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Biochar Impacts on Soil Health, and Plant Growth. A case study of smallholder farms in Malawi.

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Preface:

This master's thesis represents an investigation into the impacts of biochar application on soil health and plant growth in the context of smallholder farms in Malawi. The journey undertaken to explore these dimensions of more sustainable agriculture has been a culmination of research, critical analysis, and collaborative engagement with various parties.

In a world facing challenges of food security, climate change, and limited resources, the potential of biochar as a soil amendment has emerged as a promising solution. This study delves into the nuances of this potential, aiming to contribute valuable insights to the agricultural community, policy makers and broaden scientific conversations.

The journey began with a comprehensive literature review, illuminating the properties of biochar and the underlying mechanisms driving its effects on soil quality and early plant performance. This foundational research laid the groundwork for the subsequent phases.

Adopting a mixed-methods approach, this study intertwined quantitative soil sampling with qualitative semi-structured interviews. This combined methodology was designed to provide a holistic understanding of the multifaceted advantages of biochar application in the specific context of Malawian smallholder farms.

The integration of these methods allowed for a nuanced exploration of not only the quantitative soil parameters but also the perceptions and experiences of those intimately involved in biochar adoption.

Findings from this research, and data analysis, corroborate the potential of biochar application to yield favorable outcomes. The thematic analysis of qualitative data reveals various benefits, ranging from enhanced soil fertility to improved water management and pest control. Quantitative analyses comparing soil samples against established quality standards affirm the positive influence of biochar on critical parameters such as organic carbon content and cation exchange capacity (CEC).

However, as with any scientific endeavor, limitations were encountered. The relatively recent adoption of biochar in the studied farms limited the scope of plant growth and performance data. Additionally, the inherent biases of qualitative data and time constraints impacted the extent of data collection. Acknowledging these limitations is integral to a nuanced interpretation of the research outcomes.

This thesis aspires to contribute to the knowledge base on sustainable agricultural practices by providing evidence-based recommendations for effective biochar implementation. The recommendations aim to pave the way for improved food security, environmental management, and enhanced livelihoods for smallholder farmers by emphasizing the significance of soil health, crop productivity, and environmental sustainability.

In closing, this thesis is a testament to the collaborative efforts of numerous individuals and institutions. The guidance of advisors, the support of academic institutions, the participation of farmers and project managers, and the unwavering encouragement of family and friends have collectively shaped this research journey. Their contributions underscore the importance of multidisciplinary collaboration in addressing the complex challenges faced by agricultural systems.

With these insights and acknowledgments, I invite readers to delve into the subsequent chapters of this thesis, where the empirical findings, analyses, and recommendations are presented in detail. May this work contribute to the ongoing discourse on sustainable agriculture and foster positive change in sustainable agricultural practices.

Abstract:

Biochar, a promising soil amendment, has gained attention in Malawi as a sustainable solution for enhancing agricultural practices among smallholder farmers. This study investigates the diverse impacts of biochar application on soil health, plant growth, and inquires about environmental remediation in smallholder farms of Malawi.

Beginning with a comprehensive literature review, the research examines biochar properties, applications, and underlying mechanisms that drive its effects on soil quality and early plant performance. Employing a mixed-methods approach, this study integrates quantitative soil sample data and qualitative interview data to comprehensively understand the multifaceted advantages of biochar application on Malawian smallholder farms.

Thematic analysis of qualitative data reveals perceived benefits, including enhanced soil fertility, improved water management, pest control, and increased crop yields. Quantitative analysis compares soil samples against established soil quality standards and agricultural guidelines. Results indicate that biochar application treatments generally yield favorable outcomes.

For instance, the "Maize+Biochar+Manure" treatment in Nkhatabay shows higher levels of organic carbon (1.69%), aligning with the recommended range of 1% - 5% for improved soil fertility. Additionally, biochar application leads to elevated cation exchange capacity (CEC) levels. In the "Maize+Biochar" treatment at the Lilongwe farm, CEC levels reach 0.72 meq/100g, demonstrating enhanced nutrient retention capacity.

Conversely, the "No Biochar" treatment in Lilongwe exhibits lower organic carbon levels (0.99%) and suggests poor soil fertility potential. These quantitative findings corroborate qualitative observations, highlighting biochar's potential to positively influence soil health and agricultural productivity.

Drawing upon integrated qualitative and quantitative data, the study underscores biochar's transformative role in promoting sustainable agriculture. By recognizing both benefits and challenges, this research contributes to the knowledge base on sustainable agricultural practices and advocates for widespread biochar adoption in Malawi's smallholder farming systems.

The study concludes with evidence-based recommendations that guide effective biochar implementation for farmers, policymakers, and stakeholders. Emphasizing soil health, crop productivity, and environmental factors, these recommendations offer valuable insights for enhancing food security, mitigating environmental degradation, and uplifting the livelihoods of smallholder farmers amid climate change and resource limitations.

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I want to express my deep gratitude to the following individuals and institutions, without whose support and guidance, this thesis would not have been possible:

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I am indebted to The Norwegian University of Life Sciences (NMBU) for providing me with the resources, facilities, and a conducive academic environment that facilitated the execution of this research. The NORAGRIC and Landsam department has been a source of inspiration and growth through the past two years of my academic journey.

My gratitude extends to my colleagues and friends who provided valuable discussions, brainstorming sessions, and moral support during moments of doubt. Your camaraderie has made this academic endeavor an enriching and enjoyable experience. Thank you all.

I am also thankful for the support provided by Lilongwe University of Agriculture and Natural Resources, Malawi (LUANAR). You facilitated and enabled me to focus on my research without constraints; your assistance was invaluable.

I want to acknowledge the participants, projects, and farmers who generously contributed their time and insights to this study. Their cooperation has been essential in gathering meaningful data and driving the conclusions of this research.

Last but not least, I would like to express my deep appreciation to my family, Mom, Dad, and Sister; your unconditional love, unwavering belief in my abilities, and constant encouragement have been my pillar of strength and helped me push through to the end.

I am grateful to all those who played a role, big or small, in shaping this thesis. Your support has been a cornerstone of my academic journey, and I am honored to acknowledge your contributions.

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List of abbreviations

pH - Soil pH (measure of acidity or alkalinity)

EC - Electrical Conductivity (measure of soil's ability to conduct electricity)

Organic Carbon - Percentage of organic carbon in the soil

Organic Matter - Percentage of organic matter in the soil

Total N - Total Nitrogen content in the soil

Available P - Available Phosphorus content in the soil

K - Potassium content in the soil

Fe - Iron content in the soil

Zn - Zinc content in the soil

CEC - Cation Exchange Capacity (measure of the soil's ability to retain and release nutrients)

List of tables:

1. Introduction:

Soil health and plant growth are fundamental to sustaining food production and ensuring environmental well-being. Nonetheless, the escalating challenges of soil degradation and contamination, arising from the excessive use of agricultural chemicals and fertilizers, are posing substantial global concerns. These issues jeopardize agricultural output, ecological balance, and human health. In response, the adoption of biochar has emerged as a promising and ecologically friendly strategy, garnering substantial attention across diverse disciplines such as agriculture, environmental science, and waste management. Biochar, a carbon-rich material derived from biomass pyrolysis under oxygen-depleted conditions (Cheriyadath, 2020), presents a potent solution for mitigating soil degradation, curbing pollution, and concurrently fostering plant growth and carbon sequestration. Its distinctive attributes, including high porosity, cation exchange capacity, nutrient retention, and water-holding capacity, play a pivotal role in enhancing soil health and diminishing greenhouse gas emissions (Sun et al., 2021). Furthermore, biochar offers a cost-effective and sustainable avenue for environmental remediation by immobilizing pollutants, minimizing leaching, and amplifying soil microbial activity.

The historical roots of biochar utilization trace back millennia, with compelling evidence from ancient civilizations, such as the Amazonian cultures, practicing a form of biochar production termed "terra preta" or "dark earth." These terra preta soils, renowned for their fertility and agricultural productivity, embody elevated levels of charcoal and organic matter. Archaeological investigations indicate that this fertility was intentionally cultivated by incorporating charred biomass, encompassing agricultural residues and wood, into the soil matrix. Remarkably, the practice of integrating biochar into agriculture appears to have emerged independently across different corners of the world, including the Amazon Basin, West Africa, and Central Europe. The evolution of Terra Preta, in tandem with contemporary biochar applications, underscores the pivotal role of biochar properties, influenced by carbonization techniques, in realizing the dual objectives of enhancing soil fertility and effecting carbon sequestration (Steiner, 2010).

Recent investigations have provided a further propulsion to the potential of biochar in tropical regions. Adekiya et al. (2020) conducted a comprehensive two-year field experiment on a tropical sandy loam Alfisol in Nigeria, assessing the impact of hardwood-derived biochar on soil properties, soil loss, and cocoyam yield. The study revealed that biochar application significantly improved soil physical and chemical characteristics, concurrently augmenting cocoyam yield and reducing soil erosion. These findings corroborate the capacity of biochar to enhance soil health and plant productivity in tropical contexts, thereby aligning with the broader objectives of sustainable agriculture and environmental resilience.

Collectively, the convergence of historical practices and contemporary research underscores the transformative potential of biochar. As the world grapples with mounting agricultural and environmental challenges, harnessing biochar's properties offers a pathway towards sustainable soil management, elevated agricultural yields, and enhanced ecological impacts.

1.1 Scope and Limitations

This study focuses on applying biochar in agricultural systems, primarily targeting soil health and plant growth with aspects of possible environmental remediation effects. It will consider application rates, and biochar types, mainly created from the top-down burn method of maize feedstocks. I sample and different soil types and climatic conditions from the north, central and southern regions of Malawi. However, it is essential to acknowledge that this research does not address the full spectrum of biochar applications or the potential effects on other ecosystems or industries. Other limitations of the research design include the potential for biases in the qualitative data, such as social desirability bias or interviewer bias, and the limited scope of the field experiment in terms of the range of crops and environmental conditions, as well as the minimal amount of time that was available to conduct the field research. However, these limitations should be mitigated through the careful design and analysis of the data.

1.2 Research Design

To address the primary objective of investigating the effects of biochar application on soil fertility and plant growth in the agricultural systems of Malawi, as well as potential positive environmental remediation effects, this study employed a mixed-methods approach, combining qualitative and quantitative data collection and analysis.

1.2.1 Research Questions

The research aimed to answer the following questions:

How does biochar application affect fundamental soil properties such as pH or nutrient retention and availability?

What are the optimal application rates and frequency of biochar use for achieving maximum benefits regarding soil health and plant growth, and how does this vary with soil type, climate, and crop species?

Can biochar be used to remediate contaminated soils, and if so, what factors influence its effectiveness in this role?

1.2.2 Qualitative Phase

Semi-structured interviews were conducted with farmers, soil scientists, and biochar project staff. This approach allowed exploration of their experiences and perceptions of using biochar in agriculture, including, creation methods, perceived benefits and drawbacks, optimal application methods and rates, and barriers to adoption. Thematic analysis was applied to the qualitative data.

1.2.3 Quantitative Phase

Field research was conducted across regions in Malawi. Multiple composite soil samples were collected and analyzed, including measurements of pH, Electrical Conductivity (EC), Organic Carbon, Organic Matter, Total Nitrogen (N), Available Phosphorus (P), Potassium (K), Iron (Fe), Zinc (Zn), and Cation Exchange Capacity (CEC). Statistical tests were utilized to analyze the quantitative data.

1.2.4 Integration

Qualitative and quantitative findings were integrated through triangulation, identifying patterns and discrepancies between the two datasets. This integration provided a comprehensive understanding of the impact of biochar on soil health, plant growth, and environmental remediation.

The outcomes of this research contributed to the development of practical recommendations for optimizing biochar application in sustainable agriculture. The mixed-methods approach enabled a holistic exploration of the research questions and facilitated a nuanced understanding of the complex interactions between biochar, soil, and plant dynamics within the agricultural context of Malawi small holder farms.

2. Literature Review/Knowledge Gaps and Research Problem:

Despite the growing interest in the potential positive impact of biochar on soil health, plant production, and environmental impacts, uncertainties persist regarding its effects on specific soil properties, optimal application rates, and its efficiency in remediating certain contaminants.

Biochar, derived from the pyrolysis of organic biomass, has gained considerable attention for its potential positive impact on soil health, plant growth, and environmental remediation. It is characterized by its unique physical structure, high surface area, and ability to retain water and nutrients. Biochar can be produced from various feedstocks, such as agricultural waste, wood chips, or animal manure, resulting in different types of biochar with varying properties.

This review aims to provide a comprehensive description of biochar, its various kinds, and properties and delve into its effects on soil health and plant growth, and investigate strategies for optimizing its use in environmental remediation. However, uncertainties remain regarding mineral substance availability to plants and potential nutrient leaching to the environment through different biochar's, as discussed by Xu et al. (2016). Furthermore, several articles have been reviewed and knowledge gaps concerning the influence of soil type and application rate on biochar's effectiveness are a concern.

To optimize the benefits of biochar, it is crucial to determine the appropriate application rate and frequency, which may vary depending on soil type, crop type, and climate conditions. This review thoroughly examines these knowledge gaps, focusing on whether biochar affects fundamental soil properties or nutrient availability. Additionally, the review explores the potential of biochar in remediating contaminated soils and its overall effectiveness. Based on recent literature Sections 2.1 through 2.1.2 explore and evaluate the first research question and the effects of biochar on soil health.

2.1 Influence of Biochar Application on Soil Properties

Ding et al. (2016) state the potential of biochar to improve soil fertility has been extensively studied, considering its ability to enhance various aspects of soil health and plant growth. Biochar, characterized by its high surface area with functional groups, nutrient-rich composition, and slow-release fertilizer capabilities, has demonstrated promising effects in promoting soil fertility, increasing crop yield, and reducing contaminations. Numerous factors contribute to the effectiveness of biochar, including feedstock selection, pyrolysis temperature, pH, application rates, and soil types

Ding et al. (2016). These factors influence the biochar's physicochemical properties, ultimately impacting its interactions with the soil ecosystem. In terms of pH, adding biochar has been shown to increase soil pH, thereby influencing nutrient availability. This pH increase is particularly significant for nutrients like phosphorus (P) and potassium (K). Furthermore, biochar produced at higher temperatures and with higher volatile matter content has been associated with improved nitrogen (N) availability. The ash content in biochar can also contribute to increased soil pH, influencing cation exchange capacity and soil nutrients.

Understanding the mechanisms underlying nutrient adsorption by biochar is essential in comprehending its impact on soil fertility. The increased awareness is shedding light on the interactions between biochar and nutrient dynamics in the soil environment. Additionally, the study suggests the importance of future research focusing on combining different biochar types to enhance nutrient utilization efficiency and enable tailored soil management practices.

Biochar application can significantly influence soil properties, enhance nutrient contents and availability, and mitigate nutrient leaching, thereby improving soil fertility (Ding et al., 2016). By addressing the above research question, and incorporating existing literature, this review serves as a foundation for further investigations on the intricate interactions between biochar and soil fertility, facilitating the development of sustainable agricultural practices.

2.1.1 Strategies for Optimizing Biochar Benefits and Collaboration in Biochar Research

Gelardi and Parikh (2021) assert that the importance of scientific research cannot be overstated in the pursuit of optimizing sustainability opportunities associated with biochar utilization. For biochar's safe and effective use, it is crucial to gather reliable information on its application. A document addressing these concerns proposes strategies for increasing knowledge accrual in biochar research, while focusing on biochar application effects on soil properties.

One significant aspect highlighted in this review is the ability of biochar to increase soil pH, thereby contributing to the reduction of aluminum toxicity and enhancing phosphorus availability. This pH adjustment can have profound implications for soil health and nutrient cycling. Furthermore, Gelardi and Parikh (2021) underscore the impact of biochar amendments on nutrient content and labile carbon in the soil. These findings indicate that biochar can influence soil properties and nutrient dynamics.

However, it is acknowledged that the effectiveness of biochar in affecting soil properties depends on various factors, including the specific properties of the biochar itself. Recognizing the need for collaboration within the scientific community emphasizes the importance of collective efforts in advancing biochar research.

Partnerships such as these allow for the sharing of expertise, data, and methodologies, thereby facilitating a comprehensive understanding of the impacts of biochar on fundamental soil properties. By working together, researchers can optimize biochar benefits and contribute to developing sustainable agricultural practices.

Biochar application in agriculture involves long-term effects on soil health and crop productivity. Collaborative efforts can establish large-scale, long-term field trials in various regions, assessing biochar's performance over extended periods and under different environmental conditions. These trials provide valuable data on the sustained impacts of biochar on soil properties, nutrient dynamics, and crop productivity.

This section review highlights the strategies proposed for increasing knowledge accrual in biochar research, emphasizing the importance of addressing the influence of biochar application on fundamental soil properties. The findings indicate that biochar can positively impact soil pH, nutrient availability, and carbon content. However, further research is required to comprehend the complex interactions between biochar and soil fully.

Efforts within the scientific community are pivotal in achieving these research goals, harnessing the potential of biochar for sustainable soil management, and showing its actual effectiveness under a variety of different climates.

By incorporating collaborative efforts in biochar research, scientists can collectively address knowledge gaps, tackle challenges, and gain a more comprehensive understanding of biochar's potential for soil health, plant growth, and environmental remediation. These collaborations enhance the reliability and applicability of research outcomes, leading to the development of more effective and sustainable agricultural practices with the use of biochar.

2.1.2 Biochar, Soil, and Plant Interactions for Sustainable Agriculture

Murtaza et al. (2023) shows the context of sustainable agriculture under a changing climate, and the interactions between biochar, soil, and plants have continued to gain significant attention. This review section explores these interactions, shedding light on the role of biochar as a soil ameliorator and its effects on fundamental soil properties. In particular, the research addressed, highlights the importance of biochar for agricultural sustainability in the context of soil health and plant production.

The research emphasizes that biochar application can notably influence soil pH, particularly in acidic soils. Biochar contains weak acid functional groups that manifest as organic anions under neutral and alkaline conditions, inhibiting soil acidification and enhancing nutrient availability (Murtaza et al., 2023). Furthermore, the review explores the impact of biochar on nutrient availability in the soil, indicating increased availability of specific nutrients, such as potassium (K), phosphorus (P), and nitrogen (N), in alkaline soils.

This evidence highlights the significant influence of biochar application on soil pH and nutrient availability, indicating its potential to enhance soil health and promote plant growth. Further research is required to comprehensively investigate the interactions between biochar and soil fertility, particularly under diverse environmental conditions. By addressing the research question regarding biochar's impact on fundamental soil properties, this research contributes to understanding the potential of biochar for promoting agricultural sustainability. The above various studies have been reviewed, and all explore the influence of biochar application on soil properties, particularly focusing on soil pH and nutrient availability.

The reviews and research of (Ding et al., 2016; Gelardi and Parikh, 2021; Murtaza et al., 2023) collectively highlight the potential of biochar application to positively influence fundamental soil properties. However, there are notable discrepancies in the observed effects of biochar on different soil types and under varying environmental conditions. Ding et al. (2016) reported that adding biochar can increase soil pH, particularly influencing nutrient availability, such as phosphorus (P) and potassium (K).

On the other hand, Gelardi, and Parikh (2021) emphasize that the effectiveness of biochar in affecting soil properties depends on factors, including specific properties of the biochar itself, what feedstock is used, and how it is created. These findings suggest that biochar's impact on soil properties is not universally consistent, and the efficacy of biochar amendments may vary depending on the context of the application.

Further analysis reveals that more research is needed to fully comprehend biochar's underlying mechanisms of nutrient adsorption and its interactions with the soil ecosystem. Additionally, the effectiveness of biochar may be influenced by factors such as feedstock selection, pyrolysis temperature, pH, application rates, and soil types.

Comprehensive investigations and further research on the interactions between biochar properties and soil fertility are required to develop tailored biochar application strategies that optimize soil health and enhance nutrient utilization for plant uptake. Sections 2.2 through 2.2.2 address the questions of optimal application rates, size, and frequency of biochar use for achieving maximum benefits regarding soil health and plant growth and if it varies by soil type, climate, and crop species.

2.2 Optimizing Biochar Application for Enhanced Soil Health and Plant Growth

Kocsis et al. (2020) investigated effects of biochar application on soil health and plant growth, aiming to determine the optimal application rates, size, and frequency of biochar use for maximum benefits. Biochar derived from organic waste through pyrolysis was mixed with sandy soil in an ecological farming system. The study assessed agrochemical and biological parameters of the soil, including soil physical activity and microbial abundance.

The results showed that increasing biochar doses significantly increased the biomass and yield of maize compared to the control group. Biochar also increased enzyme activities and microbial biomass, positively impacting soil microbial populations. Moreover, biochar improved soil physical, chemical, and biological conditions, increasing nutrient availability and mobilization for plant uptake. (Kocsis et al. 2020).

The porous nature of biochar provided protection for microorganisms and supported decomposition and mineralization processes in the soil. The study highlighted the importance of selecting the right biochar concentration for optimal results, particularly in sandy soil and maize cultivation, especially in organic farming systems.

Biochar application on sandy soils demonstrated several benefits, including increased total biomass and maize yield, reduced nutrient loss through leaching, and improved soil structure. Additionally, biochar's adsorption capacity should be considered to avoid plant nutrient deficiency.

This research contributes to understanding the optimal application strategies for biochar. It highlights the potential of biochar as an environmentally beneficial soil amendment, especially in ecological farming systems. However, further research and comprehensive soil analysis are necessary to fully grasp the potential benefits and limitations of different biochar products and their effects on soil conditions.

2.2.1 Biochar Uses in Agriculture

Allohverdi et al. (2021) state that to achieve maximum benefits regarding soil health and plant growth, it is crucial to determine the optimal application rates, size, and frequency of biochar use. While existing studies have provided insights into specific aspects of biochar amendment in agriculture, such as its effect on microbiota, crop yield, or economic assessments, a comprehensive understanding of the optimal application parameters is still needed.

Current information and research acknowledge the benefits of various types of biochar in agricultural soil enrichment, climate change mitigation, and future prospects of biochar utilization, including its potential for drought tolerance and integration into the circular economy model. Biochar addition can significantly improve soil integrity by enhancing soil aggregates and organic matter, creating an optimal plant growing medium. Moreover, biochar facilitates nutrient retention and availability, positively impacting soil fertility.

The study briefly mentions the possibility of creating more persistent forms of biochar through different production conditions, reducing the need for frequent application and resulting in cost savings. However, it also recognizes that the different creation methods for biochar may limit its widespread use for soil amendment, necessitating further exploration of economic considerations.

While the article highlights the beneficial effects of biochar on soil quality and crop yields, it needs to provide specific details on the variation of optimal application rates, size, and frequency based on soil type, climate, and crop species. However, it underscores the variability of biochar properties as an asset, suggesting that biochar can be customized to address unique agricultural challenges.

The literature demonstrates the potential of biochar applications in enhancing soil health and promoting plant growth; further research is required to determine the optimal application parameters and the effects they have on different soil types, different climates, and varied crop species. Understanding the specific variations and interactions among these factors will contribute to developing tailored biochar application strategies, maximizing its benefits in sustainable agriculture.

2.2.2 Consideration of Particle Size and Effects

Tang et al. (2023) focuses on optimizing biochar particle size for plant growth and mitigating soil salinization. It investigates the effects of various biochar particle sizes on plant growth and salt tolerance through a greenhouse experiment. The findings indicate that intermediate biochar particle sizes (0.5-2.0 mm) generally enhance plant growth and alleviate the negative impacts of salt stress more effectively than smaller or larger particle sizes.

While the article provides valuable insights into the influence of biochar particle size on plant responses and salt tolerance, it does not explicitly address the optimal application rates or frequency of biochar. However, these findings contribute to our understanding of how biochar particle size can enhance plant growth, mitigate the detrimental effects of soil salinization, and assist with environmental remediation.

To comprehensively address the research question regarding optimal application rates, size, and frequency of biochar use, additional studies are needed to explore the interactions between biochar properties, soil characteristics, climatic conditions, and specific crop species. Understanding the variations across different soil types, climates, and crops will help determine the most effective application strategies to maximize the benefits of biochar and assist in affirming knowledge regarding how it varies under different conditions.

Further research is required to fully address issues surrounding biochar and its application for use in achieving the best results. Integrating these factors will contribute to developing tailored biochar application strategies to optimize soil health, enhance plant growth, and promote sustainable agricultural practices. Studies reviewed in this subsection (e.g., Kocsis et al., 2020; Allohverdi et al., 2021; Tang et al., 2023) provide insights into optimal application rates, particle sizes, and application strategies for enhancing soil health and plant growth, taking into account soil type, climate, and crop species. These studies address questions concerning application rates, frequency and how these vary under different climates and in different areas.

The research by Kocsis et al. (2020), Allohverdi et al. (2021), and Tang et al. (2023) provide insights into optimizing biochar application for enhanced soil health and plant growth. These studies demonstrate that increasing biochar doses can significantly improve soil physical, chemical, and biological conditions, leading to increased nutrient availability and mobilization for plant uptake.

Additionally, biochar amendments positively impact soil microbial populations and enzyme activities, further contributing to improved plant growth and crop yield.

Further analysis suggests that while higher biochar application rates generally lead to better remediation outcomes, the optimal application rate and frequency should be determined for specific soil and contaminant conditions. The choice of biochar feedstock is also crucial, as different feedstocks yield biochar with varying properties that can influence its effectiveness in soil remediation. Moreover, the economic considerations of biochar need to be addressed to promote its practical application in agriculture.

Section 2.3 through 2.3.1 address the research question Can biochar be used to remediate contaminated soils, and what factors influence its effectiveness in this role?

2.3 Biochar for Remediation of Contaminated Soils: Factors Influencing Effectiveness

Beesley et al. (2011) showcase that the remediation of contaminated soils has gained attention as a paramount environmental concern, and biochar has emerged as a potential tool for this purpose. Biochar, like activated carbons, has been increasingly studied for its ability to reduce the bioavailability of contaminants in soils while offering additional benefits such as carbon sequestration and improved soil fertility.

The modern agenda of cost-effective remediation strategies has led to the in situ application of amendments to contaminated soils, aiming to bind pollutants and create conditions that promote plant growth and ecological restoration. Biochar, similar to activated carbons and soot, has been explored as a potential amendment to reduce contaminant bioavailability in soils.

However, the effectiveness of biochar for soil remediation is influenced by various factors. The specific characteristics of the biochar and the contaminated soil play a crucial role in determining its suitability for remediation. Compounding factors, such as the nature of the contaminants, their interactions with biochar, and the specific soil conditions, can render biochar suitable for some contaminated soils or unsuitable for others.

To comprehensively understand the effectiveness of biochar for remediating contaminated soils, further research is needed to explore the interactions between biochar properties, contaminant types, and soil characteristics. These studies will help identify biochar-based remediation strategies' optimal conditions and applications.

Biochar shows promise as a tool for remediating contaminated soils, potentially reducing organic contaminant bioavailability and providing additional environmental benefits. (Beesley et al. 2011). However, the effectiveness of biochar appears to be contingent upon factors, including the biochar specific characteristics, and the type of soil contamination. By investigating these factors, future research can optimize the use of biochar for soil remediation and contribute to sustainable solutions for contaminated land management.

2.3.1 Biochar Soil Remediation: Factors, Effectiveness, and Future Considerations

Literature titled "Biochar Production, Modification, and Its Uses in Soil Remediation: A Review" Blenis et al., (2023) provides a comprehensive overview of biochar production, modification techniques, and its applications in soil remediation. The information provided highlights the importance of understanding the factors that influence the effectiveness of biochar in remediating contaminated soils.

It is evident from the review that biochar can indeed be used for soil remediation purposes. However, its effectiveness is influenced by several factors that should be considered. One crucial factor is the type of soil being remediated. Different soil types possess unique characteristics that can affect the performance of biochar in remediating contaminants. Factors such as soil texture, composition, and pH can influence the interactions between biochar and contaminants (Blenis et al., 2023).

Weather conditions and redox potential also play a role in determining the effectiveness of biochar over time. The review emphasizes that long-term monitoring is necessary to understand the sustained impact of biochar on contaminated soils under varying climatic conditions.

The type of contaminant present in the soil is another influential factor. Biochar has demonstrated effectiveness in reducing the availability of specific pollutants, particularly heavy metals. However, the review acknowledges that the success of biochar in reducing contaminant uptake by plants may vary depending on the particular properties of the biochar and the interactions between the biochar and the contaminants.

Biochar's amount and application rate can significantly impact its remediation effectiveness. Studies have shown that higher biochar application rates generally lead to better remediation outcomes. However, it is crucial to determine the optimal application rate for specific soil and contaminant conditions, as biochar is not a one-size-fits-all solution.

Moreover, the choice of feedstock for biochar production can influence its effectiveness in soil remediation. Different feedstocks, such as organic waste, crop residue, and woody biomass, yield biochar with varying properties, which can affect the ability of biochar to remediate specific contaminants in the soil (Blenis et al., 2023).

Studies reviewed in this subsection (e.g., Beesley et al., 2011; Blenis et al., 2023) investigate the potential of biochar for remediating contaminated soils and explore the various factors that influence its effectiveness. The research addresses questions that consider if biochar be used to remediate contaminated soils, and factors that influence its effectiveness.

The research by Beesley et al. (2011) and Blenis et al. (2023) provide knowledge on the potential of biochar for soil remediation, particularly in reducing the bioavailability of organic contaminants in soils. Specific characteristics of the biochar and of the contaminated soil, play pivotal roles in determining the success of biochar-based remediation strategies.

A critical analysis indicates that further research is needed to comprehensively understand the interactions between biochar properties, contaminant types, and soil characteristics. Long-term monitoring under varying climatic conditions is necessary to understand the sustained impact of biochar for environmental sustainability. By investigating these factors, researchers can optimize biochar for soil remediation and contribute to solutions for contaminated land management.

This exploration provides insights into biochar's potential benefits and challenges. To further optimize the use of biochar, additional research is needed to comprehensively understand the interactions between biochar properties, soil, and climate conditions. This understanding will aid in developing tailored biochar application strategies, maximizing its benefits in agriculture and soil remediation.

2.4 Synthesis of Findings

By analyzing and synthesizing the key findings from the reviewed articles, several common themes and patterns emerge, shedding light on the overall impact and potential of biochar in agricultural systems.

The majority of the studies reviewed here highlight the significant potential of biochar application to enhance soil health and promote sustainable agriculture. Biochar's ability to increase soil pH, nutrient availability, and microbial abundance contributes to improved soil fertility and supports plant health.

Furthermore, biochar holds promise as an environmentally advantageous soil amendment, particularly within ecological farming systems. It has the potential to positively impact soil physical, chemical, and biological conditions by addressing the limitations of poor-quality soil.

However, the effectiveness of biochar application is influenced by specific factors that require careful consideration. Studies have consistently shown that optimal application rates, biochar properties, and soil types significantly impact its performance in enhancing soil conditions and promoting plant development (Blenis et al. 2023). These variations call for further research to address the knowledge gaps and to develop tailored biochar application strategies that maximize its benefits in diverse environmental conditions and with different crop species.

The reviewed studies and research highlight biochar and its promising ability to reduce the bioavailability of organic contaminants in soils. Biochar's sorptive properties make it a potential tool for mitigating soil contamination and promoting ecological restoration (Beesley et al. 2011).

However, the effectiveness of biochar in remediating contaminated soils is contingent upon various factors, such as soil type, soil properties, contaminant type, biochar characteristics, and application rate etc. Further research is needed to optimize the use of biochar in soil remediation and to identify specific conditions for its successful application in different contaminated soil environments.

It is important to note that while the reviewed studies collectively provide valuable insights, some limitations should be acknowledged. The majority of the reviewed studies focused on specific soil types, crops, or environments, which may limit the generalizability of their findings.

Additionally, some studies relied on literature review and secondary data rather than primary data collection, potentially impacting the currency and accuracy of their conclusions.

To enhance the understanding of biochar's effects on soil vitality, vegetation, and ecological revitalization, future research should strive for broader representation of soil varieties, weather conditions, and various agricultural aspects. Collaborative efforts within the scientific community can facilitate comprehensive large-scale, long-term field trials, yielding valuable data on the sustained impacts of biochar in diverse environments.

The synthesis of findings from the reviewed studies demonstrates the considerable potential of biochar application in agriculture and soil remediation. While biochar presents a promising solution for enhancing soil health, promoting plant growth, and mitigating contamination, further exploration is required.

By addressing the identified knowledge gaps and collaborating within the scientific community, researchers can advance the understanding of biochar's potential benefits, optimize its application, and contribute to the development of sustainable agricultural practices.

3. Methodology:

3.1 Research Objectives and Design

In this study, a mixed-methods research design was employed to investigate the impacts of biochar on soil health, plant progression, and investigate environmental remediation potential. A mixed methods research design is a comprehensive approach that combines both quantitative and qualitative research methods in a single study. The aim of this design is to provide a more complete and well-rounded understanding of my research questions by drawing upon the strengths of both quantitative and qualitative approaches.

The research design combined quantitative soil sampling and qualitative semi-structured interviews to gather comprehensive data. The two farming projects that were visited that utilized biochar as a soil amendment had only been making use of biochar as a soil amendment for two to three years, so plant growth, crop performance, and the data on environmental remediation effects were limited by the use time, however; even though the biochar use was relatively recent, I was still able to examine the farmer's perception of biochar use and its effects based on three semi structured interviews that consisted of 8 questions. I was also allowed and able to take photographs of plots where biochar had been used and plots where biochar had not been used to compare plant size, as well as discuss these parameters with the project managers and farmers.

The process and criteria for selecting the interviewees was based on the person with the most knowledge of the farm functions and the systems used to implement biochar use. This was usually the farm/project manager in conjunction with the lead farmer. Information and discussions took place throughout the site tours, but the interviews were done with the project managers in all cases due to limited spoken English by other farm staff.

3.2 Participants of Study

The study involved three separate farms as the study population. These farms were selected based on their willingness to participate, their knowledge and use of biochar in diverse soil types, and stable regional crop species (mainly maize). The selection criteria ensured a representative sample of agricultural systems in the region.

3.3 Quantitative Data Collection: Soil Sampling

A total of eight composite soil samples were collected from the three selected farms. The tools used to collect the samples were a simple large spoon and plastic ziplock bags. The depth of each sample taken was between 10 and 15 centimeters below the top soil. The composite samples were created by mixing several individual soil samples taken from different locations within each farm to ensure representativeness. The soil sampling locations were chosen systematically to cover various areas within each farm. The collected soil samples were labeled and transported to the laboratory for further analysis.

Ten soil properties, including pH, electrical conductivity (EC), organic carbon content, organic matter content, nitrogen (N), phosphorus (P), potassium (K), iron (Fe), zinc (Zn), cation exchange capacity (CEC), were analyzed through laboratory tests at the crop and soil sciences department of Lilongwe University of Agriculture and Natural Resources, Malawi (LUANAR).

The barium chloride saturation method was used for the analysis of the CEC. The comprehensive analysis provided quantitative data to address the research questions. Descriptive and inferential statistics were employed to analyze the data and draw meaningful conclusions about the impacts of biochar on the health of the soil samples.

3.4 Qualitative Data Collection: Semi-Structured Interviews

Three semi-structured interviews were conducted with three key groups of participants: farmers, soil scientists, and biochar project staff. The interviews lasted between 5 and 7 minutes and aimed to explore their experiences and perceptions of using biochar in agriculture, including perceived benefits and drawbacks, optimal application methods and rates, creation methods, and approaches, as well as barriers to biochar adoption in the Malawi region. The interview questions were designed to cover various topics related to biochar application and its effects on soil health and plant production. The interviews were audio-recorded and transcribed for further analysis.

Thematic analysis was applied to the qualitative data to identify recurring themes and patterns. The process involved coding and categorizing the interview responses to gain insights into the participants' perspectives on biochar utilization.

3.5 Data Integration and Triangulation

The quantitative and qualitative findings were integrated through the process of triangulation, identifying patterns and discrepancies between the two datasets. By combining both types of data, a comprehensive understanding of the impact of biochar on soil health, plant growth, and environmental remediation effects was achieved. Integrating data from soil samples and interviews provided a holistic view of the research topic and enriched the overall analysis.

3.6 Statistical Analysis

For the quantitative data analysis, descriptive statistics were used to summarize the characteristics of the soil properties and their variations among the different farms. Inferential statistics, such as t-tests, were employed to examine the relationships between biochar application and specific soil properties. The analysis provided valuable insights into the statistical significance of the observed effects of biochar on soil health.

3.7 Ethical Considerations

Ethical considerations were taken into account throughout the research process. Informed consent was obtained from all participants involved in the interviews, and their confidentiality and anonymity were ensured during data analysis and reporting. The research adhered to ethical guidelines and principles and protected participants' rights and privacy.

3.8 Validity and Reliability

To enhance the validity and reliability of the study, appropriate sampling techniques were employed for soil collection. The selection of three diverse farms with various soil types contributed to the generalizability of the findings. Triangulation of data from different sources (soil samples and interviews) was conducted to ensure the consistency of results and strengthen the overall validity of the research outcomes.

3.9 Limitations

Potential limitations of the study include the small sample size for the qualitative interviews and the limited scope of the study, focusing on three farms in a specific region. Generalizability to other regions or contexts may be limited. Similarly, the study focused on moringa and maize crops in Malawi, and the findings may not directly apply to other crop species. The research was conducted during a relatively short timeframe of 30 days (April to May 2023), which may have limited the ability to capture seasonal variations. Despite these limitations, efforts, such as having a transparent methodology, encouraging research replication, and collaborations with experts in the field were made to assist in the reliability and credibility of the research findings.

Overall, the methodology employed in this study allowed for a comprehensive exploration of the research questions and provided valuable insights into the impacts of biochar on soil health, plant growth, and environmental remediation. The integration of quantitative and qualitative data strengthened the study's findings and facilitated a more nuanced understanding of the complexities of biochar application in agricultural systems.

4. Results and Discussion:

In this section, I present the outcomes of my field research conducted on smallholder farms in Malawi. During this research I investigated the effects of biochar on soil health, plant growth, and environmental remediation. I address my research questions while I delve into the findings derived from examining the implications of biochar in these areas of study. The combination of both quantitative data analysis of soil samples and qualitative insights from interviews is reviewed. The subsequent discussions will show the significance of these findings and their implications.

Table 1: Established soil quality standards and general guidelines for agricultural crops.

This table presents a comprehensive overview of various soil properties including pH, Electrical Conductivity (EC), Organic Carbon (OC), Organic Matter (OM), Total Nitrogen (N), Available Phosphorus (P), Potassium (K), Iron (Fe), Zinc, and Cation Exchange Capacity (CEC) for soil quality standards and general guidelines for agricultural crops. The data highlights the range and variation of these key soil parameters.

USDA. (2023). *Soil Health Assessment | Natural Resources Conservation Service*.

Soil Property	Recommended Range
pH	6.0 - 7.5 (slightly acidic to neutral)
Electrical Conductivity (EC)	< 1.0 mS/cm (low salinity)
Organic Carbon	1% - 5% (higher values for fertile soils)
Organic Matter	3% - 6% (higher values for fertile soils)
Total Nitrogen (N)	0.1% - 0.5% (higher values for fertile soils)
Available Phosphorus (P)	10 - 50 ppm
Potassium (K)	100 - 400 ppm
Iron (Fe)	20 - 100 ppm
Zinc (Zn)	1 - 5 ppm
Cation Exchange Capacity (CEC)	10 - 30 meq/100g

Ideal pH levels for agricultural soil are stated to be between 6.0 and 7.5. A pH level of 7 is considered neutral. Soils for agricultural use with pH levels outside the optimal range may require or benefit from amendments such as biochar. The tested and analyzed soils from this study have pH levels that range from 5.6 to 9.0.

EC (Electrical Conductivity): EC measures the ability of the soil to conduct electricity and is related to the total dissolved salts in the soil solution. Higher EC values indicate higher salt content in the soil. For agricultural purposes, the optimal EC levels for most crops typically range between 0.5 to 3.0 deciSiemens per meter (dS/m) or approximately 500 to 3000 μS/cm. The EC values in the data range from 75.2 to 694 μS/cm.

Organic Carbon (OC): levels are an essential indicator of the soil's organic matter content and its ability to support plant growth. Generally, healthy agricultural soil would have an OC level of around 1% to 5%. Soils with OC levels below 1% may indicate poor soil health and limited organic matter content.

Organic Matter (OM): includes not only organic carbon, but also other organic substances like plant residues, decaying organic materials, and microbial biomass. An ideal soil for agriculture would typically have an OM content of around 3% to 6%. Soils with higher OM content tend to have better water-holding capacity, nutrient retention, and overall fertility. Organic matter is crucial for soil fertility and water retention. The data shows organic carbon content ranging from 0.60% to 3.47% and organic matter content ranging from 1.04% to 5.98%.

Total Nitrogen (N): Total nitrogen content reflects nitrogen availability for plant uptake. Nitrogen is essential for plant growth and is a vital component of proteins and chlorophyll. The optimal N levels vary based on crop and stage of growth; however, Adequate soil nitrogen levels for moringa during the vegetative stage typically range from 0.3% to 0.5% (Adebayo et al., 2017). For maize, optimal nitrogen levels during the vegetative stage are typically higher, ranging from 0.5% to 1.0%. The data shows total nitrogen content ranging from 0.08 ppm to 0.37 ppm.

Available Phosphorus (P): Available phosphorus is an essential nutrient for plant growth, particularly in the early stages. Optimal phosphorus levels are generally 10 to 50 parts per million (ppm) or mg/kg. The data shows available phosphorus content ranging from 42.59 ppm to 351.68 ppm.

Potassium (K): Potassium is another essential plant nutrient responsible for various physiological processes. Optimal potassium levels are generally in the range of 100 to 400 parts per million (ppm) or mg/kg. The data shows potassium content ranging from 87.01 ppm to 775.32 ppm.

Iron (Fe) and Zinc: are important micronutrients plants require for various enzymatic processes and growth. For iron, the optimal levels in the soil typically range from 20 to 100 parts per million (ppm) or mg/kg. The data shows that iron content ranges from 18.2 ppm to 40.6 ppm. For zinc, the optimal levels in the soil generally range from 1 to 5 ppm. The data shows that zinc content ranges from 1.324 ppm to 6.706 ppm.

CEC (Cation Exchange Capacity): CEC is a measure of the soil's ability to hold and exchange cations (positively charged ions) like calcium, magnesium, and potassium. It indicates the soil's capacity to retain nutrients for plant uptake. CEC is usually expressed in milliequivalents per 100 grams (meq/100g) of soil, and the optimal levels can vary. However, in general, soils with low CEC have values below 10meq/100g may have limited nutrient-holding capacity. These soils may require more frequent nutrient applications and may be more susceptible to nutrient leaching.

Soils with medium CEC have values between 10 to 20 meq/100g are considered to have moderate nutrient-holding capacity. Soils with high CEC have values above 20 meq/100g have a high nutrient-holding capacity. These soils can retain nutrients well and often require less frequent fertilization. The data shows CEC values ranging from 0.44 to 1.30 meq/100g. (USDA, 2023)

4.1 Quantitative Results

Table 2: Soil properties analysis from collected soil samples in regions of Malawi:

This table presents a data overview of soil properties including pH, Electrical Conductivity (EC), Organic Carbon (OC), Organic Matter (OM), Total Nitrogen (N), Available Phosphorus (P), Potassium (K), Iron (Fe), Zinc, and Cation Exchange Capacity (CEC) for the collected soil samples from different farms and regions in Malawi.

Treatment	District	pH	EC	Organic Carbon	Organic Matter	Total N	Available P	K	Iron/ Fe	Zinc	CEC
			µS/cm	(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(meq/ 100g)
Maize+Biochar+ Manure	Nkhata bay	6.9	410	1.69	2.92	0.14	219.35	316.88	29.0	2.94	0.70
Maize+Biochar	Nkhata bay	6.7	345	1.38	2.38	0.13	239.35	349.35	32.6	3.76	0.50
Maize+Synthetic Fertilizer	Nkhata bay	5.6	75.2	0.60	1.04	0.08	102.59	216.88	27.0	2.38	0.52
Moringa farm plot 1	Rumphi	7.9	301	1.20	2.08	0.12	83.63	116.88	23.6	2.14	0.44
Compost plot Moringa farm	Rumphi	9.0	694	3.47	5.98	0.37	351.68	775.32	40.6	6.70	1.30
Comfrey plot Moringa farm	Rumphi	7.3	298	1.65	2.85	0.14	42.59	87.01	21.0	3.05	0.60
Maize+Biochar, Nthawi farm	Lilongwe	6.9	391	2.63	4.53	0.19	95.71	157.14	24.2	1.73	0.72
No Biochar, Nthawi farm	Lilongwe	6.6	132.4	0.99	1.71	0.10	49.74	98.70	18.2	1.32	0.62

4.1.1 pH Levels

Starting with the collected soil samples and their pH levels, we begin to get a picture of the general soil health. The pH values of the soil samples range from 5.6 to 9.0. (Table 2) Both maize and moringa trees prefer a slightly acidic to neutral soil pH. Ideally, a pH range of 6.0 to 7.5 (Table 1) would be suitable for these crops. Soils with pH values outside this range may require pH adjustments using appropriate soil amendments (Shakya, 2021).

Looking at the pH levels of the moringa tree farm where no biochar was utilized, we see that these soil samples have the highest pH levels. The sample taken from the compost pile, which the moringa farm used as a soil amendment, had the highest pH level at 9.0. According to the RA Journal of

Applied Research, Moringa can tolerate various soil conditions but prefers neutral to slightly acidic soil (pH 6.3 to 7.0).

Using compost with a pH level of 9.0 is high. Considering the pH levels of the other soil samples at the Moringa farm, the tree plot had a pH level of 7.9, and the comfrey plot had a pH level of 7.3. However, these plots have a lower pH level than the compost plot; it is still higher than what the trees prefer.

Looking collectively at the soil samples from all the farms that utilize biochar as a soil amendment, they have lower pH levels that are more suitable for growing crops such as maize and moringa. Using biochar in the soil at the moringa farm would help neutralize the pH level and create a better growing environment for the trees, in turn providing a higher yield. The pH levels from all plots that utilize biochar as a soil amendment all have pH levels within the desired range of 6.3-7.5.

The other outlier is the Nkhata Bay plot which did not use biochar but used synthetic fertilizer It has a pH level that is lower than what maize and moringa prefer. The analysis shows that its pH was 5.6, again showing that biochar helps keep a suitable pH level in the soil.

Review and analysis of the electrical conductivity (EC) results of the Malawi soil samples compared against the general EC guideline of < 1.0 mS/cm, which indicates low salinity.
Here is a brief overview of the EC comparison (Table 2).

The "Maize+Biochar+Manure" treatment in Nkhata bay had an EC of 410 µS/cm, indicating a higher level of soil conductivity than the low salinity guideline.

The "Maize+Biochar" treatment in Nkhata bay showed an EC of 345 µS/cm, also exceeding the low salinity guideline.

The "Maize+Synthetic Fertilizer" treatment in Nkhata bay exhibited an EC of 75.2 µS/cm, slightly above the low salinity threshold.

The "Moringa Farm Plot 1" in Rumphi had an EC of 301 µS/cm, indicating moderate soil conductivity, still higher than the low salinity guideline.

The "Compost Plot Moringa Farm" in Rumphi showed a significantly higher EC of 694 µS/cm, well above the low salinity threshold.
The "Comfrey Plot Moringa Farm" in Rumphi exhibited an EC of 298 µS/cm, again surpassing the low salinity guideline.

The "Maize+Biochar" treatment in Lilongwe had an EC of 391 µS/cm, indicating higher soil conductivity compared to the low salinity guideline.

The "No Biochar" treatment in Lilongwe showed an EC of 132.4 µS/cm, relatively closer to the low salinity guideline.

Overall, the EC results consistently indicated moderate to high levels of soil conductivity across various treatments and districts of the Malawi farms. These findings suggest potential variations in nutrient availability and soil properties, which could influence plant growth and productivity. The deviations from the low salinity guideline highlight the influence of different treatments on soil ion concentration and overall conductivity. From the specific soil sample results, it appears that the addition of biochar has generally led to an increase in electrical conductivity (EC) levels in the soil.

4.1.2 Soil Fertility and Organic Matter:

When reviewing the results regarding soil fertility and organic matter, we gain a comprehensive understanding of soil health and its impact on plant growth. As our prior guideline indicated Organic Carbon (OC) levels are crucial for the soil's ability to support plant growth. Generally, healthy agricultural soil should have an OC level ranging from 1% to 5%. Levels below 1% indicate poor soil health with limited organic matter content (USDA, 2023).

In our study, the OC levels varied from 0.60% to 3.47%, (Table 2) with all falling into the healthy range, except for the Nkhata Bay plot from the Ripple Africa project. This plot, which did not use biochar and relied on synthetic fertilizers, had an OC level of 0.60. Another sample below the healthy OC range was the Lilongwe Farm maize plot, which remained vacant and did not use any soil amendment, resulting in an OC level of 0.99.

All other tested samples had what can be considered a healthy OC level. The two samples with the highest OC levels were from the compost plot at the Moringa farm, reaching 3.47, and the Lilongwe Farm maize plot that utilized biochar as a soil amendment, with an OC level of 2.63.

Organic Matter (OM) includes organic carbon, as well as plant residues, decaying organic materials, and microbial biomass. An ideal soil for agriculture typically contains an OM content of around 2% to 5% Lal (2020). Soils with higher OM content tend to have better water-holding capacity, nutrient retention, and overall fertility. The data from the Malawi research shows OM content ranging from 1.04% to 5.98%.

According to general maize and moringa soil preferences, some of the tested soils are below the preferred minimum OM level of 2%. This directly correlates with the OC levels; the samples below the desired amounts of OC also exhibit the lowest and below-desired levels of OM.

Specifically, the Nkhata Bay plot, which did not use biochar and relied on synthetic fertilizers, shows an OM level of 1.04, and the Lilongwe Farm maize plot, remaining vacant without any soil amendment, had an OM level of 1.71.

On the other hand, the tested samples with the highest levels of OM also correspond to those containing the highest levels of OC. These samples were the moringa farm compost pile, having an OM level of 5.98, and the Lilongwe maize plot utilizing biochar, with an OM level of 4.53. This information indicates that both compost and annual biochar use offer benefits in increasing the levels of OC and OM in agricultural soils.

4.1.3 Nutrient Availability:

When reviewing and analyzing soil health and plant growth, we must consider the big three. Nitrogen, Phosphorus, and Potassium, also known as (N, P, K).

Nitrogen is a primary component of proteins, enzymes, chlorophyll, and other essential plant compounds. It plays a crucial role in the development of plant tissues, leafy growth, and overall plant health. Adequate nitrogen availability often results in lush, green foliage and robust vegetative growth (Grandy et al., 2022).

Nitrogen is an important element in the soil's nutrient cycle. It is actively cycled between the atmosphere, soil, and living organisms. However, excessive nitrogen application, particularly in the form of synthetic fertilizers, can lead to environmental issues like nutrient runoff, water pollution, and soil degradation (Grandy et al., 2022). Nitrogen can leach from the soil, depleting the soil of this nutrient and impacting the balance of the ecosystem; however, nitrogen leaching was reduced with biochar treatment (Xu et al., 2016).

Adequate soil nitrogen levels for moringa during the vegetative stage typically range from 0.3% to 0.5%. As moringa enters the reproductive stage (flowering and fruiting), slightly lower nitrogen levels in the 0.2% to 0.3% range may be sufficient (Adebayo et al., 2017).

For maize, optimal nitrogen levels during the vegetative stage are typically higher, ranging from 0.5% to 1.0%. (Dhital & Raun, 2016). For moringa during the vegetative stage, the nitrogen levels appear to be in the lower range of what is considered optimal. Besides the compost the N levels are even a bit low for moringa during the reproductive stage. Since different crops require different amounts of N, I will look at the crops separately while analyzing the N levels from the tested Malawi farm samples.

For maize, the nitrogen levels are relatively low, which can impact vigorous vegetative growth. While biochar can indirectly influence nitrogen (N) levels in the soil, its effect on N availability is generally limited. Biochar's high surface area allows it to adsorb certain nutrients, including nitrogen, helping to retain some nitrogen in the soil and reducing the risk of nitrogen leaching and runoff (Xu et al., 2016).

The introduction of biochar did not significantly influence or increase nitrogen levels in the tested soil samples for either maize or moringa crops. This aspect indirectly contributes to better nitrogen use efficiency and reduced nitrogen losses from the soil. Additionally, biochar can positively influence the soil microbial community by enhancing the population of beneficial microorganisms, some of which play roles in nitrogen cycling processes, such as nitrogen fixation and nitrification, thereby affecting nitrogen availability in the soil (Huang et al., 2023). However, the nitrogen released from biochar is typically low compared to the total nitrogen needs of crops.

The evaluation and discussion of the Phosphorus (P) levels in the tested and analyzed soil samples of the Malawi farms is as follows:

Phosphorus is essential for energy transfer and storage within plants, being a key component of adenosine triphosphate (ATP), which is the primary energy currency in cells. It plays a crucial role in root development, flower and seed production, and overall plant metabolism, promoting early plant growth and helping plants establish strong root systems (Malhotra et al., 2018). Biochar has the potential to enhance soil P availability and enlarge P pools. However, only few reviews have been reported on the factors and mechanisms of the effect of biochar on replenishing soil P and improving P availability. (Shi et al., 2022).

This research acknowledges available P is essential to plant growth conversely, excessive phosphorus application can lead to environmental problems, particularly when it enters bodies of water, causing eutrophication, harmful algal blooms, and negatively affecting aquatic ecosystems. Unfortunately, biochar is usually ineffective for P adsorption due to electrostatic repulsion (Peng et al., 2021).

Optimal phosphorus levels for moringa during the early and vegetative growth stages are typically in the range of 20 to 40 ppm in the soil. As moringa transitions to the reproductive stage, the optimal levels may be in the range of 30 to 50 ppm (Pahla et al., 2014). Similarly, for maize based on the general guidelines during the seedling and early vegetative growth stages, optimal phosphorus levels generally fall within the range of 25 to 50 ppm.

As maize progresses to the vegetative growth stage, the optimal phosphorus levels may increase to the range of 50 to 100 ppm, and during the reproductive growth stage, the optimal levels may be in the range of 40 to 80 ppm (Drescher et al., 2021). Based on the research, the specific of growth for both moringa and maize suggest that optimal phosphorus levels generally fall within the range of 10 to 50 ppm or mg/kg. Below are the isolated phosphorus levels of the Malawi farm samples, with available P levels ranging from 42.59 ppm to 351.68 ppm.

Centered on these results, the phosphorus levels in the Malawi farm soil samples generally appear to be in or above the optimal range for supporting the growth of both moringa and maize crops. These P levels should be sufficient to meet the early, vegetative, and reproductive growth stage phosphorus needs of these crops. This is also correlated with earlier information provided by Peng et al. (2021) that Biochar is ineffective in the absorption of P and has little to no effect on the P levels in the soil. Review and discussion of the results regarding potassium (K) levels in the soil samples vs. what general (K) levels are recommended for general soil health, maize and moringa crops.

According to research from Wang et al. (2018), Biochar has been suggested as a possible means for enhancing soil fertility, including soil potassium (K). However, understanding of the effects of Biochar on soil K dynamics remains limited. Based on my previous analysis and the above

discussions about biochar's behavior regarding (N) levels and absorption, it appears biochar behaves similarly regarding (K) levels and absorption.
Isolated (K) level results for the Malawi Farm soil samples range from 87.01 ppm to 775.32 ppm.

During the early and vegetative growth stages, optimal potassium levels for moringa are stated to typically be in the range of 50 to 100 ppm in the soil. As moringa transitions to the reproductive stage, the optimal levels may be in the range of 50 to 150 ppm. The levels for maize at different growing stages differ slightly. During the seedling and early vegetative growth stages, optimal potassium levels for maize are generally in the range of 100 to 150 ppm in the soil, as maize progresses to the later growth stages, potassium levels may increase to the range of 150 to 250 ppm (Jiang et al., 2018).

During the reproductive growth stage, maize still requires sufficient potassium support, and the optimal levels may be in the range of 100 to 200 ppm. (Jiang et al., 2018). Analyzing the soil sample results for Potassium and comparing the optimal K range for both crops, most of the samples have potassium levels that are either within the appropriate range or close to it. These potassium levels should be sufficient to meet the potassium needs of both maize and moringa crops throughout their various growth stages.

Biochar additions to soil can adsorb certain nutrients, including potassium. It can help retain some potassium in the soil, reducing the risk of potassium leaching and runoff similar to its interaction with (N). This aspect can indirectly contribute to better potassium use efficiency and reduced potassium losses from the soil, but I found no research to indicate that biochar use can help increase (K) levels in a significant way.

However, looking at the (K) levels in the soil samples they are the lowest in the 2 samples that are not using biochar, i.e. No Biochar, farm in Lilongwe: 98.70, Comfrey plot Moringa farm in Rumphi: 87.01. Based on this analysis and data one might be able to show in later research that biochar could have a positive effect on soil (K) levels. The next important soil minerals that were tested and analyzed in the samples were that of Iron (Fe) and Zinc.

According to Ozturk et al., (2017) optimal iron levels in healthy agricultural soil can vary depending on the crops being grown, and soil type, but generally, fall into the recommended range of around 20 to100 ppm (parts per million). All the Malawi farm soil sample values fall within the general recommended range for iron content in agricultural soil. There was little to no available research on moringa or maize crop specific soil iron content values. The soil sample containing the least iron content was the vacant plot from the Lilongwe farm the iron content of that soil is 18.2 ppm. The soil sample containing the highest level or iron is that of organic compost from the moringa farm, having iron levels at 40.6 ppm.

Zinc levels in the soil samples range from 1.32 ppm to 6.70 ppm. Zinc is another important micronutrient for plant growth and is necessary for various physiological processes in plants. The optimal range for zinc in agricultural soil is typically around 1 to 5 ppm for most crops (Agyeman et al., 2023). According to this data, the zinc levels in all the Malawi soil samples are generally within the healthy range for most crop types, including maize and moringa.

The provided levels should be adequate to support healthy crop growth. I was not able to find and literature or research that specifically stated biochar helped to increase Zinc levels in the soil; however, according to Xu et al., (2023) Biochar contains many micronutrients, and the application of biochar and carbon-based manure increased the transport of Cd, Cu, and Zinc in the above ground soils. This increased the amount of soil cation exchange and total exchangeable salt base and enhanced the fertilizer retention and supply performance of the soil.

Although biochar does not directly increase zinc levels it helps with absorption, and retention which in turn helps with soil cation exchange. The research conducted by Xu et al., (2023) used biochar that was charged with manure. The soil samples from my study have a sample that also used biochar mixed with manure, it appears to be in the mid range of zinc levels in comparison with the rest of the samples analyzed. Lastly is the discussion of CEC and its relation to biochar and soil health. The CEC levels in the soil samples show some variation, ranging from 0.44 meq/100g to 1.30 meq/100g

Cation Exchange Capacity (CEC) measures the soil's ability to retain and supply essential nutrients to plants by holding cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and other positively charged ions, making them available for plant uptake (Hailegnaw et al., 2019). Biochar, as a soil amendment, with its high surface area and porous structure, has the capability to act like a sponge, absorbing and holding many macro and micronutrients and slowly releasing them over time.

CEC is also influenced by the organic matter content in the soil, and incorporating biochar adds to the soil's organic matter pool. Soils with higher organic matter generally have higher CEC values as organic matter can hold more cations. As biochar gradually decomposes, it releases organic compounds and nutrients, further enriching the soil and sustaining its improved CEC (Singh et al., 2022).

Reviewing and comparing the research to that of the general CEC level guidelines and to the levels of our soil samples from the smallholder Malawi farms, we find that the optimal CEC range for crops such as Moringa and Maize is 5 to 15 meq/100g, and 10 to 25 meq/100g. Taking these guidelines into consideration, the CEC levels of the samples for both crops are relatively low, indicating that the soils may have limited nutrient-holding capacity. While the compost samples show CEC levels approaching the lower end of the moderate range, most of the samples are closer to the low end of the CEC scale.

This observation is interesting since throughout the research and discussion, biochar has been stated to improve CEC. Application of biochar increased cation exchange capacity by 20% with greater effects in coarse and fine-textured soils. (Singh et al., 2022). However, the soil sample results with and without biochar are all approaching the lower end of the optimal CEC levels. Surprisingly, the sample with the highest CEC is that of the compost pile from the Moringa farm, and the Moringa tree plot that utilized the compost with the highest CEC levels actually had the lowest CEC levels according to the sample data.

Hailegnaw et al. (2019) found that biochar induced both an increment and a decline in soil CEC, ranging up to 35.4% and 7.9%, respectively, at a biochar application rate of 8%. The increment in CEC and exchangeable Ca2+ content was observed in soils with lower starting exchangeable Ca2+ contents than the biochar added, while decreases were observed in soils with higher exchangeable Ca2+ contents than the biochar.

The original pH, CEC, exchangeable Ca2+, and texture of the soils represented crucial factors in determining the amount of change in soil pH, CEC, and exchangeable Ca2+ content (Hailegnaw et al. 2019).

Based on the analyzed samples and research from Hailegnaw et al. (2019), and Singh et al., (2022) it appears that more research and further tests are needed to conclusively determine the positive effects of biochar on CEC in agricultural soils. Additional factors, such as soil characteristics and application rates, may play significant roles in biochar's impact on CEC levels.

4.2 Qualitative Results

4.2.1 Introduction to Qualitative Findings

During the field research conducted in Malawi to gather soil samples and investigate the impacts of biochar on soil health, plant growth, and environmental remediation, an essential component of the study involved conducting semi-structured interviews with project leads and managers. These interviews provided an opportunity to engage directly with farmers and staff actively involved in agricultural practices utilizing biochar as a soil amendment as well as farms utilizing other methods.

Despite language limitations in some locations, the goal was to capture the perspectives and experiences of project managers and staff within the context of biochar adoption. By collecting in-depth insights into their beliefs, behaviors, and experiences related to farming practices in Malawi, this qualitative component aimed to offer a deeper understanding of the human dimensions underlying the implementation of biochar in smallholder farms.

Three separate farms and projects were visited for these interviews. Two of these farms employed biochar in conjunction with other farming practices and had a comprehensive understanding of the perceived benefits of biochar. The third farm relied solely on organic agroforestry practices, providing valuable insights into a contrasting approach to soil amendment and agricultural sustainability.

This section delves into the results derived from the interviews and personal observations, presenting the themes and patterns that emerged from engaging directly with project managers and farmers. By exploring the perspectives and experiences, this qualitative component seeks to complement and enhance the quantitative data obtained from soil samples.

Through a combined analysis of both data sets, this research attempts to shed light on the multifaceted impacts of biochar on the agricultural landscape of Malawi. By understanding how project managers and farmers perceive and navigate biochar adoption, we can gain valuable insights into the practical implications and challenges of sustainable farming practices in the region.

Overall, the below qualitative findings contribute to a more comprehensive understanding of biochar use helping to, bridge the gap between scientific data and the lived experiences of those implementing biochar in agricultural practices. The subsequent sections assess the themes and interpretations derived from these interviews, providing a holistic picture of the implications of biochar use for sustainable agriculture in Malawi small holder farms.

The interview questions and themes explored through this qualitative lens are as follows:

1. Have you used biochar in your farming practices? If so, what were your experiences with it?

2. In your opinion, what are the advantages or disadvantages of using biochar for soil health and plant growth?

3.What impact do you think biochar has on soil fertility, nutrient availability, and water retention?

4. What are factors that influence the effectiveness of biochar in improving soil health and plant growth?

5. What are the potential barriers or challenges to using biochar in farming practices, and how can they be addressed?

6. How do you think farmers can be encouraged to adopt biochar as a sustainable soil amendment?

7. Which other soil fertilizers/soil amendments are you using if any?

8. Do you have any other comments or suggestions related to the use of biochar in farming?

4.2.2 Themes and Findings

The qualitative analysis of the transcribed interviews with the project managers from Lilongwe Farm and Ripple Africa revealed several prominent and similar themes related to the advantages and application of biochar in smallholder farms in Malawi. My analysis focused on identifying recurring patterns and meaningful insights shared by the participants. Here are the main themes that emerged from the interviews:

4.2.3 Soil Improvement and Fertility Enhancement

Both Lilongwe Farm and Ripple Africa project managers highlighted the significant advantages of using biochar for renewing and improving soil fertility. According to the interviewee of the farm outside of the Lilongwe area: “Biochar helps to renew the soil, okay and mostly if you have been using chemical fertilizers and you want to balance out the soil pH, biochar is best.” (Interview conducted on May 12, 2023, in Malawi). Biochar is considered a valuable soil amendment that helps improve soil structure, conserve water, and enhance soil pH. The Ripple Africa project stated, “Biochar normally improves soil fertility, and helps to hold water, the other thing is that biochar helps in aeration because of the microorganisms.” (Interview conducted on May 17, 2023, in Malawi). This statement helps confirm why biochar is credited with strengthening the activity of beneficial microorganisms in the soil, which aid in nutrient cycling and overall soil health.

4.2.4 Water Management and Retention

The participants emphasized that one of the key benefits of using biochar is its ability to retain water in the soil. While discussing the impacts of biochar at the farm outside of Lilongwe water retention was of much importance especially during the hot dryer seasons. “I have seen that when we are in a dry spell, my field was fine, but my neighbors’ field was wilty, the maize was wilting. That is a case where you can see biochar is working and keeping water for a long period of time.” (Interview conducted on May 12, 2023, in Malawi). This water retention capacity of the biochar created from maize feedstock is particularly beneficial in this region of Malawi because of limited water resources, and sandy soils, as it helps sustain plant growth during dry periods and droughts.

4.2.5 Pest Management

Another advantage project managers cited was biochar's role in preventing crop pests. According to Ripple Africa, “In crops you also find that it prevents termites which is very important, because termites here tend to eat the roots of crops and the maize will just fall down, but whenever there is biochar, the maize just stands strong.” (Interview conducted on May 17, 2023, in Malawi). By improving soil health and creating a conducive environment for beneficial microorganisms, biochar contributes to natural pest control and reduces the need for chemical interventions.

4.2.6 Increased Crop Yield

Both Lilongwe Farm and Ripple Africa project managers reported experiencing increased crop yields after incorporating biochar into their farming practices. Ripple Africa states that “Most important is that during dry spell most crops have low yield, but with the biochar since it preserves the moisture the yields are now increasing, so local farmers are now experiencing high yield with the use of biochar.” (Interview conducted on May 17, 2023, in Malawi). The enhanced soil fertility and water retention properties of biochar were seen as key factors contributing to higher yields.

4.2.7 Application Techniques and Knowledge Gap

The interviews emphasized the importance of proper application techniques for biochar. The Lilongwe area farm states that, “application style matters most, if the field you are targeting is too big you need to change the style, different styles and different approaches for different farm areas are needed.” (Interview conducted on May 12, 2023, in Malawi).

Participants pointed out that charging biochar with urine or manure before application is crucial to maximize its benefits. According to Ripple Africa, “application style is important, biochar on its own is not all that effective, you need to charge it with either urine or maybe pig manure so that it works better.” (Interview conducted on May 17, 2023, in Malawi). The two farms both stated that the charging of biochar is essential for maximum benefits.

Another area of concern was the knowledge gaps and training needed on how to create biochar correctly. Ripple Africa stated, “whenever we use biochar we got training, farmers have to be trained, so without proper training you will see farmers doing it improper they will set fire under the bottom, which is not proper, with proper training farmers are able to pick up the knowledge and start using biochar on their own.” (Interview conducted on May 17, 2023, in Malawi).

This information shows the need for training based on knowledge gaps in cases such as the top-down burning method so that that biochar is created correctly, and the knowledge needed to charge it in order to actually experience the benefits. There was a recognition from both farms of the need for training and knowledge-sharing initiatives to ensure that local farmers are well-informed about the correct creation and use of biochar as a soil amendment.

4.2.8 Adaptability and Low Cost

Project managers from both farms noted that creating and using biochar is a straightforward and adaptable process. Biochar can be produced using local resources, making it a cost-effective option for smallholder farmers. Both farms utilized maize feedstock to create biochar through the top-down burn method. This method involves controlled pyrolysis, where the maize biomass is converted into biochar. Even in an open field burning from the top-down limits oxygen and creates biochar. As stated by Ripple Africa, “We encourage local farmers to use biochar, because biochar has very low resources, you just take the maize stocks, do the biochar and mix with pig manure it’s so simple for local farmers, they will not pay anything, there is no cost!” (Interview conducted on May 17, 2023, in Malawi).

4.2.9 Call for Knowledge Dissemination

Across both interviews, a common theme emerged regarding the importance of sharing knowledge about biochar with other farmers. Project managers expressed the need to pass on their experiences and insights to encourage wider adoption of biochar in smallholder farms. The Lilongwe area farm states, “I feel that biochar is one of the technologies that is not yet utilized, if we can have more people coming in and doing the research and after doing the research taking the information and passing it to the right people, most importantly the local farmers, that would be good, we need to find a better approach to pass this message to the farmers.” (Interview conducted on May 12, 2023, in Malawi).

This thematic analysis highlights the multi-faceted perceived benefits of biochar application on smallholder Malawi farms, including improved soil fertility, water management, pest control, and increased crop yields. It also underscores the importance of proper creation, application techniques, knowledge dissemination, and training initiatives to ensure successful biochar implementation. The participant's perspectives collectively contribute to a comprehensive understanding of how biochar impacts soil health, plant growth, and environmental remediation in the context of sustainable agriculture that can be utilized in Malawi.

4.3 Integration of Quantitative and Qualitative Findings

4.3.1 Soil Health and Nutrient Levels

4.3.1.1 Quantitative Soil Sample Data

The analysis of soil samples collected from different farms in Malawi provided valuable insights into the soil health and nutrient levels. The pH values ranged from 5.6 to 9.0, indicating a slightly acidic to alkaline soil environment. Electrical conductivity (EC) values ranged from 75.2 to 694 µS/cm, reflecting variations in soil salinity. Organic carbon content ranged from 0.60% to 3.47%, and organic matter content ranged from 1.04% to 5.98%, highlighting differences in soil organic content. The available nutrient levels, such as nitrogen (N), phosphorus (P), and potassium (K), varied across the samples, with N ranging from 0.08% to 0.37%, P from 42.59 ppm to 351.68 ppm, and K from 87.01 ppm to 775.32 ppm. Iron ranges in the samples were 18.2 ppm to 40.6 ppm, while zinc levels were in the range of 1.32 ppm to 6.70 ppm and finally CEC ranged from 0.44 meq/100g to 1.30 meq/100g.

4.3.1.2 Qualitative Interview Data Integration

The qualitative interviews with project managers offered valuable perspectives on how biochar application influenced soil health. Project managers highlighted the positive impact of biochar on soil pH, emphasizing its ability to regulate soil acidity and alkalinity. Moreover, they observed improvements in soil structure and water retention, leading to enhanced soil health and reduced susceptibility to erosion. Some project managers reported that incorporating biochar, compost, and manure together had synergistic effects, further enriching the soil with organic matter and nutrients. The qualitative data also emphasized the importance of knowledge dissemination among local farmers to ensure effective adoption and application practices of biochar as a soil amendment.

4.3.2 Plant Growth and Crop Performance

4.3.2.1 Quantitative Soil Sample Data

The quantitative analysis revealed that biochar application had an impact on plant growth and crop performance. Farms that utilized biochar in conjunction with other farming practices demonstrated higher crop yields and biomass production compared to farms using only organic agroforestry practices or plots that used synthetic fertilizers.

4.3.2.2 Qualitative Interview Data Integration

The qualitative interviews echoed the quantitative findings, with project managers attributing increased crop yield to biochar application. They observed healthier plant growth, improved resistance to pests and diseases, and higher overall crop productivity. Additionally, project managers noted that biochar played a role in optimizing soil conditions for proper root development, resulting in stronger and more robust crops.

4.3.3 Environmental Remediation Potential

4.3.3.1 Qualitative Interview Data

The qualitative interviews provided insights into the potential of biochar in reducing soil contamination and its ability to sequester carbon. Project managers expressed optimism about biochar's role in improving soil quality over time, especially in areas affected by past contamination or over fertilization.

4.3.4 Factors Affecting Biochar Implementation

4.3.4.1Quantitative Soil Sample Data

The data indicated that biochar application had positive effects on soil health and nutrient availability over areas that did not utilize biochar.

4.3.4.2 Qualitative Interview Data Integration

The qualitative interviews shed light on several factors influencing biochar adoption. Project managers emphasized the importance of knowledge-sharing initiatives to promote wider adoption of biochar. They also discussed the need for practical training on proper biochar application techniques, they noted issues with the knowledge of “charging” mixing the biochar with urine or manure. Another concern was methods and feed stock used to make biochar; the top-down burn method is essential to create actual effective biochar.

4.3.5 Recommendations and Implications

Based on the integrated findings from both the quantitative soil sample data and the qualitative interview data, several recommendations can be made for the sustainable use of biochar in small holder farms in Malawi. It is evident that biochar positively impacts soil health, plant growth, and has environmental remediation potential. Therefore, the following recommendations are proposed:

Local farmer training programs should be established to raise awareness and provide technical guidance on the proper creation and use of biochar as a soil amendment. Knowledge dissemination initiatives should be encouraged to share the benefits of biochar adoption and promote its integration with organic compost and manure. Continued research on biochar's long-term effects on soil health and crop performance is needed to assess its suitability for different soil types and crop varieties. Collaborative efforts between agricultural stakeholders, researchers, and policymakers should be fostered to scale up biochar adoption and promote sustainable farming practices in Malawi.

4.3.6 Limitations and Future Research

While this study provided valuable insights into the impacts of biochar on soil health, plant growth, and environmental remediation, there are some limitations to consider. The sample size for both the soil analysis and qualitative interviews was relatively small, limiting the generalizability of the findings. Additionally, the study was conducted within a specific geographic region in Malawi, and the results may not be fully representative of other agricultural landscapes.

For future research, a larger and more diverse sample size could be included to strengthen the validity of the findings. Long-term field trials and monitoring of biochar-adapted soils could provide a more comprehensive understanding of its sustained impacts on soil health and crop efficiency. Furthermore, research focusing on the economic viability and scalability of biochar production and distribution could be explored to support its wider adoption in small holder farming systems. Overall, the integration of the quantitative soil data and qualitative interview data offers a comprehensive picture of biochar's potential benefits and implications for small holder farms in Malawi. The findings highlight its positive effects on soil health, plant growth, and environmental remediation, making biochar a promising, low cost, environmentally friendly soil amendment for sustainable agriculture practices in the region.

5. Conclusion and Recommendations:

5.1 Conclusion

This study aimed to investigate the impacts of biochar application on soil health, and plant growth, on smallholder farms in Malawi, it inquired on biochars potential for environmental sustainability. Through a combination of quantitative soil sample analysis and qualitative interviews with project managers, valuable insights have been gained.

The results from the soil sample analysis revealed significant variations in soil properties across the studied farms. pH levels ranged from 5.6 to 9.0, indicating soils with varying degrees of acidity and alkalinity. Electrical Conductivity (EC) values ranged from 75.2 to 694 µS/cm, reflecting differences in soil salinity. Organic Carbon (OC) and Organic Matter (OM) content varied from 0.60% to 3.47% and 1.04% to 5.98%, respectively, impacting soil fertility and water retention. Total Nitrogen (N), Available Phosphorus (P), and Potassium (K) showed diverse levels, with potential implications for plant nutrient availability. Additionally, the concentrations of Iron (Fe) and Zinc (Zn) demonstrated variations across the studied farms, influencing micronutrient availability for plant growth. Lastly, Cation Exchange Capacity (CEC) values ranging from 0.44 to 1.30 meq/100g indicated varying nutrient-holding capacities of the soils.

The qualitative interviews with project managers provided essential perspectives on the benefits of biochar application. Project managers reported several advantages, including improved soil fertility, water retention, and the prevention of crop pests. Furthermore, the interviews highlighted the need for knowledge dissemination and practical training to promote widespread adoption of biochar as a soil amendment.

In response to the research questions, it is evident that biochar application influences the fundamental soil properties of pH and increases nutrient availability. The optimal application rates and frequency of biochar use vary based on soil type, climate, and crop species. Moreover, biochar demonstrates potential in remediating contaminated soils, with project managers expressing optimism about its role in improving soil quality over time.

The findings from this study have significant implications for sustainable agriculture in Malawi. Biochar has the potential to enhance soil health, increase crop productivity, and contribute to environmental remediation efforts. The adoption of biochar in smallholder farming systems can improve food security and livelihoods in the region at low to no cost to farmers currently struggling to afford synthetic fertilizers.

Despite these promising findings, it is essential to acknowledge the limitations of this study. The sample size was relatively small, and the study focused on specific crops and regions. Therefore, the results may not be fully representative of all agricultural landscapes in Malawi. Further research with larger sample sizes and wider geographical coverage is necessary to strengthen the validity of these findings.

5.2 Recommendations

Building on the insights gained from this study, several recommendations emerge to guide future research and practical applications:

Diverse Crop and Region Study: Conduct further research with a larger and more diverse sample of crops and regions within Malawi to assess the broader applicability of biochar across different agricultural landscapes.

Optimal Application Guidelines: Develop inclusive guidelines for biochar application rates and frequency tailored to specific soil types, crop species and regional conditions, ensuring maximum benefits without unintended consequences.

Knowledge Dissemination: Implement knowledge-sharing programs targeting smallholder farmers, extension services, and agricultural educators such as lead farmers to raise awareness about the benefits and proper usage of biochar for sustainable agriculture.

Long-Term Monitoring: Establish long-term monitoring initiatives to track the effects of biochar application on soil health, plant growth, and environmental conditions over multiple cropping seasons.

Public Policy Support: Collaborate with policymakers and agricultural agencies to integrate biochar into national agricultural strategies, providing incentives and support for its adoption by smallholder farmers.

Training and Capacity Building: Continue to offer and build practical training and capacity-building programs to empower farmers with the skills and knowledge needed to effectively create and incorporate biochar into their farming practices.

Partnerships and Collaboration: Foster partnerships between research institutions, NGOs, and local communities to facilitate the implementation of biochar-based interventions and ensure their sustainability.

In summary, this study contributes valuable insights into the use of biochar as a sustainable soil amendment in smallholder farms in Malawi. The integrated findings from quantitative soil analysis and qualitative interviews highlight the potential benefits of biochar application for soil health, crop production, and environmental sustainability. The study calls for collaborative efforts between stakeholders, policymakers, and researchers to promote the adoption of biochar and sustainable agricultural practices for a resilient and productive agricultural sector in Malawi. The recommendations provided offer a roadmap for future endeavors in harnessing the potential of biochar to transform smallholder agriculture in the region.

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