisms and better nutrient availability and water movement into the soil profile. Higher nutrient and water retention and better root growth yield higher crops than degraded soil with poor physical properties (Brewer *et al*., 2014; Aslam *et al*., 2017; Yadav *et al*., 2018; Rawat *et al*., 2019).

One of the main factors that affect the physical properties of soil is soil organic matter (SOM). Soil organic matter can improve the structure of soil by increasing soil aggregation; porosity due to its highly porous nature; and water retention due to its high adsorption capacity and high surface area; resulting in improved root growth and crop yield. Soil with a high concentration of organic matter results in better physical properties and yield than soil with a low concentration of organic matter (Aslam *et al*., 2017; Yadav *et al*., 2018; Huang and Gu, 2019).

Soil biological properties

Once incorporated into the soil, biochar cannot be removed or separated. Therefore, it must also benefit soil health and improve soil properties (Sohi *et al*., 2010; Bargmann *et al*., 2013; Hagemann *et al*., 2017). Soils are complex communities of organisms and frequently change in response to soil characteristics, climatic and management factors, as well as organic matter (Christensen, 2001; Sylvain and Wall, 2011; Brevik, 2012; Dungait *et al.*, 2012). Adding biochar into the soil likely affects soil biota differently than adding fresh organic matter; specifically affecting the abundance, activity, and diversity of soil biotic communities. The differences is due to the relative stability of biochar and the general lack of biologically available carbon in biochar compared with fresh organic matter. Applying biochar has been demonstrated to modify biological functionality by providing a habitat for microorganisms due to its highly porous nature or by altering substrate availability and enzyme activity on or around biochar particles (Gul *et al*., 2015; Ding *et al*., 2016; Agegnehu *et al*., 2017).

Although microorganisms are unable to utilize biochar as an energy source, adding biochar into the soil seems to kindle microbial populations and activate dormant soil microorganisms, which results in increased microbial respiration (Ameloot *et al*., 2013; Ajema 2018; Waqas *et al*., 2018; Pan *et al*., 2019). Several processes may increase CO_2 fluxes after adding biochar into the soil. These are the (i) biotic consumption of soil biochar components, (ii) abiotic release of biochar-C (carbonates or chemisorbed CO_2), and (iii) interactions between biochar and native soil organic pools (Ameloot *et al*., 2013).

Adding biochar into the soil significantly impacts plants' development and root colonization by microorganisms and nematodes. After applying biochar into the soil, interactions occur between the biochar, soil, microbes, and plant roots. The major processes that affect the weathering of biochar in the soil and the interactions with soil biota are dissolutions, hydrolysis, carbonation, decarbonization, hydration, and redox reactions (Budzianowski, 2012; Ondrasek *et al*., 2021). The occurrence rates of these reactions depend on the nature of the response of biochar and climatic conditions. In both field and laboratory conditions, biochar can influence physical and chemical properties and beneficial soil microorganisms such as bacteria, fungi, and invertebrates (Gul *et al*., 2015; Ajema, 2018).

The structure and functioning of biological communities within soils are complex, with their inhabitants grouped into algae, archaea, arthropods, bacteria, fungi, nematodes, protozoa, and other invertebrates (Brussaard, 1997; Swift and Bignell, 2001; Lartey, 2006). These groups' presence and variable abundances significantly affect soil functioning, health, and productivity, as does incorporating organic matter and biochar (Atkinson *et al*., 2010).

The Terra Preta soils in the Amazon contain a varied range of microorganisms adapted to the biochemistry and ecology of the soil (O'Neill *et al*., 2009; Factura *et al*., 2010). They are about 25% richer than surrounding soils with 14 phylogenic groups, while others have nine (Atkinson *et al*., 2010; Grossman *et al*., 2010; Lehmann *et al*., 2011).

2.6.2. Plant growth and yield

Alongside improved soil health, increased crop yield on soils treated with biochar have been reported (Sohi *et al*., 2010). However, this improvement depends on the soil properties, biochar characteristics, and plant species (due to differing growth requirements and stress tolerance). According to Li *et al*. (2018), crop productivity increased with vegetables, grasses, and legumes having higher yields than cereal crops, rice, corn, and wheat.

Over time soil nutrients may decrease, especially after harvesting, because nutrients are not returned to the soil, and plants require nutrients such as N, P, and K for their growth (Choudhary *et al*., 1996; Bashagaluke *et al*., 2018). While chemical fertilizers helps, their extensive use can lead to environmental deterioration (Sohi *et al*., 2010; Rehman and Razzaq, 2017; Wang *et al*., 2020). Increased crop production after biochar application is linked to improved N fertilizer efficiency and plant N uptake (Tisserant and Cherubini, 2019). Liu *et al.* (2018) found that when produced under high temperatures (>500 °C) from manures, biochar increased the N-uptake of plants. However, biochar significantly decreased the N-uptake of plants in soils with low pH. Overall, they estimated an increase in N uptake of 12% (Sohi *et al*., 2010; Liu *et al*., 2018; Tisserant and Cherubini, 2019).

Because it contains organic matter and nutrients, adding biochar into the soil can increase pH, organic carbon, total N, available P, and CEC. Biochar's large surface area, porous nature, and ability to act as a medium for microorganisms, in addition to the presence of plant nutrients and ash in the biochar, make it an agent for improving soil properties and increasing nutrient absorption by plants, thereby increasing their growth (Galinato *et al*., 2011; Hussain *et al*., 2017; Rawat *et al*., 2019).

2.6.3. Carbon sequestration and climate change mitigation

Climate change is a critical challenge facing humanity, with temperatures increasing at alarming rates. The most important causes of the anthropogenic greenhouse effects are CO_2, CH_4, and NO_X released through burning fossil fuels and biomass, and aboveground and belowground organic matter decomposition (Lehmann et al., 2010; Lehmann *et al*., 2021). International efforts aim to reduce avoidable GHG emissions or offset unavoidable emissions through environmental carbon sequestration. Reducing these emissions can be achieved by decreasing the heterotrophic conversion of organic carbon to CO_2 and improving the management of agricultural waste streams to minimize methane and nitrous oxide emissions (Lehmann *et al*., 2021). Current sinks include carbon stored in standing biomass and soil organic matter. These sinks can be enhanced by increasing net primary productivity (NPP), thereby actively withdrawing more CO_2 from the atmosphere (Lehmann *et al*., 2006; Lehmann *et al*., 2010; Ajema, 2018; Lehmann *et al*., 2021).

Biochar has been suggested as a means of reducing atmospheric CO_2 concentration. The potential of biochar to mitigate climate change comes from its highly recalcitrant nature, which slows the rate at which photosynthetically fixed carbon is returned to the atmosphere (Lehmann, 2007a; Woolf *et al*., 2010; Ameloot *et al*., 2013). Recent studies reported more significant carbon mineralization in soils amended with biochar than those without, and soil organisms are thought to play a fundamental role in this process. The challenges of climate change have led to the increased search for new sustainable technologies to mitigate the escalating concentrations of GHGs in the atmosphere. Reducing GHG emissions through pyrolysis is one proposed solution whereby biofuels and biochar capable of sequestering carbon in soils are formed (Sohi *et al.*, 2010; Galinato *et al.*, 2011; Ameloot *et al.*, 2013; Oliveira *et al.*, 2017; Wang *et al.*, 2020).

Multiple approaches have been taken to estimate the large-scale potential of using biochar to sequester CO_2. This must be weighed against economic and ecological constraints and extended to include an emission balance. Furthermore, comparisons to a baseline scenario must be made to show how much the emissions have been reduced by changing to a biochar sequestration system (Lehmann and Joseph, 2009; Lehmann *et al.*, 2021).

When using biochar for climate change mitigation, its effectiveness depends on its relative resistance against microbial decay and thus its slower conversion of terrestrial organic carbon to atmospheric CO_2 (Lehmann *et al.*, 2011; Oliveira *et al.*, 2017; Lehmann *et al.*, 2021).

2.6.4. Greenhouse gas emission reduction

Despite the numerous policies to reduce GHG emissions, global GHG emissions have risen to unprecedented levels. To limit the increase in global mean temperatures to 2 °C, GHG emissions must be lowered by at least 40-70% and near zero by the end of the century. Biochar applied to the soil can help sequester carbon for more extended periods. Biochar and its storage in the soil can reduce up to 12% of current anthropogenic CO_2 emissions. However, the materials used to produce the biochar must be able to decompose and must not compete with food production. Furthermore, biochar must be made in well-designed reactors. Moreover, biochar can also reduce the indirect emission of GHGs by reducing the need for N fertilizers (Brassard *et al.*, 2016; Lehmann *et al.*, 2021).

Agroecosystems are both sources and sinks of GHGs, because anthropogenic activities affect a significant fraction of the terrestrial carbon cycle. Thus, their potential role in mitigating climate change depends on a dual strategy of decreasing GHG emissions while increasing sinks so that the net impact on climate warming is less than at present (Lehmann *et al.*, 2010). Cumulative anthropogenic GHG emissions must be kept below a maximum upper limit to stabilize the global mean surface temperature. Thus, future net anthropogenic emissions must approach net zero. The maximum cumulative safe emissions threshold might have already been exceeded, implying that no emission reduction will return our climate to safe boundaries. An essential and more significant way of reducing emissions is by applying mitigation strategies that draw down excess CO_2 from the atmosphere (Lehmann, 2007a; Woolf *et al*., 2010).

Regardless of the partial biological decomposition of biochar upon addition into the soil, the long-term stability of pyrolyzed biochar under the right circumstances seems to be at least one order of magnitude greater than that of non-pyrolyzed organic matter incorporated into soils under the same environmental conditions. The potential GHG benefits of biochar relate to its long-term carbon stability (De Gryze *et al*., 2010).

2.6.5 Wastewater and soil treatment

Biochar can adsorb organic and inorganic contaminants, heavy metals, and pesticides in soil, reducing leaching to water courses. Decreased nutrient leaching after biochar application has been reported (Brassard *et al*., 2016). High pH, surface area, cation exchange capacity, and anion exchange capacity are the properties of biochar for soil enhancement, contamination remediation, and wastewater treatment. Relatively high pyrolysis temperatures typically produce biochars which are more effective in the sorption of organic contaminants (Akhil *et al*., 2021). As pollutants could be immobilized in biochar, it would reduce the risk of pollution caused by leachate and runoff, which is beneficial from an environmental perspective. Nonetheless, the sorption capacity of biochar can compromise the efficiency of some pesticides, which should be considered before applying biochar to soil (Brassard *et al*., 2016; Akhil *et al*., 2021).

2.6.6 Reclamation of contaminated soils

Soil contamination is a serious problem, resulting mainly from chemical compounds such as pesticides, acidic substances, persistent organic matter, petroleum, and heavy metals (Yang *et al*., 2019). Soil contaminants include heavy metals, such as Cd, Pb and Cr, and organic compounds, such as pesticides, antibiotics, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs). These pollutants negatively impact crop yields, water, and soil quality. Other negative impacts include teratogenic, mutagenic, and carcinogenic effects, which pose a danger to human health through the food chain (He *et al*., 2018; Yang *et al*., 2019; Yuan *et al*., 2019). As they move through the soil, to crops and soil biota, or leach into groundwater, these pollutants may have toxic effects on the ecosystem (Tang *et al*., 2013).

Traditional methods of remediating contaminated soils, such as off-site landfill, soil leaching, thermal desorption, steam extraction, immobilization-stabilization techniques, surfactant cleaning, and organic matter improvements, may no longer be feasible due to the high costs and risks of secondary diffusion (Yang *et al*., 2019). Applying biochar has been proposed as a cost-effective and environmentally friendly remediation approach to treating contaminated soils. Biochar has been shown to effectively decrease the mobility and bioavailability of heavy metals in contaminated soils, and thus their uptake by crops, leading to an improvement in plant growth (He *et al*., 2018; Yuan *et al*., 2019). Due to its large surface area and spectral structure, biochar is a sorbent of various organic and inorganic contaminants. An investigation into the capability of biochar produced from dairy manure at 500 °C to remove Pb and atrazine from aqueous solutions showed a high capability of adsorption for Pb (100% removal) and atrazine (77% removal) (Tang *et al*., 2013).

2.7 Challenges and limitations

Biochar is a lower-risk approach than other soil remediation and carbon sequestration options. Once biochar has been added to the soil no incident or change in practice would cause an unexpected loss of stored carbon (Fruth and Ponzi, 2010; Vaccari *et al*., 2011; Jones *et al*., 2012; Mekuria and Noble, 2013; Li *et al*., 2015). Thus, given a certain amount of carbon that cycles annually through plants, half of it can be taken out of its natural process and sequestered in a much slower biochar cycle. Biochar sequestration directly removes CO_2 from the atmosphere by eliminating organic carbon from photosynthesis and decomposition (Lehmann, 2007b; Jones *et al*., 2012; Li *et al*., 2015). However, there are concerns with biochar systems, and further studies are needed focusing on feedstock availability, biochar handling, and biochar system deployment.

2.7.1 Feedstock availability

In some regions, feedstock availability for biochar production can be challenging, depending on land use practices, population density, and climate. Moreover, competition for biomass resources between different industries or sectors can also limit feedstock availability. The quality and composition of waste can vary greatly, affecting the resulting biochar's quality and sustainability. The environmental impact of the production process and biomass collection is another issue of concern with feedstock availability. For example the use of energy crops for biochar production, can lead to changes in land use which can negatively impact biodiversity and carbon sequestration (Bracmont, 2010; Kwapinski *et al.*, 2010; Thomas and Gale, 2015; Mirkouei *et al.*, 2017; Chiappero *et al.*, 2020; Ghodake *et al.*, 2021).

2.7.2 Soil contamination

Biochar has risks when used as a soil amendment. Biochar may carry a variety of hazardous compounds such as Cd, Cu, Cr, Ni, Zn and PAHs, and other toxins that include volatile organic compounds (VOCs), xylenols, cresols, and formaldehyde. The PAHs are especially harmful to many plant and microbial communities (Atkinson *et al.*, 2010; Pratt and Moran, 2010; Hussain *et al.*, 2017; Zhang *et al.*, 2019). Rogovska *et al.* (2012a), showed that germination and plant growth decreased with biochar due to some phytotoxic compounds.

2.7.3 Reduction in the efficiency of pesticides

Biochar tends to reduce soil-applied pesticides' efficacy due to reduced soil bioavailability, increased residual life, and reduced plant uptake (Ogbonnaya and Semple, 2013; Hussain *et al.*, 2017; Khalid *et al.*, 2020). Biochar sorption of soil-applied pesticides may reduce their efficiency by reducing their bioavailability to organisms (Ogbonnaya and Semple, 2013; White *et al.*, 2015; Hussain *et al.*, 2017; Liu et *al.*, 2018).

2.7.4 Biochar handling

The ideal time to apply biochar and how to ensure that it remains in place once used and does not cause a risk to human health or degrade air quality, should be considered. Furthermore, the particulate matter may be dust that is hard for the human body to filter implying that the biochar needs to be appropriately handled. Since it is a flammable substance, there are also possible public safety concerns regarding handling biochar (Verheijen *et al.*, 2009; Bracmont, 2010; Downie *et al.*, 2012; Montanarella and Lugato, 2013; Rodriguez-Franco and Page-Dumroese, 2021).

2.7.5 Biochar system deployment

The choice of biochar system is based on the feedstock, and the operation's energy needs (Bracmort, 2010; Whitman *et al*., 2010; Li *et al*., 2016a). Because the design of biochar systems is based on the feedstock used and the energy needs of the operation, it is difficult to have a versatile standard biochar system. (Bracmort, 2010). A series of mass-produced biochar systems designed for the needs of the agricultural or forestry communities may be viable for example, for forestry communities in the southeastern regions, corn growers in the midwestern regions or poultry producers in the mid-Atlantic region (reference). Widespread distribution of biochar systems would depend on the system costs, operation time, partnership with utility providers for the sale of bio-oil, and availability of information about the reliability of the technology (Bracmort, 2010).

2.7.6 Climate change debate

A carbon offset is defined as "a measurable avoidance, reduction, or sequestration of CO_2 or other GHG emissions." Carbon sequestration projects are an example of carbon offset (Weisberg *et al*., 2010; Hughes, 2017). Establishing an offset program, identifying suitable project types, and verifying offset may apply to implementing biochar production technology (De Gryze *et al*., 2010; Sohi *et al*., 2010; Stavi and Lal, 2012).

2.7.7 Policy implication

There is no practical way of removing biochar from the soil, so special attention must be paid before applying it to the soil. The type of feedstock used and the pyrolysis conditions under which it was produced make each biochar type with different chemical and physical characteristics (Luo *et al*., 2014; Hyväluoma *et al*., 2017; Shaaban *et al*., 2018; Wang and Wang 2019; Medyńska-Juraszek and Ćwieląg-Piasecka, 2020). As some biochar may have detrimental effects on the environment, policies were developed and implemented to control the use of biochar. Regulations state that biochar can be considered a waste or hazardous material, and its application can be prohibited. In Canada, for example, special authorization must be obtained from the Canadian Food Inspection Agency before biochar can be applied to agricultural soil (Downie *et al*., 2012; Jones and Quilliam, 2014; Racek *et al*., 2019).

Biochar must be proven to be safe for the environment. In 2013 the IBI launched the IBI Biochar Certification Program, which enables biochar manufacturers to certify that their product meets the approved quality standards and is safe for application to soils. This allowed legislators to adjust regulations to permit soil amendment with certified biochars. Nevertheless, long-term experiments must still be carried out to confirm the absence of adverse side effects of soil amendment with biochar (Downie *et al*., 2012; Brassard *et al*., 2016; Jones and Quilliam, 2014).

2.8 Conclusion

Globally, communities struggle to cope with land degradation resulting from climate change and land use or cover change. Biochar potentially offers a solution to both the problem of climate change and land degradation. Biochar can be beneficial to soil structure and properties and contribute to climate change mitigation through carbon sequestration, directly because of its recalcitrance, or indirectly through enhanced plant growth. Although many studies have observed the effects of biochar on soil, plant growth, and climate change mitigation, more evidence is needed on biochar effects on soil properties, especially in field experiments. This knowledge gap makes it difficult to recommend the use of biochar in agriculture.

CHAPTER 3: MATERIAL AND METHODS

3.1 Study site description

3.1.1 Local setting

The study was carried out at Lapalala Wilderness Reserve (LWR), a privately owned game reserve in the Waterberg District (Fig. 5). It is positioned 50 km to the north-north-east of Vaalwater Town and 100 km west of Polokwane in the Limpopo Province, South Africa. Lapalala covers about 36 000 ha of land and is located at 23.8422° S 28.3663° E (McKenzie, 2016; Ruwanza, 2018; Martindale 2021).

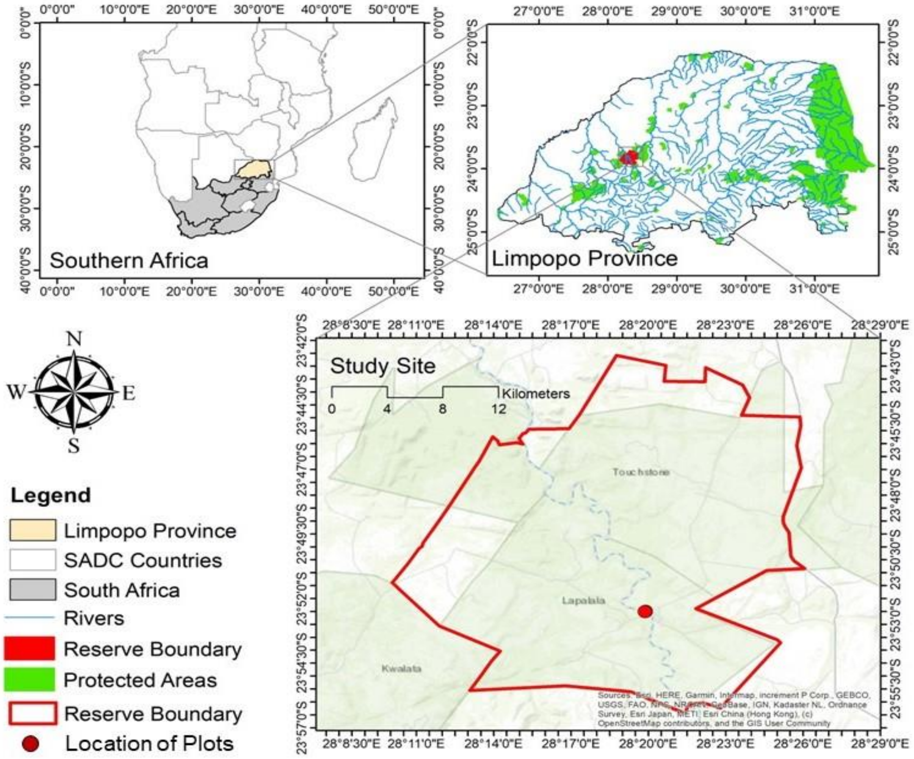


Figure 5: The location of the study area in Lapalala Wilderness Reserve in the Waterberg District, Limpopo Province, South Africa.

Lapalala Wilderness has been a private game reserve since 1981 and grew with the amalgamation of farms from 1981 to 1999. At present, it covers 16 farms or parts thereof. The reserve falls within and forms part of the Waterberg Biosphere Reserve, as declared by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in March

2001. Lapalala is part of the upper catchment of the Palala River, which drains into the Limpopo River (Kearney *et al*., 2008). The Palala and Blokland Rivers are two perennial rivers that converge within the reserve (Ruwanza 2018).

3.1.2 Climate

Waterberg District falls within the summer rainfall region with a mid-summer seasonality and an overall estimated rainfall of 500 mm, ranging from 400 mm in the low-lying area in the north to 600mm on the higher-lying southwestern border. The inter-annual coefficient of variation is between 30 and 35%, and the mean annual evapotranspiration is 2200 mm to 2400 mm (Lapalala Wilderness Masterplan, 2004).

The mean minimum and maximum monthly temperatures are 2 °C and 20 °C in July, and 14 °C and 30 °C in January, and frost is a common occurrence in winter, with an average of 61 to 90 days of frost annually (Lapalala Wilderness Masterplan, 2004).

3.1.3 Geology and soil type

The ancient acid sandstones of the Kransberg Subgroup of the Waterberg Group primarily underlie Lapalala. In the central part of the reserve, Moerdyk farm, recent intrusions of basic norite or epidiorite are found. Soils that result from the sandstones are significantly leached and are poor in nutrient content (dystrophic), and those derived from the bare intrusive substrate are more clayey and richer in nutrients (Martindale, 2021).

3.1.4 Topography

Lapalala Wilderness Nature Reserve has a mountainous and varied topography consisting of high-lying areas in the northern and southern parts of the reserve and deeply incised valleys or gorges concomitant with the rivers that run through the reserve. The highest point in the reserve is found on the southern boundary at 1300 m above sea level, and the lowest point at 900 m above sea level, where the Palala River flows out of the reserve. This altitudinal gradient, which is more than 400 m, highlights the importance of the reserve in terms of climate change adaptation, as it will permit the movement of species along altitudinal gradients as temperature and other climate variables change over time (Martindale, 2021).

3.1.5. Hydrology

The Palala River, also known as the Lephalale River, and its tributary, the Bloklandspruit, also known as the Kong River, are the main rivers in the LWR and are both perennial. Both rivers flow in a northerly direction and have a confluence within the reserve before the Palala River flows out of the reserve at the north-western boundary (Martindale, 2021).

3,1.6. Flora and fauna

The vegetation found at Lapalala belongs to the savanna biome, with the Mixed Bushveld and Sour Bushveld. The Sour Bushveld is found mainly in the southern and western high-lying areas, and the Mixed Bushveld is on the lower elevations. The dolerite-derived soils influenced the vegetation (Kearrney *et al*., 2008). The most dominant plant species in the natural areas include *Aristida adscensionis*, *Aristida congesta*, *Dichrostachys cinerea*, *Eragrostis rigidior*, *Panicum maximum*, *Sclerocarya birrea*, *Vachellia tortilis*, *Ziziphus mucronate*, and *Grewia* spp. (Ruwanza and Mulaudzi, 2018).

Lapalala Wilderness Nature Reserve has a high diversity of wildlife and can consequently be described as a keystone reserve within the Waterberg Biosphere Reserve and the Limpopo Province. Several threatened species naturally occur or have been reintroduced into the reserve, including *Diceros bicornis*, *Panthera leo*, *Panthera pardus*, *Loxodonta africana*, *Acinonyx jubatus*, *Crocuta crocuta*, *Mellivora capensis*, *Leptailurus serval*, *Lycaon pictus and Lupulella adusta.* Generally, there has been a decrease in wildlife numbers since 2018, primarily due to the introduction of lions and persisting drought conditions in recent years (Martindale, 2021).

3.1.7. Land uses

According to the Lapalala Masterplan (2004), Lapalala is characterized by a long and diverse land-use history, which has influenced many elements of the local ecosystem. Previously, the old lands were used for cattle and tobacco farming. These are characterized by a few scattered woody pioneer species and low grass cover. Growing crops and farming cattle represented the primary land use forms that impacted the vegetation and wildlife of Lapalala (Ruwanza and Mulaudzi, 2018).

3.1.8. Socio-economic significance

The LWR is in the Waterberg District Municipality (WDM) and falls within two local municipalities, the Lephalale and Mogalakwena Local Municipalities in the Limpopo Province. The WDM's vision and mission both mention ecotourism and its role in developing a sustainable economy for the benefit of all communities.

3.2. Experimental setup and data collection

3.2.1 Randomized Block Design

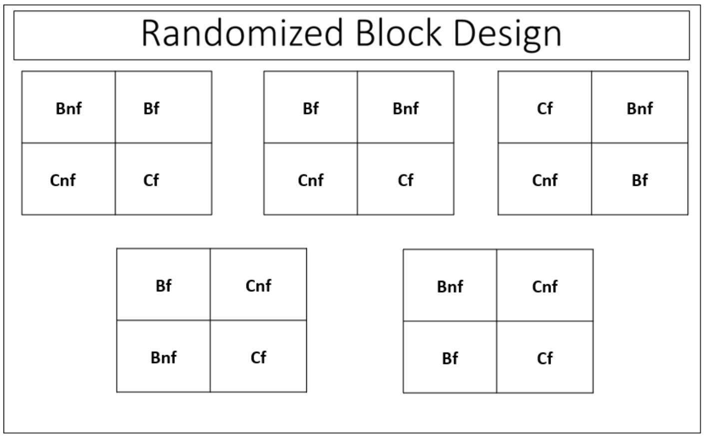


Figure 6: The Randomized Block Design used for the experimental setup; each of the five blocks had four plots with four treatments; Biochar with fertilizer (Bf), Bnf (Biochar without fertilizer), Cf (Control with fertilizer) and Cnf (Control without fertilizer).

The experiment was established in June/July 2021. Experiments were carried out in the field from October 2021 to April 2022, the summer season, with high rainfall, making it a suitable season for sowing. The experiment used a randomized block design with four plots of different treatments in each of five blocks (Fig. 6). The 1 m^2 plots were placed 30 cm apart from each other within each block. A unique combination of non-overlapping factor levels defined the treatment groups, and the experimental units were randomly selected from a known population. Each experimental unit was assigned to one block such that the variability within the blocks was less than the variability between the blocks. The number of experimental units within each block equaled the number of treatment groups. Each experimental unit within each block was randomly assigned to a different treatment group.

There was a total of four treatments, control without biochar and fertilizer (Cnf), control with fertilizer (Cf), biochar with fertilizer (Bf), and biochar without fertilizer (Bnf) (Fig. 6). There were five replicates (Blocks) for each treatment, totaling 20 plots. All the plots were seeded with a mix of grass species common to the Lapalala Wilderness Reserve (Table 1). Figure 7 illustrates the placement of the blocks within the study site. Table 2 gives a summary of the treatments and grass seeds amounts applied per plot.

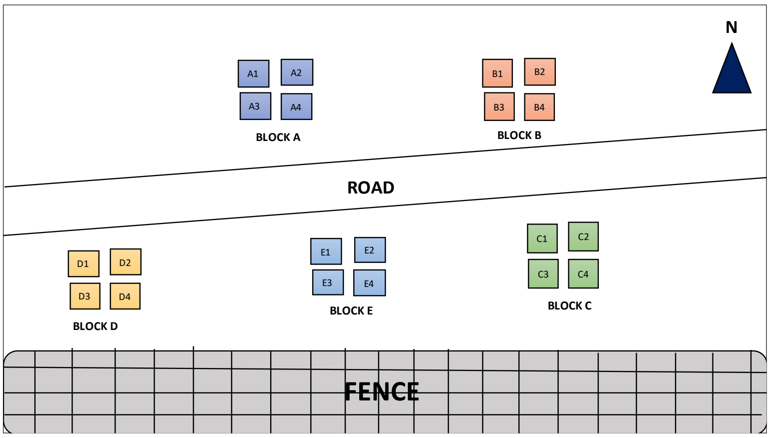


Figure 7: An illustration of the locations of the plots and treatments at the study site. The treatments are Biochar with fertilizer (Bf), Bnf (Biochar without fertilizer), Cf (Control with fertilizer) and Cnf (Control without fertilizer).

The NPK fertilizer (granular) with the ratio 2:3:2 was used for this study. The fertilizer properties were as follows: 40 g kg^{-1} N, 60 g kg^{-1} P, 40 g kg^{-1} K, and 80 g kg^{-1} C. An amount of 50 g fertilizer was applied to the respective plots according to the manufacturer's instructions (Table 2).

Table 1: The 14-grass species mixture used for the experiment. The mixture consisted of grasses common in the Lapalala Wilderness Reserve.

Species	**Common name**	**Variety**	**Weight (g)**
Brachiaria brizantha	Common signal grass	Marandu	14,2
Cenchrus ciliaris	Blue buffalo grass	Gayanda	43,3
Cenchrus ciliaris	Blue buffalo grass	Molopo	66,7
Chloris gayana	Rhodes grass	Reclaimer	1
Digitaria eriantha	Smuts finger grass	Irene	1,2
Digitaria eriantha	Wool finger grass	Mix	1,2
Eustachys paspaloides	Brown Rhodes grass	Mix	3,4
Panicum coloratum	Small buffalo grass	Verde	3,4
Panicum maximum	White buffalograss	Gatton	2,1

Setaria sphacelata sericea	Golden bristle grass	Mix	1,2
Sporobolus fimbriatus	Dropseed grass	Mix	0,2
Urochloa mosambicensis	Bushveld signal grass	Sabie	2,2
Urochloa oligotricha	Perennial signal grass	Mix	3,1
Urochloa panicoides	Garden signal grass	Mix	1,6
Total			**145**

Table 2: Amount of treatments (biochar and fertilizer) and grass seeds applied per plot. The treatments are Biochar with fertilizer (Bf), Bnf (Biochar without fertilizer), Cf (Control with fertilizer) and Cnf (Control without fertilizer).

Treatment	Biochar (kg)	Fertilizer (g)	Grass seeds (g)
Bnf	1	0	30
Bf	1	50	30
Cnf	0	0	30
Cf	0	50	30

3.2.2. Biochar production and preparation

Biochar made from *Senagalia burkei* under the carbonization (slow pyrolysis) process was purchased from Dziphathu Organics. The biomass was collected, dried, and cut smaller. The temperature during production ranged from 280-500 ºC for 80 hours. After the carbonization process, the main product, char (biochar), was removed and broken into smaller pieces. The fine biochar particles were then charged with an organic liquid fertilizer solution to make a complete organic fertilizer. One kilogram of biochar was applied to every biochar treated plot, except for the plots in block E, which were treated with 500 g biochar due to a biochar shortage. The biochar was weighed using a kitchen scale.

3.2.3. Soil preparation, soil sampling, and sowing

The soil was broken using a pickaxe, and lumps were broken using a hoe to loosen the soil for sowing. After the soil was prepared, all 20 plots were sowed with 14 of the most common grass species found in the Lapalala Wilderness Reserve (Table 1). Of this seed mix, 30 g was sown in each plot. After sowing, the seeds were incorporated into the soil and compacted to promote germination. After sowing and soil compaction, all plots were caged using 1 m^2 cages to protect the plants from grazers (Fig. 8).

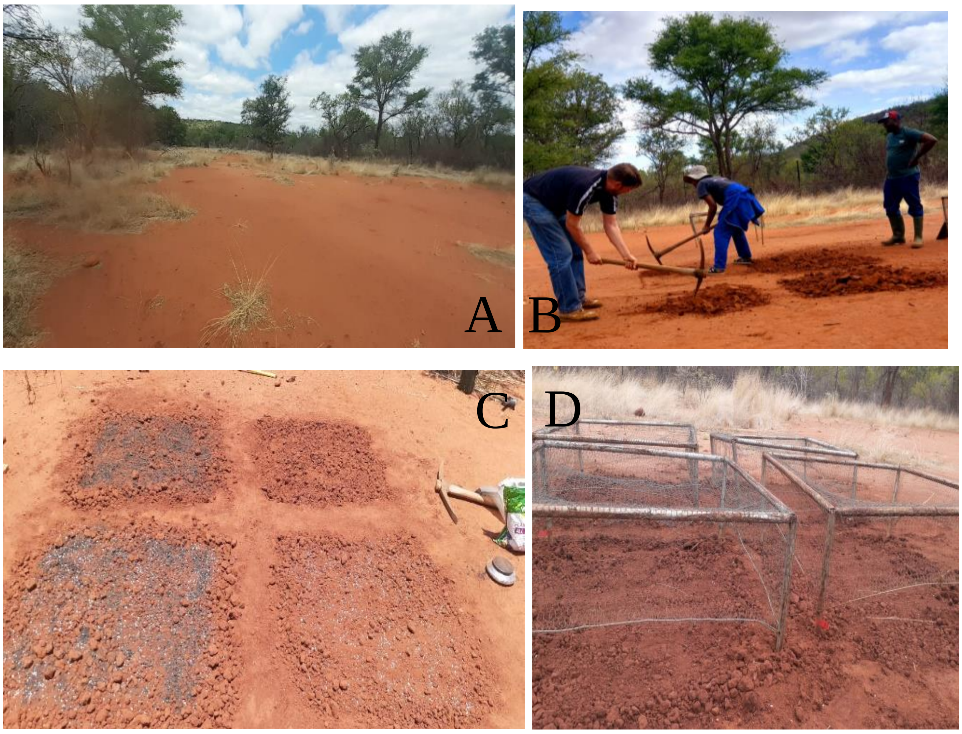


Figure 8: Soil preparation process with A showing the study site before soil preparation, B the soil tilling process, C the prepared plots after application of treatments and seed, and D the prepared plots after the placement of cages.

Soil samples were collected to measure the bulk density of the soil from the start until the end of the experiments by comparing the soil's bulk density before and after treatment. The soil samples were collected using a 98.17 cm^3 core sampler before the soil was turned. One soil sample was taken for each of the 20 plots for bulk density determination. The collected soil was oven-dried at 70 °C for 72 hr. Additional soil samples were collected from each plot after six months for the chemical analysis of pH, soil C, N, P, K, Ca, and Mg concentrations.

Soil texture was tested using the Hydrometer method (Ashworth *et al*., 2007). Five soil samples were used for the test, with one sample per block. The results of the analysis are presented in Table 3. Blocks A, B, C, and E had Sandy Clay Loam. Sample D has the lowest clay and highest sand content and is the only sample in the Sandy Loam class. All the samples had high sand content and low silt content.

Table 3: Soil texture classification. Samples were collected from the five sites before preparation, sowing and treatment application.

Sample	**Sand%**	**Clay%**	**Silt%**	**Class**
A	70	28	2	Sandy Clay loam
B	65	30	5	Sandy Clay loam
C	70	24	6	Sandy Clay loam
D	76	17	7	Sandy Loam
E	66	24	10	Sandy Clay Loam

3.3.3 Species diversity analysis

Alpha diversity was calculated using the Simpson's diversity index. Alpha diversity was then decomposed into species richness and evenness components. All the indices were calculated in R (version 4.1.2).

$$Simpson\ Index: D = 1 - \left(\sum_{i=1}^{S} \frac{n_i(n_i-1)}{N(N-1)}\right) \qquad [2]$$

Where, n_i is the total number of individuals of species i, N is the total number of individuals of all species. The value of D ranges between zero and one.

3.2.4 Species composition

Species composition was determined at month three and month six using Simpson's diversity index to determine the species diversity and evenness for all the sites and treatments.

3.2.5 Plant biomass

Above ground plant parts (biomass) were collected and placed in paper bags at month six. The bags were then placed inside an oven and dried at 70 °C for 72 hr. After drying, the biomass was weighed using an analytical balance (RADWAG PS 6000/C/2).

3.3 Data analysis

3.3.1 Above-ground and below-ground biomass

The total dry weight was determined from the oven-dried biomass. The below-ground biomass was assumed to be 20% of the above-ground biomass (Atsbha *et al*., 2019). After the total dry weight of the biomass was obtained for each plot, the C stored in the biomass was calculated. The C stored for dry biomass was calculated to be 47% of the total dry biomass (IPCC 2007; Atsbha *et al*., 2019).

3.3.2 Soil bulk density

Soil bulk density was calculated using equation 1. This was repeated twice; once at the beginning of the experiments (month zero) and once at the end of the experiments (month six).

$$SBD = \frac{Mass\ of\ soil\ in\ g}{Volume\ of\ core\ sampler\ in\ cm^3} \qquad [1]$$

3.3.4 Species composition

3.3.4.1 Distance matrices

Ecological distance summarizes the differences between sites in a single statistic. Sites that share most species have a small ecological distance, and sites that share a few species have a significant ecological distance. The Euclidean, Bray-Curtis, and Kulczynski distances were used to provide ecological distance information between the pairs of sites within the dataset.

Euclidean distance

$$d(p,q) = \sqrt{\sum_{i=1}^{n} (qi - pi)^2} \qquad [3]$$

Where; p,q is the two points in Euclidean n-space, qi,pi is the Euclidean vectors starting from the initial point, and n is n-space.

The Euclidean distance is calculated using each species as a different axis to plot each site and then measuring the distance between the sites.

Bray-Curtis and Kulczynski distances

Some distances are restricted to within the range of zero to one. When the distance is zero, the two sites are identical for every species. When the distance is equal to one, they are maximally dissimilar, meaning they do not share any similarities or species.

$$Bray\text{-}Curtis: BCij = 1 - \frac{2Cij}{Si+Sj} \qquad [4]$$

$$Kulczynski: D = \frac{a}{(b+c)} \qquad [5]$$

3.3.5 Statistical analysis

The statistical analysis was completed using R software version 4.1.2 (2021-11-01). For all experiments, a Shapiro-Wilk test of Normality was used to determine the normality of distribution and a Bartlett test of Homogeneity of Variance was used to test homogeneity. It was tested for significance with p<0.05 unless otherwise stated. Data was log-transformed in case of non-normality. A three-way repeated measures ANOVA was applied to assess the effects of treatments on soil bulk density and species diversity. A randomized block ANOVA was used to assess the effects of treatments on soil chemical and physical properties, plant biomass and species diversity indices.

CHAPTER 4: RESULTS

4.1 Soil physical properties

4.1.1 Soil bulk density

Table 4: Soil bulk density repeated measures ANOVA table. Biochar and fertilizer had no significant effect on the growth of grasses (p>0.05).

Effect	**DFn**	**DFd**	**F**	***P (p<0.05)***
Biochar	1	3	7.274000	0.074
Fert	1	3	0/003000	0.962
Time	1	3	13.994000	0.033
Biochar: Fert	1	3	0.026000	0.883
Biochar: Time	1	3	0.937000	0.404
Fert: Time	1	3	0.000138	0.991
Biochar: Fert: Time	1	3	2.084000	0.245

Table 4 shows the results from the three-way repeated measures ANOVA. Soil bulk density decreased with time from month zero to month six after the application of treatments. The means for all treatments decreased from month zero to month six, showing a potential effect of the treatments on the soil's bulk density over time. The biochar treatments (Bnf and Bf) had the lowest soil bulk density, with no significant differences (*p*>0.05). Only time had a significant effect on soil bulk density (*p*=0.033). It is important to note that at month zero, no treatments were applied to the soil when the soil bulk density was collected. Treatments were only applied after the soil bulk density was collected for month zero.

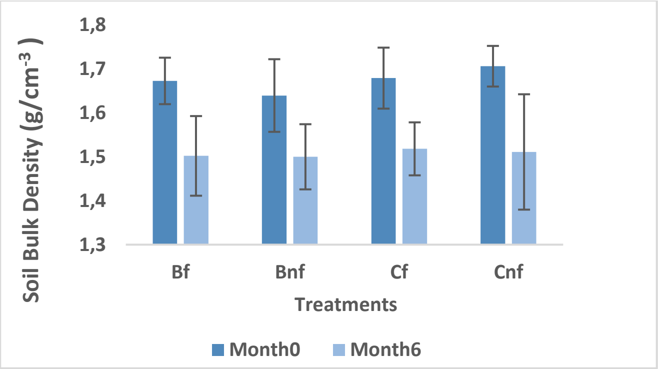


Figure 99: Soil bulk density bar plots. The bars represent the means, and the error bars represent the standard deviation. The treatments are Biochar with fertilizer (Bf), Biochar without fertilizer (Bnf), Control with fertilizer (Cf) and Control without fertilizer (Cnf).

4.2 Soil chemical properties

Table 5 summarizes the results from the randomized block ANOVA. Biochar had a significant effect on Total C (*p*=0.01). The effect of the fertilizer on total C was not significant *(p*=0.37). The combination of biochar and the fertilizer did not have a significant effect on Total C. The treatments did not have any significant effect on Total N, K, Ca, and P. Biochar had a significant effect on Na levels (*p*=0.02), but the effects of biochar and fertilizer combination was not significant (*p*=0.79). The combination of biochar and fertilizer did not have a significant effect on pH (*p*=0.45), but biochar and fertilizer had significant effects on pH (*p*=0.03 and *p*=0.04, respectively). Figure 10 summarizes the means and standard deviations for all the soil chemical properties.

Table 5: Soil properties ANOVA Table summarizing the dry weight biomass, Total C, Total N, K, Ca, Mg. Na, pH and P. The table shows the degree of freedom (Df), Sum of squares, Mean of squares, F values and P values for all the aforementioned properties.

	Df	**Sum of Squares**	**Mean of Squares**	**F value**	**Pr (>F)**
	Dry weight (Biomass)				
Biochar	1	3570	3570	0.976	0.343
Fertilizer	1	1958	1958	9.535	0.478
Blocks	4	35637	8909	2.436	0.104
Biochar: Fertilizer	1	2643	2643	0.723	0.412
Residuals	12	43892	3658		
	Total C				
Biochar	1	0.04675	0.04675	8.287	0.013861*
Fertilizer	1	0.00490	0.00490	0.868	0.369802
Blocks	4	0.21813	0.05453	9.666	0.000985***
Biochar: Fertilizer	1	0.00022	0.00022	0.040	0.845241
Residuals	12	0.06770	0.00564		
	Total N				
Biochar	1	0.0000018	1.800e-06	0.078	0.784999
Fertilizer	1	0.0000200	2.000e-05	0.865	0.370712
Blocks	4	0.0009777	2.444e-04	10.570	0.000662***
Biochar: Fertilizer	1	0.0000072	7.200e-06	0.311	0.587112
Residuals	12	0.0002775	2.313e-05		
	K				
Biochar	1	28	28	0.047	0.8317
Fertilizer	1	410	410	0.688	0.4230
Blocks	4	140628	35157	59.068	8.56e-08 ***
Biochar: Fertilizer	1	2254	2254	3.786	0.0755
Residuals	12	7142	595		
	Ca				
Biochar	1	24851	24851	2.296	0.156
Fertilizer	1	24851	24851	2.296	0.156
Blocks	4	853715	213429	19.716	3.29e-05 ***
Biochar: Fertilizer	1	1748	1748	0.162	0.695
Residuals	12	129904	10825		
	Mg				
Biochar	1	5	5.0	0.013	0.90944
Fertilizer	1	819	819.2	2.211	0.16282
Blocks	4	10339	2584.8	6.977	0.00384 **
Biochar: Fertilizer	1	442	441.8	1.192	0.29628
Residuals	12	4446	370.5		
	Na				
Biochar	1	40.70	40.70	7.213	0.0198 *
Fertilizer	1	3.07	3.07	0.543	0.4752
Blocks	4	58.21	14.55	2.579	0.0912
Biochar: Fertilizer	1	0.40	0.40	0.071	0.7944
Residuals	12	67.71	5.64		
	pH				
Biochar	1	0.1584	0.15842	6.536	0.02516 *
Fertilizer	1	0.1217	0.12168	5.020	0.04475 *
Blocks	4	0.7398	0.18496	7.631	0.00268 **
Biochar: Fertilizer	1	0.0146	0.01458	0.602	0.45302
Residuals	12	0.2909	0.02424		
	P				
Biochar	1	9	8.8	0.088	0.771675
Fertilizer	1	172	172.0	1.729	0.213056
Blocks	4	4468	1117.1	11.229	0.000504 ***
Biochar: Fertilizer	1	108	108.1	1.087	0.317738
Residuals	12	1194	99.5		

* 0.01 – 0.05, ** 0.001- 0.01, *** <0.001

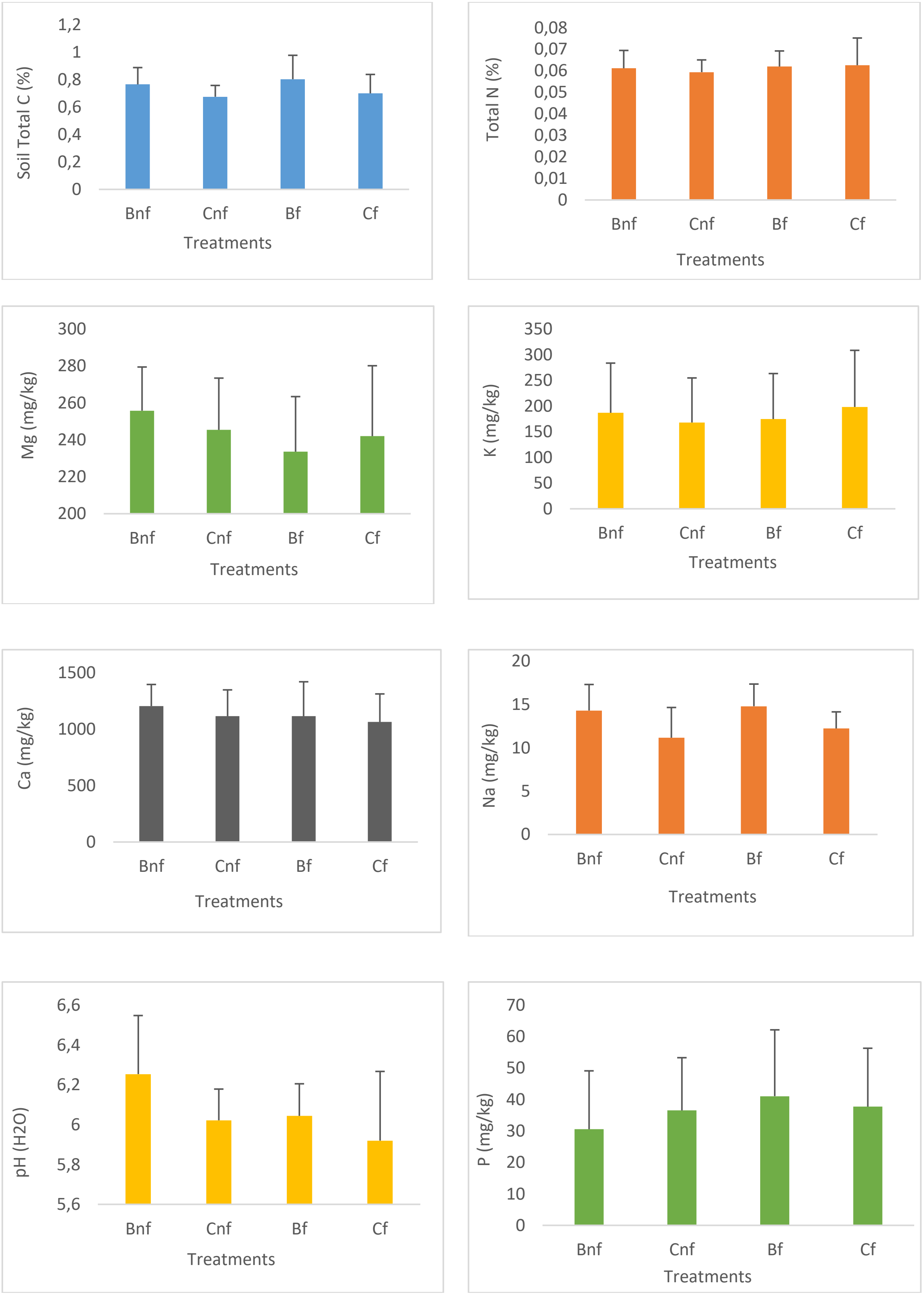


Figure 100: Soil chemical properties. The bars represent the means, and the error bars represent the standard deviation. The treatments are Biochar with fertilizer (Bf), Biochar without fertilizer (Bnf), Control with fertilizer (Cf) and Control without fertilizer (Cnf).

Table 6: J'evenness and Simpson diversity index ANOVA table.

	Df	Sum of Sq	Mean Sq	F Value	Pr (>F)
Month 3	*J'eveness*				
Biochar	1	0.07200	0.071997	1.9085	0.1923
Fertilizer	1	0.00000	0.000003	0.0001	0.9936
Block	4	0.31912	0.079780	2.1148	0.1417
Biochar: Fertilizer	1	0.01897	0.018970	0.5029	0.4918
Residuals	12	0.45270	0.037725		
	Simpson				
Biochar	1	0.06532	0.075316	2.0454	0.1782
Fertilizer	1	0.00220	0.002196	0.0688	0.7976
Block	4	0.25904	0.064761	2.0280	0.1543
Biochar: Fertilizer	1	0.02460	0.024605	0.7705	0.3973
Residuals	12	0.38319	0.031933		
Month 6	*J'eveness*				
Biochar	1	0.37528	0.37528	11.6674	0.005118 **
Fertilizer	1	0.00457	0.00457	0.1420	0.712895
Block	4	1.01064	0.25266	7.8553	0.002380 **
Biochar: Fertilizer	1	0.04265	0.04265	1.3259	0.271958
Residuals	12	0.38597	0.03216		
	Simpson				
Biochar	1	0.20233	0.202333	9.4934	0.009518**
Fertilizer	1	0.03276	0.32762	1.5372	0.238737
Block	4	0.41171	0.102928	4.8294	0.014878*
Biochar: Fertilizer	1	0.00215	0.002145	0.1007	0.756491
Residuals	12	0.25575	0.021313		

* 0.01 - 0.05, ** 0.001 - 0.01, *** <0.001

4.3 Biomass

None of the treatments had a significant effect on plant biomass ($p > 0.05$). The belowground biomass was not measured but calculated as a fixed proportion of the aboveground biomass. Treatment Bnf performed better compared with the other treatments in increased biomass, although, the effect of treatments on the biomass was statistically insignificant (Fig. 11).

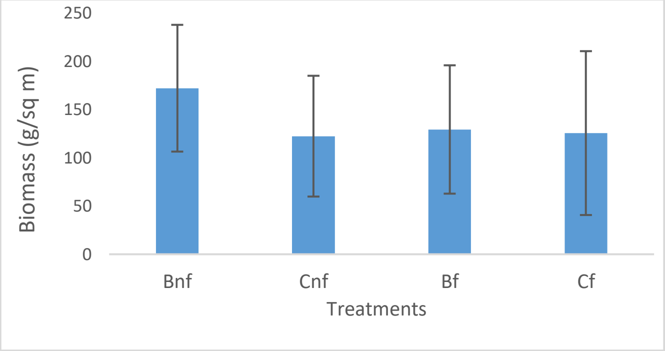


Figure 111: Plant biomass. The bar errors represent the standard deviation. The treatments are Biochar with fertilizer (Bf), Biochar without fertilizer (Bnf), Control with fertilizer (Cf) and Control without fertilizer (Cnf).

4.5 Carbon stock

Biochar treatment (Bnf) had the highest carbon stock (0.809 t·ha^{-1}). The carbon stock for Bf, Cnf and Cf showed little variation (0.607, 0.575 and 0.59 t·ha^{-1}, respectively) (Fig. 12). The differences were non-significant across all treatments ($p > 0.05$).

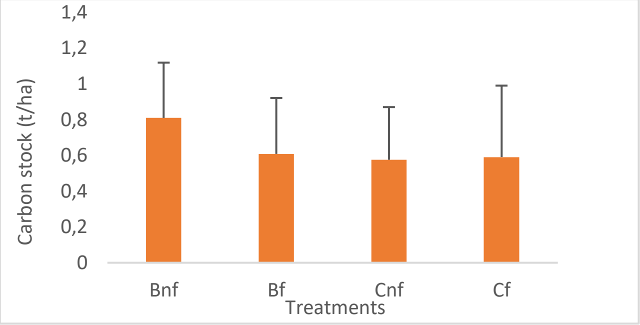


Figure 122: Total carbon stock by treatment. The bars represent the means, and the error bars represent the standard deviation. The treatments are Biochar with fertilizer (Bf), Biochar without fertilizer (Bnf), Control with fertilizer (Cf) and Control without fertilizer (Cnf).

4.6 Species richness evenness and diversity

Species richness increased from 14 in month three to 16 in month six (pooled species richness). In month three, treatment Bf (*S*=13) had the highest species richness, and in month six, Cf had the highest species richness (*S*=14). The biochar treatment had the lowest species richness in both months (Fig. 13).

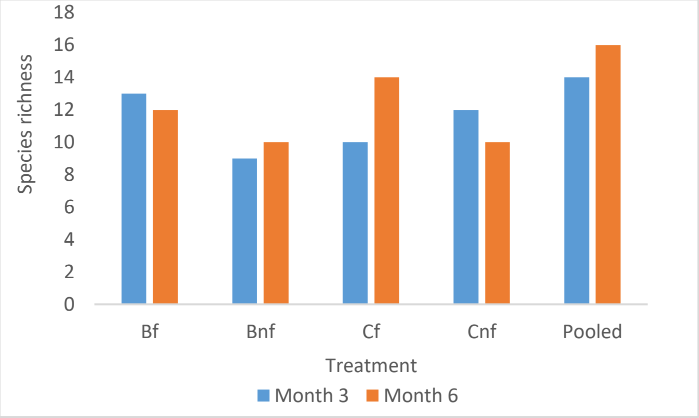


Figure 133: Species richness per treatment at months three and six. The bars represent the means, and the error bars represent the standard deviation. The treatments are Biochar with fertilizer (Bf), Biochar without fertilizer (Bnf), Control with fertilizer (Cf) and Control without fertilizer (Cnf)

Treatments Bnf and Cnf had the lowest species richness at *S*=10 for both months. The species richness for Bf decreased from *S*=13 in month three to *S*=12 in month six, and Cnf decreased from *S*=12 to *S*= 10. Species richness for Bnf increased from 9 in month three to *S*=10 in month six; treatment Cf increased from *S*=10 to *S*=14.

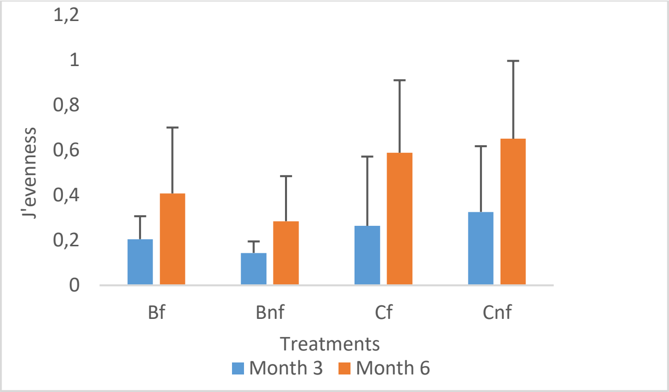


Figure 144: J evenness for months three and six. The bars represent the means, and the error bars represent the standard deviation. The treatments are Biochar with fertilizer (Bf), Biochar without fertilizer (Bnf), Control with fertilizer (Cf) and Control without fertilizer (Cnf).

At month three none of the treatments had a significant effect on the species evenness ($p>0.05$) (Table 6). At month six, only biochar had a significant effect on species evenness ($p=0.005$). The species diversity at month three was not significant for all treatments and at month six, only biochar had a significant effect ($p=0.009518$). The means for the treatments did not show any significant variation for species evenness for both months (Fig. 14). The Simpson Diversity means also did not show any significant differences between the treatments (Fig. 15). The difference between index values is mostly due to the difference in evenness, as opposed to the difference in species richness (Fig. 14, Fig. 15 and Fig. 16).

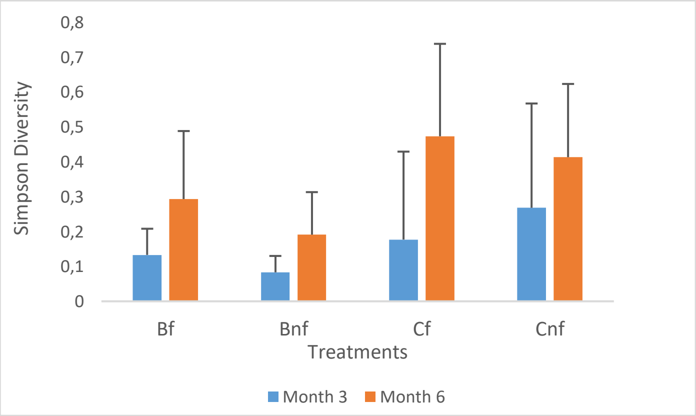
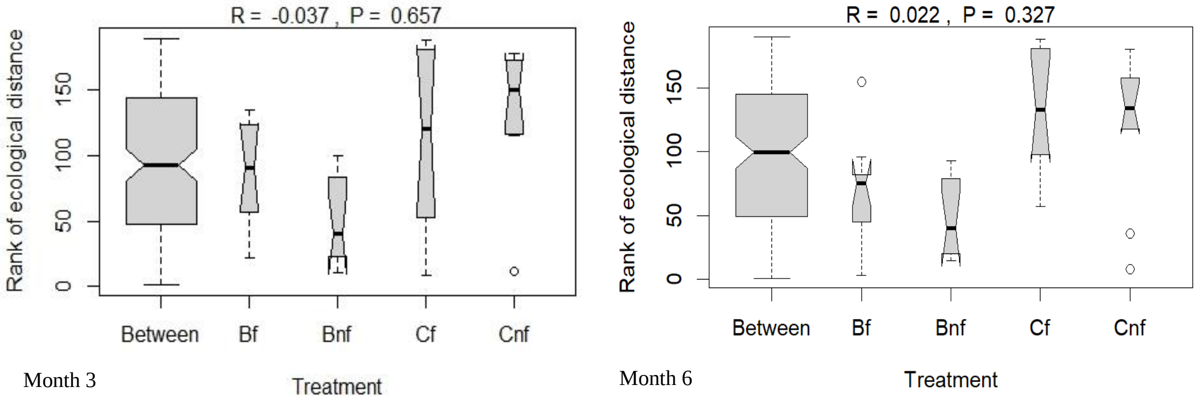


Figure 155: Simpson diversity index for months three and six. The bars represent the means, and the error bars represent the standard deviation. The treatments are Biochar with fertilizer (Bf), Biochar without fertilizer (Bnf), Control with fertilizer (Cf) and Control without fertilizer (Cnf).

4.7 Analysis of similarity (ANOSIM)

The results for months three and six were not significant (*p*=0.327). This means that the species composition between the treatments is not more dissimilar than the compositions within treatments (Fig. 16). Therefore, there was no similarity in species composition between the treatments.



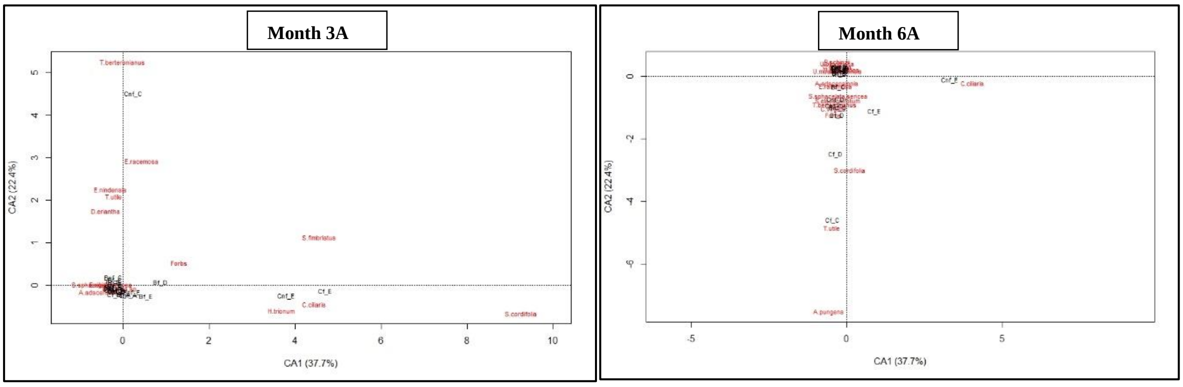
Month 3

Month 6

Figure 166: Analysis of similarity (ANOSIM) for months three and six. The R value represents the ANOSIM statistic and the P value is the significance. The treatments are Biochar with fertilizer (Bf), Biochar without fertilizer (Bnf), Control with fertilizer (Cf) and Control without fertilizer (Cnf).

4.8 Species composition

There was no significant difference in species composition across treatments. Some blocks and treatments had more species than others. All the blocks had a low abundance of *Solanum cordifolia* at month three. The ordination plots showed little difference in species composition across the sites (Fig. 17).



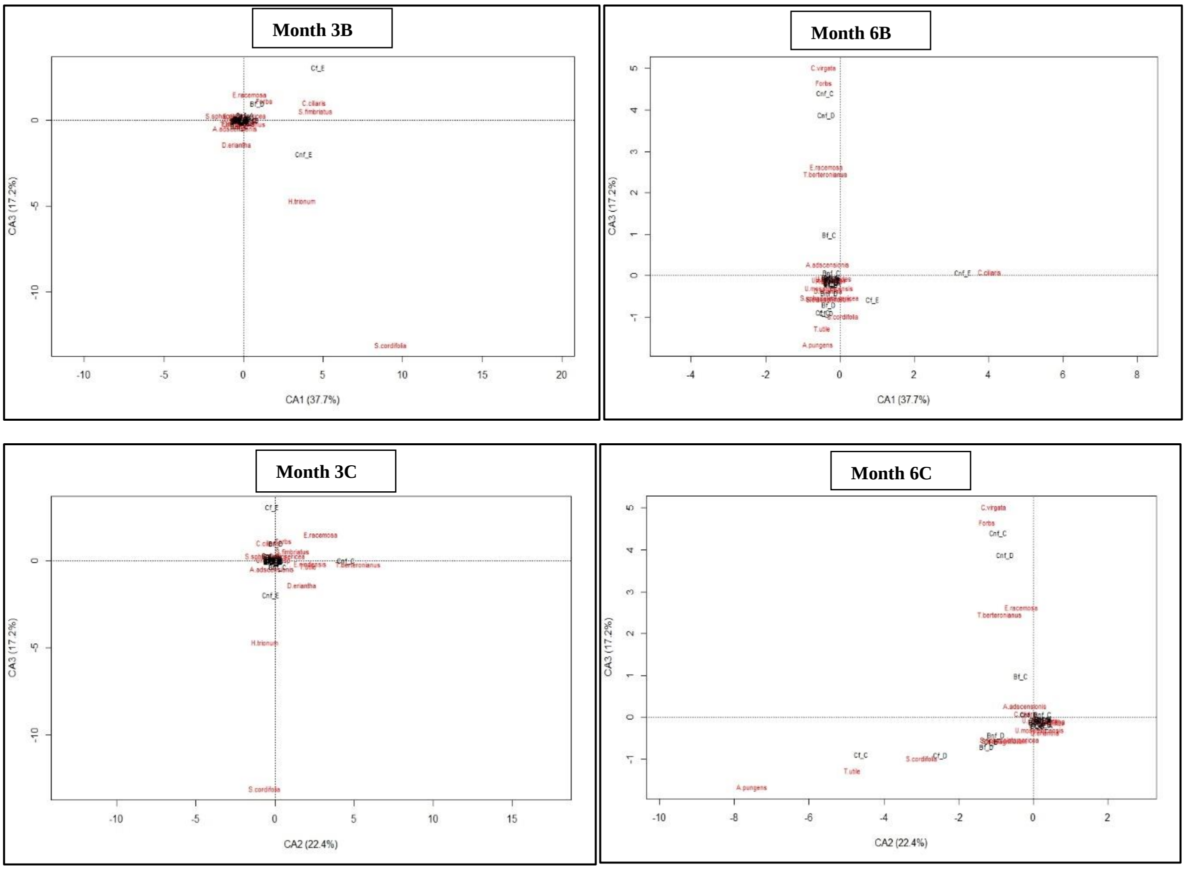


Figure 177: Correspondence Analysis (CA) showing the species composition at months three (on the left) and month six (on the right). The treatments are Biochar with fertilizer (Bf), Biochar without fertilizer (Bnf), Control with fertilizer (Cf) and Control without fertilizer (Cnf).

4.9 Cluster analysis

At month three, none of the blocks clustered together (Fig. 18). At month six, block A clusters with block B and block C clusters with block D (Fig. 19). Block E was found in both clusters. Blocks A and B were on the northern side near the edge of the forest. Blocks C, D and E were on the southern side near the fence.

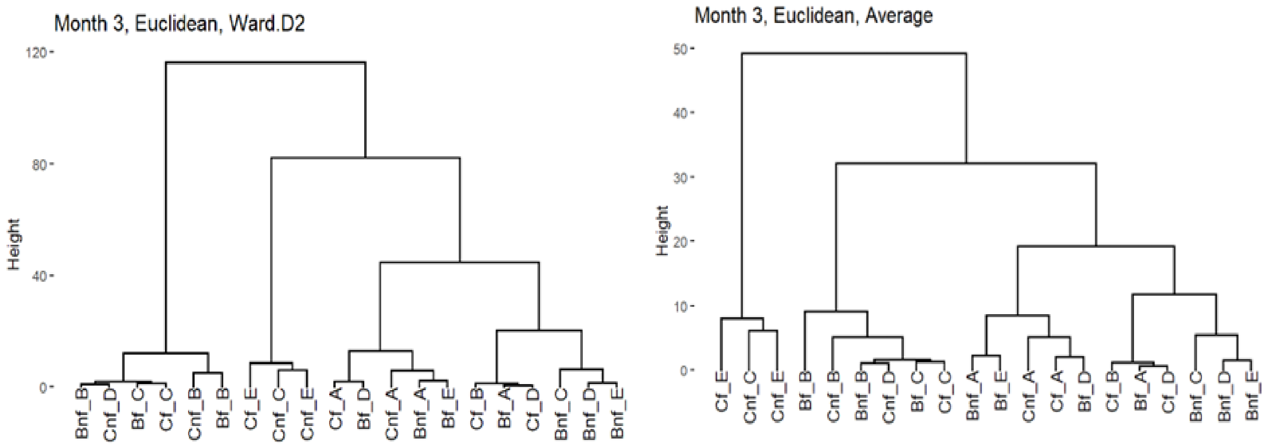


Figure 188: Dendrograms showing the clustering of blocks at month three. The treatments are Biochar with fertilizer (Bf), Biochar without fertilizer (Bnf), Control with fertilizer (Cf) and Control without fertilizer (Cnf).

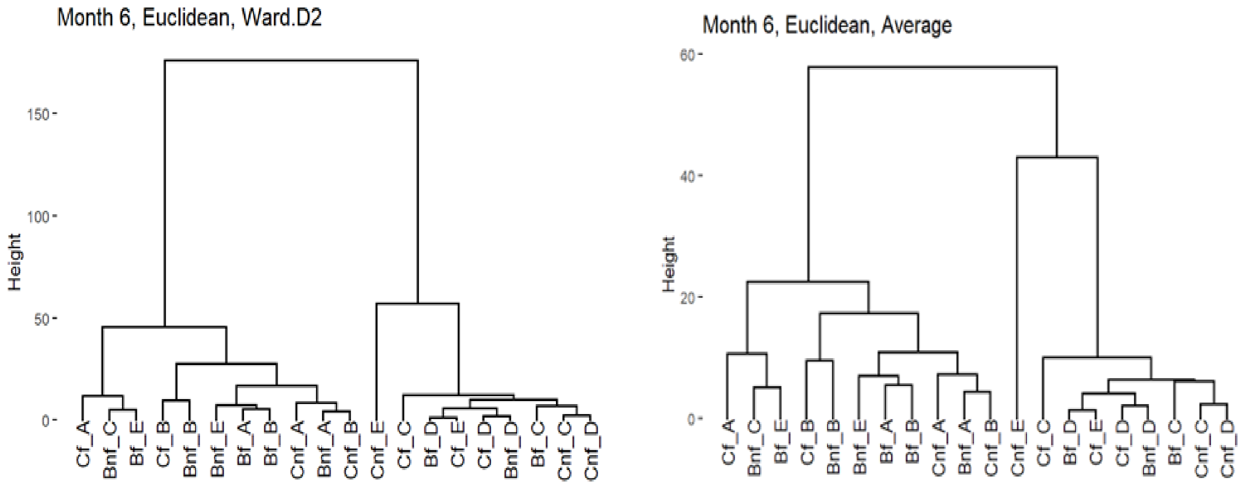


Figure 1919: Dendrograms showing the clustering of blocks at month six. The treatments are Biochar with fertilizer (Bf), Biochar without fertilizer (Bnf), Control with fertilizer (Cf) and Control without fertilizer (Cnf).

CHAPTER 5: DISCUSSION

This study aimed to assess the effectiveness of biochar to store carbon and improve soil properties and plant growth in the severely degraded lands of Lapalala Wilderness Reserve. Data was collected over a period of six months and analyzed to determine the effectiveness of biochar. In this chapter, the results are discussed, and placed in the context of previous studies that investigated the use of biochar to improve soil properties and plant growth.

5.1 Soil bulk density

Soil bulk density decreased over time, but there were no significant differences across treatments. In Vaccari *et al.* (2011), soil bulk density decreased with increasing biochar concentrations (from 9 t·ha^{-1}, 30 t·ha^{-1} and 60 t·ha$^{-1)}$. Major *et al.* (2010) reported a decrease in soil bulk density with biochar concentration of 116.6 t·ha^{-1}, suggesting that higher concentrations of biochar could possibly lead to lower soil bulk density. The decrease in soil bulk density could have been caused by loosening the soil. Over the duration of the experiment, the soil did not return to its compacted state. Other studies have also reported no significant effects of biochar application on soil bulk density (Li *et al*., 2018). In a study by Mertens *et al* (2017), *Prosopis juliflora*-biochar application had no significant effect on the soil bulk density of a sandy soil that was sowed with *Spondias tuberosa* Arruda seedlings. The lack of effect was due to the low pyrogenic nanopore number of the biochar caused by the low pyrolysis temperature (Li *et al*., 2018). Therefore, it should be noted that the differences in biochar materials, pyrolysis processes, application rates and soil types affect changes in soil bulk density (Li *et al*., 2018). In addition, Prober *et al.* (2014) reported a significantly lower soil bulk density on plots treated with biochar made from green waste at a rate of 20 t·ha^{-1} in a mesic woodland after two years compared to the control. This was attributed to the addition of low bulk density biochar material into the soil (Prober *et al.*, 2014). The insignificant effect of biochar on soil bulk density in the current study could be explained by the type of biochar used, the application rate and short experiment time of six months.

5.2 Soil chemical properties

The effects of all treatments on Total C, Total N, N, K, Ca, Mg, Na, pH, and P were not significant. Faye *et al.* (2021) evaluated the long-term effects of a single application of different biochar types (rice husk or *Typha australis*) and quantities in combination with cow manure and inorganic fertilizer on soil properties and grain yield under millet monocropping and millet-peanut rotation in the sandy soils of the peanut basin of Senegal. In the first year of the study, they reported an increase in total C for all treatments, including organic material. Their results over six years showed that a single application of biochar at a rate of 5-10 $t \cdot ha^{-1}$ and/or manure significantly increased total C from 1.84% to an average of 2.69%. The increase in total C was attributed to C addition from the rice husk biochar (0.1% C; 2% organic matter), *Typha australis* biochar (0.9% C; 3% organic matter) and cattle manure (13% C). In the current study, biochar showed an improvement in total C, implying that the application rate used (1 $kg\ m^{-2}$) was sufficient to have an effect on total C in six months.

Another important characteristic of biochar is pH. In the current study there was a small but significant increase in the pH of the biochar treated plots. This result agrees with the findings of several other studies (Novak *et al*., 2009; Hossain *et al*., 2010; Nielsen *et al*., 2018; Faye *et al*., 2021). The increase in pH could lead to higher plant productivity in the long-term (Schulz and Glaser, 2012). However, in the current study no significant difference in biomass was found after six months, possibly because this period was too short to yield a significant treatment effect.

None of the treatments had a significant effect on Total N. This could be linked to mineral N being used quickly by plants or retained by biochar. The N content has been shown to decrease with the application of biochar since N is included in biochar due to its sorption properties (Haring *et al*., 2017; Faye *et al*., 2021). Jia *et al.* (2015) reported that biochar could absorb leachate, which can help absorb organic matter, total soluble N, plant available P, and K, thereby increasing the soil's nutrient retention capacity. In contrast to Jeffery *et al*. (2022), there was no significant effect of biochar on K found in the present study. The difference could be explained by the use of different feedstock since the application rates were similar. This study used biochar made from *Senegalia burkei* and Jeffery *et al.* (2022) used biochar made of grass cuttings.

5.3 Plant growth

The total number of species increased from month three to six, with the addition of new species that were not present at month three. The new species that were not included in the grass mixture came from the surroundings and could have been dispersed into the plots either by animals or wind or could have been from the soil seed bank. Slow germination could explain the absence of some of the grass species that were included in the grass mixture. Germination rates of the 14 grass species sown in the field experiment differed between species but were not affected by either biochar or fertilizer application. Van de Voorde *et al*. (2014) did not find any effect of biochar application on germination. Similar to the findings in the current study, Gundale *et al*. (2016) did not find any effect of biochar on vegetation cover. Van de Voorde *et al*. (2014) found that legume cover was significantly higher in the biochar plots than in the control plots. Jeffrey *et al*. (2022) reported higher legume cover in biochar treated plots compared to plots treated with other treatments.

5.4 Plant biomass and carbon stock

The biochar treatment had no significant effect on biomass after six months. There are three possible explanations for this. First, biochar simply has no effect. Second, the application rate was too low. Third, the duration of the experiment was insufficient. Before we can draw the first conclusion, we have to exclude the other explanations. To test the second, I compared studies with similar or lower application rates. For example Faye *et al.* (2021), Major *et al.* (2010), and Yan *et al.* (2022) did find significant positive effects of biochar on plant growth. However, the duration of these studies ranged between three, four and eight years, respectively. Major *et al.* (2010), on the other hand found no significant effect of biochar on growth in the first year of their study. This supports the third hypothesis that the duration of the experiment was insufficient. This hypothesis could be confirmed by revisiting the study site after three years.

Wang *et al.* (2021) reported that adding biochar might increase crop productivity but that this does not correlate with the application rate. When the application rates were 10, 25, 50 and 100 t·ha^{-1}, crop productivity was significantly increased. But at application rates of 40 and 65 t·ha^{-1} there was no effect of biochar on crop yield (Wang *et al*., 2021). Another study by Leng *et al*. (2018) investigated the effect of biochar on the growth of wheat plants in a field experiment. The study reported that biochar showed a 22.2% increase in wheat's dry-weight biomass compared to the control groups. In addition, Warren (2012) reported a 25% increase in above ground biomass yield in switchgrass and sorghum with higher biochar application rates.

5.5 Species richness, diversity, and composition

Species richness increased with time and was not necessarily affected by the treatments. Species richness between the treatments was also not significant. None of the treatments had a significant effect on Simpson's diversity at month three. The diversity was largely determined by the number of seeds in the grass seeds mixture and a few that were dispersed into the plots from the surrounding environment. Hence, there was no significant difference in species richness between the treatments. However, there was a difference in evenness at month six, which was lower for the plots that were treated with biochar. This suggests that biochar could have created conditions conducive for germination and establishment of species.

At month six, Simpson's diversity index was higher than in month three. This increase can be explained by the effect of seed dispersal and late germination. Where the biochar treatment plots had higher index values than the control plots, while the species richness values were not significantly different.

Low evenness could be explained by the randomness of seed sowing the amount of seeds applied for each species were not equal. The other contributing factors could have been seed dormancy and environmental conditions that were not conducive for germination to take place.

Species composition did not differ between the plots at months three and six. Many species were established at month six (Fig. 18). These were *Panicum schinzii*, *Tragus berteronianus*, *Eragrostis nindensis*, *Eragrostis recemosa*, *Eragrostis rigidior*, *Chloris virgata*, *Aristida adscensionis*, *Hibiscus trionum*, *Solanum cordifolia*, *Solanum elaeagnifolium*, *Thesium utile*, *Alternanthera pungens* and unknown forbs. Some of these species were included in the grass seed mixture.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study aimed to assess the potential of biochar to restore degraded lands at Lapalala Wilderness Reserve. In order to do so, four objectives were tested. The first objective was to determine the amount of carbon stored in the soil before and after biochar application. The second objective was to determine the potential of biochar to alleviate degraded soil and restore soil fertility. The third objective was to assess temporal changes in soil chemical and physical properties under biochar treatment. The fourth and last objective was to determine the impact of biochar on the growth of selected grasses common at Lapalala Wilderness Reserve. After three and six months, data were collected and analyzed in order to draw conclusions on the effectiveness of biochar. The study results were placed in context of the previous studies, and this was used to draw a conclusion and make recommendations for future research purposes.

The results presented and discussed in this study provided essential evidence that biochar can successfully promote carbon storage in the soil and plant biomass. Although not significant in the current study, biochar can help sequester atmospheric carbon by storing carbon directly in the soil through photosynthesis by plants grown in biochar-treated soils. Adding biochar into the soil also stores carbon in a more stable form. Using biochar might contribute to the objective of the UNFCCC (Cowie *et al*., 2011; Fawzy *et al*., 2020; Vaccari *et al*., 2011), which considers agronomic strategies to reduce carbon losses from soils and to increase soil organic carbon (Lehamnn *et al*., 2006). Large-scale biochar application might also successfully combine carbon sequestration and overall amelioration of agricultural soils, leading to increased crop yields.

With regards to improving soil properties, the results presented in this study show that biochar had no significant effects on either the soil properties, plant biomass or diversity. There could be several reasons for these findings, such as inadequate biochar preparation, low application rates, unsuitable biochar type or feedstock and or unsuitable soil type and the short experimental period. Although not significant, these results do not necessarily mean that biochar is not effective in restoring degraded lands or improving the growth of crops. Moreover, these studies should consider longer term experimentation (more than three years) with higher biochar rates (over 10 t·ha^{-1}) using different biochar materials. Experiments should also be established in different study areas with varying environmental conditions (i.e., climate, soil, geography, and vegetation). Future studies should also include a methodical appreciation of different biochar types and manipulative experiments that clearly identify the interactions between biochar, soil properties and soil fauna and flora.

6.2 Recommendations

In the case of restoring severely degraded lands at Lapalala Wilderness Reserve, tilling the soil, sowing, and fencing the area for protection against animals should be sufficient. Also, the use of unpalatable pioneer species is recommended to avoid grazing by animals.

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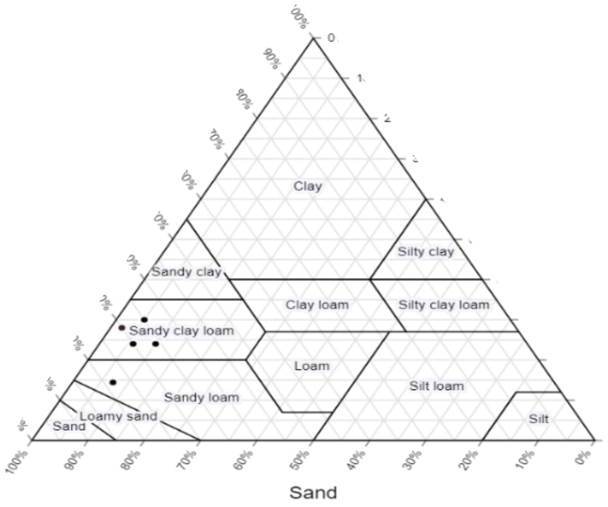
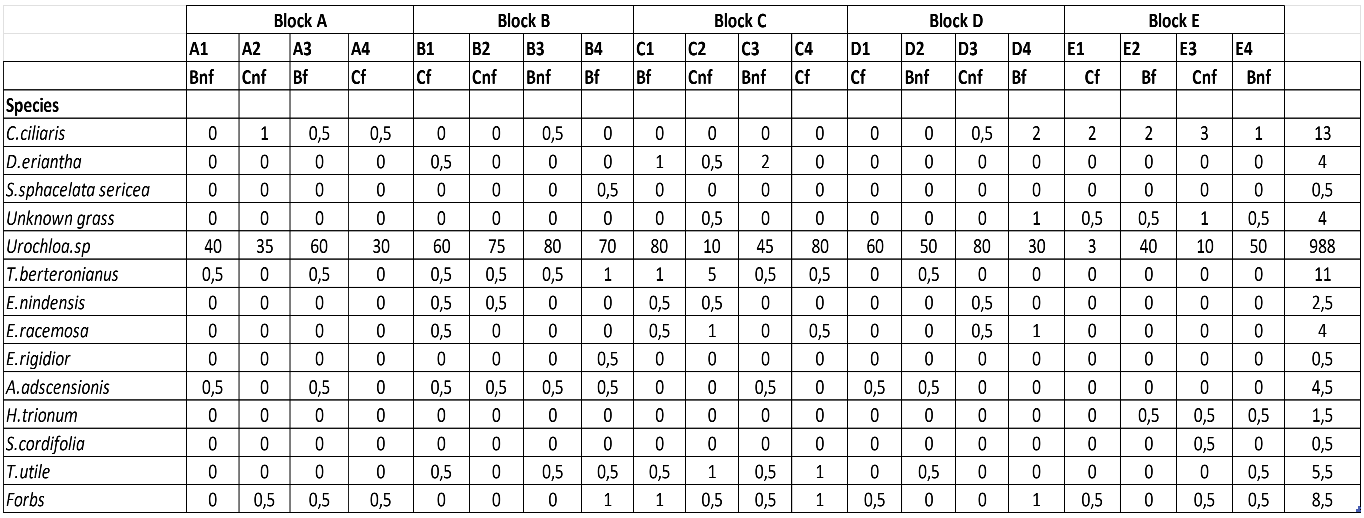
Appendix A: Soil texture pyramid



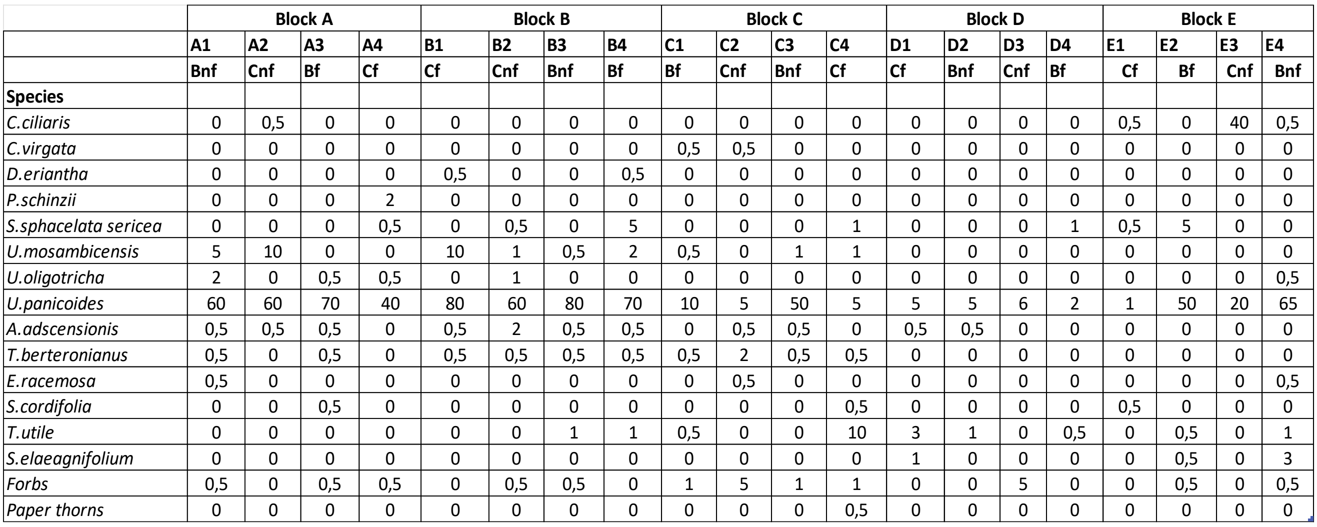
Made with TernaryPlot.com

Appendix B: Species cover percentage at month three



	Block A				Block B				Block C				Block D				Block E				
	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	D1	D2	D3	D4	E1	E2	E3	E4	
	Bnf	Cnf	Bf	Cf	Cf	Cnf	Bnf	Bf	Bf	Cnf	Bnf	Cf	Cf	Bnf	Cnf	Bf	Cf	Bf	Cnf	Bnf	
Species																					
C.ciliaris	0	1	0,5	0,5	0	0	0,5	0	0	0	0	0	0	0	0,5	2	2	2	3	1	13
D.eriantha	0	0	0	0	0,5	0	0	0	1	0,5	2	0	0	0	0	0	0	0	0	0	4
S.sphacelata sericea	0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0	0	0	0	0	0,5
Unknown grass	0	0	0	0	0	0	0	0	0	0,5	0	0	0	0	0	1	0,5	0,5	1	0,5	4
Urochloa.sp	40	35	60	30	60	75	80	70	80	10	45	80	60	50	80	30	3	40	10	50	988
T.berteronianus	0,5	0	0,5	0	0,5	0,5	0,5	1	1	5	0,5	0,5	0	0,5	0	0	0	0	0	0	11
E.nindensis	0	0	0	0	0,5	0,5	0	0	0,5	0,5	0	0	0	0	0,5	0	0	0	0	0	2,5
E.racemosa	0	0	0	0	0,5	0	0	0	0,5	1	0	0,5	0	0	0,5	1	0	0	0	0	4
E.rigidior	0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0	0	0	0	0	0,5
A.adscensionis	0,5	0	0,5	0	0,5	0,5	0,5	0,5	0	0	0,5	0	0,5	0,5	0	0	0	0	0	0	4,5
H.trionum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,5	0,5	0,5	1,5
S.cordifolia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,5	0	0,5
T.utile	0	0	0	0	0,5	0	0,5	0,5	0,5	1	0,5	1	0	0,5	0	0	0	0	0	0,5	5,5
Forbs	0	0,5	0,5	0,5	0	0	0	1	1	0,5	0,5	1	0,5	0	0	1	0,5	0	0,5	0,5	8,5

Appendix C: Species cover percentage at month six



	Block A				Block B				Block C				Block D				Block E			
	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**C1**	**C2**	**C3**	**C4**	**D1**	**D2**	**D3**	**D4**	**E1**	**E2**	**E3**	**E4**
	Bnf	**Cnf**	**Bf**	**Cf**	**Cf**	**Cnf**	**Bnf**	**Bf**	**Bf**	**Cnf**	**Bnf**	**Cf**	**Cf**	**Bnf**	**Cnf**	**Bf**	**Cf**	**Bf**	**Cnf**	**Bnf**
Species																				
C.ciliaris	0	0,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,5	0	40	0,5
C.virgata	0	0	0	0	0	0	0	0	0,5	0,5	0	0	0	0	0	0	0	0	0	0
D.eriantha	0	0	0	0	0,5	0	0	0,5	0	0	0	0	0	0	0	0	0	0	0	0
P.schinzii	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S.sphacelata sericea	0	0	0	0,5	0	0,5	0	5	0	0	0	1	0	0	0	1	0,5	5	0	0
U.mosambicensis	5	10	0	0	10	1	0,5	2	0,5	0	1	1	0	0	0	0	0	0	0	0
U.oligotricha	2	0	0,5	0,5	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0,5
U.panicoides	60	60	70	40	80	60	80	70	10	5	50	5	5	5	6	2	1	50	20	65
A.adscensionis	0,5	0,5	0,5	0	0,5	2	0,5	0,5	0	0,5	0,5	0	0,5	0,5	0	0	0	0	0	0
T.berteronianus	0,5	0	0,5	0	0,5	0,5	0,5	0,5	0,5	2	0,5	0,5	0	0	0	0	0	0	0	0
E.racemosa	0,5	0	0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0	0	0,5
S.cordifolia	0	0	0,5	0	0	0	0	0	0	0	0	0,5	0	0	0	0	0,5	0	0	0
T.utile	0	0	0	0	0	0	1	1	0,5	0	0	10	3	1	0	0,5	0	0,5	0	1
S.elaeagnifolium	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0,5	0	3
Forbs	0,5	0	0,5	0,5	0	0,5	0,5	0	1	5	1	1	0	0	5	0	0	0,5	0	0,5
Paper thorns	0	0	0	0	0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0

Appendix D: Species absence and presence at month three and month six

	Species	**Month 3**	**Month 6**
1	*Brachiaria brizantha*	Absent	Absent
2	*Cenchrus ciliaris*	Present	Present
3	*Chloris gayana*	Absent	Absent
4	*Digitaria eriantha*	Present	Present
5	*Eustachys paspaloides*	Absent	Absent
6	*Panicum coloratum*	Absent	Absent
7	*Panicum maximum*	Absent	Absent
8	*Panicum schinzii*	Absent	Present
9	*Setaria sphacelata sericea*	Present	Present
10	*Sporobolus fimbriatus*	Present	Absent
11	*Urochloa mosambicensis*	Present	Present
12	*Urochloa oligotricha*	Present	Present
13	*Urochloa panicoides*	Present	Present
14	*Tragus berteronianus*	Present	Present
15	*Eragrostis nindensis*	Present	Absent
16	*Chloris virgata*	Absent	Present
17	*Eragrostis racemosa*	Present	Present
18	*Eragrostis rigidior*	Present	Absent
19	*Aristida adscensionis*	Present	Present
20	*Hibiscus trionum*	Present	Absent
21	*Solanum cordifolia*	Present	Present
22	*Solanum elaeagnifolium*	Absent	Present
23	*Thesium utile*	Present	Present
24	*Alternanthera pungens*	Absent	Present
25	Unknown Forbs	Present	Present