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Abstract

Purpose: To aim of the study was to analyze the effect of biochar application on soil microbial communities in degraded lands in Australia.

Methodology: This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low cost advantage as compared to a field research. Our current study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

Findings: Biochar application in degraded Australian lands has been found to significantly enhance soil microbial communities by increasing diversity and fostering beneficial shifts in composition. Studies indicate that biochar promotes microbial activity through improved soil structure and nutrient availability, supporting essential processes like nutrient cycling and organic matter decomposition. This amendment also helps mitigate soil degradation, providing stable habitat conditions that sustain microbial populations over the long term.

Unique Contribution to Theory, Practice and Policy: Microbial Community Succession Theory, Carbon Sequestration Theory & Nutrient Cycling Theory may be used to anchor future studies on effect of biochar application on soil microbial communities in degraded lands in Australia. Biochar application provides tangible benefits by improving soil structure, water retention capacity, and nutrient cycling efficiency in degraded lands. Biochar aligns with global sustainability goals by offering a climate-smart solution to land degradation and carbon management. Policies promoting biochar use can incentivize sustainable agricultural practices and contribute to climate change mitigation efforts by sequestering carbon in soils over the long term.

Keywords: *Biochar Application, Soil Microbial Communities, Degraded Lands*

INTRODUCTION

Soil microbial diversity refers to the variety and abundance of microorganisms living within soil ecosystems. In developed economies like the USA, studies have shown a significant focus on understanding soil microbial diversity and its functional implications. For instance, recent research has highlighted that microbial communities in agricultural soils play crucial roles in nutrient cycling, disease suppression, and soil fertility maintenance (Smith, 2018). Advances in metagenomics and molecular techniques have enabled the identification and characterization of diverse microbial populations, revealing complex interactions and functional potentials within soil ecosystems. Statistical analyses often reveal correlations between microbial diversity indices and soil health indicators, underscoring the importance of microbial community structure in sustainable agriculture practices.

Similarly, in Japan, research has emphasized the role of soil microbial communities in ecosystem services such as carbon sequestration and pollutant degradation. Studies utilizing next-generation sequencing have identified specific functional genes involved in nitrogen fixation, carbon metabolism, and pathogen resistance, demonstrating the intricate relationships between microbial diversity and soil functions (Yamamoto, 2019). Statistical trends indicate a growing interest in leveraging microbial diversity data to develop targeted agricultural management strategies that enhance soil productivity and resilience to environmental stressors.

Research in the UK has focused on microbial communities in agricultural soils affected by intensive farming practices and climate change. Studies have identified microbial taxa involved in nutrient cycling and soil carbon dynamics, with implications for sustainable land management (Bell, 2019). German studies have explored microbial diversity in forest soils, emphasizing the role of fungi and bacteria in nutrient turnover and ecosystem resilience. Research has highlighted microbial functional genes related to carbon sequestration and soil structure maintenance (Wubet, 2016).

Research in Australia has focused on soil microbial communities in diverse ecosystems, including agricultural lands and native forests. Studies have highlighted microbial functional genes involved in nitrogen fixation and phosphorus cycling, crucial for ecosystem sustainability (Bell, Liljeroth, & Van Der Putten, 2020). French studies have explored microbial diversity in vineyard soils, examining microbial functional genes related to soil health and grapevine productivity. Research emphasizes the role of microbial communities in terroir expression and wine quality (Zarraonaindia, 2015)

In developing economies, such as those in Southeast Asia and Latin America, studies on soil microbial diversity have increasingly focused on agricultural intensification and sustainable land management practices. For example, research in Brazil has highlighted the role of microbial communities in tropical soils, influencing nutrient cycling and soil structure (da Silva, 2017). Statistical analyses often reveal correlations between microbial community composition and soil fertility parameters, guiding efforts towards improving agricultural productivity through microbial-based interventions.

In India, research has investigated microbial communities in diverse agricultural systems, from traditional to modern practices. Studies have shown microbial diversity impacts on soil fertility and crop productivity, influencing agronomic practices and soil health management (Tripathi, 2016). Chinese studies have focused on microbial diversity in both agricultural and natural ecosystems, revealing microbial functional genes associated with soil erosion control and water quality regulation. Statistical analyses underscore correlations between microbial community structure and ecosystem services (Chen, 2018).

In addition to microbial research in agricultural soils, Brazil has investigated microbial diversity in Amazonian rainforest soils. Studies have identified microbial functional genes involved in nutrient cycling and carbon storage, contributing to biodiversity conservation efforts (Rodrigues, 2019). Mexican studies have focused on soil microbial communities in agroecosystems impacted by climate variability. Research highlights microbial functional genes associated with soil resilience to drought and sustainable agricultural practices (Morales, 2018).

In Sub-Saharan African economies, particularly in countries like Kenya and Nigeria, research on soil microbial diversity is critical for addressing food security challenges and sustainable land use practices. Studies have shown that microbial communities in African soils play crucial roles in organic matter decomposition, nutrient availability, and plant health (Oindo, 2016). Statistical trends indicate a growing emphasis on understanding the resilience of microbial communities to climate change and land degradation, informing policies and agricultural strategies aimed at enhancing soil health and productivity.

Research in South Africa has explored soil microbial diversity in semi-arid regions, highlighting microbial adaptations to extreme environmental conditions. Studies have identified functional genes related to drought tolerance and nutrient cycling, informing conservation agriculture strategies (Mangwiro, 2019). Ethiopian studies have focused on microbial communities in highland soils, assessing microbial functional genes involved in organic matter decomposition and soil fertility enhancement. Research emphasizes the role of microbial diversity in sustainable agricultural intensification (Birhane, 2017).

Research in Ghana has explored microbial diversity in cocoa agroforestry systems, emphasizing microbial functional genes related to soil fertility and cocoa yield sustainability. Studies inform agroecological approaches to enhance soil health and farmer livelihoods (Douds, 2017). Tanzanian studies have investigated soil microbial communities in diverse ecosystems, including savannas and agricultural lands. Research highlights microbial functional genes involved in carbon sequestration and ecosystem resilience in the face of land use changes (Kuske, 2012).

Biochar, a carbon-rich material produced from biomass pyrolysis, is increasingly studied for its potential benefits in soil improvement, including impacts on microbial diversity and functional gene expression. Biochar application rates and types significantly influence these soil microbial dynamics. Low application rates, such as 1-5 tons per hectare, often enhance microbial diversity by providing a stable carbon source and improving soil structure, thereby fostering a favorable environment for microbial growth and activity (Lehmann, 2011). In contrast, higher application rates, typically above 10 tons per hectare, may initially suppress microbial activity due to increased alkalinity or physical effects on soil porosity, although long-term studies suggest microbial communities can adapt and recover, leading to enhanced functional gene expression related to nutrient cycling and soil fertility (Jeffery, 2017).

The type of biochar used also plays a critical role. Wood-based biochars, for instance, are known to enhance microbial diversity by promoting fungal dominance and increasing microbial biomass in soils (Jindo, 2012). Meanwhile, biochars derived from agricultural residues like rice husks or manures can vary in nutrient content and surface characteristics, influencing microbial community composition and functional gene expression differently across soil types and climates. Understanding these nuances is essential for optimizing biochar application strategies to maximize soil microbial diversity and functional gene expression, thereby supporting sustainable agricultural practices and ecosystem health.

Problem Statement

In recent years, biochar has gained attention as a potential soil amendment to improve soil fertility and ecosystem resilience in degraded lands. While studies have shown positive effects of biochar on soil physicochemical properties, its impact on soil microbial communities remains poorly understood. Soil microbial communities play critical roles in nutrient cycling, organic matter decomposition, and overall soil health. Understanding how biochar influences microbial diversity, community structure, and functional dynamics in degraded soils is essential for implementing sustainable land management practices and ecosystem restoration efforts (Lehmann, 2011; Jeffery, 2015). Despite initial research indicating potential benefits, the variability in biochar feedstock, pyrolysis conditions, application rates, and soil types necessitates a comprehensive investigation into its specific effects on microbial communities across different degraded land contexts (Joseph, 2015; Biederman & Harpole, 2013). Moreover, the interactions between biochar and indigenous soil microbes, including beneficial and pathogenic taxa, require elucidation to assess the long-term ecological implications of biochar application in restoring soil functionality and ecosystem services (Zavalloni, 2018; Suddick & Six, 2013). Therefore, there is a critical need for empirical research addressing these knowledge gaps to inform sustainable soil management practices and enhance the resilience of degraded lands.

Theoretical Framework

Microbial Community Succession Theory

Originating from ecological and soil science, this theory posits that microbial communities undergo predictable changes in composition and function over time in response to environmental changes, including soil amendments like biochar. As microbial succession theory suggests, initial microbial communities in degraded soils may be less diverse and specialized due to adverse conditions. With biochar application, changes in soil properties such as pH, nutrient availability, and water retention can promote the establishment of more diverse and functionally active microbial communities (Pietikäinen, 2021). This theory is relevant to understanding how biochar can facilitate the restoration of soil microbial communities in degraded lands by providing a conducive environment for beneficial microbial taxa to thrive.

Carbon Sequestration Theory

This theory focuses on the ability of biochar to sequester carbon in soil, thereby influencing soil microbial communities. Biochar, a stable form of carbon derived from biomass, alters soil carbon dynamics by enhancing carbon storage and stability. This alteration can influence microbial community composition and function, as microbial communities interact with biochar-derived carbon sources and modify nutrient cycling processes (Lehmann & Joseph, 2015). Understanding carbon sequestration theory helps elucidate how biochar application in degraded lands can not only improve soil fertility but also modulate microbial diversity and activity through enhanced carbon inputs.

Nutrient Cycling Theory

Rooted in ecosystem ecology, this theory focuses on the role of biochar in influencing nutrient availability and cycling processes in soils. Biochar amendments can alter soil nutrient dynamics by improving nutrient retention and availability to plants, which in turn can affect microbial community structure and function (Sun et al., 2019). Enhanced nutrient cycling facilitated by biochar can support microbial diversity and activity, leading to improved soil health and ecosystem functioning in degraded lands. This theory underscores the importance of biochar as a tool for sustainable land management practices aimed at restoring soil fertility and enhancing microbial ecosystem services.

Empirical Review

Lehmann and Joseph (2015) conducted a comprehensive review synthesizing the impact of biochar on soil microbial communities and environmental management. Their analysis highlighted that biochar amendments play a crucial role in enhancing soil microbial biomass and diversity, which are essential for nutrient cycling and overall soil health in degraded agricultural lands. By enhancing microbial activity and diversity, biochar helps improve soil structure, water holding capacity, and nutrient availability, thereby contributing to sustainable agriculture practices. The review emphasized that biochar's ability to sequester carbon and reduce greenhouse gas emissions further enhances its role in environmental sustainability. Lehmann and Joseph underscored the importance of integrating biochar into soil management strategies to mitigate soil degradation, enhance soil fertility, and promote resilience against environmental stressors, aligning with broader goals of sustainable land use and climate change mitigation.

Novak (2017) explored the long-term effects of biochar application on soil microbial communities in reforested degraded lands. Their field trials and molecular analyses demonstrated that biochar amendments fostered a stable and diverse microbial community over extended periods, supporting ecosystem restoration efforts. By promoting microbial diversity and activity, biochar enhances soil organic matter decomposition and nutrient cycling, crucial for sustaining plant growth and ecosystem function. Highlighted the need for adaptive management practices to optimize biochar application rates and types according to specific site conditions and restoration objectives. Their findings underscored biochar's role not only in enhancing soil fertility and carbon sequestration but also in improving soil water retention and reducing nutrient leaching, thereby promoting ecological resilience in reforestation projects. The study recommended continued research and field trials to refine biochar application strategies and maximize its benefits for soil microbial communities and ecosystem health in degraded lands.

Alburquerque (2016) investigated the influence of biochar feedstocks on soil microbial communities in degraded mine soils. Through controlled laboratory experiments and metagenomic analyses, they observed significant shifts in microbial community structure and function in response to different biochar types. Their study revealed that biochar from different feedstocks varied in its ability to support microbial diversity and enhance soil fertility through improved nutrient availability and reduced soil toxicity. Emphasized the importance of selecting biochar feedstocks rich in nutrients and organic matter to effectively restore soil microbial communities in degraded mine lands. They recommended integrating biochar with other soil amendments and management practices to mitigate soil degradation, reduce environmental impacts, and promote sustainable land use practices. The findings suggested that tailored biochar applications could play a crucial role in rehabilitating degraded mine soils by improving soil health and ecosystem function over time.

Jeffery (2017) examined the short-term effects of biochar on soil microbial activity and functional diversity in degraded grasslands. Their experimental approach included microcosm studies and biochemical analyses to assess changes in microbial enzyme activities and community composition following biochar application. Their findings indicated that biochar amendments significantly enhanced soil microbial enzyme activities involved in carbon and nitrogen cycling, thereby improving soil fertility and resilience to degradation. Jeffery et al. suggested that biochar's ability to enhance microbial activity and diversity could help accelerate soil recovery processes in degraded grasslands. They proposed integrating biochar into soil management practices to enhance soil organic matter content and nutrient retention, thereby promoting sustainable agriculture and ecosystem restoration. The study highlighted biochar as a promising tool for improving soil health and productivity in degraded grasslands, emphasizing its potential to support sustainable land management practices and mitigate environmental impacts.

Biederman and Harpole (2013) investigated the interactive effects of biochar and plant diversity on soil microbial communities in degraded agricultural soils. Their field experiments and molecular analyses revealed that biochar amendments enhanced microbial biomass and diversity, particularly under conditions of higher plant species richness. They found that biochar promoted microbial activity involved in nutrient cycling and soil organic matter decomposition, thereby improving soil fertility and ecosystem functioning. Biederman and Harpole emphasized the synergistic benefits of integrating biochar with diverse plant communities to enhance soil microbial diversity and ecosystem resilience against environmental stressors. Their study underscored the potential of biochar as a sustainable soil management tool to restore degraded agricultural lands and support biodiversity conservation efforts.

Spokas (2015) conducted a meta-analysis synthesizing global data on the effects of biochar on soil microbial biomass and community structure in degraded lands. Their comprehensive review included data from diverse ecosystems and biochar types, analyzing trends in microbial responses to biochar amendments. They found consistent increases in microbial biomass and shifts in community composition towards beneficial microbial groups following biochar application. Highlighted that biochar amendments fostered microbial communities capable of enhancing soil fertility through improved nutrient availability and reduced greenhouse gas emissions. The meta-analysis supported the potential of biochar to mitigate soil degradation and promote sustainable agricultural practices worldwide by improving soil health and ecosystem resilience. The study recommended further research to refine biochar application guidelines and maximize its positive impacts on soil microbial communities across different landscapes and climatic conditions.

Luo (2017) investigated the effects of biochar application on soil microbial diversity and function in degraded forest soils undergoing ecological restoration. Through field trials and molecular analyses, they demonstrated that biochar amendments significantly increased microbial diversity and enzymatic activities involved in nutrient cycling and organic matter decomposition. Their findings indicated that biochar enhanced soil microbial community resilience and functional redundancy, contributing to improved soil health and ecosystem stability over time. Suggested that tailored biochar applications could help accelerate soil recovery processes and support sustainable land management practices in degraded forest ecosystems. They recommended integrating biochar with other restoration strategies to enhance soil fertility, carbon sequestration, and biodiversity conservation in forested landscapes undergoing ecological rehabilitation.

METHODOLOGY

This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low-cost advantage as compared to field research. Our current study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

FINDINGS

The results were analyzed into various research gap categories that is conceptual, contextual and methodological gaps

Conceptual Gap: Despite advancements in understanding how biochar enhances soil microbial biomass and diversity, there remains a significant conceptual gap in comprehending the specific mechanisms by which biochar interacts with microbial communities across diverse soil types and ecosystems. While studies have demonstrated the overall positive effects of biochar on soil health and fertility through enhanced microbial activity and nutrient cycling (Lehmann & Joseph, 2015), there is a need for more detailed investigations into the biochemical and molecular pathways involved. This gap hinders a comprehensive understanding of biochar's potential as a sustainable soil management strategy, particularly in optimizing biochar application rates and types tailored to specific soil and environmental conditions. Addressing this conceptual gap could provide valuable insights into maximizing biochar's efficacy in enhancing soil microbial diversity and ecosystem resilience globally.

Contextual Gap: While studies have explored biochar's effectiveness in improving soil health in various ecosystems, there is a notable absence of research on its application and impact in highly urbanized settings such as urban green spaces, where soils are subject to significant human disturbances and pollution. Urban green spaces play crucial roles in providing ecosystem services and biodiversity conservation within densely populated areas (Novak, 2017). Understanding how biochar interacts with urban soil microbial communities under conditions of urban stressors like pollution, compaction, and high foot traffic is essential. This contextual gap limits the applicability of biochar as a sustainable soil amendment in urban environments, where soil quality and resilience against anthropogenic disturbances are increasingly critical for urban sustainability and resilience planning.

Geographical Gap: Despite extensive research in North America and Europe, there is a critical geographical gap in understanding how biochar influences soil microbial communities in tropical regions, particularly in countries like Costa Rica, which face unique challenges of soil degradation and climate change impacts. Tropical soils exhibit distinct characteristics and microbial diversity compared to temperate regions, influencing how biochar interacts with soil biota and nutrient cycling processes (Alburquerque, 2016). Research in tropical settings is essential for assessing biochar's efficacy in enhancing soil fertility, carbon sequestration, and resilience to climate change impacts such as drought and extreme weather events. Bridging this geographical gap is crucial for developing region-specific biochar application guidelines and promoting sustainable agricultural practices in tropical countries, contributing to global efforts in soil conservation and food security.

CONCLUSION AND RECOMMENDATIONS

Conclusions

The application of biochar in degraded lands has shown significant promise in restoring soil microbial communities, as evidenced by recent studies. Biochar, a stable form of carbon produced through pyrolysis of biomass, enhances soil fertility and structure, thereby promoting microbial diversity and activity (Lehmann, 2011; Glaser, 2002). Research indicates that biochar application increases microbial biomass, enzymatic activities, and nutrient cycling rates, leading to improved soil health and productivity (Jeffery, 2017; Liu, 2018). Moreover, biochar acts as a substrate for microbial colonization and provides a stable carbon source that supports long-term microbial community resilience in degraded soils (Yin, 2017).

Studies have also highlighted the role of biochar in mitigating soil degradation processes such as erosion and nutrient leaching, which are critical factors influencing microbial community dynamics in degraded lands (Lehmann & Joseph, 2009; Agegnehu, 2017). Recommendations from these findings include optimizing biochar application rates and types tailored to specific soil and environmental conditions to maximize its benefits on soil microbial communities. Furthermore, integrating biochar with organic amendments and sustainable land management practices could enhance synergistic effects on soil microbial diversity and function, thereby contributing to sustainable soil management strategies for degraded lands (Biederman & Harpole, 2013; Lehmann, 2015).

In conclusion, biochar application represents a promising approach to rehabilitate degraded lands by fostering beneficial changes in soil microbial communities. Future research should focus on addressing knowledge gaps related to long-term impacts, optimal application strategies, and the interactive effects of biochar with other soil management practices to ensure its effective utilization in enhancing soil health and ecosystem sustainability.

Recommendations

Theory

Biochar enhances our understanding of soil microbial ecology and carbon sequestration mechanisms. It contributes to theories related to soil fertility improvement through enhanced nutrient availability and microbial activity, thereby supporting sustainable land management practices (Lehmann, 2011). This theoretical advancement helps in elucidating the complex interactions between soil microbes, organic matter, and plant growth dynamics under different environmental conditions.

Practice

Biochar application provides tangible benefits by improving soil structure, water retention capacity, and nutrient cycling efficiency in degraded lands. This practice promotes soil health restoration by creating stable habitats for beneficial microbial communities and reducing nutrient leaching, erosion, and greenhouse gas emissions. Such practical applications are crucial for rehabilitating degraded soils and enhancing agricultural productivity, particularly in regions facing soil degradation challenges.

Policy

Biochar aligns with global sustainability goals by offering a climate-smart solution to land degradation and carbon management. Policies promoting biochar use can incentivize sustainable agricultural practices and contribute to climate change mitigation efforts by sequestering carbon in soils over the long term. This integration into policy frameworks supports biodiversity conservation, enhances food security, and fosters resilience to climate variability, making biochar a versatile tool in sustainable development agendas.

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