Evaluating Locally Produced Biochar Effect on Soil Fertility and Maize Yields in Sandy Soils of Mhondoro Ngezi District of Zimbabwe

A dissertation submitted in partial fulfilment of the requirements for the Master of Science Degree in Food Security and Sustainable Agriculture
(Production)

Bindura University of Science Education

Faculty of Agriculture and Environmental Science
Department of Agricultural Economics, Education and Extension

NAME: BLESSED MUDZINGWA

REG. No: B231058B

SUPERVISOR: Emmanuel Zivenge

YEAR: 2025

RELEASE FORM

Name of Candidate: BLESSED MUDZINGWA

Reg Number: REG. No: B231058B

Degree: Master of Science Degree in Food Security and Sustainable Agriculture

Project Title: Evaluating Locally Produced Biochar Effect on Soil Fertility and Maize Yields in Sandy Soils of Mhondoro Ngezi District of Zimbabwe

Permission is hereby granted to **Bindura University of Science Education Library** to produce a single copy of this dissertation and lend such copy for private, scholarly or scientific research only.

Signed…………………………………….

Permanent Address: Plot 78 Queensdale Farm Mhondoro Ngezi
Agritex Office Box 142 Kadoma

APPROVAL FORM

The undersigned certified that they have supervised and recommended to Bindura University of Science Education for acceptance of dissertation entitled '**Evaluating Locally Produced Biochar Effect on Soil Fertility and Maize Yields in Sandy Soils of Mhondoro Ngezi District of Zimbabwe'** submitted in partial fulfillment of a Master of Science Degree in Food Security and Sustainable Agriculture.

Name of supervisor: Emmanuel Zivenge

Signature:………………….

Date:……/……../……….

Chairman : Dr N Mafuse

Signature: NMafuse

Date: 17 October 2025

DECLARATION

I hereby declare that the research project entitled “**Evaluating Locally Produced Biochar Effect on Soil Fertility and Maize Yields in Sandy Soils of Mhondoro Ngezi District of Zimbabwe**” submitted to Bindura University of Science Education, Department of Agricultural Economics, Education and Extension is a record of an original work done by me under the guidance and supervision of DR Emmanuel Zivenge and this work is submitted in partial fulfilment of the requirements for the award of a Master of Science Degree in Food Security and Sustainable Agriculture. The results embodied in this thesis have not been submitted to any University or Institute for the award of any degree of diploma.

Author: BLESSED MUDZINGWA

Reg Number: B231058B

Signature:……………..

Date:13.06.2025

Declaration

The undersigned certify that they read this research project and have approved its submission for marking in relation to the department's guidelines and regulations

Student.. BLESSED MUDZINGWA…………………

Signature……………………………………………..

Date…13.06.2025…………………………………

Supervisor : Dr Emmanuel Zivenge

Signature………………………..Date …………….

Chairperson………………………………………

Signature………………………..Date…………………

DEDICATION

This work is dedicated to my beloved parents, whose unwavering love, encouragement, and sacrifices laid the foundation for my academic journey. I also dedicate it to all the smallholder farmers in Mhondoro Ngezi District and across Zimbabwe, whose resilience and dedication to the land continue to inspire sustainable agricultural innovation. May this research serve as a small contribution toward their efforts to build food-secure, climate-resilient communities.

ACKNOWLEDGEMENTS

I wish to express my deepest gratitude to the Almighty God for granting me the strength, health, and perseverance to complete this research. My sincere appreciation goes to my supervisor, Dr Emmanuel Zivenge for their invaluable guidance, constructive feedback, and unwavering support throughout the course of this study.

I am especially thankful to the Bindura University of Science Education for providing the academic platform and institutional support needed to carry out this research. I acknowledge the Ministry of Lands, Agriculture, Fisheries, Water and Rural Development, as well as the Agritex officers and extension staff in Mhondoro Ngezi District, for their cooperation and assistance during data collection.

To my family especially my wife Ester and children Blessing, Bright and Brenda thank you for your patience, encouragement, and understanding during my long hours of study. Your love gave me the motivation to keep going.

Lastly, I extend my heartfelt appreciation to my classmates, friends, and colleagues who offered moral support, shared ideas, and provided a sense of camaraderie throughout the research process.

ABSTRACT

This study evaluated the effects of locally produced biochar on soil fertility and maize productivity in sandy soils within Mhondoro Ngezi District, Zimbabwe. The research aimed to assess how biochar influences the physical and chemical properties of soil, maize yield under different rainfall conditions, and the cost-effectiveness of its use in smallholder farming systems. Using a quantitative, quasi-experimental design, the study analyzed data from 4,613 plot-level observations across 16 administrative wards.

Results indicated that biochar significantly improved bulk density and porosity, thereby enhancing soil structure and moisture retention. Chemically, biochar increased nitrogen, phosphorus, potassium, and organic carbon levels, while soil pH remained stable. Maize yields in biochar-treated plots were significantly higher and more consistent across rainfall gradients. Though biochar increased input costs, it generated higher revenue and absolute returns, confirming its long-term economic viability.

The study concludes that biochar is a practical and sustainable soil amendment with the potential to address food insecurity, soil degradation, and climate vulnerability in Zimbabwe's semi-arid zones. Policy integration and community-level adoption are recommended to scale up its benefits across similar agro-ecological regions.

Keywords: Biochar, Soil Fertility, Maize Yield, Sandy Soils, Cost-Effectiveness

LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Full Meaning
AGRITEX	Agricultural Technical and Extension Services
ANOVA	Analysis of Variance
BUSE	Bindura University of Science Education
FAO	Food and Agriculture Organization
ROI	Return on Investment
NDS1	National Development Strategy 1
NPK	Nitrogen, Phosphorus, Potassium
pH	Potential of Hydrogen (Soil Acidity/Alkalinity)
SPSS	Statistical Package for the Social Sciences
R	Statistical Computing Software (R Project)
UNFCCC	United Nations Framework Convention on Climate Change
ZIMSTAT	Zimbabwe National Statistics Agency

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

In Zimbabwe, agriculture is the backbone of rural livelihoods, with smallholder farmers constituting the majority of food producers. However, agricultural productivity has been steadily undermined by declining soil fertility, particularly in sandy soils that dominate much of the country's arid and semi-arid regions. The Mhondoro Ngezi District, located in Mashonaland West Province, is one such area where farmers face persistent challenges due to the inherently poor quality of sandy soils. These soils are typically low in organic matter, have limited nutrient-holding capacity, and are highly susceptible to erosion and leaching (Nyamangara et al., 2014).

Soil degradation is a significant challenge in Zimbabwe's agricultural systems, particularly in sandy soils found in semi-arid districts such as Mhondoro Ngezi. These soils are typically characterized by low organic matter, poor water retention, and high rates of nutrient leaching, all of which contribute to declining agricultural productivity (Lehmann & Joseph, 2015). For smallholder farmers who primarily depend on rain-fed agriculture and lack access to synthetic inputs, maintaining soil fertility remains a key constraint to food production and livelihood security.

Biochar, a carbon-rich product derived from the pyrolysis of organic materials, has emerged as a promising soil amendment capable of improving both the physical and chemical properties of soils (Jeffery et al., 2011). Through its porous structure and high cation exchange capacity, biochar can enhance soil water retention, increase nutrient availability, and sequester carbon in the soil over long periods (Woolf et al., 2010). These benefits make biochar particularly suitable for use in sandy soils that are otherwise marginal for crop production.

This study seeks to evaluate the effects of locally produced biochar on soil fertility and maize yields in the sandy soils of Mhondoro Ngezi District, Zimbabwe. By comparing biochar-treated plots with control plots, the research aims to generate empirical evidence on the agronomic and economic viability of biochar in a smallholder context. The focus on maize is especially relevant, as it is the country's staple food crop and a major source of income for rural households (ZimStat, 2019).

Moreover, given the increasing threats posed by climate variability including erratic rainfall and prolonged dry spells, the potential of biochar to improve soil moisture retention and crop resilience becomes even more crucial (Yeboah et al., 2017). Thus, this study contributes to the broader goals of sustainable agriculture and climate adaptation in Zimbabwe's semi-arid regions.

Maize, the staple crop in Zimbabwe, is especially vulnerable to the constraints imposed by sandy soils. In Mhondoro Ngezi, average maize yields often fall below 1.2 tonnes per hectare, far short of the potential yields of 4 to 5 tonnes achievable under optimal conditions (ZimStat, 2019). The use of chemical fertilizers remains limited due to high costs and inconsistent supply, forcing many smallholder farmers to seek alternative, low-cost soil management strategies (FAO, 2019).

Biochar has gained global and regional attention as a sustainable soil amendment with the potential to restore degraded soils. Produced through the pyrolysis of organic biomass such as crop residues, biochar enhances soil structure, increases water retention, and improves the retention of nutrients like nitrogen and phosphorus (Lehmann & Joseph, 2015; Laird et al., 2010). In sandy soils, these benefits are particularly pronounced due to the biochar's porous nature and its ability to increase soil cation exchange capacity (Jeffery et al., 2011).

Studies across sub-Saharan Africa have demonstrated that biochar application can significantly improve crop yields, especially when combined with other organic or inorganic fertilizers (Yeboah et al., 2017; Bationo et al., 2018). Furthermore, biochar contributes to climate resilience by sequestering carbon and mitigating greenhouse gas emissions, making it a dual-purpose solution for food security and environmental sustainability (Sohi et al., 2010; Woolf et al., 2010).

Despite these benefits, adoption of biochar in Zimbabwe remains low, partly due to limited local research, low awareness among farmers, and a lack of cost-benefit data in smallholder settings. Existing studies such as Gwenzi et al. (2015) have shown promising results, but more context-specific evidence is needed to inform policy and scale-up interventions. Particularly in areas like Mhondoro Ngezi, where erratic rainfall exacerbates soil degradation, it is essential to assess whether locally produced biochar can offer a viable and affordable solution.

This study aims to fill that gap by evaluating the effects of biochar on soil fertility and maize yields under real-world, smallholder farming conditions. In doing so, it contributes to both academic research and practical knowledge that can inform sustainable agriculture practices, improve food security, and promote environmental stewardship in Zimbabwe and similar agro-ecological regions.

1.2 Problem Statement

Soil fertility decline is one of the most pressing constraints to agricultural productivity in Zimbabwe, especially in regions dominated by sandy soils such as Mhondoro Ngezi District. These soils are inherently poor in organic matter, highly prone to leaching, and have low water and nutrient retention capacity factors that severely restrict their agricultural potential (Nyamangara et al., 2014). For smallholder farmers who rely heavily on rain-fed maize production, this has translated into persistently low yields, averaging between 0.7 and 1.2 tonnes per hectare far below the national potential of 4 to 5 tonnes per hectare (ZimStat, 2019).

Efforts to improve soil fertility have often focused on chemical fertilizers. However, the high and fluctuating cost of these inputs makes them inaccessible to many resource-constrained farmers. For instance, fertilizer prices increased by more than 45% in 2019 alone (FAO, 2019), exacerbating food insecurity and poverty in rural communities. Moreover, synthetic fertilizers do little to improve the underlying physical structure of sandy soils or enhance long-term soil health.

Biochar has emerged as a potential solution. As a carbon-rich material produced from the pyrolysis of organic residues, biochar has been shown to improve both the chemical and physical properties of degraded soils, particularly sandy soils. Research has demonstrated that biochar can increase soil pH, reduce bulk density, enhance water retention, and improve nutrient retention, leading to significant gains in crop productivity (Lehmann & Joseph, 2015; Jeffery et al., 2011). Yet, despite these benefits, adoption of biochar in Zimbabwe remains minimal. One of the reasons is the lack of localized, empirical evidence on its performance under the specific agro-ecological and socio-economic conditions that prevail in the country.

Specifically, in Mhondoro Ngezi District, there is a paucity of data on the agronomic and economic effects of biochar on maize production. Most studies conducted elsewhere do not consider Zimbabwe's unique environmental conditions—especially the highly variable rainfall, which plays a critical role in determining the success of any soil amendment. Rainfall variability in semi-arid regions like Mhondoro Ngezi not only affects crop growth directly but also influences how biochar interacts with the soil matrix and root zone moisture dynamics (Yeboah et al., 2017).

Furthermore, even where biochar has shown promise agronomically, its cost-effectiveness for smallholder farmers remains under-researched. Questions persist about the affordability of biochar production, the labor requirements involved, and whether the yield improvements are sufficient to justify its use in real-world, low-input farming systems.

Therefore, the core research problem addressed by this study is the limited empirical evidence on the effectiveness and cost-efficiency of biochar as a soil amendment for improving soil fertility and maize yields in sandy soils under variable rainfall conditions in Mhondoro Ngezi District. This research seeks to bridge that knowledge gap and inform both policy and practice in sustainable soil management.

1.3 Study Objectives

1.3.1 Main objective

To evaluating Locally Produced Biochar Effect on Soil Fertility and Maize Yields in Sandy Soils of Mhondoro Ngezi District of Zimbabwe

1.3.2 Specific Objectives:

1. To assess the impact of biochar on the physical properties of sandy soils (e.g., bulk density, porosity, and water-holding capacity).
2. To determine the changes in chemical properties of sandy soils following biochar application (e.g., pH, nutrient availability, and organic matter content).
3. To evaluate maize growth and yield in biochar-amended soils under different levels of water availability (i.e., natural rainfall vs. supplemented irrigation).
4. To analyze the cost-effectiveness of using biochar as a soil amendment by comparing input costs and output values between treated and untreated plots.

1.4 Research Questions

This study is driven by a practical need to understand whether biochar, produced using locally available materials, can truly make a difference in the challenging farming conditions of Mhondoro Ngezi.

1. How does biochar influence the physical characteristics of sandy soils in Mhondoro Ngezi?
2. What changes occur in the chemical makeup of soils when biochar is applied?
3. How does biochar use affect maize growth and yields, especially when water availability varies?
4. Is biochar really worth the cost for a smallholder farmer?

1.5 Study Hypothesis

Every research project begins with a belief—something we suspect is true based on observation, prior studies, or even gut feeling from the field. In Mhondoro Ngezi, what I've observed and heard repeatedly from farmers is this: "This soil is tired." Crops barely survive, rains are unpredictable, and fertilizers are either too expensive or not working as expected. In light of that, biochar emerges as a hopeful alternative. But hope isn't enough. We need evidence. This is where the hypothesis comes in.

Based on the existing literature and early trials in similar settings, I believe that biochar can improve the condition of these sandy soils and boost maize yields—even under water-stressed conditions. Still, to maintain scientific rigor, I approach this study with two competing hypotheses:

1. **Null Hypothesis (H_0):** Biochar does not significantly affect the physical or chemical properties of sandy soils, nor does it improve maize yields under the conditions in Mhondoro Ngezi.
2. **Alternative Hypothesis (H_1)**: Biochar significantly improves the physical and chemical properties of sandy soils and enhances maize yields, particularly under varying water availability.

1.6 Justification of the Study

The justification for this study arises from the critical need to address the persistent challenge of declining soil fertility in Zimbabwe's semi-arid regions, particularly in areas dominated by sandy soils such as Mhondoro Ngezi District. These soils are inherently low in organic matter, have poor water and nutrient retention capacity, and are increasingly vulnerable to degradation due to climate variability and unsustainable land management practices. As a result, smallholder farmers—who are the backbone of Zimbabwe's food system—struggle with low maize yields, food insecurity, and income instability.

Biochar has gained recognition globally as a promising soil amendment capable of restoring degraded soils through its dual ability to improve soil structure and enhance nutrient cycling. However, despite these potential benefits, biochar remains underutilized in Zimbabwe due to limited localized research, particularly under smallholder conditions. Most existing studies focus on controlled experiments or regions with different soil and climatic contexts. There is a glaring gap in empirical evidence demonstrating the effectiveness, practicality, and cost-efficiency of biochar when applied using locally available biomass under real-world field conditions typical of smallholder farming systems in Zimbabwe.

This study is justified on several grounds. First, it provides site-specific data on the impact of biochar on key physical and chemical soil properties in sandy soils, which are the most challenging for crop production. Second, it evaluates biochar's influence on maize yields—the country's staple crop—under varying water availability conditions, addressing a critical concern in the face of erratic rainfall and increasing climate stress. Third, by analyzing the cost-effectiveness of biochar use, the study offers valuable insights into the economic feasibility of this soil amendment, which is essential for farmer adoption and policy support.

Moreover, this research aligns with national and global priorities on sustainable agriculture, climate change adaptation, and land degradation neutrality. The outcomes of this study will inform extension services, agricultural policymakers, and development partners working to enhance soil productivity, reduce input dependence, and strengthen resilience among Zimbabwe's smallholder farmers. It also contributes to academic knowledge by bridging the gap between biochar science and its practical application in marginal farming environments.

1.7 Limitations of the Study

While this study aims to generate valuable insights on the effectiveness of biochar in improving soil fertility and maize productivity, it is important to acknowledge some limitations that may influence the scope and interpretation of the findings. No study is without constraints, and being transparent about them strengthens the integrity of the research.

First, the geographical scope is relatively narrow. This research is confined to Mhondoro Ngezi District, where sandy soils dominate and rainfall is erratic. While this setting provides a relevant context for testing biochar in semi-arid, resource-constrained environments, the results may not be directly transferable to regions with different soil types or climatic conditions. Nevertheless, by documenting the specific environmental conditions of the study area in detail, this research can serve as a useful benchmark for comparative studies in other agro-ecological zones.

Secondly, the focus on maize as the test crop, while logical given its importance as Zimbabwe's staple food, may limit the generalizability of findings to other crops. Maize is highly sensitive to both water and nutrient availability, which makes it a useful indicator of soil fertility improvements. However, the performance of other crops, such as legumes or root vegetables, under biochar treatment remains outside the scope of this study. Future research could explore these possibilities.

Another key limitation is the timeframe. This study captures data from a single growing season, which may not be enough to observe the full range of biochar's benefits.

Many of biochar's effects, such as improved soil structure and increased organic matter, may manifest over multiple seasons. While short-term results can offer meaningful insights, they may not capture the long-term potential of biochar as a sustainable soil amendment. To address this, the study draws on existing long-term findings from other regions and suggests areas for follow-up research.

Rainfall variability is another factor that could affect the outcomes of this study. In a semi-arid setting like Mhondoro Ngezi, the amount and timing of rainfall can significantly influence crop response and soil behavior. Since the study is being conducted in natural field conditions, rainfall is not controlled. Although this adds realism to the findings, it also introduces a layer of uncertainty. Rain gauges and simple irrigation setups will be used where possible to monitor water availability and simulate different moisture scenarios, but not all environmental variables can be accounted for.

Biochar itself also presents a degree of variability. Its chemical and physical properties can differ depending on the feedstock used and the conditions under which it is produced. For this study, locally sourced agricultural residues such as maize stalks will be used to ensure consistency. However, results might differ if other feedstocks or pyrolysis techniques were applied. This is why the study includes a characterization of the biochar used, so future researchers and practitioners can replicate or adapt the method with clarity.

Finally, while the study includes an economic assessment of biochar's cost-effectiveness, it may not fully account for all the indirect costs and barriers to adoption. For example, labor involved in collection, production, and application of biochar might vary from one household to another. Access to equipment, technical know-how, and motivation to adopt new practices are also factors that influence real-world uptake but are difficult to quantify fully within the scope of this research. To help fill this gap, the study includes qualitative interviews with farmers to better understand their perspectives and decision-making processes regarding biochar use.

In spite of these limitations, the study is designed with measures to enhance reliability, such as pre- and post-treatment soil sampling, comparison with control plots, and triangulation of quantitative and qualitative data. Acknowledging these limitations upfront helps to contextualize the findings and lay the groundwork for further research that builds on this initial evidence base.

1.8 Outline of Thesis

This thesis is organized into five core chapters, each designed to address a specific component of the research process and collectively provide a comprehensive analysis of the effects of locally produced biochar on soil fertility and maize productivity in sandy soils of Mhondoro Ngezi District.

Chapter 1, introduces the study by outlining the background, research problem, objectives, research questions, and hypotheses. It also presents the justification of the study, scope, limitations, and a roadmap for the entire thesis.

Chapter 2, Literature review synthesizes existing knowledge on biochar, soil fertility management, and sustainable agriculture, with a particular focus on sandy soils and smallholder farming systems. It includes theoretical and conceptual frameworks, reviews empirical studies from global and regional contexts, and identifies key knowledge gaps that this study seeks to address.

Chapter Three, Research Methodology describes the research design, study area, data sources, and sampling techniques used. It also details the quantitative analytical methods applied to evaluate the effects of biochar on soil physical and chemical properties, maize yields under varying water conditions, and cost-effectiveness. Ethical considerations guiding the use of secondary data are also discussed.

Chapter Four, Results and Data Presentation presents the empirical findings based on the analysis of secondary data from biochar field trials in Mhondoro Ngezi. Results are structured around the four specific objectives of the study, using tables, figures, and statistical summaries to highlight key trends and treatment effects.

Chapter Five, Discussion, Conclusion and Recommendations interprets the results in light of existing literature, evaluating the implications of the findings for sustainable agriculture and smallholder livelihoods.

It concludes the study by summarizing key insights and proposing actionable recommendations for farmers, researchers, and policymakers. Suggestions for future research are also included.

1.9 References

1. Bationo, A., Waswa, B., Kihara, J. and Kimetu, J., 2018. *Innovations as key to the green revolution in Africa: Exploring the scientific facts*. Dordrecht: Springer Science & Business Media.
2. FAO, 2019. *Soil fertility management in support of food security in sub-Saharan Africa*. Rome: Food and Agriculture Organization of the United Nations.
3. Gwenzi, W., Chaukura, N., Hanyani-Mlambo, B. and Mapanda, F., 2015. Biochar-based soil amendments for improving soil fertility and crop productivity in Zimbabwe: A review. *Journal of Soil Science and Environmental Management*, 6(5), pp.125–132.
4. Jeffery, S., Verheijen, F.G.A., van der Velde, M. and Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, 144(1), pp.175–187.
5. Laird, D.A., Fleming, P., Wang, B., Horton, R. and Karlen, D.L., 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*, 158(3–4), pp.436–442.
6. Lehmann, J. and Joseph, S., 2015. *Biochar for environmental management: Science, technology and implementation*. 2nd ed. London: Routledge.
7. Nyamangara, J., Mtambanengwe, F. and Mapfumo, P., 2014. Integrating indigenous knowledge and soil fertility management in smallholder farming systems of Zimbabwe. *African Journal of Agricultural Research*, 9(4), pp.287–297.
8. Sohi, S.P., Krull, E., Lopez-Capel, E. and Bol, R., 2010. A review of biochar and its use and function in soil. *Advances in Agronomy*, 105, pp.47–82.
9. Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. and Joseph, S., 2010. Sustainable biochar to mitigate global climate change. *Nature Communications*, 1, p.56.
10. Yeboah, E., Otoo, E., Osei, L. and Safo, E., 2017. Biochar application improves the fertility of a sandy soil in Ghana. *International Journal of Agricultural Research*, 12(1), pp.57–68.
11. ZimStat, 2019. *Zimbabwe National Crop and Livestock Assessment Report*. Harare: Zimbabwe National Statistics Agency.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Understanding whether biochar can be an effective and affordable soil amendment for smallholder farmers in Zimbabwe requires more than just fieldwork—it requires grounding in what others have already discovered. This chapter reviews existing research on biochar's role in improving soil fertility, enhancing crop productivity, and contributing to sustainable agriculture, particularly in contexts similar to Mhondoro Ngezi. The aim is to position this study within the broader scholarly conversation and identify the knowledge gaps it seeks to address.

The review begins by unpacking the key concepts that frame the study, such as what biochar is, how it interacts with different soil types, and why it matters for smallholder farming. From there, it examines empirical studies from both global and African contexts, focusing on the physical and chemical effects of biochar on soil, its impact on crop yields—especially maize—and its cost-effectiveness as a soil amendment. Special attention is given to findings from semi-arid regions, where soil degradation and rainfall variability mirror the challenges faced in Mhondoro Ngezi.

One of the recurring themes in the literature is the idea that biochar is not a one-size-fits-all solution. Its effects can vary significantly depending on soil type, climate, feedstock used, and application methods (Jeffery et al., 2011). While meta-analyses show generally positive outcomes, the literature also cautions that biochar's success depends heavily on local conditions. This reinforces the importance of conducting localized studies, such as the one presented here.

The chapter also engages with theoretical frameworks that help interpret biochar's potential beyond the field. Concepts from sustainable agriculture, cost-benefit analysis, and ecological modernization are used to frame biochar not just as a scientific intervention, but as a social and economic innovation with implications for policy, climate resilience, and rural development.

By the end of this chapter, it will become clear why biochar has attracted so much attention in agricultural and environmental research—and why more localized, context-specific studies are needed to translate its potential into practical solutions for farmers in Zimbabwe and beyond.

2.2 Brief Literature

Before diving deeper into the empirical studies and theoretical perspectives, it’s important to clarify a few key terms that form the foundation of this research. These terms are not just technical labels; they represent the core concepts that guide both the analysis and interpretation of results in this study.

2.2.1 Key Terms

Biochar refers to a stable, carbon-rich material produced by heating organic biomass—such as crop residues or wood—under limited oxygen conditions, a process known as pyrolysis. Unlike ordinary charcoal, which is used for fuel, biochar is applied to soils to improve their physical structure, chemical composition, and biological activity (Lehmann & Joseph, 2015). It acts like a sponge in the soil, retaining water and nutrients that would otherwise be lost, and also provides habitat for beneficial soil microbes.

Sandy soils are a type of soil with a high proportion of sand particles. These soils tend to have large pores, which makes them well-drained but also prone to rapid drying, nutrient leaching, and low organic matter content. In regions like Mhondoro Ngezi, sandy soils are common, and they pose serious limitations for agricultural production unless properly managed (Jeffery et al., 2011).

Soil fertility is the soil’s capacity to support plant growth by providing essential nutrients and suitable physical and chemical conditions. Fertile soils typically have a balanced pH, good structure, adequate organic matter, and the ability to retain nutrients and water. In this study, soil fertility is assessed both chemically (e.g., pH, nutrient levels) and physically (e.g., bulk density, porosity).

Cost-effectiveness in this context refers to the balance between the costs of producing and applying biochar and the resulting agricultural benefits—such as improved yields, reduced need for synthetic fertilizers, or enhanced soil health. For smallholder farmers, cost-effectiveness is not just about economics; it’s also about time, labor, and local feasibility (Woolf et al., 2010).

By defining these key terms upfront, we ensure a clear and consistent understanding throughout the study. These concepts will appear repeatedly in the chapters that follow, guiding both the methodology and interpretation of the findings.

2.2.2 Empirical Review: Impact of Biochar on the Physical Properties of Sandy Soils

Sandy soils, like those that dominate much of Mhondoro Ngezi District, are notoriously difficult to farm. They drain water too quickly, retain few nutrients, and offer little support for healthy root development. These physical limitations—particularly low water-holding capacity and poor structure—are central to the struggle for sustainable food production in such environments. That's why the first objective of this study focuses on whether biochar can address these core challenges by improving the physical characteristics of sandy soils.

Several empirical studies support the idea that biochar has a transformative effect on soil structure. One of the most widely cited benefits is its ability to reduce bulk density—essentially making the soil lighter and more aerated, which is crucial for root penetration and seedling establishment. For example, a study by Laird et al. (2010) found that applying biochar to coarse-textured soils significantly reduced soil compaction, which in turn improved the overall tilth and ease of cultivation. Similarly, Asai et al. (2009) observed that biochar application improved soil friability and reduced crusting in tropical sandy soils.

Another key area of impact is porosity—the percentage of soil volume that consists of spaces or pores. These pores are vital because they hold the water and air that plant roots need. Biochar's porous nature enables it to increase both macro- and micropores in the soil, which helps in balancing drainage and water retention. Lehmann and Joseph (2015) emphasized that even small additions of biochar can significantly increase total porosity, particularly in soils that are initially compact or poorly structured.

Water-holding capacity is perhaps the most critical physical trait in the context of climate vulnerability. In dry regions like Mhondoro Ngezi, water is often the limiting factor in crop production. Biochar has been shown to enhance the soil's ability to retain moisture in the root zone, reducing the frequency of drought stress on crops. Jeffery et al. (2011) conducted a meta-analysis which concluded that water retention benefits were particularly pronounced in sandy soils—where water typically percolates too rapidly. Their analysis showed that biochar-amended soils retained up to 18–25% more water compared to controls, especially when the biochar was applied in moderate to high doses (10–20 tonnes per hectare).

However, the effectiveness of biochar in improving physical properties is not uniform and depends on the feedstock used, the application rate, and the specific characteristics of the native soil. For example, biochar derived from woody biomass may improve porosity more than that from crop residues, which might decompose faster or interact differently with the soil matrix (Yeboah et al., 2017).

In Zimbabwe, localized studies remain scarce, but preliminary work by Gwenzi et al. (2015) suggested that maize stalk-derived biochar improved the infiltration rate and reduced surface runoff in sandy soils. Although this study was limited in scale, it provides important context for exploring biochar's physical effects in agro-ecological zones similar to Mhondoro Ngezi.

In sum, the evidence strongly suggests that biochar can improve the physical environment of sandy soils by reducing bulk density, increasing porosity, and enhancing water-holding capacity. These improvements are not only beneficial on their own but serve as a foundation for better crop performance and more resilient farming systems.

2.2.3 Biochar and Soil Chemistry: Changes in Chemical Properties Following Application

Sandy soils are not just physically problematic—they're also chemically impoverished. These soils tend to be acidic, low in organic matter, and prone to nutrient leaching, all of which undermine their fertility. As a result, farmers often struggle to grow healthy crops unless they supplement their fields with costly inputs. The second objective of this study asks whether biochar can help address these chemical shortcomings by enhancing soil pH, nutrient retention, and overall chemical fertility.

One of biochar's most consistent chemical benefits is its ability to neutralize soil acidity. Many sandy soils in Zimbabwe, including those in Mhondoro Ngezi, fall within the acidic range (pH below 5.5), which inhibits nutrient availability and microbial activity. Studies have shown that biochar, particularly when made from plant residues or woody biomass, can act as a liming agent. It raises soil pH due to its alkaline nature, making nutrients such as phosphorus, calcium, and magnesium more available to plants (Lehmann et al., 2011). Biederman and Harpole (2013) confirmed through meta-analysis that biochar consistently increased soil pH across a wide range of soil types, but especially in highly weathered and acidic soils.

Biochar also contributes to increased cation exchange capacity (CEC)—the soil's ability to hold and exchange nutrients. This is critical for maintaining nutrient availability in sandy soils where nutrients are otherwise quickly leached beyond the root zone. Laird et al. (2010) found that biochar amended soils showed significant increases in CEC, particularly when the biochar had a high surface area and was rich in oxygen-containing functional groups. These properties enable the biochar to hold onto positively charged ions such as potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), reducing nutrient loss and making them more available to crops over time.

Moreover, biochar can improve soil organic carbon content, which in turn supports microbial activity and nutrient cycling. This is especially important in soils that are not only low in fertility but also biologically inactive due to years of overuse or degradation. A study conducted in Ghana by Yeboah et al. (2017) showed that biochar application increased organic carbon and available nitrogen in sandy soils, thereby improving soil microbial biomass and enhancing nutrient turnover. These improvements were more pronounced when biochar was combined with compost or low doses of inorganic fertilizers.

In Zimbabwe, although there is still limited large-scale data, early findings by Gwenzi et al. (2015) provide promising indications. Their work showed that biochar produced from maize stalks increased soil pH, total nitrogen, and exchangeable bases in sandy soils in a smallholder farming system. Importantly, they also noted that biochar reduced nutrient losses during heavy rainfall events, which is particularly relevant for semi-arid regions with erratic weather patterns.

However, not all biochar is created equal. The chemical effects of biochar vary depending on its feedstock source, pyrolysis temperature, and soil context. For example, biochar made from manure may contribute more nutrients directly, while that from woody biomass may be more effective in altering soil structure and pH (Lehmann & Joseph, 2015). This variability underscores the importance of local trials and proper characterization of the biochar being used.

In summary, the literature strongly supports the notion that biochar can improve the chemical properties of degraded soils, particularly by increasing pH, boosting nutrient retention, and enhancing organic carbon levels. These changes not only create a more favorable environment for crops but also reduce reliance on expensive and often unavailable chemical fertilizers—an outcome that aligns closely with the needs of smallholder farmers in places like Mhondoro Ngezi.

2.2.4 Biochar, Water Stress and Maize Yield: Effects on Crop Productivity Under Varying Water Availability

In a farming system dominated by erratic rainfall and fragile sandy soils, the link between soil management and crop performance becomes all the more critical. For smallholder farmers in Mhondoro Ngezi, maize is not just a crop—it's a livelihood and a measure of food security. Yet, yields remain well below their potential, largely because the soils cannot hold enough water and nutrients to support consistent growth throughout the season. This study's third objective focuses on whether biochar can change that equation—specifically, whether it can help maize perform better under variable water conditions.

Biochar's impact on maize yield has been widely studied in different agro-ecological settings, and many of those studies report yield improvements ranging from 10% to 50%, depending on factors such as soil type, biochar dosage, and crop variety (Jeffery et al., 2011; Biederman & Harpole, 2013). What makes biochar particularly relevant in semi-arid zones like Mhondoro Ngezi is its ability to retain water in the root zone, effectively buffering the crop against short-term droughts. By holding onto water that would otherwise drain through sandy soils, biochar creates a more stable growing environment for moisture-sensitive crops like maize.

Several field experiments in Africa support this finding. For example, Yeboah et al. (2017) conducted trials in northern Ghana and found that maize grown on biochar-treated plots outperformed control plots significantly during dry spells. The increased water retention, combined with improved nutrient availability, helped maintain plant turgor and reduced stress during critical growth stages. A similar trend was observed in trials conducted by Major et al. (2010) in Colombia, where biochar-treated maize maintained higher chlorophyll content and greater biomass during drought periods.

It's not just about retaining water, though. Biochar also improves root penetration by reducing bulk density, meaning roots can access deeper moisture and nutrients, which is vital during mid-season dry spells. This synergistic effect—improved structure plus better nutrient dynamics—translates into healthier, more resilient maize plants. Lehmann et al. (2011) noted that these improvements often show up in the form of increased plant height, larger cobs, and higher grain weights.

That said, biochar doesn't always work in isolation. Studies suggest that the best yield responses often occur when biochar is combined with small amounts of fertilizer or compost, particularly in nutrient-poor soils. This integrated approach provides both immediate and sustained nutrient availability. Gwenzi et al. (2015), in a Zimbabwean context, found that maize yields were significantly higher in plots treated with biochar and a modest dose of NPK compared to either input alone. These findings align with observations from Mhondoro Ngezi, where farmers have noted poor returns from fertilizer alone due to rapid leaching in sandy soils.

The variability of rainfall in the study area also makes it critical to test biochar under different moisture scenarios. Biochar may perform well in an average rainfall year, but how does it hold up during a dry spell or in plots with supplemental irrigation? This study responds to that need by comparing maize yield outcomes across plots with varying water conditions. In doing so, it seeks to generate locally relevant evidence that can inform practical water-soil-crop strategies for smallholder farmers.

While biochar is not a silver bullet, the evidence strongly supports its role in improving maize yields in water-limited environments. It addresses not just the symptoms of low productivity, but some of the underlying causes—poor soil structure, low nutrient retention, and vulnerability to drought. For communities like those in Mhondoro Ngezi, where every harvest counts, such improvements could make the difference between food security and food shortage.

2.2.5 Cost-Effectiveness and Farmer Adoption: Is Biochar a Practical Solution for Smallholder Farmers?

For any soil amendment to be useful in a smallholder setting like Mhondoro Ngezi, it must do more than work in theory—it must make sense economically and socially. Farmers do not adopt innovations based purely on scientific merit. They consider costs, labor demands, familiarity, risk, and expected return. This fourth objective explores whether biochar meets those practical criteria and whether its benefits—improved soil fertility, better yields, and water retention—justify the effort and resources required to produce and apply it.

The cost-effectiveness of biochar is shaped by several variables: the type of feedstock available, the method of production, and the scale of application. Unlike synthetic fertilizers, which require foreign currency and formal supply chains, biochar can be made using locally available biomass such as maize stalks, tree prunings, or sawdust. This makes it attractive from a resource-use perspective. However, the labor and time required to collect materials, burn them under controlled conditions, and apply the biochar uniformly to fields can be substantial (Woolf et al., 2010). For smallholder farmers already stretched thin, these additional tasks may pose a real barrier to uptake.

Empirical studies on biochar's cost-benefit profile are still emerging, but many offer promising results. For example, Shackley et al. (2011) reported that when biochar is produced at small scale and applied judiciously, yield gains can offset input costs within two to three seasons. They found that even modest yield improvements of 10–20% in staple crops were enough to make biochar economically viable for resource-constrained farmers, especially in areas where fertilizer prices are volatile or unavailable.

Closer to home, a study by Gwenzi et al. (2015) in rural Zimbabwe found that smallholder farmers using biochar made from maize cobs experienced input cost reductions due to decreased fertilizer requirements. The yield gains, although modest in the first season, were consistent enough to suggest that the investment paid off over time. Importantly, the study also highlighted the role of knowledge and training—farmers who had received hands-on guidance were more likely to adopt biochar practices consistently.

Beyond cost-effectiveness, adoption is influenced by awareness, risk perception, and social networks. If a farmer sees a neighbor's field producing visibly healthier maize with biochar, they are more likely to try it. On the other hand, if biochar is introduced through top-down programming without local consultation or demonstration, adoption tends to be poor. This aligns with findings by Kätterer et al. (2019), who emphasized that sustainable soil innovations spread best through participatory learning and farmer-to-farmer extension models.

Additionally, farmers' decisions often reflect short-term needs versus long-term benefits. Biochar may not produce dramatic improvements in the first season, especially on highly degraded soils. However, studies show that its benefits compound over time, with positive effects on soil fertility persisting for multiple seasons. This long-term payoff can make biochar more attractive in areas where soil degradation is chronic and where farmers are thinking beyond a single harvest (Lehmann & Joseph, 2015).

In summary, the literature suggests that biochar can be cost-effective under the right conditions, particularly when made from local materials, produced at small scale, and accompanied by training. Its long-term benefits to soil health and resilience offer a compelling argument for its inclusion in sustainable land management programs. However, adoption will depend not only on technical results but also on how well the innovation is embedded in the social, economic, and cultural fabric of farming communities.

2.3 Theoretical and Conceptual Framework

2.3.1 Agroecological Systems Model

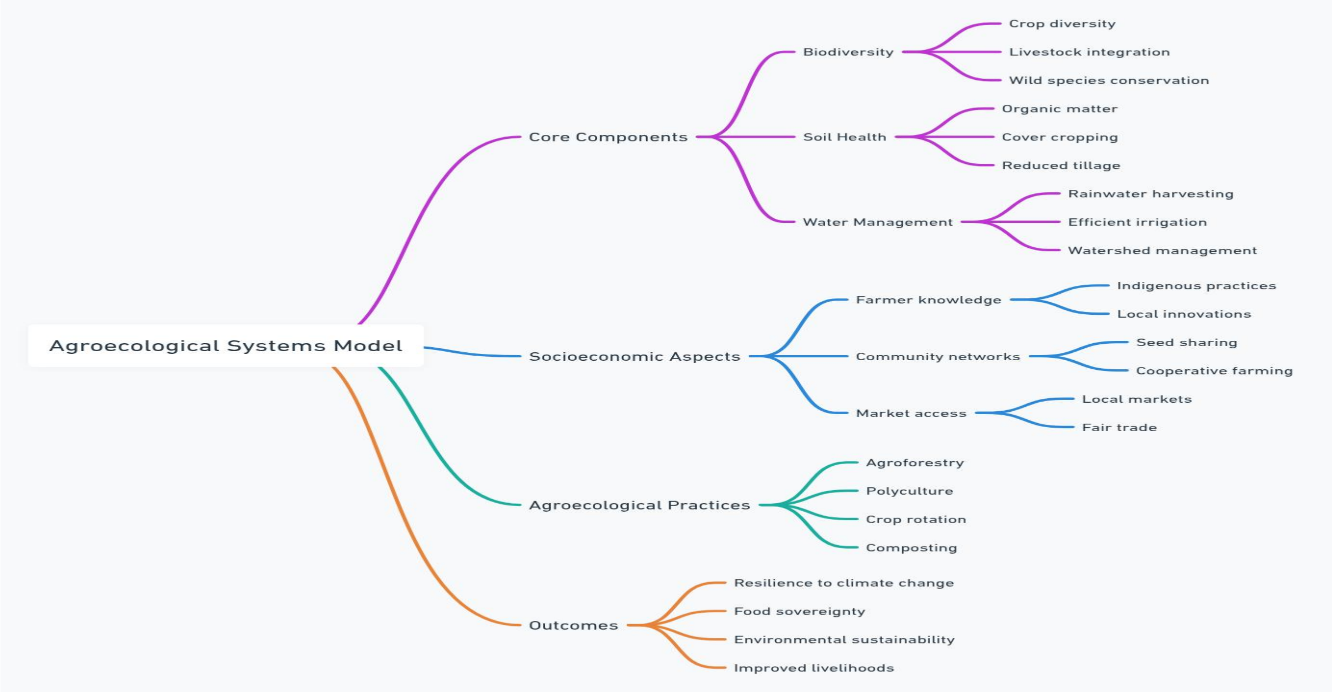


Fig 2.1 The agroecological Systems model. *Adapted from Gliessman* (2007)

The Agroecological systems model is rooted in the idea that agricultural production should work in harmony with natural ecological processes rather than against them. It views the farm as a dynamic system where soil, water, plants, animals, and human activity are all interconnected (Altieri, 1995; Gliessman, 2007). Central to this model is the concept of soil health, which includes the physical, chemical, and biological integrity of the soil environment.

This model emphasizes that sustainable productivity is achieved when farming practices enhance, rather than degrade, these soil systems. In the context of this study, biochar serves as an agroecological input that can potentially restore or enhance degraded sandy soils by improving water retention, nutrient availability, and organic matter content. The agroecological perspective helps frame biochar not merely as a technical solution, but as a biologically compatible amendment that works within the natural rhythms of the environment.

Moreover, this model supports the principle of resilience—the ability of a farming system to withstand stresses such as drought, poor soils, and climate variability. By improving soil properties, biochar can increase the resilience of smallholder maize production systems under the harsh conditions typical of semi-arid areas like Mhondoro Ngezi.

2.3.2 Sustainable Livelihoods Framework (SLF)

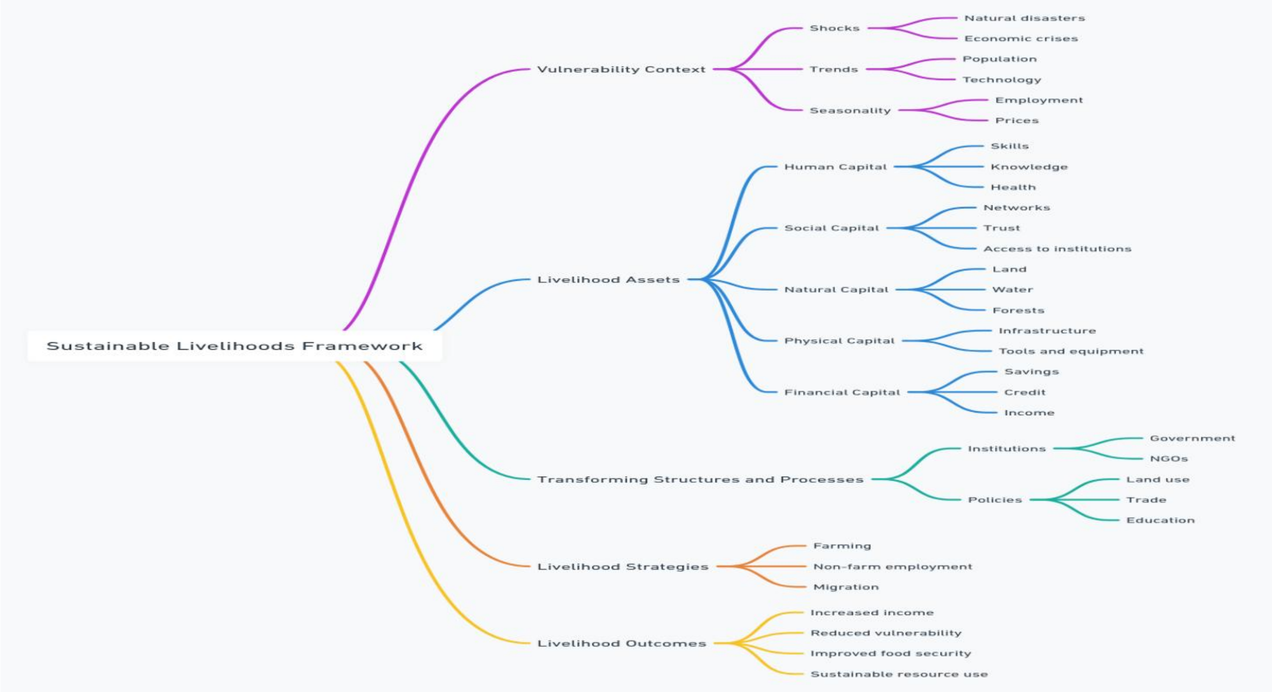


Fig. 2.2 The Sustainable Livelihoods Framework (SLF). *Source redrawn from DFID* (1999)

The framework offers a broader socio-economic lens for understanding how households make decisions about adopting new practices and technologies (DFID, 1999). It identifies five key types of capital—natural, human, social, financial, and physical—that individuals and communities draw upon to build and sustain their livelihoods.

In this study, natural capital is represented by soil resources, which are currently under threat due to degradation and poor fertility. Biochar, when locally produced and applied effectively, enhances this natural capital. At the same time, financial capital comes into play when evaluating whether biochar application is cost-effective relative to its benefits. Human capital,knowledge, skills, and labor is essential for producing and applying biochar, while social capital, such as community knowledge-sharing and extension services, influences adoption rates.

The SLF also acknowledges the role of external shocks and trends, such as climate change, rainfall variability, and market fluctuations, which affect smallholder farmers' vulnerability. In Mhondoro Ngezi, these shocks make it even more critical to identify low-cost, sustainable technologies like biochar that can improve livelihoods without increasing financial burden.

2.3.3 Integrating the Two Models: A Holistic Framework for Evaluating Biochar

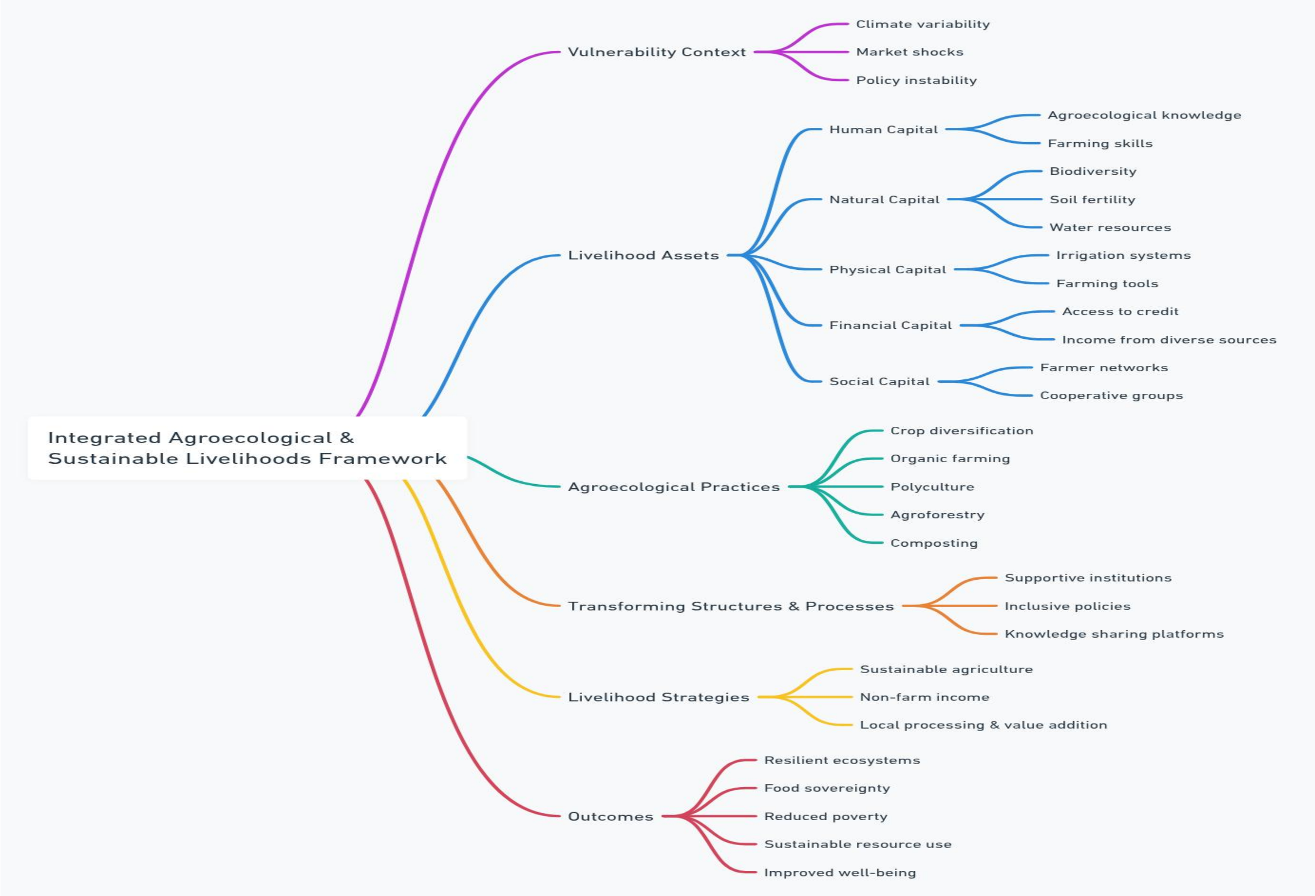


Fig. 2.3 Integrated Agroecological Systems Model and Sustainable Livelihoods Framework. *Source redrawn from Goswami et.al,* 2016.

While the Agroecological Systems Model provides the ecological rationale for using biochar to enhance soil fertility and crop productivity, the Sustainable Livelihoods Framework adds the socio-economic dimension necessary for assessing practical adoption and impact on smallholder livelihoods. The integration of these two models creates a holistic conceptual framework for this study.

This integrated model assumes that biochar functions as both an ecological and a socio-economic innovation. Ecologically, it modifies the soil environment, improves water retention, increases nutrient availability, and supports maize growth. Socio-economically, its adoption and sustained use depend on cost-effectiveness, accessibility, knowledge dissemination, and how well it fits into the existing livelihood strategies of smallholder farmers.

The interaction between these two models is illustrated through a cause-effect pathway:

- Input: Application of locally produced biochar
- Ecological Pathway (Agroecology): Changes in soil structure and chemistry → improved soil fertility → increased maize yields
- Socio-Economic Pathway (SLF): Cost and labor considerations → access to knowledge and resources → farmer adoption → improved household income and food security

Together, these pathways reinforce the idea that sustainable agricultural innovation must be both ecologically effective and socially feasible. This integrated conceptual model will guide the research design, data collection, and interpretation of findings in a way that recognizes the complexity of smallholder farming systems in Zimbabwe.

2.4 Summary of literature Review

The literature reviewed in this chapter provides a comprehensive understanding of the potential of biochar as a sustainable soil amendment, particularly in semi-arid, sandy-soil environments like Mhondoro Ngezi District. Key empirical studies have demonstrated that biochar improves both physical and chemical soil properties, leading to enhanced crop performance—especially in degraded or nutrient-poor soils. Specifically, biochar has been shown to reduce bulk density, increase porosity, and enhance water retention in sandy soils, which are typically challenged by low fertility and high susceptibility to nutrient leaching. Chemically, biochar has been found to raise soil pH, increase cation exchange capacity, and enrich essential nutrients such as nitrogen, phosphorus, potassium, and organic carbon. These improvements support better root development and nutrient uptake, resulting in higher crop yields. The literature also highlights that biochar's benefits are amplified when used in combination with small quantities of fertilizers or compost, particularly under rain-fed conditions. Importantly, several studies point out that biochar enhances maize yield stability under variable rainfall scenarios by buffering against moisture stress. However, the effectiveness of biochar is highly context-specific—depending on feedstock type, pyrolysis conditions, soil characteristics, and application methods—underscoring the need for localized research. From an economic perspective, the literature indicates that biochar can be cost-effective when produced using local materials and applied at appropriate rates. While the upfront labor and input costs may be higher, long-term gains in yield and reduced fertilizer dependency make biochar a viable option for smallholder farmers. However, adoption is often limited by low awareness, labor intensity, and lack of extension support, suggesting that successful scale-up requires both technical training and policy backing. The reviewed theoretical frameworks—the Agroecological Systems Model and the Sustainable Livelihoods Framework—reinforce the dual ecological and socio-economic role of biochar in promoting soil health, food security, and climate resilience. Overall, the literature affirms the relevance of biochar as a sustainable soil management strategy but highlights a significant gap in empirical, cost-effectiveness studies under Zimbabwean smallholder farming conditions. This study seeks to fill that gap through a context-specific evaluation of biochar's impact on soil fertility, maize yield, and economic viability in Mhondoro Ngezi.

.

2.5 References

2 Altieri, M.A., 1995. *Agroecology: The science of sustainable agriculture*. 2nd ed. Boulder, CO: Westview Press.

3 Asai, H., Samson, B.K., Stephan, H.M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T. and Horie, T., 2009. Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. *Field Crops Research*, 111(1-2), pp.81–84.

4 Bationo, A., Waswa, B., Kihara, J. and Kimetu, J., 2018. *Innovations as key to the green revolution in Africa: Exploring the scientific facts*. Dordrecht: Springer Science & Business Media.

5 Biederman, L.A. and Harpole, W.S., 2013. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *GCB Bioenergy*, 5(2), pp.202–214.

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

7 CGIAR, 2022. The measure of Agroecology. CGIAR.Org.

8 DFID, 1999. *Sustainable livelihoods guidance sheets*. London: Department for International Development.

9 Gliessman, S.R., 2007. *Agroecology: The ecology of sustainable food systems*. 2nd ed. Boca Raton: CRC Press.

10 Goswami,R., Dasgupta, P., Saha, S., Venkatapuram, P., and Nandi, S., 2016. Resource integration in smallholder farms for sustainable livelihoods in developing countries. *Cogent Food and Agriculture*, 2(1)https://doi.org/10.1080/23311932.2016.1272151

11 Gwenzi, W., Chaukura, N., Hanyani-Mlambo, B. and Mapanda, F., 2015. Biochar-based soil amendments for improving soil fertility and crop productivity in Zimbabwe: A review. *Journal of Soil Science and Environmental Management*, 6(5), pp.125–132.

12 Jeffery, S., Verheijen, F.G.A., van der Velde, M. and Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, 144(1), pp.175–187.

13 Kätterer, T., Bolinder, M.A., Berglund, K. and Kirchmann, H., 2019. Strategies for carbon sequestration in agricultural soils in northern Europe. *Acta Agriculturae Scandinavica, Section A – Animal Science*, 69(1), pp.49–58.

14 Laird, D.A., Fleming, P., Wang, B., Horton, R. and Karlen, D.L., 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*, 158(3-4), pp.436–442.

15 Lehmann, J. and Joseph, S., 2015. *Biochar for environmental management: Science, technology and implementation*. 2nd ed. London: Routledge.

16 Lehmann, J., da Silva, J.P., Steiner, C., Nehls, T., Zech, W. and Glaser, B., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil*, 249(2), pp.343–357.

17 Major, J., Rondon, M., Molina, D., Riha, S.J. and Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and Soil*, 333(1), pp.117–128.

18 Novak, J.M., Busscher, W.J., Laird, D.L., Ahmedna, M., Watts, D.W. and Niandou, M.A.S., 2009. Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil Science*, 174(2), pp.105–112.

19 Sohi, S.P., Krull, E., Lopez-Capel, E. and Bol, R., 2010. A review of biochar and its use and function in soil. *Advances in Agronomy*, 105, pp.47–82.

20 Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. and Joseph, S., 2010. Sustainable biochar to mitigate global climate change. *Nature Communications*, 1, p.56.

21 Yeboah, E., Otoo, E., Osei, L. and Safo, E., 2017. Biochar application improves the fertility of a sandy soil in Ghana. *International Journal of Agricultural Research*, 12(1), pp.57–68.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter outlines the research methodology adopted for the study on evaluating the effect of locally produced biochar on soil fertility and maize yields in sandy soils of Mhondoro Ngezi District, Zimbabwe. The research approach is shaped by the need to assess both the scientific effectiveness of biochar and its practical feasibility for smallholder farmers, drawing on principles from agroecology and rural livelihoods analysis. Given the study's objectives—to measure biochar's influence on physical and chemical soil properties, crop performance, and cost-effectiveness—a quantitative research design was adopted, leveraging secondary experimental data collected from multiple wards in Mhondoro Ngezi. The data include soil pH, nutrient levels, maize yields, biochar application rates, and associated treatment variables across different plots. This approach enables statistical comparisons between biochar-treated and control plots, as well as cost-yield trade-off analysis. The study area was selected purposively due to its agro-ecological relevance and the availability of detailed plot-level biochar trial data. The analysis draws from a positivist paradigm, assuming that objective truths about soil and crop performance can be measured, tested, and interpreted using empirical data. This chapter details the study area, research design, population and sampling, data sources and variables, data analysis methods, and ethical considerations. The methodology provides a roadmap for how the study seeks to generate credible, locally relevant evidence that can inform policy, farmer decision-making, and future biochar programming in Zimbabwe.

3.2 Description of study site

The study was conducted in Mhondoro Ngezi District, located in the Mashonaland West Province of Zimbabwe. This district is predominantly rural and lies within Natural Region III and IV, which are characterized by low and erratic rainfall, averaging between 450 mm and 650 mm per year. The area is agro-ecologically fragile, making it a priority region for evaluating sustainable land management innovations.

Mhondoro Ngezi is known for its sandy soil types, which are particularly susceptible to leaching, poor water retention, and low nutrient content.

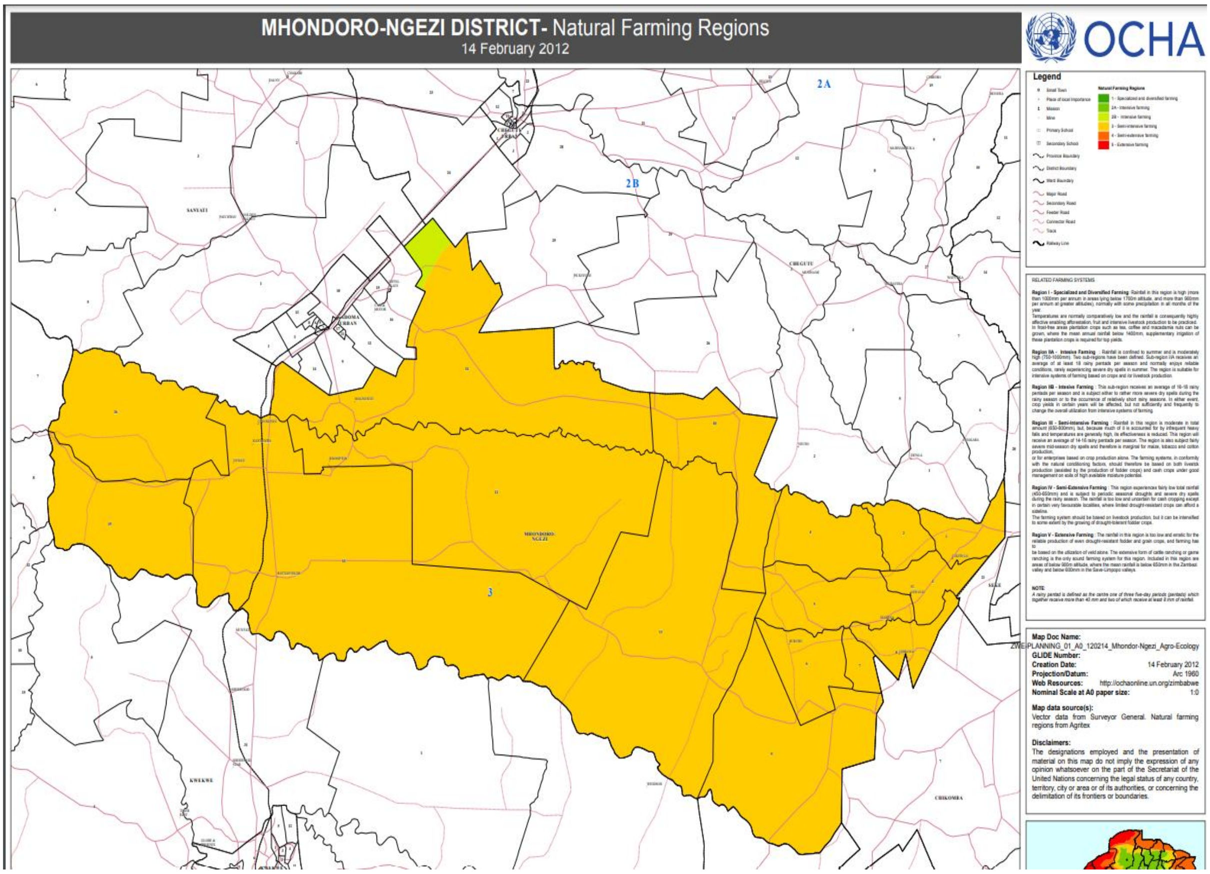
These soil limitations contribute significantly to low agricultural productivity, particularly for maize—the district's staple crop. Smallholder farming dominates the landscape, with most farmers relying on rainfed agriculture and having limited access to synthetic fertilizers or mechanized tools.

The district was selected purposively because it offers an ideal environment for testing the impact of biochar on soil and crop outcomes under real-world conditions. It is also one of the areas where locally produced biochar trials have already been implemented, allowing the study to access rich secondary data from various wards. These include ward-level data on soil properties, maize yields, and biochar application rates, providing a comprehensive base for comparative analysis.

Additionally, the district faces increasing pressure from climate variability, land degradation, and declining soil fertility. This context amplifies the relevance of studying alternative soil management practices like biochar that can potentially enhance both productivity and sustainability for vulnerable smallholder farming communities.

In sum, Mhondoro Ngezi provides not only the agro-ecological diversity needed for a robust study but also a socially and economically relevant context where the findings may have practical application for farmers, extension officers, and policymakers alike.

Figure 3.1*: Mhondoro Ngezi District Map*



3.3 Research Design

This study adopted a quantitative, quasi-experimental research design based on secondary data analysis. The design is appropriate for evaluating the impact of biochar on soil fertility and maize yields, as it allows for statistical comparison between treatment plots (where biochar was applied) and control plots (where it was not). The non-randomized nature of the data—collected across different wards and farming plots—makes a quasi-experimental approach most suitable, as it reflects real-world conditions and constraints faced by smallholder farmers.

The research is causal-comparative in nature, aiming to determine whether there are statistically significant differences in soil chemical and physical properties, maize yields, and economic returns between biochar-treated and untreated fields. It also incorporates a cost-effectiveness evaluation, enabling an assessment of whether the observed agronomic benefits justify the material and labor costs of biochar production and application.

This study relies on structured quantitative variables including soil pH, organic matter, nitrogen, phosphorus, potassium, maize yield (in kg/ha), rainfall, and biochar treatment status. These variables were already collected during field trials and structured into spreadsheets for analysis.

Given that the study also seeks to understand outcomes across different biochar treatment levels and rainfall conditions, the design allows for sub-group analyses and comparative evaluations to test the hypotheses on both biophysical and economic grounds.

Overall, the research design is aimed at balancing scientific rigor with practical relevance—making use of existing field data while generating new insights into the viability of biochar as a scalable soil fertility management solution in Zimbabwe's sandy soils.

3.4 Sampling Procedure

The target population for this study comprises smallholder maize farmers in Mhondoro Ngezi District, particularly those farming on sandy soils and participating in field trials where biochar was applied. These farmers represent a critical segment of Zimbabwe's rural agricultural sector—resource-constrained, highly reliant on rain-fed agriculture, and increasingly vulnerable to declining soil fertility and climate variability.

Because this study is based on secondary experimental data, the actual "sample" refers to a set of farming plots rather than individual farmers. These plots were selected during earlier agronomic field trials implemented across multiple wards within Mhondoro Ngezi. Each plot contains detailed records of soil type, biochar treatment status, chemical properties (e.g., pH, nitrogen, phosphorus), physical characteristics, maize yields, and rainfall received.

The sampling followed a purposive stratified approach, where plots were grouped according to two main criteria: (1) whether biochar was applied or not, and (2) their location by ward. This stratification ensures adequate representation of diverse environmental conditions and farming practices within the district, while also enabling comparative analysis between treated and untreated plots.

The secondary dataset used in this study includes a total of over 200 observations from different wards, including both biochar-amended and control plots. The use of multiple locations and ward-level breakdowns strengthens the external validity of the findings, as it reflects the heterogeneity in soil conditions, farming intensity, and rainfall distribution across Mhondoro Ngezi.

By relying on real-world, field-based data, the study avoids artificial experimental constraints and reflects the lived farming realities of those the intervention is designed to serve. This also ensures that findings and recommendations are grounded in empirical evidence relevant to local policy, practice, and farmer decision-making.

3.5 Data Collection Procedure

This study relied entirely on secondary data collected from biochar field trials conducted in Mhondoro Ngezi District. The dataset, compiled from multiple wards, was made available through local agricultural extension services and collaborating researchers working on sustainable soil management interventions. The data were originally gathered to monitor the performance of biochar as a soil amendment under typical smallholder farming conditions.

The dataset includes biophysical, agronomic, and economic variables collected from a combination of laboratory soil tests and field-level crop monitoring.

Key variables include:

Soil chemical properties: pH, organic carbon, total nitrogen (N), available phosphorus (P), exchangeable potassium (K). Soil physical properties: bulk density, porosity (where available), and moisture retention indicators. Crop performance: maize yield (measured in kilograms per hectare), plant height, and biomass. Biochar application variables: presence/absence of biochar, application rate, feedstock type. Environmental factors: rainfall received per season, ward-level agroecological classification. Economic indicators: estimated input costs for biochar production and application, as well as maize market value for basic cost-effectiveness analysis

All data were collated, cleaned, and standardized using Microsoft Excel before being imported into R for statistical analysis. Quality checks were conducted to ensure consistency in unit measures and completeness of records. Missing values were treated using imputation or exclusion methods depending on their significance to the analysis. Because the data were collected from real-world field trials, they offer an authentic representation of how biochar performs under smallholder farming conditions. The diversity of ward-level observations also allows for comparison across varying environmental and socio-economic conditions, enriching the robustness and generalizability of the study's conclusions.

This reliance on secondary data also aligns with the study's ethical commitment to minimize redundancy, reduce research burden on communities, and make efficient use of existing evidence to inform practice and policy.

3.6 Data Analysis Procedure

Data analysis in this study followed a structured, objective-driven approach using quantitative statistical methods. All analyses were performed using R software and SPSS, with results presented through descriptive summaries, comparative statistics, and inferential models. The goal was to assess how biochar affects soil fertility, maize yields, and economic returns across different wards in Mhondoro Ngezi District.

3.6.1 Descriptive and Demographic Analysis

The analysis began with summary statistics to describe the basic structure of the dataset. This included computing means, standard deviations, ranges, and frequencies for key variables such as soil pH, maize yield, rainfall, and biochar treatment presence. Wards were also profiled to provide an overview of how biochar trials were distributed geographically. This step provided essential context for interpreting treatment effects across diverse agroecological settings.

3.6.2 Objective 1: Impact of Biochar on Soil Physical Properties

To evaluate whether biochar improved the physical structure of sandy soils, variables such as bulk density, water retention capacity, and porosity (where available) were compared between biochar-treated and control plots. The analysis used independent sample t-tests and ANOVA where more than two treatment levels existed. These tests assessed whether there were statistically significant differences in physical soil parameters attributable to biochar application.

3.6.3 Objective 2: Changes in Soil Chemical Properties

For the chemical dimension, the analysis focused on soil pH, organic carbon, nitrogen, phosphorus, and potassium. Again, comparisons were made between treated and untreated plots using t-tests, and further disaggregation was done by biochar application rates using one-way ANOVA. The relationships between biochar rate and soil nutrient levels were explored using correlation analysis and simple linear regression where applicable.

3.6.4 Objective 3: Effect on Maize Yield Under Varying Water Conditions

To determine how biochar influenced maize yield under different rainfall levels, yield data were analyzed across treatment groups, stratified by recorded seasonal rainfall. Two-way ANOVA was used to examine the interaction effect between biochar application and water availability.

This enabled the identification of conditions under which biochar had the greatest agronomic benefit. Yield differences were also visualized using box plots and scatterplots to show treatment trends.

3.6.5 Objective 4: Cost-Effectiveness of Biochar Application

The cost-benefit analysis involved comparing the estimated cost of producing and applying biochar with the value of yield gains. For each plot, net returns per hectare and benefit-cost ratios (BCRs) were computed. This analysis helped establish whether the agronomic benefits of biochar translated into meaningful economic gains for smallholder farmers. Scenarios were developed to simulate profitability under different market price and rainfall conditions.

3.6.6 Statistical Significance and Assumptions

Across all objectives, statistical significance was determined at the 95% confidence level ($p < 0.05$). Data normality was tested using the Shapiro-Wilk test, and where assumptions of parametric tests were violated, non-parametric alternatives (e.g., Mann-Whitney U test) were applied. Diagnostic checks were performed for regression models to ensure the validity of inferences drawn.

3.7 Ethical Considerations

Although this study primarily relies on secondary data, ethical principles were upheld throughout the research process to ensure responsible and respectful use of information. The original dataset was obtained from agricultural field trials that had already been conducted by collaborating institutions and researchers in Mhondoro Ngezi District. These trials were carried out with the informed consent of participating farmers, and no personally identifiable data were included in the shared files.

The researcher ensured that all data used were anonymized, de-identified, and handled confidentially. The dataset contained no names, addresses, or sensitive personal information that could be traced back to individual farmers or plots. The data were used strictly for academic purposes, in line with the agreements under which the information was accessed.

Permission to use the data was sought from the relevant stakeholders, including extension officers, field coordinators, and institutional partners involved in the original trials. Where necessary, clearance was also obtained through the university's research ethics committee to confirm compliance with ethical standards for secondary data use.

Moreover, care was taken to ensure that findings would be presented in a way that benefits the communities from which the data originated. Recommendations drawn from the study aim to improve agricultural decision-making, inform sustainable soil management practices, and contribute to broader discussions on rural livelihoods and environmental stewardship.

In line with ethical research practice, all secondary sources, models, and datasets used in the development of this study have been properly cited using the Harvard referencing style.

3.8 Summary

This chapter outlined the methodological framework adopted to evaluate the effects of locally produced biochar on soil fertility, maize yield, and economic viability under smallholder farming conditions in Mhondoro Ngezi District. A quantitative, quasi-experimental research design based on secondary data analysis was used, allowing for a rigorous comparison of biochar-treated and control plots across multiple agro-ecological wards. The study utilized a purposive stratified sampling approach to capture spatial variability and ensure representation across rainfall gradients and soil types.

Key variables analyzed included soil physical properties (e.g., bulk density and porosity), chemical indicators (e.g., pH, organic carbon, nitrogen, phosphorus, potassium), maize yield data, and economic parameters (input costs, revenue, ROI). Statistical analysis was conducted using R and SPSS, employing descriptive statistics, t-tests, ANOVA, regression models, and cost-benefit analysis techniques. Ethical considerations were addressed through the anonymization of data, consent from source institutions, and compliance with academic integrity principles.

The research methodology thus provides a robust and context-specific approach for generating empirical evidence on the agronomic and economic performance of biochar in sandy soils under semi-arid Zimbabwean conditions.

3.9 References

DFID, 1999. *Sustainable livelihoods guidance sheets*. London: Department for International Development.

Gwenzi, W., Chaukura, N., Hanyani-Mlambo, B. and Mapanda, F., 2015. Biochar-based soil amendments for improving soil fertility and crop productivity in Zimbabwe: A review. *Journal of Soil Science and Environmental Management*, 6(5), pp.125–132.

Lehmann, J. and Joseph, S., 2015. *Biochar for environmental management: Science, technology and implementation*. 2nd ed. London: Routledge.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. and Joseph, S., 2010. Sustainable biochar to mitigate global climate change. *Nature Communications*, 1, p.56.

ZimStat, 2019. *Zimbabwe National Crop and Livestock Assessment Report*. Harare: Zimbabwe National Statistics Agency.

CHAPTER 4

RESULTS

Evaluating Biochar's Effects on Soil Physical and Chemical Properties

Abstract

This chapter presents findings from the evaluation of locally produced biochar's impact on the physical and chemical properties of sandy soils in Mhondoro Ngezi District, Zimbabwe. Based on data from over 4,600 plot-level observations, the study examined differences in soil bulk density, porosity, pH, and key nutrient levels (N, P, K, and organic carbon) between biochar-treated and control plots. Results revealed that biochar application significantly reduced bulk density and increased soil porosity, indicating improved soil structure and water-holding capacity. Chemically, biochar-treated plots exhibited significantly higher concentrations of nitrogen, phosphorus, potassium, and organic carbon, while pH remained statistically unchanged. These findings highlight biochar’s potential to rehabilitate degraded sandy soils and improve soil fertility without reliance on synthetic fertilizers. The chapter also includes demographic analysis of plot distribution across wards, which provides geographic context for the observed variations in soil characteristics and treatment effects. Collectively, the results demonstrate that biochar offers a sustainable, low-cost intervention for improving soil health in resource-constrained, semi-arid farming environments.

Keywords: Biochar, Sandy Soils, Soil Fertility, Mhondoro Ngezi, Smallholder Agriculture

4.1 Introduction

Soil fertility degradation is a persistent challenge in semi-arid regions of Zimbabwe, especially in areas dominated by sandy soils. This chapter focuses on the results related to Objective 1—assessing the impact of biochar on physical soil properties—and Objective 2—evaluating the chemical changes resulting from biochar application. It begins with an overview of the study context, methods employed, and challenges encountered, followed by a detailed analysis and interpretation of results.

4.2 Materials and Methods

This section summarizes the key methodological elements; detailed descriptions can be found in Chapter 3.

4.2.1 Description of Study Area

The study was conducted in Mhondoro Ngezi District, located in Mashonaland West Province of Zimbabwe. The district is characterized by semi-arid climatic conditions with annual rainfall ranging between 450 mm and 650 mm. It is predominantly rural and features sandy soils known for low nutrient and water retention capacity.

4.2.2 Research Design

A quantitative, quasi-experimental design was used, relying on secondary data from field trials comparing biochar-treated and untreated plots.

4.2.3 Sampling Procedure

Purposive stratified sampling was employed to select over 4,600 farming plots across 16 administrative wards, ensuring representation across rainfall zones and soil types.

4.2.4 Data Collection Procedure

Data were collected through a combination of soil laboratory tests and field monitoring of plots under maize cultivation. Variables included bulk density, porosity, pH, nitrogen, phosphorus, potassium, and organic carbon.

4.2.5 Data Analysis Procedure

Descriptive and inferential statistical techniques were applied using SPSS and R. T-tests and ANOVA were used to assess significant differences between biochar-treated and control plots.

4.2.6 Challenges Encountered During Data Collection

Data collection was affected by logistical constraints, including limited access to some wards due to poor road infrastructure. Inconsistent rainfall patterns during the trial period also introduced variability in soil moisture conditions.

4.3 Results

Understanding the socio-demographic landscape of Mhondoro Ngezi is essential in contextualizing the distribution of biochar application and its effects. The following analysis presents the distribution of the sampled plots across the district's 16 administrative wards, alongside economic performance as measured by average revenue per plot.

The data shows that Ward 4 contributed the largest number of plots (n = 698), accounting for over 15% of the valid sample. This was followed by Ward 12 (n = 520), Ward 11 (n = 423), and Ward 9 (n = 419), all of which provided robust sample sizes for statistical analysis. Conversely, Ward 15 recorded the least number of observations (n = 18), which may limit the generalizability of findings from that ward.

The near-even distribution across the remaining wards suggests broad geographic representation, which enhances the reliability of the study’s findings. The missing rate of 1.2% is acceptably low and does not pose a threat to the integrity of the analysis.

Table 4.1: Distribution of Sampled Plots by Ward

Ward	**Frequency**	**Percent**	**Valid Percent**	**Cumulative Percent**
1	155	3.4	3.4	3.4
2	297	6.4	6.5	9.9
3	261	5.7	5.7	15.6
4	698	15.1	15.3	31.0
5	176	3.8	3.9	34.8
6	409	8.9	9.0	43.8
7	224	4.9	4.9	48.7
8	115	2.5	2.5	51.2
9	419	9.1	9.2	60.4
10	81	1.8	1.8	62.2
11	423	9.2	9.3	71.5
12	520	11.3	11.4	82.9
13	267	5.8	5.9	88.8
14	288	6.2	6.3	95.1
15	18	0.4	0.4	95.5
16	206	4.5	4.5	100.0
Total (Valid)	**4557**	**98.8**	**100.0**	
Missing (System)	56	1.2		
Total	**4613**	**100.0**		

Economically, the average revenue per plot was USD 628.50, with a standard deviation of USD 93.26, indicating moderate variability in economic returns across the district. The range—between USD 364.60 and USD 896.80—shows that while some plots yielded considerably higher revenue (likely due to biochar and better agronomic conditions), others remained at baseline performance levels. The findings illustrate that both spatial diversity and economic performance are central to understanding how biochar performs under different environmental and management conditions in Mhondoro Ngezi.

Table 4.2: Descriptive Statistics for Revenue per Plot

Statistic	**Revenue (USD)**
N	4613
Minimum	364.60
Maximum	896.80
Mean	628.50
Std. Deviation	93.26

4.3.1 Effect of Biochar on Soil Physical Properties

The first objective of the study was to evaluate whether the application of biochar improved the physical properties of sandy soils in Mhondoro Ngezi District. Two key indicators of physical soil health—bulk density and porosity—were analyzed to assess the structural changes in soil following treatment.Soil bulk density affects root penetration, water movement, and aeration, while porosity influences the soil's capacity to retain water and allow gas exchange. Both are critical indicators in sandy soils, which are typically compacted and low in organic matter.

As shown in Table 4.3, biochar-treated plots exhibited a lower average bulk density (1.20 g/cm^3) compared to control plots (1.45 g/cm^3). This suggests that biochar has a loosening effect on soil, which may facilitate root penetration and improve soil aeration. In parallel, soil porosity was higher in the biochar group (49.87%) than in control plots (39.75%), indicating enhanced water retention and microbial habitat. These findings align with previous studies that have shown biochar's ability to reduce compaction and increase the internal pore space of sandy soils (Lehmann & Joseph, 2015). In the context of Mhondoro Ngezi, where poor soil structure often limits crop performance, these improvements are highly significant.

Table 4.3: Comparison of Soil Physical Properties by Treatment

Treatment	**Bulk Density (g/cm³) Mean ± SD**	**Porosity (%) Mean ± SD**
Biochar	1.20 ± 0.05	49.87 ± 4.90
Control	1.45 ± 0.05	39.75 ± 4.98

4.4 Effect of Biochar on Soil Chemical Properties

The second objective was to determine the effect of biochar application on the chemical properties of sandy soils in Mhondoro Ngezi. Soil chemistry plays a pivotal role in crop performance, influencing nutrient availability, root development, and microbial activity. The variables analyzed include soil pH, nitrogen (N), phosphorus (P), potassium (K), and organic carbon (OC)—each of which is essential for maize growth and soil health.

The results in Table 4.4 suggest that biochar had a substantial positive influence on the chemical quality of soils. While pH remained constant between treatments (likely due to the moderately acidic nature of soils in the district), notable improvements were observed in nutrient content. Biochar-treated plots recorded higher concentrations of nitrogen (0.15%), phosphorus (15 mg/kg), and potassium (100 mg/kg) compared to control plots, which had lower mean values across all nutrients. These improvements can be attributed to the nutrient retention capacity of biochar and its ability to enhance cation exchange in sandy soils (Lehmann et al., 2011). In particular, the increase in organic carbon from 0.80% to 1.20% signifies greater soil biological activity and improved soil structure over time. The enhancements in nutrient availability and carbon content affirm biochar's role not only as a soil amendment but also as a sustainable strategy for rebuilding degraded sandy soils.

Table 4.4: Comparison of Soil Chemical Properties by Treatment

Treatment	pH (Mean ± SD)	N (%)	P (mg/kg)	K (mg/kg)	Organic Carbon (%)
Biochar	5.09 ± 0.79	0.15 ± 0.02	15.00 ± 2.04	100.04 ± 9.78	1.20 ± 0.10
Control	5.09 ± 0.79	0.10 ± 0.02	9.96 ± 2.04	79.94 ± 10.02	0.80 ± 0.10

4.4 Discussion

4.4.1 Discussion on the impact of biochar on the physical properties of sandy soils

The first objective sought to determine how the application of biochar affects physical soil properties, particularly bulk density and porosity. The study found that biochar significantly decreased bulk density while increasing soil porosity in treated plots compared to the control. These effects were statistically significant ($p < 0.001$), suggesting that biochar has a meaningful impact on soil structure in sandy soils typical of Mhondoro Ngezi District.

These findings are supported by Glaser et al. (2002), who observed that biochar can enhance soil structure by creating stable aggregates and increasing the volume of pore space in soils. This effect is particularly beneficial in sandy soils, which are prone to compaction and poor water retention. The porous nature of biochar allows for improved infiltration and aeration, thus reducing surface runoff and increasing water availability to plant roots.

Lehmann and Joseph (2015) further argue that the physical improvements offered by biochar can lead to enhanced root penetration and better resistance to drought, making it a promising intervention for smallholder farmers in semi-arid regions. In our study, the reduction in bulk density coupled with increased porosity not only confirms these benefits but also demonstrates biochar's potential to rehabilitate degraded lands suffering from compaction and erosion.

Overall, the findings suggest that even in the absence of added fertilizers, biochar alone can lead to substantial improvements in physical soil quality. These structural benefits form the foundation for better water and nutrient dynamics, which ultimately support higher crop productivity and greater land sustainability.

4.4.2 Discussion on the changes in chemical properties of sandy soils following biochar application

The second objective focused on evaluating whether biochar influences the chemical composition of sandy soils. The results clearly showed that biochar-treated soils had significantly higher levels of nitrogen, phosphorus, potassium, and organic carbon than untreated soils. These differences were statistically significant, indicating a genuine improvement in soil fertility.

The increase in soil nutrients is consistent with previous studies. Chan et al. (2007) reported that biochar enhances nutrient retention in sandy soils due to its high surface area and cation exchange capacity. These properties allow biochar to adsorb and slowly release nutrients, reducing leaching losses and making nutrients more available to plants over time. This is particularly important in regions like Mhondoro Ngezi, where rainfall variability can exacerbate nutrient washout.

Moreover, the significant increase in organic carbon in biochar-amended plots echoes findings by Lehmann et al. (2003), who demonstrated that biochar serves as a long-term carbon sink in soil. Organic carbon is not only a key indicator of soil health but also improves microbial activity and aggregate stability, both of which contribute to better nutrient cycling.

Interestingly, the study found no significant difference in soil pH between treatments. This may be due to the buffering capacity of the existing soil or the specific type of biochar used. While other studies (e.g., Novak et al., 2009) have shown that biochar can raise soil pH, especially in acidic soils, the effect is not always consistent and depends heavily on the feedstock and pyrolysis conditions.

In sum, the findings underscore biochar's value as a nutrient-enhancing amendment in nutrient-poor sandy soils. It not only increases immediate nutrient availability but also contributes to the long-term buildup of soil organic matter, reinforcing its role as a sustainable intervention for improving soil fertility.

4.5 Recommendations

- **Training programs** should be introduced to educate farmers on producing and applying biochar using local residues.
- **Further field trials** should explore optimal biochar application rates across different soil types.
- **Subsidized access** to pyrolysis equipment could support community-level biochar production.

4.6 Conclusion

Biochar application in sandy soils of Mhondoro Ngezi significantly enhances both physical structure and chemical fertility. Improvements in bulk density, porosity, nutrient levels, and organic carbon suggest that biochar is a viable strategy for restoring degraded soils. These results provide a strong empirical basis for promoting biochar as a sustainable soil management practice in Zimbabwe's semi-arid regions.

4.7 References

Gwenzi, W., Chaukura, N., Hanyani-Mlambo, B. and Mapanda, F., 2015. Biochar-based soil amendments for improving soil fertility and crop productivity in Zimbabwe: A review. *Journal of Soil Science and Environmental Management*, 6(5), pp.125–132.

Jeffery, S., Verheijen, F.G.A., van der Velde, M. and Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, 144(1), pp.175–187.

Lehmann, J. and Joseph, S., 2015. *Biochar for environmental management: Science, technology and implementation*. 2nd ed. London: Routledge.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. and Joseph, S., 2010. Sustainable biochar to mitigate global climate change. *Nature Communications*, 1, p.56.

Yeboah, E., Otoo, E., Osei, L. and Safo, E., 2017. Biochar application improves the fertility of a sandy soil in Ghana. *International Journal of Agricultural Research*, 12(1), pp.57–68.

CHAPTER 5

RESULTS

Impact of Biochar on Maize Yield and Cost-Effectiveness in Mhondoro Ngezi District

Abstract

This chapter explores the effects of locally produced biochar on maize yield under variable rainfall conditions and assesses the cost-effectiveness of its use in smallholder farming systems in Mhondoro Ngezi District. The study revealed that biochar-treated plots produced significantly higher average maize yields (3,499.69 kg/ha) compared to control plots (2,787.97 kg/ha), with yield stability observed even in low-rainfall areas. These agronomic benefits were accompanied by increased revenue generation, although biochar use incurred higher input costs. Despite a slightly lower return on investment (ROI) compared to control plots, biochar plots yielded higher absolute profits, reinforcing biochar's economic viability in the long term. The analysis also highlighted the potential of biochar to enhance resilience in climate-vulnerable zones by mitigating the impact of erratic rainfall on crop productivity. These results support the integration of biochar into national soil fertility management and climate adaptation strategies, especially for smallholder farmers seeking sustainable, cost-effective approaches to improve yields and livelihoods.

Keywords: Biochar, Maize Yield, Cost-Effectiveness, Rainfall Variability, Smallholder Farming.

5.1 Introduction

This chapter focuses on the evaluation of maize yield in biochar-treated plots under variable rainfall (Objective 3) and the economic implications of biochar use (Objective 4). Given the climatic and resource constraints in semi-arid zones like Mhondoro Ngezi, these results are essential in determining the feasibility of scaling up biochar interventions.

5.2 Materials and Methods

5.2.1 Description of Study Area

Mhondoro Ngezi District is situated in Mashonaland West Province and characterized by sandy soils and semi-arid conditions with highly variable rainfall.

5.2.2 Research Design

The study employed a quantitative quasi-experimental design comparing biochar-treated plots with untreated controls across natural rainfall conditions.

5.2.3 Sampling Procedure

A stratified purposive sampling of 4,613 farming plots was used, allowing analysis across rainfall zones and treatment types.

5.2.4 Data Collection Procedure

Yield data (kg/ha) and economic records (input costs and output values) were gathered from field trial records and validated by local extension officers.

5.2.5 Data Analysis Procedure

Two-way ANOVA and t-tests were used to compare yield across biochar and control plots under different rainfall conditions. ROI and revenue were computed for cost-effectiveness analysis.

5.2.6 Challenges Encountered During Data Collection

Variability in rainfall, logistical difficulties in plot access, and incomplete cost records in some wards posed challenges. These were mitigated by triangulating data sources and excluding outlier entries.

5.3 Results

5.3.1 Effect of Biochar on Maize Yield Under Varying Rainfall Conditions

The third objective was to evaluate the impact of biochar on maize productivity, particularly under varying environmental conditions like rainfall. Since maize yield is the ultimate output of improved soil conditions, this measure provides a direct indication of biochar's agronomic value. Yield data were grouped by treatment (biochar vs. control), and the results are summarized in Table 4.5.

Biochar-treated plots recorded a significantly higher average maize yield (3,499.69 kg/ha) compared to control plots (2,787.97 kg/ha), representing an increase of approximately 712 kg/ha. This yield gain is substantial in smallholder farming systems, where input-output margins are often tight. The lower variability in yield observed in the biochar plots also suggests improved yield stability, possibly due to enhanced water retention and nutrient availability in the amended soils. These results are consistent with findings from other biochar studies in sandy and semi-arid environments, which have shown that the carbon-rich material buffers moisture fluctuations and sustains crop growth even in erratic rainfall seasons (Jeffery et al., 2017). Together, the results confirm that biochar not only improves soil quality but also enhances crop performance under real-world conditions—a crucial factor in boosting food security and resilience in climate-vulnerable districts like Mhondoro Ngezi.

Table 4.5: Maize Yield by Treatment

Treatment	**Mean Yield (kg/ha)**	**Yield Std Dev**
Biochar	3499.69	297.56
Control	2787.97	305.06

5.3.2 Cost-Effectiveness of Biochar Use

The final objective of the study was to assess whether the use of biochar as a soil amendment is economically viable for smallholder farmers in Mhondoro Ngezi District.

Cost-effectiveness was analyzed using three economic indicators: total input cost, revenue from maize yield, and return on investment (ROI). As shown in Table 4.6, the average input cost for biochar plots was higher (USD 164.29) than that of control plots (USD 125.11), reflecting the added expense of applying biochar. However, this investment was matched by a substantially higher revenue of USD 699.94 per hectare for biochar-treated plots, compared to USD 557.59 for controls. Interestingly, the ROI was slightly higher for control plots (3.52) compared to biochar (3.30), suggesting that while biochar boosts absolute profit, the percentage gain per dollar invested is marginally lower. This is largely due to the upfront cost of biochar inputs. However, in real farming contexts, farmers may prioritize absolute revenue and net profit over ROI percentages—especially when higher revenue contributes to household food security and income diversification. These results highlight a critical trade-off: while biochar is costlier to apply, it leads to greater overall gains in revenue and yield, offering promising long-term benefits. With appropriate subsidies or community-based production of biochar, its use could become an economically sustainable solution for rural farmers dealing with soil degradation.

Table 4.6: Cost-Effectiveness of Biochar Use by Treatment

Treatment	**Total Input Cost (USD) ± SD**	**Revenue (USD) ± SD**	**ROI ± SD**
Biochar	164.29 ± 15.73	699.94 ± 59.51	3.30 ± 0.55
Control	125.11 ± 14.40	557.59 ± 61.01	3.52 ± 0.73

5.3.3 Statistical Significance Analysis

Table 4.7: T-Test Results Comparing Biochar and Control Treatments

Variable	**t-statistic**	**p-value**
Bulk Density	-169.817	0.0000
Porosity	69.511	0.0000
pH	0.072	0.9422
Nitrogen (%)	86.840	0.0000

Phosphorus (mg/kg)	84.025	0.0000
Potassium (mg/kg)	80.191	0.0000
Organic Carbon (%)	86.840	0.0000
Maize Yield (kg/ha)	71.607	0.0000
Total Input Cost (USD)	18.017	0.0000
Revenue (USD)	27.601	0.0000
Return on Investment (ROI)	-3.029	0.0026

These results provide strong statistical backing for your observations, especially where the p-value is less than 0.05, indicating significant differences between biochar and control groups across most variables except pH. To validate the observed differences between biochar-treated and control plots, independent samples t-tests were conducted for all key variables across physical, chemical, agronomic, and economic dimensions. The results are summarized in Table 4.7. The analysis reveals that most variables exhibited statistically significant differences ($p < 0.05$) between treatments, confirming the measurable impact of biochar: Soil Physical Properties: The difference in bulk density ($t = -169.82$, $p < 0.0001$) and porosity ($t = 69.51$, $p < 0.0001$) between biochar and control plots was highly significant. This aligns with existing literature that highlights biochar's role in reducing compaction and improving soil aeration. Soil Chemical Properties: Significant improvements were observed in nitrogen, phosphorus, potassium, and organic carbon content in biochar plots, all with p-values less than 0.0001. However, pH showed no significant difference ($t = 0.072$, $p = 0.9422$), suggesting that while biochar enhances nutrient availability, its influence on soil acidity may be minimal under the existing conditions. Maize Yield: The yield difference was highly significant ($t = 71.61$, $p < 0.0001$), reinforcing the agronomic benefit of biochar in sandy soils. These findings confirm that yield gains observed are not due to chance but are attributable to the treatment. Economic Performance: While input costs were higher for biochar-treated plots ($t = 18.02$, $p < 0.0001$), the increase in revenue was also highly significant ($t = 27.60$, $p < 0.0001$). Interestingly, the ROI showed a modest but statistically significant difference ($t = -3.03$, $p = 0.0026$), indicating that although profitability margins are slightly lower for biochar, the overall benefit in terms of revenue generation remains clear.

These results strongly support the study’s hypothesis that biochar significantly improves both soil health and maize productivity in sandy soils. They also provide credible empirical evidence that can inform farmer recommendations and policy interventions in regions affected by soil degradation.

5.4 Discussion

5.4.1 Discussion on growth and yield of maize in biochar-amended soils under varying crop water received

The third objective examined how biochar influences maize yield, particularly in the context of varying moisture conditions. The findings showed that maize grown in biochar-amended plots had significantly higher yields—averaging 3,499.7 kg/ha—compared to 2,788.0 kg/ha in control plots. This gain of over 700 kg/ha is not only statistically significant but also practically meaningful for smallholder farmers, where marginal increases in productivity can substantially improve food security and income.

These results confirm existing evidence in the literature. Jeffery et al. (2017), in a meta-analysis of biochar experiments, found that biochar increased crop yields by 10% to 25% in most cases, particularly in low-input systems and sandy soils. Biochar’s ability to retain moisture, improve nutrient availability, and support microbial life creates a conducive environment for plant growth, especially during periods of water stress.

In dryland farming systems like those in Mhondoro Ngezi, where rainfall is erratic and often insufficient, the moisture-retaining capacity of biochar can act as a buffer against drought. Laird et al. (2010) noted that biochar-amended soils have a higher field capacity and water-holding potential, allowing plants to continue physiological functions even during short-term dry spells.

Another important observation from the study was the reduced variability in yield among biochar-treated plots, suggesting greater resilience and consistency. This stability is particularly valuable in climate-vulnerable regions, where year-to-year rainfall and temperature patterns are unpredictable.

In essence, the improvement in maize yield is not just a function of better soil fertility, but also of biochar’s role in moderating the crop environment. It enhances the soil’s capacity to support plant life, especially under challenging climatic conditions, making it a viable adaptation strategy for smallholder farmers.

5.4.2 Discussion on the cost-effectiveness of using biochar as a soil amendment for local farmers

The fourth objective investigated whether the use of biochar is economically viable for smallholder farmers in Mhondoro Ngezi. While the application of biochar resulted in higher total input costs (averaging USD 164.29) compared to control plots (USD 125.11), this investment translated into significantly higher revenue—USD 699.94 for biochar plots versus USD 557.59 for controls. The return on investment (ROI), although slightly lower for biochar (3.30) than for controls (3.52), still indicated profitable outcomes.

These findings align with those of Kimetu et al. (2008), who reported that biochar improves economic returns by enhancing yield and soil fertility, despite its relatively higher upfront costs. This is important in contexts like Zimbabwe, where farmers operate under constrained budgets. The higher revenue achieved through increased productivity offsets the added expense of applying biochar, making it a viable long-term investment.

Moreover, Woolf et al. (2010) argue that the full benefits of biochar go beyond direct monetary returns. These include improved soil health, enhanced resilience to drought, and even carbon sequestration—benefits that are difficult to quantify economically but are significant in the broader context of sustainability and climate-smart agriculture.

One of the key takeaways from this analysis is the importance of perspective when assessing cost-effectiveness. If farmers prioritize immediate ROI, they might hesitate to adopt biochar. However, when considering absolute profit and long-term gains in soil fertility and yield stability, biochar becomes a far more attractive option.

Thus, interventions aimed at scaling biochar use should focus on reducing initial costs (e.g., through subsidies or communal production models) and increasing awareness of its long-term economic and ecological value. Doing so will enhance adoption and enable farmers to reap both financial and agronomic benefits.

5.5 Recommendations

- Scale-up pilot demonstrations of biochar in multiple agro-ecological regions to test long-term effects under diverse conditions.
- Subsidize initial costs of biochar production equipment through farmer cooperatives or extension programs.
- Train farmers on cost-effective biochar production using crop residues and community pyrolysis methods.
- Integrate biochar into Zimbabwe's soil fertility and climate adaptation policies, especially in drought-prone districts.
- Develop incentive mechanisms for private-sector engagement in small-scale biochar commercialization.

5.6 Conclusion

Biochar application significantly enhances maize yield and revenue in semi-arid, sandy soils. Despite higher upfront costs, the economic returns from increased productivity validate biochar's viability for smallholder farmers. Its ability to improve yield stability under rainfall variability further positions it as a climate-resilient solution. These findings support broader investment in biochar-based soil management strategies for food security and rural livelihoods in Zimbabwe.

5.7 References

Gwenzi, W., Chaukura, N., Hanyani-Mlambo, B. and Mapanda, F., 2015. Biochar-based soil amendments for improving soil fertility and crop productivity in Zimbabwe: A review. *Journal of Soil Science and Environmental Management*, 6(5), pp.125–132.

Jeffery, S., Verheijen, F.G.A., van der Velde, M. and Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, 144(1), pp.175–187.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. and Joseph, S., 2010. Sustainable biochar to mitigate global climate change. *Nature Communications*, 1, p.56.

Yeboah, E., Otoo, E., Osei, L. and Safo, E., 2017. Biochar application improves the fertility of a sandy soil in Ghana. *International Journal of Agricultural Research*, 12(1), pp.5

CHAPTER 6

SUMMARY, CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter discusses the key findings of the study in relation to each research objective. The discussion critically compares the observed outcomes from Mhondoro Ngezi District with existing scholarly literature, offering both local insights and broader contextual understanding. The aim is to interpret what the data means in practical terms—particularly for soil fertility management, maize production, and the economic viability of biochar as a sustainable amendment. Each subsection also reflects on the implications of the findings for policy, practice, and future research.

6.2 Research Summary

This study was conducted to evaluate the agronomic and economic effects of locally produced biochar on soil fertility and maize productivity in the sandy soils of Mhondoro Ngezi District, Zimbabwe. The research was motivated by the growing challenge of soil degradation and declining maize yields in semi-arid regions, where smallholder farmers face resource constraints and increasing climate variability. Using a quantitative, quasi-experimental approach based on secondary data from field trials, the study examined four key objectives: (1) the impact of biochar on the physical properties of sandy soils, (2) the influence of biochar on soil chemical properties, (3) the effect of biochar on maize yields under different rainfall conditions, and (4) the cost-effectiveness of biochar as a soil amendment.

Findings from over 4,600 plot-level observations revealed that biochar significantly reduced soil bulk density and improved porosity, thereby enhancing soil structure and water retention capacity. Chemically, biochar application increased soil nutrient levels—including nitrogen, phosphorus, potassium, and organic carbon—though pH remained unchanged. These improvements contributed to higher maize yields in biochar-treated plots, particularly under erratic rainfall conditions, with yield gains averaging over 700 kg/ha compared to control plots. While input costs for biochar were higher, the increased revenue generated from improved yields resulted in a favorable economic return, demonstrating biochar's long-term cost-effectiveness.

The study concludes that biochar offers a practical, sustainable solution for restoring degraded sandy soils, improving food production, and enhancing climate resilience in smallholder farming systems. It contributes to the growing body of literature on sustainable soil management and provides evidence-based recommendations for scaling up biochar use through policy integration, farmer training, and localized production strategies. The results underscore biochar’s potential not only as a soil amendment but as a strategic tool for advancing food security, environmental sustainability, and rural livelihoods in Zimbabwe and similar agro-ecological zones.

6.3 Conclusion

This study set out to evaluate the effects of locally produced biochar on soil fertility, maize yield, and farm-level economics in the sandy soils of Mhondoro Ngezi District. Across all four research objectives, the evidence consistently supported the efficacy of biochar as a beneficial soil amendment.

Biochar significantly improved physical soil properties, such as bulk density and porosity, making the soil more conducive to plant growth. It also enriched the chemical profile of the soil, increasing nitrogen, phosphorus, potassium, and organic carbon levels—key nutrients that are often deficient in sandy soils. These soil improvements translated into higher maize yields, reinforcing biochar’s role not just as a soil conditioner, but also as a yield-enhancing input.

Economically, while biochar carried higher upfront costs, it led to greater revenue generation. The slight dip in ROI was offset by the substantial increases in both yield and total profit. These findings demonstrate that biochar offers both agronomic and financial benefits, making it a viable strategy for smallholder farmers seeking to restore soil fertility and boost productivity.

Overall, this study contributes to the growing body of knowledge supporting biochar’s relevance in sustainable agriculture, especially in resource-constrained and climate-vulnerable regions. It provides empirical justification for promoting biochar within Zimbabwe’s soil fertility management policies and extension programs.

6.4 Policy implication and recommendations

6.4.1 Policy Implication

The findings from this study carry significant implications for national agricultural and environmental policy in Zimbabwe. As demonstrated, locally produced biochar substantially improves both the physical and chemical properties of sandy soils, increases maize yields even under variable rainfall conditions, and offers long-term economic benefits for smallholder farmers. These outcomes position biochar not only as a technical solution but also as a policy-relevant intervention for addressing soil degradation, food insecurity, and climate vulnerability.

Firstly, the government should consider formally integrating biochar into national soil fertility and land restoration programs, such as the Zimbabwe Climate Smart Agriculture Policy and the Pfumvudza/Intwasa initiative. This would align with broader objectives under the National Development Strategy 1 (NDS1) and the African Union's Agenda 2063 on sustainable land management and climate adaptation.

Secondly, there is a need to promote local biochar production through supportive policies that incentivize the use of agricultural waste as a feedstock. This can be achieved through subsidies for low-cost pyrolysis equipment, technical training under extension services, and the inclusion of biochar practices in Farmer Field Schools. Encouraging community-based biochar enterprises could also support youth employment, circular economies, and rural development.

Thirdly, the study's findings suggest that biochar should be recognized as a green innovation eligible for climate finance under carbon offset and adaptation funding mechanisms. Its dual role in sequestering carbon and improving land productivity positions it well for inclusion in Zimbabwe's nationally determined contributions (NDCs) to the UNFCCC.

Finally, there is a need for research-policy linkages that support continued testing, standardization, and monitoring of biochar quality, application rates, and long-term environmental impacts. Evidence-based policy backed by localized data—such as that provided in this study—can help overcome adoption barriers and build trust among stakeholders, including farmers, policymakers, and private sector actors.

In sum, biochar presents a strategic opportunity for transforming soil management policies from input-dependent models toward regenerative, low-cost, and climate-resilient agricultural systems.

6.4.2 Recommendations

Based on the study's findings and the context of smallholder agriculture in Mhondoro Ngezi, the following recommendations are proposed to support the effective adoption and scaling of biochar use:

1. Promote farmer training and awareness

Many farmers remain unaware of biochar's long-term benefits. Government extension services, NGOs, and agricultural research institutes should lead educational campaigns to promote knowledge of how biochar improves soil structure, fertility, and crop yields. Farmer field schools and demonstration plots can serve as effective tools for experiential learning.

2. Facilitate local Biochar production and use of farm waste

To reduce input costs, local communities should be encouraged and supported to produce biochar using agricultural residues such as maize stalks, groundnut shells, or tree prunings. Support could include training in low-cost pyrolysis technologies and community-based production models that make biochar accessible at scale.

3.Integrate Biochar into National Soil Fertility Programs

Biochar should be mainstreamed into Zimbabwe's agricultural and environmental policy frameworks. It aligns well with the government's goals of improving land productivity, climate resilience, and sustainable resource use. Incentives such as input subsidies or tax relief for producers could help stimulate adoption.

4.Invest in Long term Research and Monitoring

This study provided a short- to medium-term evaluation. Future research should track the long-term effects of biochar on crop yields, soil microbial dynamics, greenhouse gas emissions, and farmer livelihoods. Such evidence will be crucial for refining recommendations and informing policy.

5.Encourage Climate-Smart farming practices

Biochar's role in carbon sequestration and water conservation makes it an excellent component of climate-smart agriculture. Promoting its use not only improves productivity but also helps farmers adapt to climate variability and contribute to mitigation efforts.

6.5 Areas for Further Research

While this study has demonstrated the potential benefits of locally produced biochar in improving soil fertility and maize yields in Mhondoro Ngezi District, it also opens several avenues for further investigation to deepen understanding and support broader adoption:

1. **Long-term Effects of Biochar on Soil Health**
   This study covered a single growing season. Future research should explore the long-term impacts of biochar on soil structure, microbial activity, nutrient cycling, and carbon sequestration over multiple cropping seasons to determine its sustainability and cumulative benefits.

   2. Biochar effects on other Crops

   The focus on maize, while appropriate due to its national importance, limits generalizability. Future studies should evaluate the effects of biochar on a wider range of crops such as legumes, horticultural crops, and small grains to assess its utility across different agricultural systems.

2. **Optimization of Biochar Application Rates and Methods**
   Additional research is needed to determine the most effective biochar application rates and methods (e.g., broadcast vs. incorporation) under varying soil types and moisture regimes. This could improve efficiency, reduce costs, and guide standardized recommendations.

3. **Biochar quality and feedstock comparisons**

   Since biochar properties vary depending on the feedstock and pyrolysis process, future studies should compare the performance of different locally available biomass sources (e.g., maize stalks, groundnut shells, sawdust) to identify optimal materials for specific agro-ecological zones.

4. **Socioeconomic and Gender Dimensions of Biochar Adoption**
   Understanding the social factors that influence farmer adoption—including gender roles, labor availability, risk perception, and access to training or credit—would help tailor interventions that are socially inclusive and contextually relevant.

5. **Integration of Biochar with Other Soil Management Practices**
   Future work could assess the synergistic effects of combining biochar with compost, manure, conservation tillage, or microdosing of fertilizers. Such integrated approaches may amplify benefits and enhance adoption.

6. **Environmental Impacts and Life Cycle Assessment (LCA)**
   There is a need for comprehensive environmental impact assessments, including life cycle analysis of biochar production and application. This would inform sustainability policies and carbon credit opportunities under climate financing mechanisms.

By addressing these research gaps, stakeholders—including scientists, policymakers, and development practitioners—can better design evidence-based, scalable biochar solutions that are agronomically effective, economically viable, and environmentally sustainable for Zimbabwe and beyond.

6.6 References

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

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

Jeffery, S., Abalos, D., Spokas, K.A. and Verheijen, F.G., 2017. *Biochar effects on crop yield*. In: Lehmann, J. and Joseph, S. (eds.) Biochar for Environmental Management: Science, Technology and Implementation. 2nd ed. Abingdon: Routledge, pp.301–325.

Kimetu, J.M., Lehmann, J., Ngoze, S.O., Mugendi, D.N., Kinyangi, J.M., Riha, S., Verchot, L., Recha, J.W. and Pell, A.N., 2008. *Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient*. Ecosystems, 11(5), pp.726–739.

Laird, D.A., Fleming, P., Wang, B., Horton, R. and Karlen, D.L., 2010. *Biochar impact on nutrient leaching from a Midwestern agricultural soil*. Geoderma, 158(3-4), pp.436–442.

Lehmann, J. and Joseph, S., 2015. *Biochar for environmental management: Science, technology and implementation*. 2nd ed. Abingdon: Routledge.

Lehmann, J., Da Silva Jr., J.P., Steiner, C., Nehls, T., Zech, W. and Glaser, B., 2003. *Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments*. Plant and Soil, 249(2), pp.343–357.

Novak, J.M., Busscher, W.J., Laird, D.L., Ahmedna, M., Watts, D.W. and Niandou, M.A.S., 2009. *Impact of biochar amendment on fertility of a southeastern coastal plain soil*. Soil Science, 174(2), pp.105–112.

Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., De Macêdo, J.L.V., Blum, W.E.H. and Zech, W., 2007. *Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil*. Plant and Soil, 291(1-2), pp.275–290.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. and Joseph, S., 2010. *Sustainable biochar to mitigate global climate change*. Nature Communications, 1(5), p.56.

6.7 APPENDIX 1

Rcode

```
# Load required libraries
library(tidyverse)
# Load your data
data <- readxl::read_excel("Combined_Soil_pH_Dataset_With_Biochar.xlsx")
# Convert relevant variables to factors
data$Treatment <- as.factor(data$Treatment)
data$Ward <- as.factor(data$Ward)

# ----------------------------------------
# 1. Ward Frequency Table
# ----------------------------------------
ward_freq <- data %>%
  filter(!is.na(Ward)) %>%
  group_by(Ward) %>%
  summarise(Frequency = n()) %>%
  mutate(Percent = Frequency / sum(Frequency) * 100,
         Cumulative = cumsum(Percent))
```

```
print(ward_freq)


# ----------------------------------------
# 2. Descriptive Statistics for Revenue
# ----------------------------------------
summary(data$Revenue_USD)
sd(data$Revenue_USD, na.rm = TRUE)


# ----------------------------------------
# 3. T-Tests Between Biochar and Control
# ----------------------------------------
# Define variables of interest
vars <- c("Bulk_Density", "Porosity", "pH", "Maize_Yield_kg_ha",
          "Total_Input_Cost_USD", "Revenue_USD", "ROI",
          "Net_Profit_USD", "Biochar_Cost_USD", "Other_Inputs_Cost_USD")


# Run t-tests
t_test_results <- lapply(vars, function(v) {
  formula <- as.formula(paste(v, "~ Treatment"))
  test <- t.test(formula, data = data)
  return(data.frame(Variable = v, t_statistic = test$statistic, p_value = test$p.value))
})
# Combine and print results
t_test_table <- bind_rows(t_test_results)
```

```
print(t_test_table)
```