Molecular Soil Biology 2024, Vol.15, No.2, 59-70
http://bioscipublisher.com/index.php/msb

Review Article Open Access

Microbial Decomposition and Soil Health: Mechanisms and Ecological Implications

Chunyang Zhan
Hainan Institute of Biotechnology, Haikou, 570206, Hainan, China
Corresponding email: chunyang.zhan@hitar.org
Molecular Soil Biology, 2024, Vol.15, No.2 doi: 10.5376/msb.2024.15.0007
Received: 07 Jan., 2024
Accepted: 09 Mar., 2024
Published: 21 Mar., 2024
Copyright © 2024 Zhan, This is an open access article published under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
Preferred citation for this article:
Zhan C.Y., 2024, Microbial decomposition and soil health: mechanisms and ecological implications, Molecular Soil Biology, 15(2): 59-70 (doi: 10.5376/msb.2024.15.0007)

Abstract Microbial decomposition is a critical process in soil ecosystems, facilitating the breakdown of organic matter to release and recycle nutrients, thus maintaining soil health and promoting plant growth. Microbial decomposition not only influences the carbon cycle but also plays a crucial role in mitigating climate change and supporting ecosystem stability. This study reviews the latest research literature, analyzing the definition and stages of microbial decomposition, the key microbial species involved, and the environmental factors that affect this process. The focus is on the role of microbial communities in nutrient cycling and their relationship with soil health indicators. The findings demonstrate that microbial decomposition plays a pivotal role in the carbon cycle and can improve soil structure and fertility by promoting organic matter breakdown. Appropriate soil management practices, such as the use of organic amendments and biofertilizers, can significantly enhance the efficiency of microbial decomposition, thereby strengthening soil health and ecosystem resilience. Understanding the mechanisms and ecological significance of microbial decomposition is essential for improving soil management practices and increasing agricultural productivity. This study explores the key role of microbial decomposition in the carbon cycle, soil structure improvement, and ecosystem resilience, and proposes strategies to enhance microbial decomposition activity to promote soil health, providing theoretical and practical guidance for soil management and sustainable agriculture.
Keywords Microbial decomposition; Soil health; Carbon cycle; Ecosystem stability; Nutrient cycling

1 Introduction

Soil health is a critical component of terrestrial ecosystems, acting as a dynamic living system that delivers multiple ecosystem services. These services include sustaining water quality, plant productivity, nutrient cycling, and decomposition, as well as removing greenhouse gases from the atmosphere (Tahat et al., 2020). The health of soil is closely linked to its biological, chemical, and physical properties, which are influenced by the diversity and activity of soil microorganisms (Sahu et al., 2019).

Sustainable agriculture relies heavily on maintaining soil health, as it ensures the continuous production of food without causing environmental degradation. Healthy soils support crop productivity by enhancing water use efficiency, nutrient availability, and plant resistance to environmental stresses. Agricultural practices such as organic farming and conservation tillage have been shown to improve soil health by increasing the abundance, diversity, and activity of soil microorganisms (Tahat et al., 2020). However, agricultural intensification can place tremendous pressure on soil's capacity to maintain its functions, leading to ecosystem degradation and loss of productivity (Trivedi et al., 2016).

Microbial decomposition is the process by which microorganisms break down organic matter, releasing nutrients back into the soil and contributing to soil fertility and structure. This process is essential for nutrient cycling and the maintenance of soil health (Delgado-Baquerizo et al., 2017). Soil microbes, including bacteria, fungi, and archaea, play a crucial role in decomposing organic matter and regulating biogeochemical cycles (Crowther et al., 2019). The diversity and composition of microbial communities are key drivers of soil multifunctionality, influencing processes such as nutrient cycling, decomposition, and climate regulation (Delgado-Baquerizo et al., 2017; Sahu et al., 2019). Understanding the mechanisms of microbial decomposition is vital for predicting the effects of global change on ecosystem functions and for formulating sustainable management and conservation policies (Delgado-Baquerizo et al., 2017).

This study synthesizes current knowledge on the mechanisms and ecological significance of microbial decomposition in soil ecosystems. It explores the role of microbial diversity and composition in driving soil multifunctionality, the impact of soil structure on decomposition processes, and the potential of soil microorganisms in restoring degraded lands. By examining these aspects, the study provides insights into the critical role of microbial decomposition in maintaining soil health and supporting sustainable agriculture. Through a comprehensive analysis of recent research findings, this study highlights the importance of microbial communities in soil ecosystems and their potential applications in sustainable land management.

2 Microbial Decomposition: An Overview

2.1 Definition and stages of microbial decomposition

Microbial decomposition refers to the process by which microorganisms, such as bacteria, fungi, and actinomycetes, break down organic matter into simpler substances. This process is crucial for nutrient cycling and soil health, as it transforms complex organic materials into forms that can be utilized by plants and other organisms. The stages of microbial decomposition typically include the initial breakdown of organic matter, the release of nutrients, and the formation of stable soil organic matter (SOM) (Cotrufo et al., 2013; Hicks et al., 2021).

The initial stage involves the enzymatic breakdown of complex organic compounds, such as cellulose and lignin, into simpler molecules. This is followed by the microbial assimilation of these simpler molecules, during which microorganisms utilize the carbon and energy contained within the organic matter for growth and reproduction. The final stage involves the stabilization of the remaining organic matter, which contributes to the formation of SOM. This stabilized SOM plays a critical role in soil structure, water retention, and long-term carbon storage (Cotrufo et al., 2013; Huang et al., 2018).

2.2 Key microbial players involved in decomposition

The primary microbial players in decomposition are bacteria, fungi, and actinomycetes. Bacteria are highly versatile and can decompose a wide range of organic materials, particularly those that are easily degradable. They are known for their rapid growth rates and ability to quickly colonize new substrates. Bacterial decomposition is often associated with the fast turnover of easily available substrates, which supports rapid nutrient cycling (Murphy et al., 2007; Hicks et al., 2021).

Fungi, on the other hand, are more efficient at breaking down complex organic compounds, such as lignin and cellulose, which are found in plant cell walls. Fungal decomposition leads to the slower turnover of more complex organic matter, contributing to the formation of stable SOM. Actinomycetes, a group of filamentous bacteria, also play a significant role in the decomposition of complex organic materials. They are particularly important in the later stages of decomposition, where they break down more recalcitrant compounds (Murphy et al., 2007; Brabcová et al., 2016; Hicks et al., 2021).

2.3 Factors influencing microbial decomposition

Several factors influence microbial decomposition, including the type of organic matter and environmental conditions. The quality and composition of organic matter, such as its carbon-to-nitrogen (C/N) ratio, significantly affect the rate and efficiency of decomposition. High-quality organic matter with a low C/N ratio is more readily decomposed by microorganisms, while low-quality organic matter with a high C/N ratio decomposes more slowly (Hicks et al., 2021).

Environmental conditions, such as temperature, moisture, and soil structure, also play crucial roles in microbial decomposition. Optimal temperature and moisture levels enhance microbial activity and decomposition rates. Soil structure affects the physical protection of organic matter and the accessibility of substrates to microorganisms. For instance, soil compaction can limit microbial access to organic matter, while soil aggregation can protect organic matter from rapid decomposition (Bhanja et al., 2019; Crowther et al., 2019).

3 Mechanisms of Microbial Decomposition

3.1 Enzymatic breakdown of organic matter

Microbial decomposition of organic matter is primarily driven by the enzymatic activities of soil microorganisms, including bacteria and fungi. These microorganisms secrete extracellular enzymes that break down complex organic compounds into simpler molecules that can be assimilated and utilized for growth and metabolism. For instance, enzymes such as cellulases, ligninases, and proteases play crucial roles in the degradation of plant residues and other organic materials in the soil (Murphy et al., 2007; Arcand et al., 2016). The activity of these enzymes is influenced by various factors, including the chemical composition of the organic matter, soil pH, temperature, and moisture content. Studies have shown that the enzymatic breakdown of organic matter is a critical step in the nutrient cycling process, as it releases essential nutrients such as nitrogen, phosphorus, and sulfur, which are then available for plant uptake and microbial use (Murphy et al., 2007).

The efficiency of enzymatic breakdown can vary significantly depending on the microbial community composition and the quality of the organic matter. For example, research has demonstrated that soils with higher microbial diversity tend to have more efficient decomposition processes due to the presence of a wider range of enzymatic capabilities. Additionally, the presence of specific microbial taxa that are specialized in degrading certain types of organic matter can enhance the overall decomposition rate. This highlights the importance of maintaining diverse and functionally rich microbial communities in soil ecosystems to ensure effective organic matter decomposition and nutrient cycling (Maron et al., 2018; Raczka et al., 2021).

3.2 Role of microbial communities in nutrient cycling

Microbial communities play a pivotal role in nutrient cycling by mediating the transformation and movement of nutrients through the soil ecosystem. These communities are involved in various biogeochemical processes, including the decomposition of organic matter, mineralization of nutrients, and the formation of stable soil organic matter (SOM) (Schimel and Schaeffer, 2012; Crowther et al., 2019). For instance, the decomposition of plant residues by soil microorganisms leads to the release of carbon dioxide (CO_2) and the conversion of organic nitrogen into inorganic forms that are readily available for plant uptake (Schimel and Schaeffer, 2012). This process is essential for maintaining soil fertility and supporting plant growth.

The composition and diversity of microbial communities can significantly influence nutrient cycling dynamics. Studies have shown that different microbial taxa have distinct functional roles in the decomposition process, with some groups being more efficient at breaking down specific types of organic matter (Raczka et al., 2021; Ma et al., 2023). For example, fungi are often more effective at decomposing complex organic compounds such as lignin, while bacteria are more efficient at degrading simpler substrates (Hicks et al., 2021; Ma et al., 2023). The interaction between these microbial groups can enhance the overall decomposition process and promote the cycling of nutrients in the soil. Additionally, the presence of diverse microbial communities can increase the resilience of soil ecosystems to environmental changes and disturbances, ensuring the continued functioning of nutrient cycling processes (Raczka et al., 2021; Ma et al., 2023).

3.3 Interaction between different microbial species in the decomposition process

The decomposition of organic matter in soil is a complex process that involves interactions between different microbial species. These interactions can be synergistic, antagonistic, or neutral, and they play a crucial role in determining the efficiency and outcome of the decomposition process. For example, certain bacteria and fungi may work together to break down complex organic compounds more efficiently than they could individually. This synergistic interaction can lead to the rapid decomposition of organic matter and the release of nutrients (Metcalf et al., 2016; Geisen et al., 2020). On the other hand, competition between microbial species for resources can slow down the decomposition process and affect nutrient cycling dynamics.

Research has shown that the presence of specific microbial species can influence the overall structure and function of the microbial community during decomposition. For instance, the introduction of predatory protists into microbial communities has been found to increase CO_2 release and litter mass loss, indicating that trophic interactions can significantly impact decomposition rates. Additionally, the succession of microbial communities during decomposition is often predictable, with certain species dominating at different stages of the process. This predictable pattern of microbial succession highlights the importance of understanding the interactions between different microbial species to better predict and manage decomposition and nutrient cycling in soil ecosystems (Metcalf et al., 2016; Geisen et al., 2020).

4 Soil Health Indicators and Microbial Decomposition

4.1 Definition and key indicators of soil health

Soil health is defined as the capacity of soil to function as a vital living system within ecosystem boundaries, sustaining plant and animal productivity, maintaining or enhancing environmental quality, and promoting plant and animal health (Doran and Zeiss, 2000; Yang et al., 2020). This concept extends beyond traditional soil assessments focused solely on crop production to include the role of soil in water quality, climate change, and human health (Lehmann et al., 2020). Key indicators of soil health encompass a range of physical, chemical, and biological properties. Physical indicators include soil structure and porosity, while chemical indicators involve nutrient content and pH levels. Biological indicators, which are increasingly recognized for their importance, include microbial biomass, diversity, and activity, as well as the presence of specific functional groups such as nitrogen-fixing bacteria and mycorrhizal fungi (Figure 1) (Alkorta et al., 2003; Tahat et al., 2020; Bhaduri et al., 2022).

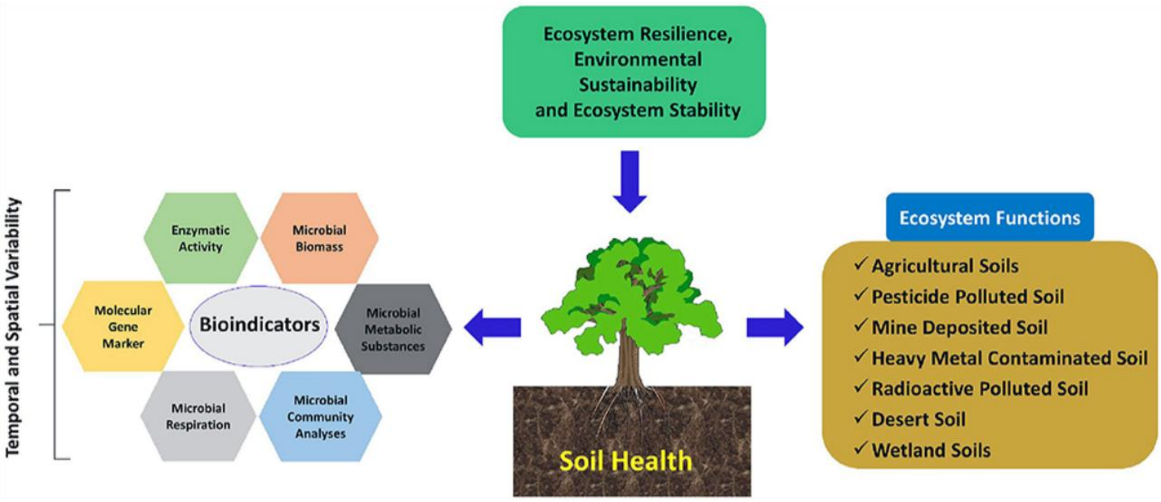

Figure 1 Soil health as a key indicator of ecosystem resilience and stability (Adapted from Bhaduri et al., 2022)

Biological indicators are particularly valuable because they provide insights into the dynamic processes occurring within the soil. For instance, microbial diversity and activity are crucial for nutrient cycling, organic matter decomposition, and the suppression of soil-borne diseases (Sahu et al., 2019; Tahat et al., 2020). Advances in molecular techniques have enhanced our ability to assess microbial communities and their functions, allowing for more precise monitoring of soil health (Alkorta et al., 2003). These indicators are essential for developing sustainable land management practices that maintain or improve soil health over time.

4.2 Relationship between microbial activity and soil organic matter

Microbial activity plays a pivotal role in the decomposition of soil organic matter (SOM), which is a key component of soil health. Soil microbes, including bacteria, fungi, and actinomycetes, break down organic residues, converting them into simpler compounds that can be utilized by plants and other soil organisms (Delgado-Baquerizo et al., 2017; Sahu et al., 2019). This process not only recycles essential nutrients but also contributes to the formation of stable organic matter fractions that enhance soil structure and water-holding capacity (Maron et al., 2018). The relationship between microbial activity and SOM is complex and influenced by various factors, including soil type, climate, and land management practices (Trivedi et al., 2016; Yang et al., 2020).

Studies have shown that microbial diversity and composition are critical determinants of SOM decomposition rates and efficiency. For example, the presence of specific microbial taxa such as Bacteroidetes and Actinobacteria has been linked to enhanced multifunctionality in soils, including higher rates of organic matter decomposition and nutrient cycling (Delgado-Baquerizo et al., 2017). Additionally, agricultural practices that promote microbial diversity, such as organic farming and reduced tillage, have been found to improve SOM content and overall soil health (Doran and Zeiss, 2000; Tahat et al., 2020). Understanding the interactions between microbial communities and SOM is essential for developing strategies to maintain or enhance soil fertility and productivity.

4.3 Impact of microbial decomposition on soil structure and fertility

Microbial decomposition significantly impacts soil structure and fertility by breaking down organic matter and releasing nutrients that are essential for plant growth. The decomposition process produces humic substances, which contribute to the formation of soil aggregates and improve soil structure (Maron et al., 2018; Sahu et al., 2019). Well-aggregated soils have better aeration, water infiltration, and root penetration, all of which are crucial for healthy plant growth. Moreover, the by-products of microbial decomposition, such as organic acids, can enhance the availability of nutrients like phosphorus and micronutrients, further boosting soil fertility (Delgado-Baquerizo et al., 2017; Bhaduri et al., 2022).

The impact of microbial decomposition on soil fertility is also evident in the cycling of key nutrients such as nitrogen and carbon. Microbial processes, including nitrogen fixation, nitrification, and denitrification, regulate the availability of nitrogen in the soil, which is a critical nutrient for plant growth (Doran and Zeiss, 2000; Sahu et al., 2019). Similarly, the decomposition of organic matter by microbes releases carbon dioxide, which can be utilized by plants for photosynthesis, and contributes to the formation of stable organic carbon pools that enhance soil fertility over the long term (Maron et al., 2018; Lehmann et al., 2020). Therefore, maintaining a diverse and active microbial community is essential for sustaining soil health and fertility in agricultural and natural ecosystems.

5 Ecological Implications of Microbial Decomposition

5.1 Contribution to carbon cycling and climate change mitigation

Microbial decomposition plays a pivotal role in the carbon cycle by breaking down organic matter and releasing carbon dioxide (CO_2) back into the atmosphere. This process is crucial for maintaining soil health and fertility. For instance, the decomposition of plant inputs, such as litter and roots, significantly affects soil organic carbon (SOC) pools and microbial biomass. The addition of litter has been shown to stimulate SOC pools, suggesting that aboveground litter inputs can enhance SOC sequestration despite accelerated decomposition rates (Feng et al., 2022). Furthermore, microbial diversity is essential for efficient carbon cycling, as it influences the decomposition of both easily degradable and recalcitrant carbon sources, thereby affecting global CO_2 emissions (Maron et al., 2018). The role of microbial communities in carbon cycling is also highlighted by their ability to regulate soil fertility, plant growth, and climate through the turnover of organic matter (Crowther et al., 2019). Understanding the functional traits of microbial communities can improve predictions of soil carbon responses to climate change, thereby aiding in climate change mitigation efforts (Malik et al., 2019).

5.2 Influence on soil biodiversity and ecosystem resilience

Microbial decomposition significantly influences soil biodiversity and ecosystem resilience. High microbial diversity promotes soil ecosystem functioning by enhancing the decomposition of organic matter and nutrient cycling. This diversity is crucial for maintaining ecosystem resilience, especially in the face of global changes such as nutrient inputs and climate change (Maron et al., 2018). The composition and diversity of soil microbial communities can shift in response to environmental changes, such as nitrogen addition, which can alter microbial functions and slow carbon cycling, leading to increased SOC sequestration (Tian et al., 2019). Additionally, the interactions between different microbial groups, such as bacteria and fungi, play a critical role in decomposition processes and can affect the overall stability and resilience of soil ecosystems (Hicks et al., 2021). The presence of protists, for example, can enhance microbial-driven CO_2 release and litter mass loss, indicating their functional importance in decomposition and carbon cycling (Geisen et al., 2020).

5.3 Effects on plant health and productivity

Microbial decomposition has direct and indirect effects on plant health and productivity. The breakdown of plant residues and organic matter by microbes releases essential nutrients, such as nitrogen and phosphorus, which are vital for plant growth. The input of fresh plant materials into the soil can initially inhibit but eventually stimulate the decomposition of soil organic carbon, providing a continuous supply of nutrients for plants (Yu et al., 2020). Moreover, the microbial community composition and functions can be influenced by long-term nutrient additions, which in turn affect plant growth and soil carbon storage (Tian et al., 2019). The balance between microbial decomposition and stabilization of organic carbon is crucial for maintaining soil fertility and supporting plant productivity (Malik et al., 2019). By understanding the microbial mechanisms underlying decomposition, we can better manage soil health and enhance plant productivity in various ecosystems.

6 Enhancing Microbial Decomposition for Soil Health

6.1 Strategies to promote beneficial microbial activity

Promoting beneficial microbial activity in soil is crucial for enhancing soil health and fertility. One effective strategy is crop rotation, which helps in diversifying the microbial community and reducing the build-up of soil-borne pathogens. Crop rotation can improve soil structure and nutrient availability, thereby fostering a more resilient microbial ecosystem (Arcand et al., 2016).

Organic amendments, such as compost and manure, are another vital strategy. These amendments provide essential nutrients and organic matter that stimulate microbial activity and diversity. For instance, the addition of composted sugar beet residue has been shown to significantly increase the nutrient content and microbial activity in soil, thereby improving plant establishment and soil rehabilitation under semiarid conditions (Mengual et al., 2014). Similarly, long-term organic fertilization has been found to enhance microbial biomass and activity, promoting the degradation of complex organic compounds and improving soil fertility (Francioli et al., 2016).

6.2 Use of microbial inoculants and biofertilizers

Microbial inoculants and biofertilizers are increasingly recognized for their role in sustainable agriculture. These products contain beneficial microorganisms that can enhance nutrient availability, improve soil structure, and promote plant growth. For example, bacterial and fungal inocula can increase nutrient bioavailability through nitrogen fixation and mobilization of key nutrients like phosphorus, potassium, and iron. The co-inoculation of bacteria and fungi with organic fertilizers has been shown to be particularly effective in reinstating soil fertility and organic matter content (Rashid et al., 2016).

Biofertilizers such as Bacillus, Pseudomonas, and Trichoderma species are commonly used due to their plant growth-promoting properties (Figure 2). These microorganisms can enhance nutrient uptake, improve plant defense mechanisms, and reduce the need for chemical fertilizers (Ortiz and Sansinenea, 2022; Palma et al., 2022). However, the effectiveness of these biofertilizers can vary depending on the specific microbial strains used and their interactions with the native soil microbiota (Schweinsberg-Mickan and Müller, 2009).

6.3 Impact of soil management practices on microbial decomposition

Soil management practices such as tillage and cover cropping have significant impacts on microbial decomposition processes. Tillage can disrupt soil structure and microbial habitats, leading to a decrease in microbial biomass and activity. Conversely, reduced or no-till practices can enhance microbial diversity and activity by preserving soil structure and organic matter (Arcand et al., 2016).

Cover cropping is another beneficial practice that can enhance microbial decomposition. Cover crops provide continuous organic inputs to the soil, which serve as substrates for microbial activity. This practice can improve soil organic carbon content and nutrient cycling, thereby supporting a healthy and active microbial community. Long-term studies have shown that organic management systems, which often include cover cropping, result in higher microbial biomass and enzyme activities compared to conventional systems (Arcand et al., 2016).

Figure 2 Common microorganisms in biofertilizers (Adapted from Ortiz and Sansinenea, 2022)

7 Case Studies

7.1 Enzymatic activities in composting systems

The addition of biochar and compost to soils has been shown to significantly influence enzymatic activities, which are crucial for microbial decomposition processes. For instance, a study on sulfamethoxazole-polluted wetland soil demonstrated that biochar and compost amendments could enhance enzymatic activities such as dehydrogenase and urease, thereby improving the degradation efficiency of pollutants (Liang et al., 2019). Similarly, the application of biochar and vermicompost in greenhouse soils increased the activities of urease and alkaline phosphatase, which are essential for nutrient cycling and soil health (Figure 3) (Wu et al., 2023). These findings highlight the potential of organic amendments to boost enzymatic activities and improve soil quality.

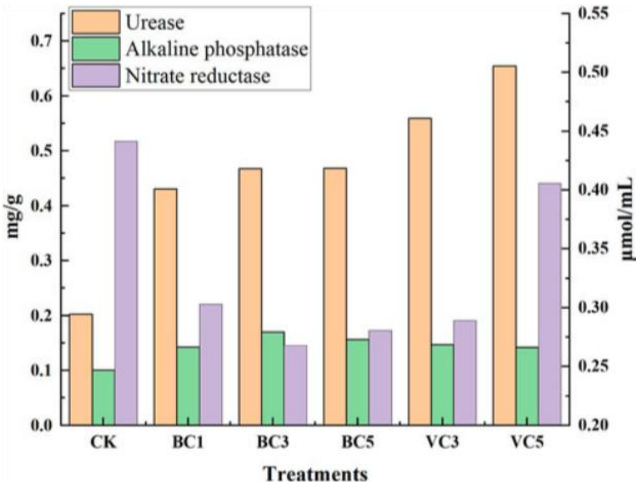

Figure 3 Effects of different treatments on enzyme activity in greenhouse soil (Adapted from Wu et al., 2023)

Image caption: CK: Untreated control group; BC1: Addition of 1% biochar; BC3: Addition of 3% biochar; BC5: Addition of 5% biochar; VC3: Addition of 3% vermicompost; VC5: Addition of 5% vermicompost (Adapted from Wu et al., 2023)

The study by Wu et al. (2023) shows that the application of biochar (BC1, BC3, BC5) and vermicompost (VC3, VC5) significantly increases the activity of urease and nitrate reductase in soil, while having a lesser impact on alkaline phosphatase. Notably, the high-dose vermicompost treatment (VC5) significantly enhanced urease activity, indicating the potential of vermicompost in promoting nitrogen transformation. Additionally, biochar treatments also demonstrated an ability to improve soil enzyme activity, especially at higher doses (BC5) (Figure 3). This suggests that the appropriate application of biochar and vermicompost can enhance soil enzyme activity, thereby improving soil fertility and crop yield.

7.2 Soil Organic matter changes in different agricultural practices

Agricultural practices significantly impact soil organic matter (SOM) and microbial communities. A study comparing organic and conventional management systems found that organic practices led to higher microbial biomass and enzyme activities, particularly in soils with crop residue amendments (Arcand et al., 2016). This suggests that organic management can enhance SOM decomposition and nutrient cycling, thereby improving soil fertility. Additionally, the use of household compost in Typic Acrustox soils resulted in increased microbial activity and organic carbon content, further emphasizing the benefits of organic amendments in maintaining soil health (Vinhal-Freitas et al., 2020).

7.3 Microbial decomposition in agroforestry systems

Agroforestry systems, which integrate trees with crops or livestock, can influence microbial decomposition processes. Although specific studies on agroforestry were not provided, the principles observed in other agricultural systems can be applied. For example, the addition of organic amendments such as biochar and compost has been shown to support diverse microbial populations capable of decomposing both labile and recalcitrant carbon compounds (Risueño et al., 2021). This diversity is crucial for the resilience of agroforestry systems, as it ensures efficient nutrient cycling and soil health maintenance.

7.4 The role of biochar in enhancing microbial decomposition and soil health

Biochar has been extensively studied for its role in enhancing microbial decomposition and soil health. A meta-analysis revealed that biochar addition significantly increased microbial biomass and activities, particularly in soils with low pH and nutrients (Zhang et al., 2018). The structural properties of biochar, such as surface area and porosity, were found to be critical in enhancing microbial activity and community structure. These improvements in microbial functions can lead to better nutrient cycling and carbon sequestration, ultimately enhancing soil health and crop yields.

7.5 Emerging technologies for monitoring and enhancing microbial activity in soils

Emerging technologies are being developed to monitor and enhance microbial activity in soils. High-throughput sequencing, for example, has been used to assess the impact of biochar and compost amendments on microbial communities in polluted wetland soils (Liang et al., 2019). This technology allows for detailed analysis of microbial diversity and function, providing insights into how different amendments influence soil health. Additionally, the use of stable isotope probing (SIP) has been employed to trace microbial utilization of crop residues, revealing differences in microbial succession between organic and conventional management systems (Arcand et al., 2016). These advanced techniques are crucial for developing strategies to optimize microbial activity and improve soil health.

8 Challenges and Future Directions

8.1 Challenges in studying and managing microbial communities in soil

Studying and managing soil microbial communities present several challenges due to the inherent complexity and diversity of these ecosystems. One significant challenge is the hyperdiverse nature of local soil communities, which has traditionally obscured efforts to identify general global patterns in soil biodiversity and biogeochemistry (Crowther et al., 2019). The complexity of community composition and interactions within the soil environment further complicates our understanding, especially when conventional culture-based methods are often biased and unable to fully capture the functional diversity of soil microbes (Lahlali et al., 2021). Additionally, the impact of agricultural practices on soil microbial communities varies significantly across different biomes, making it difficult to develop universal indicators for soil health and productivity (Trivedi et al., 2016). The stratification and distinct spatial distribution of microbial taxa within soil horizons also add another layer of complexity to studying these communities (Baldrian et al., 2011).

8.2 Advances in molecular techniques for studying microbial decomposition

Recent advances in molecular techniques have significantly enhanced our ability to study soil microbial communities and their roles in decomposition. High-throughput molecular technologies, such as metagenomics, metaproteomics, metatranscriptomics, and proteogenomics, have been increasingly used to unravel the diversity and dynamics of soil microbial communities (Lahlali et al., 2021). These techniques allow for the direct analysis of nucleic acids, proteins, and lipids, bypassing the limitations of culture-based methods. The use of 13C-labelled substrates in combination with phospholipid fatty acid (PLFA) analysis has provided insights into the microbial utilization of fresh inputs of crop residues and the succession of microbial communities during decomposition (Arcand et al., 2016). Additionally, the independent analysis of DNA and RNA has enabled the identification of active microbial decomposers and their specific roles in organic matter transformation (Baldrian et al., 2011). These molecular approaches have revealed that microbial diversity is crucial for organic matter decomposition and that changes in microbial diversity can significantly impact soil ecosystem functions (Maron et al., 2018).

8.3 Future research needs and potential areas for exploration

Future research should focus on addressing the remaining knowledge gaps in soil microbial biogeography and the functional implications of microbial diversity. There is a need for a clearer concept of microbial species and their ecological roles, as well as projections of soil microbial distributions under future global change scenarios (Chu et al., 2020). Understanding the mechanisms that determine microbial community composition and their influence on soil ecosystem functions is critical for predicting the consequences of environmental changes (Prosser, 2019). Additionally, research should explore the trade-offs in organic matter use by microorganisms and the factors that drive selective microbial mining for nutrients from persistent soil organic matter (Hicks et al., 2020). Developing a continental-scale, cross-biome approach to assess soil microbial communities and their functional potential will help identify unifying principles governing the susceptibility of soil biodiversity to land conversion (Trivedi et al., 2016). Embracing culture and isolation approaches alongside molecular techniques will also be essential to determine microbial functional profiles and improve our ability to manage soil health sustainably (Chu et al., 2020).

9 Concluding Remarks

Microbial activity in forest soils is influenced by various factors such as root activity, seasonality, and climatic events, with fungi playing a major role in decomposing complex plant biomass and shaping bacterial communities. High microbial diversity is essential for effective carbon cycling and soil ecosystem functioning, with a decrease in diversity significantly impacting CO_2 emissions and nutrient availability. Intensive agricultural practices, such as the excessive use of synthetic fertilizers, have led to soil microbial deterioration, necessitating measures like rational fertilization and crop rotation to restore soil health. Microbial traits and their physiological responses to environmental changes are crucial for predicting soil carbon dynamics and climate change feedbacks. Soil microbes balance nutrient demands and environmental preservation, playing a pivotal role in nutrient cycling, organic matter decomposition, and climate regulation. Both microbial richness and composition independently drive soil multifunctionality, emphasizing the need to consider these factors in sustainable management practices. Novel technologies, such as biopolymer composite sensors, offer new ways to monitor microbial decomposition activity and soil health. Finally, the interplay between fungi and bacteria in nutrient cycling and organic matter decomposition is complex, with both groups contributing to the breakdown of organic matter and nutrient mineralization.

The findings underscore the importance of maintaining high microbial diversity and balanced microbial communities for sustainable soil management. Practices such as reducing chemical fertilizer use, incorporating organic manure, and adopting crop rotation and intercropping can help restore and maintain soil microbial health. Understanding microbial traits and their responses to environmental changes can improve predictions of soil carbon dynamics, aiding in the development of strategies to mitigate climate change. The use of advanced monitoring technologies, like biopolymer composite sensors, can provide real-time insights into microbial activity, enabling more precise soil management. Additionally, promoting microbial richness and composition through sustainable practices can enhance soil multifunctionality, supporting nutrient cycling, decomposition, and climate regulation. These strategies are crucial for ensuring long-term soil fertility, agricultural productivity, and ecosystem resilience.

Microbial decomposition is fundamental to soil health and ecosystem stability, driving essential processes such as nutrient cycling, organic matter breakdown, and carbon sequestration. The intricate interactions between fungi and bacteria, along with their diverse metabolic capabilities, ensure the continuous transformation and stabilization of organic matter in soils. Maintaining microbial diversity and promoting balanced microbial communities are vital for sustaining these processes, particularly in the face of global environmental changes and intensive agricultural practices. By optimizing microbial functions through sustainable soil management practices, we can enhance soil health, improve agricultural productivity, and contribute to global sustainability and food security. The ongoing research and technological advancements in monitoring microbial activity will further our understanding and ability to manage soil ecosystems effectively, ensuring their stability and resilience for future generations.

Acknowledgments
Thank you to the anonymous peer reviewers for their suggestions on improving this study.

Conflict of Interest Disclosure
The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References
Alkorta I., Amezaga I., Albizu I., Aizpurua A., Onaindia M., Buchner V., and Garbisu C., 2003, Molecular microbial biodiversity assessment: a biological indicator of soil health, Reviews on Environmental Health, 18: 131-151.
https://doi.org/10.1515/REVEH.2003.18.2.131

Arcand M., Helgason B., and Lemke R., 2016, Microbial crop residue decomposition dynamics in organic and conventionally managed soils, Applied Soil Ecology, 107: 347-359.
https://doi.org/10.1016/J.APSOIL.2016.07.001

Baldrian P., Kolařík M., Štursová M., Kopecký J., Valášková V., Větrovský T., Žifčáková L., Šnajdr J., Rídl J., Vlček Č., and Voříšková J., 2011, Active and total microbial communities in forest soil are largely different and highly stratified during decomposition, The ISME Journal, 6: 248-258.
https://doi.org/10.1038/ismej.2011.95

Bhaduri D., Sihi D., Bhowmik A., Verma B., Munda S., and Dari B., 2022, A review on effective soil health bio-indicators for ecosystem restoration and sustainability, Frontiers in Microbiology, 13: 938481.
https://doi.org/10.3389/fmicb.2022.938481

Bhanja S., Wang J., Shrestha N., and Zhang X., 2019, Microbial kinetics and thermodynamic (MKT) processes for soil organic matter decomposition and dynamic oxidation-reduction potential: model descriptions and applications to soil N2O emissions, Environmental Pollution, 247: 812-823.
https://doi.org/10.1016/j.envpol.2019.01.062

Brabcová V., Nováková M., Davidova A., and Baldrian P., 2016, Dead fungal mycelium in forest soil represents a decomposition hotspot and a habitat for a specific microbial community, The New Phytologist, 210(4): 1369-1381.
https://doi.org/10.1111/nph.13849

Chu H., Gao G., Ma Y., Fan K., and Delgado-Baquerizo M., 2020, Soil microbial biogeography in a changing world: recent advances and future perspectives, mSystems, 5(2): 10.1128.
https://doi.org/10.1128/mSystems.00803-19

Cotrufo M., Wallenstein M., Boot C., Denef K., and Paul E., 2013, The microbial efficiency-matrix stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? Global Change Biology, 19(4): 988-995.
https://doi.org/10.1111/gcb.12113

Crowther T., Hoogen J., Wan J., Mayes M., Mayes M., Keiser A., Keiser A., Mo L., Averill C., Averill C., and Maynard D., 2019, The global soil community and its influence on biogeochemistry, Science, 365(6455): eaav0550.
https://doi.org/10.1126/science.aav0550

Delgado-Baquerizo M., Trivedi P., Trivedi C., Eldridge D., Reich P., Jeffries T., and Singh B., 2017, Microbial richness and composition independently drive soil multifunctionality, Functional Ecology, 31: 2330-2343.
https://doi.org/10.1111/1365-2435.12924

Doran J., and Zeiss M., 2000, Soil health and sustainability: managing the biotic component of soil quality, Applied Soil Ecology, 15: 3-11.
https://doi.org/10.1016/S0929-1393(00)00067-6

Feng J., He K., Zhang Q., Han M., and Zhu B., 2022, Changes in plant inputs alter soil carbon and microbial communities in forest ecosystems, Global Change Biology, 28: 3426-3440.
https://doi.org/10.1111/gcb.16107

Francioli D., Schulz E., Lentendu G., Wubet T., Buscot F., and Reitz T., 2016, Mineral vs. organic amendments: microbial community structure, activity and abundance of agriculturally relevant microbes are driven by long-term fertilization strategies, Frontiers in Microbiology, 7: 1446.
https://doi.org/10.3389/fmicb.2016.01446

Geisen S., Hu S., Cruz T., and Veen G., 2020, Protists as catalyzers of microbial litter breakdown and carbon cycling at different temperature regimes, The ISME Journal, 15: 618-621.
https://doi.org/10.1038/s41396-020-00792-y

Hicks L., Lajtha K., and Rousk J., 2021, Nutrient limitation may induce microbial mining for resources from persistent soil organic matter, Ecology, e03328.
https://doi.org/10.1002/ecy.3328

Huang Y., Guenet B., Ciais P., Janssens I., Soong J., Wang Y., Goll D., Blagodatskaya E., and Huang Y., 2018, ORCHIMIC (v1.0), a microbe-mediated model for soil organic matter decomposition, Geoscientific Model Development, 11: 2111-2138.
https://doi.org/10.5194/GMD-11-2111-2018

Lahlali R., Ibrahim D., Belabess Z., Roni M., Radouane N., Vicente C., Menéndez E., Mokrini F., Barka E., Mota M., and Peng G., 2021, High-throughput molecular technologies for unraveling the mystery of soil microbial community: challenges and future prospects, Heliyon, 7(10): e08142.
https://doi.org/10.1016/j.heliyon.2021.e08142

Lehmann J., Bossio D., Kögel-Knabner I., and Rillig M., 2020, The concept and future prospects of soil health, Nature Reviews Earth & Environment, 1: 544-553.
https://doi.org/10.1038/s43017-020-0080-8

Liang J., Tang S., Gong J., Zeng G., Tang W., Song B., Zhang P., Yang Z., and Luo Y., 2019, Responses of enzymatic activity and microbial communities to biochar/compost amendment in sulfamethoxazole polluted wetland soil, Journal of Hazardous Materials, 385: 121533.
https://doi.org/10.1016/j.jhazmat.2019.121533

Ma C., Wang X., Wang J., Zhu X., Qin C., Zeng Y., Zhen W., Fang Y., and Shangguan Z., 2023, Interactions of soil nutrients and microbial communities during root decomposition of gramineous and leguminous forages, Land Degradation & Development, 34: 3250-3261.
https://doi.org/10.1002/ldr.4680

Malik A., Martiny J., Brodie E., Martiny A., Treseder K., and Allison S., 2019, Defining trait-based microbial strategies with consequences for soil carbon cycling under climate change, The ISME Journal, 14(1): 1-9.
https://doi.org/10.1038/s41396-019-0510-0

Maron P., Sarr A., Kaisermann A., Lévêque J., Mathieu O., Guigue J., Karimi B., Bernard L., Dequiedt S., Terrat S., Chabbi A., and Ranjard L., 2018, High microbial diversity promotes soil ecosystem functioning, Applied and Environmental Microbiology, 84(9): e02738-17.
https://doi.org/10.1128/AEM.02738-17

Mengual C., Schoebitz M., Azcón R., and Roldán A., 2014, Microbial inoculants and organic amendment improves plant establishment and soil rehabilitation under semiarid conditions, Journal of Environmental Management, 134: 1-7.
https://doi.org/10.1016/j.jenvman.2014.01.008

Metcalf J., Xu Z., Weiss S., Lax S., Treuren W., Hyde E., Song S., Amir A., Larsen P., Sangwan N., Haarmann D., Humphrey G., Ackermann G., Thompson L., Lauber C., Bibat A., Nicholas C., Gebert M., Petrosino J., Reed S., Gilbert J., Lynne A., Bucheli S., Carter D., and Knight R., 2016, Microbial community assembly and metabolic function during mammalian corpse decomposition, Science, 351: 158-162.
https://doi.org/10.1126/science.aad2646

Murphy D., Stockdale E., Brookes P., and Goulding K., 2007, Impact of microorganisms on chemical transformations in soil, In: Abbott, L.K., Murphy, D.V. (eds), Soil Biological Fertility, Springer, Dordrecht, pp.37-59.
https://doi.org/10.1007/978-1-4020-6619-1_3

Ortiz A., and Sansinenea E., 2022, The role of beneficial microorganisms in soil quality and plant health, Sustainability, 14(9): 5358.
https://doi.org/10.3390/su14095358

Palma M., Scotti R., D'Agostino N., Zaccardelli M., and Tucci M., 2022, Phyto-friendly soil bacteria and fungi provide beneficial outcomes in the host plant by differently modulating its responses through (in)direct mechanisms, Plants, 11(20): 2672.
https://doi.org/10.3390/plants11202672

Prosser J., 2019, Exploring soil microbial communities: opportunities for soil ecology research, Soil Ecology Letters, 1: 1-2.
https://doi.org/10.1007/s42832-019-0001-2

Rashid M., Mujawar L., Shahzad T., Almeelbi T., Ismail I., and Oves M., 2016, Bacteria and fungi can contribute to nutrients bioavailability and aggregate formation in degraded soils, Microbiological Research, 183: 26-41.
https://doi.org/10.1016/j.micres.2015.11.007

Raczka N., Piñeiro J., Tfaily M., Chu R., Lipton M., Paša-Tolić L., Morrissey E., and Brzostek E., 2021, Interactions between microbial diversity and substrate chemistry determine the fate of carbon in soil, Scientific Reports, 11: 19320.
https://doi.org/10.1038/s41598-021-97942-9

Risueño Y., Petri C., and Conesa H., 2021, A critical assessment on the short-term response of microbial relative composition in a mine tailings soil amended with biochar and manure compost, Journal of Hazardous Materials, 417: 126080.
https://doi.org/10.1016/j.jhazmat.2021.126080

Sahu P., Singh D., Prabha R., Meena K., and Abhilash P., 2019, Connecting microbial capabilities with the soil and plant health: options for agricultural sustainability, Ecological Indicators, 105: 601-612.
https://doi.org/10.1016/J.ECOLIND.2018.05.084

Schimel J., and Schaeffer S., 2012, Microbial control over carbon cycling in soil, Frontiers in Microbiology, 3: 348.
https://doi.org/10.3389/fmicb.2012.00348

Schweinsberg-Mickan M., and Müller T., 2009, Impact of effective microorganisms and other biofertilizers on soil microbial characteristics, organic-matter decomposition, and plant growth, Journal of Plant Nutrition and Soil Science, 172: 704-712.
https://doi.org/10.1002/JPLN.200800021

Tahat M., Alananbeh K., Othman Y., and Leskovar D., 2020, Soil health and sustainable agriculture, Sustainability, 12(12): 4859.
https://doi.org/10.3390/su12124859

Tian J., Dungait J., Lu X., Yang Y., Hartley I., Zhang W., Mo J., Yu G., Zhou J., and Kuzyakov Y., 2019, Long-term nitrogen addition modifies microbial composition and functions for slow carbon cycling and increased sequestration in tropical forest soil, Global Change Biology, 25: 3267-3281.
https://doi.org/10.1111/gcb.14750

Trivedi P., Delgado-Baquerizo M., Anderson I., and Singh B., 2016, Response of soil properties and microbial communities to agriculture: implications for primary productivity and soil health indicators, Frontiers in Plant Science, 7: 990.
https://doi.org/10.3389/fpls.2016.00990

Vinhal-Freitas I., Wangen D., Ferreira A., Corrêa G., and Wendling B., 2010, Microbial and enzymatic activity in soil after organic composting, Revista Brasileira De Ciencia Do Solo, 34: 757-764.
https://doi.org/10.1590/S0100-06832010000300017

Wu Q., Zhang J., Liu X., Chang T., Wang Q., Shaghaleh H., and Hamoud Y., 2023, Effects of biochar and vermicompost on microorganisms and enzymatic activities in greenhouse soil, Frontiers in Environmental Science, 10: 1060277.
https://doi.org/10.3389/fenvs.2022.1060277

Yang T., Siddique K., and Liu K., 2020, Cropping systems in agriculture and their impact on soil health-a review, Global Ecology and Conservation, 23: e01118.
https://doi.org/10.1016/j.gecco.2020.e01118

Yu G., Zhao H., Chen J., Zhang T., Cai Z., Zhou G., Li Z., Qiu Z., and Wu Z., 2020, Soil microbial community dynamics mediate the priming effects caused by in situ decomposition of fresh plant residues, The Science of the Total Environment, 737: 139708.
https://doi.org/10.1016/j.scitotenv.2020.139708

Zhang L., Jing Y., Xiang Y., Zhang R., and Lu H., 2018, Responses of soil microbial community structure changes and activities to biochar addition: a meta-analysis, The Science of the Total Environment, 643: 926-935.
https://doi.org/10.1016/j.scitotenv.2018.06.231

Disclaimer/Publisher's Note
The statements, opinions, and data contained in all publications are solely those of the individual authors and contributors and do not represent the views of the publishing house and/or its editors. The publisher and/or its editors disclaim all responsibility for any harm or damage to persons or property that may result from the application of ideas, methods, instructions, or products discussed in the content. Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.