

Review article

Effects of Some Organic Fertilizer Sources on the Biological Health of Agricultural Soils

Tülay Dizikisa ^{a *} & Nesrin Yıldız ^b

^a Department of Plant and Animal Production, Vocational School, Ağrı İbrahim Çeçen University, Ağrı, Türkiye

^b Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Atatürk University, Erzurum, Türkiye

Abstract

Organic fertilizers directly shape microbial activity and biological cycles, which form the heart of the soil ecosystem. The effects of organic fertilizer sources of animal and plant origin on soil biological health vary depending on the form of the nutrients they contain and the quality of their carbon. In this review, the effects of certain animal- and plant-based fertilizers, compost, vermicompost, biochar-enriched organic materials, and waste-based organic sources on soil biological health were examined comparatively based on microbial biomass, enzyme activities, microbial diversity, carbon dynamics, and nutrient element transformations. The results of the study indicate that the biological effects of animal- and plant-based organic materials added to agricultural soils are determined by carbon quality, the carbon-to-nitrogen ratio, decomposition rate, nutrient composition, biologically active components, and application conditions. While animal-based manures support microbial activity and nutrient transformations in the short term due to their easily degradable organic compounds and high nutrient content, compost, vermicompost, biochar, and other carbon-stable organic materials play significant roles in maintaining the continuity of microbial habitats, conserving organic carbon, and supporting long-term biological functions. Furthermore, the effects of organic inputs cannot be explained solely by an increase in microbial biomass; they must also be evaluated in conjunction with changes in carbon use efficiency, enzyme activities, functional microbial capacity, and nutrient cycles. However, it is essential to acknowledge that organic amendments may contain hazardous residues and could pose potential risks to agricultural product safety and agroecosystems. Current findings indicate that, in sustainable soil management, integrated application strategies that leverage the complementary properties of diverse organic sources are more effective than relying on the superiority of a single organic material. It has been emphasized that, in the future evaluation of organic fertilizers, the use of next-generation molecular analyses which reveal the structure and function of microbial communities in conjunction with traditional biological indicators will contribute to a more comprehensive understanding of soil biological processes.

Keywords: Soil Biological Health, Organic Fertilizers, Soil Microbiome, Microbial Activity, Soil Enzyme Activities, Carbon-to-Nitrogen Ratio (C/N Ratio), Soil Organic Carbon, Soil Biota

Received: 08 August 2026 * **Accepted:** 21 September 2026 * **Published:** 30 September 2026

* Corresponding author:

Tulay Dizikisa is an associate professor in the Department of Plant and Animal Production at Ağrı İbrahim Çeçen University in Ağrı, Türkiye. Her research interests include Soil Sciences, Fertilizers and Plant Nutrition. She has lived, worked, and studied in Ağrı, Türkiye.
Email: dizikisa@agri.edu.tr

INTRODUCTION

Today, the unconscious or indiscriminate use of all inputs employed in soil management (organic and inorganic fertilizers, water, and other amendment materials, etc.) results in the deterioration of soil physical, chemical, and biological health and quality, giving rise to problems that threaten food security and the environment. Organic amendment materials play an important role in improving soil properties, helping to stabilize and increase crop yield (Diacono and Montemurro, 2010). Numerous studies (Lammey and Angers, 2012; Angelova et al., 2013; Singh et al., 2024) have investigated the effects of organic amendments on various aspects of crop production, including soil biology and biochemistry. However, these studies have predominantly focused on isolated aspects rather than adopting a comprehensive perspective. Therefore, a comprehensive analysis of the positive and negative effects of organic amendments is important for optimizing fertilizer use in order to meet the nutrient requirements of crops and advance carbon-neutral agriculture. As an important category of fertilizers, organic amendments (conditioners) are derived from plant residues, animal manures, composted materials, and other sources of biological origin. There are six types of organic amendments applied to soils: plant, human, and animal manure, municipal biosolids, green manure and crop residues, food residues and waste, waste from production processes, and composts. Organic amendments can replenish soil organic matter, reactivate microbial communities, improve soil structure, alleviate soil acidification, and reduce environmental pollution (Lammey and Angers, 2012 and Angelova et al., 2013). Consequently, they enable sustainable increases in crop yield without degrading agricultural land, while also enhancing crop quality and nutritional value. Organic amendments primarily contain nutrients in organic forms that cannot be directly utilized by plants. These amendments are produced by microorganisms through anaerobic and aerobic processes. During this biochemical transformation, essential mineral nutrients such as carbon dioxide (CO₂), H₂O, nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca) are produced, and humic substances are formed.

Numerous studies (Angelova et al., 2013 and Singh et al., 2024) have reported that organic amendments, characterized by high organic matter content, comprehensive nutrient profiles, and long-lasting fertilization effects, can effectively enhance soil microbial communities, improve soil fertility, and elevate the quality of agricultural products. Moreover, organic amendments play an important role in recycling and environmental protection, in line with the requirements of organic and eco-agricultural practices (Aytenew and Bore, 2020). In addition, modern organic amendments are highly effective in preserving soil ecology. Amendments such as biochar-based organic fertilizer (a carbon-rich substance) have, in recent years, attracted wide interest and found broad application as a new type of ecological fertilizer. Research has shown that adding 10% biochar to the composting process can significantly reduce the combined emissions of ammonia (NH₃) and greenhouse gases (Chung et al., 2021). Therefore, applying an appropriate amount of organic additives to agricultural land is a promising approach for resource utilization and sustainable development, effectively converting waste into

valuable resources. However, it is essential to acknowledge that organic amendments may contain hazardous residues and pose potential risks to agricultural product safety and agroecosystems. For instance, most organic amendments, such as animal manure, generally contain more harmful compounds than chemical fertilizers, including heavy metals, amendment residues, and even microbial pathogens. Moreover, the application of organic amendments to soil can lead to an increase in greenhouse gas emissions. Reports indicate that more than 80% of anthropogenic nitrous oxide (N₂O) emissions and 70% of anthropogenic NH₃ emissions in agriculture are primarily attributed to the application of animal manure and inorganic fertilizers.

In addition, a study by He et al. (2023) showed that replacing chemical fertilizers with organic amendments significantly reduces N₂O emissions but increases methane (CH₄) and carbon dioxide (CO₂) emissions, thereby worsening the global warming potential (GWP). Excessive use of organic fertilizers can exceed the soil's self-digestion capacity, leading to secondary pollution that may hinder long-term crop productivity. Unlike fast-release nutrient fertilizers, organic amendments are highly diverse, possess complex components, and undergo complex reactions in the soil, making their effects on soil ecosystems uncertain. This review aims to summarize the effects of organic amendment application on the physicochemical and biological properties, soil heavy metals, and greenhouse gas emissions of agricultural land soils, to examine the mechanisms underlying the impact of organic amendments on soil health and fertility, and to compare their effects with those of chemical fertilizers, thereby providing a comprehensive understanding of the advantages and disadvantages of organic amendments. This information can serve as a valuable reference for the rational application of organic amendments in agricultural practices (Xu et al., 2025).

In recent years, in the development of sustainable agricultural systems, it has become a fundamental approach to regard soil not merely as a growth medium supporting plant development, but as a living, dynamic, and multifunctional system that, through continuous interactions among its physical, chemical, and biological components, drives fundamental ecosystem processes such as carbon transformation, nutrient element cycling, aggregate formation, water regulation, and environmental resilience (Jansson & Hofmockel, 2020; Karlen et al., 2003; Bünemann et al., 2018; Hartmann & Six, 2023). Therefore, the concepts of soil quality and soil health are today evaluated holistically, not only in terms of organic matter content or nutrient element levels, but also in terms of the structure and functional capacity of microbial communities and their contributions to ecosystem processes (Delgado-Baquerizo et al., 2021; Dikici et al., 2017).

Soil biological health is one of the fundamental components of this holistic approach, referring to soil's capacity to sustain biological diversity, microbial functions, and ecosystem processes. However, intensive tillage, excessive reliance on and indiscriminate use of mineral fertilizers, losses of organic matter, and other intensive agricultural practices can adversely affect biological health by reducing soil organic carbon, weakening microbial diversity, and disrupting nutrient element cycles (Hartmann & Six,

2023). Therefore, microbial biomass, microbial diversity, soil enzyme activities, and carbon use efficiency are regarded among the most sensitive “soil biological quality indicators” for evaluating soil's biological functions and its responses to management practices (Fierer, 2017; Sokol et al., 2022; Hartmann & Six, 2023). In particular, carbon use efficiency (CUE) reflects the partitioning of carbon taken up by microorganisms between biomass formation and carbon released to the atmosphere through respiration, thereby providing important information about both microbial carbon use strategies and the long-term preservation of soil organic carbon. For this reason, CUE is regarded as an integrative biological indicator that reveals not only microbial biomass but also the efficiency of carbon utilization within the soil ecosystem (Figure 1).

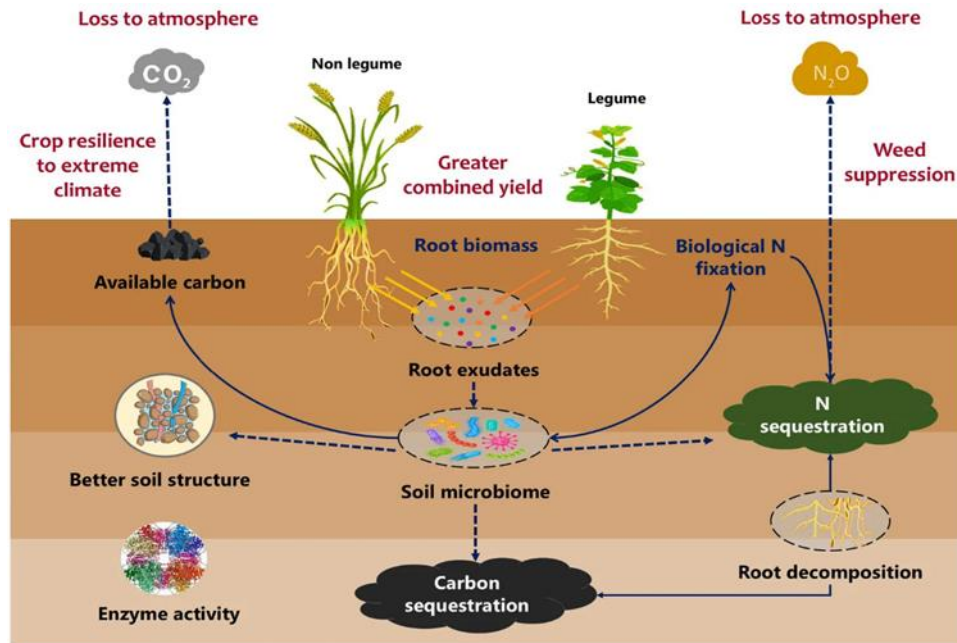


Figure 1. Fundamental microbial functions and organic matter transformation processes in the plant-soil system. Source: Hartmann and Six, 2023.

Organic fertilizer applications are recognized as one of the most important sustainable management strategies for preserving and improving soil biological health. Organic materials are not merely inputs that supply macro- and micronutrient elements to plants; they also serve as a carbon and energy source for soil microorganisms, thereby regulating the structure, diversity, and functional activities of microbial communities, and supporting fundamental biological processes such as carbon storage, nutrient element transformations, and soil aggregate formation (Trivedi et al., 2020). However, the biological effects of organic fertilizers vary considerably depending on carbon quality, the carbon/nitrogen (C/N) ratio, the chemical structure of organic compounds, decomposition rate, degree of humification, and the biologically active compounds they contain (Bonanomi et al., 2018; Lehmann et al., 2020; Hartmann & Six, 2023; İlay et al., 2021). In general, easily decomposable organic materials accelerate microbial activity and nutrient transformations in the short term, while materials with a more stable carbon structure provide more pronounced contributions in the long term in terms of preserving

organic carbon, ensuring the continuity of microbial habitats, and enhancing ecosystem resilience (Lavallee et al., 2020).

In addition to animal manures, compost, vermicompost, and green manures, alternative organic sources such as biochar, biosolids, and appropriately processed organic wastes are also gaining increasing importance in agricultural production systems alongside the development of circular bioeconomy and sustainable waste management approaches. However, the biological effects of different organic sources are shaped not only by their chemical composition but also by their production processes, application conditions, stability characteristics, and environmental safety criteria. Therefore, in evaluating organic fertilizers, attention should be paid not only to the nutrient elements they provide but also to how they affect the soil microbiome, carbon dynamics, and long-term ecosystem functions (Agegnehu et al., 2017; Lehmann et al., 2020; Hartmann & Six, 2023; Howe et al., 2024).

Past studies have predominantly focused on the effects of organic fertilizers and other organic soil amendments on crop yield, soil organic carbon, nutrient element dynamics, and physical and chemical soil properties. Furthermore, although the effects of organic materials on soil microbial communities have been addressed in numerous reviews, these evaluations have largely concentrated on specific materials (e.g., biochar or compost) or single biological indicators. In contrast, studies that comparatively and holistically assess the effects of different organic fertilizer sources on microbial biomass, enzyme activities, carbon use efficiency (CUE), microbial diversity, and functional microbial processes-the determinants of soil biological health-remain limited. Therefore, there is a need to re-evaluate the effects of organic fertilizers on soil biological health on the basis of ecosystem functions and microbial processes (Lehmann et al., 2020; Siedt et al., 2021; Blanco-Canqui, 2021; Hartmann & Six, 2023).

Recent meta-analyses have demonstrated that the combined use of carbon-stable organic materials with microbial inputs can support soil microbial functions, highlighting the importance of complementary use strategies for organic materials (Ross & Emery, 2025).

Therefore, organic-based soil amendments are regarded not merely as inputs supplying plant nutrient elements, but as biological management tools that increase soil organic matter, support microbial activity, regulate nutrient cycles, and contribute to the restoration of ecosystem functions in degraded soils (İlay et al., 2021; Larney & Angers, 2012; Okur et al., 2008).

Studies conducted in recent years show that the effects of organic fertilizers on soil biological health cannot be explained solely by changes occurring in microbial biomass; rather, these effects can be more accurately elucidated through the joint evaluation of complementary biological processes such as microbial community structure, functional genes, enzyme activities, carbon use efficiency, and ecosystem resilience (Moorhead et al., 2013; Shu et al., 2022; Cui et al., 2023; Hartmann & Six, 2023).

The aim of this review is to comparatively evaluate the effects of different organic fertilizer sources on the biological health of agricultural soils on the basis of microbial biomass, enzyme activities, carbon use efficiency, microbial diversity, carbon dynamics, and ecosystem resilience. In this context, animal-derived manures, compost, vermicompost, biochar-supported organic materials, plant-derived inputs, and waste-based organic sources are examined in light of current literature in terms of their contributions to shaping the soil microbiome, regulating biological processes, and the long-term functionality of sustainable agroecosystems.

Comparative Effects of Different Organic Fertilizer Sources On Soil Biological Health

Microbial Diversity and Population Dynamics

Animal Manures: Manures from animals such as cattle, sheep, and poultry release high proportions of readily available nitrogen and easily decomposable carbon into the soil. This causes a very rapid increase in microbial biomass, particularly stimulating bacteria involved in the nitrogen cycle. However, fresh animal manures can exert short-term pressure on soil microflora due to the antibiotic residues and pathogens they contain.

Plant-Based Fertilizers: Plant-derived sources such as green manure, straw, compost, and press cake/meal are rich in complex carbon compounds such as cellulose and lignin. These compounds decompose more slowly, providing long-term, balanced microbial diversity in the soil. They steadily increase the population of plant growth-promoting rhizobacteria (PGPR) and beneficial fungi.

Soil Enzyme Activities

Both sources significantly increase the activity of enzymes, the biocatalysts of soil:

Carbon and Nitrogen Cycle Enzymes: Plant-based sources promote the secretion of β -glucosidase and cellulase enzymes to break down complex carbon bonds. Animal manures, on the other hand, rapidly drive urease enzyme activity to its peak owing to their high nitrogen content.

Phosphorus Cycle Enzymes: Phosphatase enzyme, which solubilizes phosphorus that cannot otherwise be taken up by plants, increases in both sources depending on organic matter input. This reduces dependence on chemical fertilizers.

Soil Food Web and Pest Suppression

Beneficial Nematodes and Earthworms: The stable organic matter layer formed by plant-derived fertilizers creates a sustainable food base for earthworms and beneficial nematodes. Soil porosity and aggregate stability increase as a result.

Biocontrol (Disease Suppression): Plant-based composts and matured animal manures multiply beneficial microorganisms such as *Trichoderma*, *Bacillus*, and *Pseudomonas* in the soil. These

beneficial species compete with and suppress harmful fungi that attack plant roots (*Fusarium*, *Phytophthora*), leading to the formation of disease-suppressive soils.

Table 1. Comparison summary of animal-derived and plant-derived sources

Parameter	Animal-Derived Manures	Plant-Derived Fertilizers
Decomposition Rate	Very rapid / Effective in the short term	Slow and steady / Effective in the long term
C/N (Carbon/Nitrogen) Ratio	Low (rapidly consumed by microorganisms)	High (leaves persistent humus in the soil)
Microbial Response	Rapid bacterial bloom	Balanced bacterial and fungal (mycorrhizal) development
Risk Factors	Salinity, pathogen, and antibiotic risk	Temporary nitrogen immobilization at high C/N ratio

Source: Chen et al., 2025.

The effects of different organic fertilizer sources on soil biological health (Table 1) vary depending on the materials carbon structure, nutrient element content, and decomposition characteristics (Chen et al., 2025). Animal-derived manures generally support short-term microbial processes owing to their rapidly decomposable organic compounds and high nutrient element content, whereas materials containing more stable carbon, such as compost, vermicompost, and biochar, produce more pronounced effects on long-term carbon dynamics and the continuity of microbial functions (Liu et al., 2023). Therefore, the biological effects of organic sources should be evaluated not only in terms of the nutrient elements they provide but also jointly in terms of their contributions to the soil microbiome and ecosystem processes (Lori et al., 2017; Bonanomi et al., 2018; Lehmann et al., 2020; Hartmann & Six, 2023).

Classifications based solely on origin are insufficient for evaluating the biological effects of organic fertilizer sources. The fundamental functions of these materials within the soil ecosystem should be assessed by taking into account their decomposition rate, carbon stability, nutrient element release capacity, and their properties in directing microbial processes. Therefore, in terms of their biological effects, organic sources can be functionally grouped as materials that support rapid microbial activation, materials that provide carbon stabilization, and materials that contribute to nutrient recovery (Thapa et al., 2025; Caldara et al., 2026; Xing et al., 2025).

Animal-derived organic fertilizers are among the important organic inputs that rapidly affect soil biochemical processes owing to their high nutrient element content and decomposable organic carbon fractions. The effects of farmyard manure, poultry manure, horse manure, and other animal-derived materials are determined not only by the nutrient elements they contain but also by properties such as the chemical structure of carbon, the C/N ratio, the amount of decomposable carbon, and the degree of maturity (Okur et al., 2008; Çengel et al., 2009; Bonanomi et al., 2018; Lehmann et al., 2020).

The carbon quality of organic material is an important factor determining the functional characteristics of microbial communities. While easily usable carbon fractions support fast-growing

microorganism groups, more recalcitrant carbon compounds can promote the development of communities with high resource use efficiency and the ability to adapt to low-nutrient conditions (Fierer et al., 2007; Fontaine et al., 2007; Lehmann et al., 2020).

Applications of animal manure have been reported to support carbon, nitrogen, and phosphorus transformations by increasing microbial biomass carbon, microbial biomass nitrogen, soil respiration, and enzyme activities such as β -glucosidase, urease, phosphatase, and dehydrogenase (Burns et al., 2013; Lori et al., 2017; Bünemann et al., 2018; Liu et al., 2020). However, different animal sources do not produce the same biological response. Farmyard manure, owing to its varied decomposable carbon fractions, can support both short- and long-term processes; poultry manure, due to its low C/N ratio, provides rapid nutrient release but exhibits more limited carbon stabilization. Horse manure, on the other hand, can display more balanced decomposition characteristics owing to its higher carbon content (Lori et al., 2017; Rayne & Aula, 2020; Hartmann & Six, 2023; Howe et al., 2024).

Guano and manure-derived materials obtained after anaerobic fermentation are also organic sources that can be utilized in agricultural production owing to their high nutrient content. However, the low content of easily decomposable carbon in these materials may limit long-term microbial carbon input (Agegnehu et al., 2017; Hartmann & Six, 2023). Therefore, using animal-derived manures together with carbon-rich materials can help balance rapid nutrient release with the formation of more persistent organic matter (Lavalley et al., 2020; Hartmann & Six, 2023). Nevertheless, the biological effects of animal-derived manures are not limited solely to increases in microbial biomass. These materials can also alter the rate and direction of soil nutrient cycles, particularly through nitrogen mineralization, phosphorus solubilization, and enzyme-mediated nutrient transformations.

Carbon-stable, plant-derived, and processed waste-based organic materials are important organic sources in terms of carbon preservation, the development of microbial habitats, and the continuity of biological processes in soil. The effects of these materials are determined by the chemical structure of the carbon compounds, their resistance to decomposition, degree of humification, and the capacity of microbial communities to utilize these carbon fractions (Lehmann et al., 2020; Lavalley et al., 2020; Hartmann & Six, 2023).

Compost and vermicompost are important organic amendments that form as a result of the controlled biological transformation of organic materials and contain more stable carbon compounds. The decrease in easily decomposable carbon fractions and the increase in humified organic compounds during the composting process contribute to the longer-term preservation of carbon in soil (Bernal et al., 2009). In addition, applications of mature compost have been reported to produce positive effects on microbial diversity, the continuity of decomposer communities, and organic matter transformation processes (Mäder et al., 2002; Arancon et al., 2005; Lazcano & Domínguez, 2011). Vermicompost, owing to the humic substances, microbial metabolites, and biologically active components it contains,

can support microbial interactions and plant-microbe relationships, particularly in the rhizosphere (Joshi et al., 2015; Kraut-Cohen et al., 2023; Pan & Huang, 2024; Toprak & Kızılkaya, 2026).

Biochar is one of the important organic materials that supports long-term carbon storage in soil, owing to its high aromatic carbon content, which confers high carbon stability and resistance to decomposition. However, the effects of biochar on soil biological processes are not limited solely to carbon stabilization. Its porous structure and large surface area create protective microhabitats for microorganisms, supporting microbial colonization and potentially influencing the mobility of carbon and nutrient elements in the rhizosphere (Agegehu et al., 2017; Lehmann et al., 2020). Applying biochar together with compost or other organic materials can produce complementary effects in terms of improving carbon quality and supporting microbial functions (Irmak Yılmaz & Kurt, 2018). The biological effects of these materials are not explained solely by the physical preservation of carbon; they are also associated with their effects on the functional diversity of microbial communities, enzyme production, and the capacity to adapt to environmental changes.

Plant residues and green manures play a determining role in decomposition processes and the selection of microbial communities by providing important carbon inputs to agricultural ecosystems. The biological effects of these materials largely depend on structural properties such as the C/N ratio and lignin and cellulose content. Materials with a low C/N ratio decompose more rapidly, whereas plant residues with high structural carbon content can contribute to the longer retention of carbon in soil (Diacono & Montemurro, 2010; Lal, 2020; Lavallee et al., 2020). Biosolids and other waste-derived organic materials are sources with potential for reintroducing organic carbon and nutrient elements into agricultural cycles. However, the use of these materials requires appropriate processing methods and quality standards to be ensured, owing to their heavy metal content, organic pollutants, and microbiological risks (Edwards & Someshwar, 2000; Epstein, 2003; Shober et al., 2003; Kätterer et al., 2012).

Meta-analysis studies conducted in recent years show that organic amendments generally produce positive effects on soil microbial communities, microbial biomass, and enzyme activities, but that these effects are substantially regulated by the properties of the organic material, application conditions, and the soil environment (Cui et al., 2023; Kumar et al., 2025; Gil-Martínez et al., 2025). These findings support the notion that, in evaluating organic fertilizers, it is not a single biological indicator but rather microbial structure, function, and carbon transformation processes that must be considered together. Microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), soil respiration, and carbon use efficiency (CUE) are the key indicators used to evaluate the effects of organic inputs on soil biological processes. These parameters reveal the manner in which organic carbon is utilized by microbial communities and its orientation within biological processes (Bünemann et al., 2018; Lehmann et al., 2020; Ouyang et al., 2022).

The effects of organic fertilizers on microbial biomass are determined less by the amount of carbon applied than by the chemical structure and decomposability of that carbon. Materials containing easily decomposable carbon accelerate microbial growth and nutrient transformations in the short term, whereas resistant carbon fractions contribute to longer-term carbon preservation and the development of stable microbial communities (Geisseler & Scow, 2014; Lavalley et al., 2020). Animal sources such as farmyard manure and poultry manure produce rapid responses in microbial biomass and mineralization processes owing to their high nutrient element content and easily usable organic compounds. Farmyard manure provides a more balanced decomposition process owing to its varied carbon fractions, while poultry manure, due to its low C/N ratio, particularly accelerates nitrogen transformations (Lori et al., 2017; Howe et al., 2024).

In stabilized materials such as compost and vermicompost, the slower decomposition of carbon creates a more balanced carbon source that supports the continuity of microbial processes. These materials provide significant advantages, particularly in terms of long-term organic matter management and carbon stabilization (Bernal et al., 2009; Lazcano & Domínguez, 2011). In biochar applications, biological effects are largely associated with the microhabitats formed by the porous structure and with stable carbon fractions. The combined use of biochar with compost or other organic materials can support the balance between microbial activity and carbon preservation (Agegnehu et al., 2017; Jeffery et al., 2017). Recent meta-analysis studies show that biochar applications can increase microbial biomass carbon under field conditions, but that this effect varies depending on soil properties, climatic conditions, and biochar characteristics (Kumar et al., 2025).

The effects of biochar on soil biological processes are not limited solely to carbon stabilization but also manifest through changes in microbial biomass and enzyme activities. Consequently, the biological effects of organic fertilizers should be evaluated not only in terms of changes occurring in microbial biomass but also together with the manner in which carbon is utilized by microbial communities and its circulation within the ecosystem. Soil enzyme activities are important indicators for evaluating how organic fertilizer applications translate into biological functions. Enzymes such as β -glucosidase, dehydrogenase, urease, and phosphatase play roles in fundamental biochemical processes such as carbon decomposition, nitrogen mineralization, and phosphorus transformation (Dick, 1994; Burns et al., 2013; Nannipieri et al., 2018). Animal manures, owing to their easily decomposable organic compounds, can cause increases in enzyme activities particularly in the short term. In contrast, mature materials such as compost and vermicompost support the continuity of enzymatic processes owing to their more balanced carbon structures (Bonanomi et al., 2018).

New-generation molecular approaches show that organic fertilizers affect not only the diversity of microbial communities but also their functional capacities involved in carbon, nitrogen, and phosphorus cycles. Therefore, in evaluating the biological effects of organic sources (Table 2), functional microbial capacities should be considered in addition to taxonomic diversity (Semenov et al.,

2025). These findings show that organic fertilizers primarily affects soil biological health by regulating the functional capacity of microbial communities and nutrient cycles.

Table 2. Comparative effects of different organic fertilizer sources on soil biological health

Organic source	Dominant characteristics	Effect on soil biological processes	Key findings reported in the literature	Management evaluation
Farmyard manure	Balanced C/N ratio; structure rich in organic carbon and nutrient elements	Supports microbial biomass, enzyme activities, and organic matter transformation	Long-term applications have been reported to increase MBC, soil respiration, and biological activity (Lori et al., 2017; Hartmann & Six, 2023)	A balanced organic source that can provide both short- and long-term biological gains together
Poultry manure	Low C/N ratio, high N and P content, rapidly decomposable carbon	Increases rapid microbial activation and nutrient element mineralization	Strong increases in nitrogen transformation and microbial activity have been shown; however, high mineralization may increase environmental loss risks (Ma et al., 2020; Howe et al., 2024)	More sustainable when used together with carbon-rich materials
Compost	Stable carbon fractions, humic substances, low decomposition rate	Supports microbial diversity, carbon stabilization, and aggregate formation	Meta-analyses show that compost applications produce positive effects on microbial functions and soil organic carbon (Bonanomi et al., 2018; Cui et al., 2023)	An important material for improving long-term soil biological quality
Vermicompost	Rich in humic substances, biologically active compounds, and beneficial microorganisms	Supports the rhizosphere microbiome and plant-microbe interactions	Increases in microbial activity, enzyme activities, and plant growth have been reported (Lazcano & Domínguez, 2011; Joshi et al., 2015)	Particularly valuable in systems targeting high biological activity and plant growth
Biochar + organic materials	Stable aromatic carbon, high porosity and surface area	Increases microbial habitat formation, carbon preservation, and nutrient retention	Biochar-organic fertilizer combinations yield more successful results in terms of carbon sequestration and microbial stabilization (Jeffery et al., 2017; Agegnehu et al., 2017)	Combined applications may be more effective than use alone
Green manure and plant residues	Plant-derived carbon input, variable C/N ratio	Provides a microbial energy source and supports the carbon cycle	Green manures have been shown to support microbial biomass and nutrient cycles (Diacono & Montemurro, 2010; Lori et al., 2017)	Of strategic importance in increasing soil organic carbon
Manure (excreta)	Rich in mineral N and P, low easily decomposable carbon	Supports nutrient element recovery and mineralization processes	Effective for plant nutrition, but microbial carbon input may be limited (Hartmann & Six, 2023; Howe et al., 2024)	Should be evaluated together with carbon-rich organic materials
Sewage sludge (biosolids)	Source of organic matter and	Can increase microbial activity but	Properly stabilized materials can contribute to soil organic matter;	Can be considered an alternative

nutrient elements, variable quality	requires quality control	pollutant risk should be monitored (Epstein, 2003; Kätterer et al., 2012)	source when safety standards are met
--	-----------------------------	--	--

Source: Epstein, 2003; Diacono & Montemurro, 2010; Lazcano & Domínguez, 2011; Kätterer et al., 2012; Joshi et al., 2015 Agegnehu et al., 2017; Jeffery et al., 2017; Lori et al., 2017; Bonanomi et al., 2018; Ma et al., 2020; Cui et al., 2023; Hartmann & Six, 2023; Howe et al., 2024.

CURRENT LIMITATIONS and FUTURE RESEARCH PRIORITIES

Although significant progress has been achieved regarding the effects of organic fertilizers on soil biological health, certain fundamental uncertainties persist concerning how different organic sources direct microbial processes and ecosystem functions. Existing studies are predominantly conducted using traditional biological indicators such as microbial biomass, soil respiration, and enzyme activities. While these parameters reveal general changes in biological activity, they cannot fully explain the functional capacity, metabolic potential, or specific roles of microbial communities in the transformation of carbon and nutrient elements (Bünemann et al., 2018; Hartmann & Six, 2023).

An important research gap in evaluating the effects of organic fertilizers on soil biological health is determining how carbon is utilized within microbial metabolism, beyond microbial activity alone. Although microbial biomass and enzyme activities are important indicators of biological responses, they cannot directly reveal whether carbon is directed toward microbial growth or lost through respiration. At this point, carbon use efficiency (CUE) is regarded as a complementary indicator for understanding the effects of organic fertilizer applications on long-term carbon preservation and microbial functions, by showing the partitioning of carbon supplied from organic inputs between microbial growth and carbon loss. In future organic fertilizer research, addressing CUE together with microbial functional genes, microbial community structure, and carbon transformation processes will enable a more mechanistic explanation of the ecological effects of different organic sources.

Therefore, in future evaluations of organic fertilizers, methods aimed at directly determining microbial functions should be used more extensively, rather than relying solely on approaches based on microbial quantity. Next-generation molecular approaches, such as metagenomics, metatranscriptomics, and functional gene analyses, enable a more detailed assessment of biological processes related to carbon decomposition, nitrogen mineralization, phosphorus transformation, and stress tolerance. Furthermore, using these methods together with traditional biological indicators will contribute to a more comprehensive understanding of the true functional effects of organic inputs on soil ecosystems (Hartmann & Six, 2023; Semenov et al., 2025).

Another important limitation is that the majority of organic fertilizer sources have been evaluated individually. However, the chemical and biological properties of different materials can be complementary in nature. While rapidly decomposing, nutrient-rich organic sources support microbial activation, carbon-stable materials can contribute to carbon preservation and the development of

microbial habitats. Therefore, future studies are needed to determine the long-term biological effects of combinations of compost, biochar, animal manures, and plant-derived materials at different ratios (Lehmann et al., 2020; Cui et al., 2023).

Table 3. Current research limitations and future priorities in evaluating the effects of organic fertilizers on soil biological health

Research area	Current level of knowledge	Key limitations	Future research priorities
Microbial biological indicators	Microbial biomass, soil respiration, and enzyme activities are widely used	These indicators are limited in explaining the full range of microbial functions and genetic mechanisms	Integrating metagenomic, metatranscriptomic, and multi-omics approaches into soil biological assessments
Comparisons of organic materials	Most studies evaluate the effects of a single organic fertilizer source	The long-term effects of combinations of different organic sources are not sufficiently known	Investigating combinations of compost, biochar, animal manure, and plant-derived inputs at different ratios
Carbon transformation and sequestration	It is known that organic inputs can increase soil organic carbon	The microbial pathways through which carbon is stabilized and its persistence are not fully explained	Jointly examining carbon use efficiency (CUE), microbial necromass formation, and carbon stabilization mechanisms
Long-term field effects	Numerous studies exist under short-term and controlled conditions	Transferability of laboratory results to different agroecological conditions is limited	Increasing long-term, standardized field trials under different climate and soil conditions
Microbial network structures and functional relationships	It is known that organic inputs affect microbial diversity	Relationships between species diversity and ecosystem functions have not been fully elucidated	Jointly evaluating microbial network analyses, functional genes, and ecosystem processes
Climate change effects	Evidence exists that organic fertilizers may increase soil resilience	Effects under drought, rising temperatures, and extreme climate events are not sufficiently known	Developing long-term models explaining climate-soil-microbiome interactions
Digital soil health monitoring	Sensor technologies and data analysis methods are advancing	Standard measurement and evaluation systems for biological indicators are limited	Developing AI-supported biological monitoring systems and decision-support models

Lehmann et al. (2020); Hartmann & Six (2023); Cui et al. (2023); Howe et al. (2024); Semenov et al. (2025).

CONCLUSION AND RECOMMENDATIONS

Conclusion

Organic fertilizer sources significantly improve the biological health of agricultural soils by increasing microbial diversity, elevating soil enzyme activities, and enriching beneficial taxa. Different source materials, such as plant residues and animal manures, lead to distinct microecological changes from one another.

Microbial Community and Diversity: Animal-derived manures (e.g., cattle or poultry manure) tend to substantially increase overall microbial species richness and enrich nitrogen cycling pathways.

Plant-derived fertilizers (e.g., green manure, straw, or bean press cake) preserve stable microbial communities, support root development, and present a lower risk profile in terms of antibiotic resistance genes. Beneficial taxa such as Actinobacteria, Proteobacteria, and Gemmatimonadota proliferate rapidly in response to the carbon substrates supplied by organic fertilizers.

In particular, carbon use efficiency offers an important conceptual framework for understanding the effects of organic fertilizer applications on microbial processes. What should be considered is not merely whether organic inputs increase microbial biomass, but the extent to which microbially utilized carbon is directed toward growth, necromass formation, and long-term carbon storage. Nevertheless, the evaluation of soil biological health should not be limited to carbon fluxes alone; it should be addressed together with indicators such as nitrogen and phosphorus transformations, enzyme activities, microbial diversity, and functional gene profiles. This perspective shows that the effects of organic fertilizers on soil biological health can be more accurately revealed not through quantity-based indicators alone, but through the joint evaluation of microbial functions and carbon fluxes. In this way, the evaluation of soil biological health is evolving from the question of "how much microbial activity is there?" toward the question of "which ecological functions does this activity support?"

However, the existing literature shows that the effects of organic fertilizers are substantially shaped by soil type, climatic conditions, application dose, the maturity level of the material, and management practices. Therefore, rather than determining the effect of a single organic source, future research should evaluate the long-term biological outcomes of combinations of different organic materials under diverse agroecological conditions. In particular, the use of metagenomics, metatranscriptomics, microbial network analyses, and carbon-nutrient flux models together with traditional biological indicators will enable a more mechanistic understanding of the true functions of organic inputs within soil ecosystems.

Recommendations

To sustain agricultural productivity, implementing optimal nutrient management strategies that increase nutrient use efficiency and preserve soil fertility and functionality, in addition to the use of chemical fertilizers, has become an urgent necessity in agricultural production. Future research should focus on the following areas:

Greater emphasis should be placed on returning organic materials to agricultural land. Organic amendment materials obtained from agriculture, livestock farming, industry, and household waste can be recycled as fertilizers and largely assimilated within the soil system. This practice significantly reduces emissions to water resources and the atmosphere, mitigating the continuous cycling of pollutants within ecosystems. Increasing the amount of organic waste returned to the field is the most effective proactive measure for reducing and preventing organic pollution in the ecological environment. The

recycling of these organic materials serves not only the purpose of fertilization but, more importantly, also serves the preservation of the ecological environment.

The investigation and development of appropriate collection and processing systems for organic waste arising from plant and livestock activities at different scales. In modern agricultural production practices, the spatial separation between crop cultivation and livestock farming has become increasingly pronounced, making the on-site recycling of organic fertilizer nutrients to agricultural land more difficult. Developing appropriate collection and processing systems for organic waste arising from agricultural activities at various scales will enrich the soil organic matter pool by enabling a large proportion of organic material to be scientifically processed and subsequently returned to the fields.

Application technologies for organic fertilizers should be developed. The management of organic fertilizers in agricultural production should be strengthened. Strict regulations should be introduced regarding the application standards of organic fertilizers. High-quality organic fertilizers with low heavy metal and persistent pollutant content should be selected. Integrated application technologies should be established for organic fertilizers, and the application method should be optimized through region-specific and time-appropriate application and the combination of organic and inorganic fertilizers. These measures will minimize the environmental risks associated with the application of organic fertilizers (Xu et al., 2025).

In conclusion, sustainable organic fertilizer management should be approached not so much through the question of "which organic fertilizer is the most effective?" but rather through the question of "which organic strategy supports which soil biological function?" Future soil management systems should be based on management models that holistically consider ecosystem processes and take advantage of the complementary properties of organic sources that provide rapid biological stimulation and materials that support long-term carbon and microbial stabilization. This approach forms the foundation of next-generation soil management, aiming not only to increase productivity but also to preserve the biological resilience, functionality, and sustainability of soils under changing environmental conditions.

Additional Declaration

Author Contributions

In this study, the contribution of the authors was equal; both authors contributed equally to the development of the research idea, data analysis, writing and proofreading stages.

Funding

This study was not funded by any institution or organization.

Responsible Artificial Intelligence Statement

In this study, artificial intelligence tools grammarly were used in language editing. The artificial intelligence tool was used to correct language errors by the authors.

Conflicts of Interest

The authors declare that there are no conflicts of interest related to the publication of this study.

Ethics Approval

In all processes of this study, the principles of Pen Academic Publishing Research Ethics Policy were followed.

This study does not require ethics committee approval as it does not involve any direct application on human or animal subjects.

REFERENCES

- Agegnehu, G., Srivastava, A. K., & Bird, M. I. (2017). The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Applied Soil Ecology*, 119, 156-170.
- Angelova, V. R., Akova, V. I., Artinova, N. S., & Ivanov, K. I. (2013). The effects of organic amendments on soil chemical characteristics. *Bulgarian Journal of Agricultural Science*, 19(5), 958-971.
- Arancon, N. Q., Edwards, C. A., Bierman, P., Metzger, J. D., & Lucht, C. (2005). Effects of vermicomposts produced from cattle manure, food waste and paper waste on the growth and yield of peppers in the field. *Pedobiologia*, 49(4), 297-306.
- Aytenew, M., & Bore, G. (2020). Effects of organic amendments on soil fertility and environmental quality: A review. *Plant Science*, 8(5), 112-119.
- Bernal, M. P., Albuquerque, J. A., & Moral, R. (2009). Composting of animal manures and chemical criteria for compost maturity assessment: A review. *Bioresource Technology*, 100(22), 5444-5453.
- Blanco-Canqui, H. (2021). Does biochar improve all soil ecosystem services? *GCB Bioenergy*, 13(2), 291-304.
- Bonanomi, G., Lorito, M., Vinale, F., & Woo, S. L. (2018). Organic amendments, beneficial microbes, and soil microbiota: Toward a unified framework for disease suppression. *Annual Review of Phytopathology*, 56, 1-20.
- Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Flesskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality A critical review. *Soil Biology and Biochemistry*, 120, 105-125.
- Burns, R. G., DeForest, J. L., Marx, M. C., Stott, D. E., Smalla, K., Tebbe, C. C., Freeman, C., Mitchell, R. J., & Whiteley, A. S. (2013). Soil enzymes in a changing environment: Current knowledge and future directions. *Soil Biology and Biochemistry*, 58, 216-234.
- Caldara, M., Di Gregorio, L., Sarvi, M., Graziano, S., Bindo, A., Salo, T., Nolfi, L., Costanzo, M., Lamanna, G., Scanferla, V., Varese, G. C., Bernini, R., Palojarvi, A., Marmioli, N., & Bevivino, A. (2026). Impacts on soil health of soil improvers derived from agri-food processing residues: A systematic

- review with a focus on European field studies. *Journal of Soil Science and Plant Nutrition*, 26, 2858-2883.
- Çengel, M., Okur, N., & Yılmaz, F. İ. (2009). Organik bağ topraklarında yeşil gübre bitkileri ve çiftlik gübresi uygulamalarının topraktaki mikrobiyal aktiviteye etkileri. *Journal of Agriculture Faculty of Ege University*, 46(1), 25-31.
- Chen, X., Ma, X., Liu, Z., Gu, H., Fang, H., Shen, Z., Zhang, H., Wan, S., Li, W., Hao, X., Clarke, N. J., & Liu, J. (2025). Organic fertilizers increase microbial community diversity and stability slowing down the transformation process of nutrient cycling. *Environmental Microbiome*, 20, Article 91.
- Chung, W. J., Chang, S. W., Chaudhary, D. K., Shin, J., Kim, H., Karmegam, N., Govrathanan, M., & Ravindran, B. (2021). Effect of biochar amendment on compost quality gaseous emissions and pathogen reduction during in-vessel composting of chicken manure. *Chemosphere*, 289, 131129.
- Cui, J., Yang, B., Zhang, M., Song, D., Xu, X., Ai, C., Liang, G., & Zhou, W. (2023). Investigating the effects of organic amendments on soil microbial composition and its linkage to soil organic carbon: A global meta-analysis. *Science of the Total Environment*, 894, 164899.
- Delgado-Baquerizo, M., Eldridge, D. J., Liu, Y.-R., Sokoya, B., Wang, J.-T., Hu, H.-W., He, J.-Z., Bastida, F., Moreno, J. L., Bamigboye, A. R., Blanco-Pastor, J. L., Cano-Díaz, C., Illán, J. G., Makhallanyane, T. P., Siebe, C., Trivedi, P., Zaady, E., Verma, J. P., Wang, L., . . . Fierer, N. (2021). Global homogenization of the structure and function in the soil microbiome of urban greenspaces. *Science Advances*, 7(28), 1-14.
- Diacono, M., & Montemurro, F. (2010). Long-term effects of organic amendments on soil fertility: A review. *Agronomy for Sustainable Development*, 30, 401-422.
- Dick, R. P. (1994). Soil enzyme activities as indicators of soil quality. In J. W. Doran, D. C. Coleman, D. F. Bezdicek, & B. A. Stewart (Eds.), *Defining soil quality for a sustainable environment* (pp. 107-124). Soil Science Society of America. <https://doi.org/10.2136/sssaspecpub35.c7>
- Dikici, H., Qader, R. K., & Demir, Ö. F. (2017). Karbon/Azot oranının organik toprakların bazı özellikleri üzerine etkisi. *Toprak Su Dergisi, Özel Sayı*, 66-70.
- Edwards, J. H., & Someshwar, A. V. (2000). Chemical, physical, and biological characteristics of agricultural and forest by-products for land application. In J. F. Power, W. A. Dick, R. M. Kashmanian, J. T. Sims, R. J. Wright, M. D. Dawson, & D. Bezdicek (Eds.), *Land application of agricultural, industrial, and municipal by-products* (pp. 1-62). Soil Science Society of America.
- Epstein, E. (2003). *Land application of sewage sludge and biosolids*. CRC Press.
- Fierer, N. (2017). Embracing the unknown: Disentangling the complexities of the soil microbiome. *Nature Reviews Microbiology*, 15, 579-590.
- Fontaine, S., Barot, S., Barré, P., Bdioui, N., Mary, B., & Rumpel, C. (2007). Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature*, 450(7167), 277-280.
- Geisseler, D., & Scow, K. M. (2014). Long-term effects of mineral fertilizers on soil microorganisms-A review. *Soil Biology and Biochemistry*, 75, 54-63.
- Gil-Martínez, M., Madejón, P., Madejón, E., & de Sosa, L. L. (2025). Compost and vegetation cover drive soil fertility, microbial activity, and community in organic farming soils. *Plant and Soil*, 516(1-2), 299-321.

- Hartmann, M., & Six, J. (2023). Soil structure and microbiome functions in agroecosystems. *Nat Rev Earth Environ*, 4, 4-18.
- He, Z., Ding, B., Pei, S., Cao, H., Liang, J., & Li, Z. (2023). The impact of organic fertilizer replacement on greenhouse gas emissions and its influencing factors. *Science of the Total Environment*, 905, 166917.
- Howe, J. A., McDonald, M. D., Burke, J., Robertson, I., Coker, H., Gentry, T. J., & Lewis, K. L. (2024). Influence of fertilizer and manure inputs on soil health: A review. *Soil Security*, 16, 100155.
- İlay, R., Aktaş, M., Aslantekin, N. B., & Özcan, H. (2021). Farklı kaynaklardan elde edilen organik materyalin kumlu tın bünyeli toprağın bazı özellikleri üzerine etkileri. *Toprak Bilimi ve Bitki Besleme Dergisi*, 9(1), 30-38.
- Irmak Yılmaz, F., & Kurt, S. (2018). Biyokömür ve vermikompost uygulamalarının toprağın bazı biyolojik özellikleri üzerine etkisi. *Toprak Bilimi ve Bitki Besleme Dergisi*, 6(2), 143-150.
- Jansson, J. K., & Hofmockel, K. S. (2020). Soil microbiomes and climate change. *Nature Reviews Microbiology*, 18(1), 35-46.
- Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., van Groenigen, J. W., Hungate, B. A., & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters*, 12(5), 053001.
- Joshi, R., Singh, J., & Vig, A. P. (2015). Vermicompost as an effective organic fertilizer and biocontrol agent: Effect on growth, yield and quality of plants. *Reviews in Environmental Science and Bio/Technology*, 14, 137-159.
- Karlen, D. L., Ditzler, C. A., & Andrews, S. S. (2003). Soil quality: Why and how? *Geoderma*, 114(3-4), 145-156.
- Kätterer, T., Bolinder, M. A., Berglund, K., & Kirchmann, H. (2012). Strategies for carbon sequestration in agricultural soils in northern Europe. *Acta Agriculturae Scandinavica, Section A-Animal Science*, 62(4), 181-198.
- Kraut-Cohen, J., Zolti, A., Rotbart, N., Bar-Tal, A., Laor, Y., Medina, S., Shawahna, R., Saadi, I., Raviv, M., Green, S. J., Yermiyahu, U., & Minz, D. (2023). Short- and long-term effects of continuous compost amendment on soil microbiome community. *Computational and Structural Biotechnology Journal*, 21, 3280-3292.
- Kumar, Y., Ren, W., Tao, H., Tao, B., & Lindsey, L. E. (2025). Impact of biochar amendment on soil microbial biomass carbon enhancement under field experiments: A meta-analysis. *Biochar*, 7, Article 2.
- Lal, R. (2020). Soil organic matter and water retention. *Agronomy Journal*, 112(5), 3265-3277.
- Larney, F. J., & Angers, D. A. (2012). The role of organic amendments in soil reclamation: A review. *Canadian Journal of Soil Science*, 92(1), 19-38.
- Lavallee, J. M., Soong, J. L., & Cotrufo, M. F. (2020). Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change. *Global Change Biology*, 26(1), 261-273.
- Lazcano, C., & Domínguez, J. (2011). The use of vermicompost in sustainable agriculture: Impact on plant growth and soil fertility. In M. Miransari (Ed.), *Soil nutrients*. Nova Science Publishers.
- Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, 1, 544-553.

- Liu, S., Wang, J., Pu, S., Blagodatskaya, E., Kuzyakov, Y., & Razavi, B. S. (2020). Impact of manure on soil biochemical properties: A global synthesis. *Science of the Total Environment*, 745, 141003.
- Liu, W., Yang, Z., Ye, Q., Peng, Z., Zhu, S., Chen, H., Liu, D., Li, Y., Deng, L., Shu, X., & Huang, H. (2023). Positive effects of organic amendments on soil microbes and their functionality in agro-ecosystems. *Plants*, 12(22), 3790.
- Lori, M., Symnaczik, S., Mäder, P., De Deyn, G., & Gatteringer, A. (2017). Organic farming enhances soil microbial abundance and activity-A meta-analysis and meta-regression. *PLOS ONE*, 12(7), e0180442.
- Ma, Q., Wen, Y., Wang, D., Sun, X., Hill, P. W., Macdonald, A., Chadwick, D. R., Wu, L., & Jones, D. L. (2020). Farmyard manure applications stimulate soil carbon and nitrogen cycling by boosting microbial biomass rather than changing its community composition. *Soil Biology and Biochemistry*, 144, Article 107760.
- Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., & Niggli, U. (2002). Soil fertility and biodiversity in organic farming. *Science*, 296(5573), 1694-1697.
- Moorhead, D. L., Rinkes, Z. L., Sinsabaugh, R. L., & Weintraub, M. N. (2013). Dynamic relationships between microbial biomass, respiration, inorganic nutrients and enzyme activities: Informing enzyme-based decomposition models. *Frontiers in Microbiology*, 4, Article 223.
- Nannipieri, P., Trasar-Cepeda, C., & Dick, R. P. (2018). Soil enzyme activity: A brief history and biochemistry as a basis for appropriate interpretations and meta-analysis. *Biology and Fertility of Soils*, 54, 11-19.
- Okur, N., Kayıkçıoğlu, H. H., Okur, B., & Delibacak, S. (2008). Organic amendment based on tobacco waste compost and farmyard manure: Influence on soil biological properties and butter-head lettuce yield. *Turkish Journal of Agriculture and Forestry*, 32(2), 91-99.
- Ouyang, Y., Reeve, J. R., & Norton, J. M. (2022). The quality of organic amendments affects soil microbiome and nitrogen-cycling bacteria in an organic farming system. *Frontiers in Soil Science*, 2, Article 869136.
- Pan, C.-C., & Huang, C.-H. (2024). Cow dung compost and vermicompost amendments promote soil carbon stock by enhancing labile organic carbon and residual oxidizable carbon fractions in maize field soil. *Soil Use and Management*, 40(4), e13122.
- Rayne, N., & Aula, L. (2020). Livestock manure and the impacts on soil health: A review. *Soil Systems*, 4(4), Article 64.
- Ross, A. T., & Emery, S. M. (2025). Microbial inocula enhance effects of biochar amendments on crop productivity, soil health, and microbial communities: A meta-analysis. *Soil Science Society of America Journal*, 89(1), e20792.
- Semenov, M. V., Zhelezova, A. D., Ksenofontova, N. A., Ivanova, E. A., Nikitin, D. A., & Semenov, V. M. (2025). Microbiological indicators for assessing the effects of agricultural practices on soil health: A review. *Agronomy*, 15(2), 335.
- Shober, A. L., Stehouwer, R. C., Macneal, K. E., & McNitt, A. S. (2003). On-farm assessment of biosolids effects on soil and crop tissue quality. *Journal of Environmental Quality*, 32(5), 1873-1880.
- Shu, X., He, J., Zhou, Z., Xia, L., Hu, Y., Zhang, Y., Zhang, Y., Luo, Y., Chu, H., Liu, W., Yuan, S., Gao, X., & Wang, C. (2022). Organic amendments enhance soil microbial diversity, microbial functionality and crop yields: A meta-analysis. *Science of the Total Environment*, 829, 154627.

- Siedt, M., Schäffer, A., Smith, K. E. C., Nabel, M., Roß-Nickoll, M., & van Dongen, J. T. (2021). Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Science of the Total Environment*, 751, 141607.
- Singh, N. K., Sachan, K., Bp, M., Panotra, N., & Katiyar, D. J. A. J. O. S. S. (2024). Building soil health and fertility through organic amendments and practices: A review. *Asian Journal of Soil Science and Plant Nutrition*, 10(1), 175-197.
- Sokol, N. W., Slessarev, E., Marschmann, G. L., Nicolas, A., Blazewicz, S. J., Brodie, E. L., Firestone, M. K., Foley, M. M., Hestrin, R., Hungate, B. A., Koch, B. J., Stone, B. W., Sullivan, M. B., Zablocki, O., LLNL Soil Microbiome Consortium, & Pett-Ridge, J. (2022). Life and death in the soil microbiome: How ecological processes influence biogeochemistry. *Nature Reviews Microbiology*, 20(7), 415-430.
- Thapa, B., Awal, R., Fares, A., Rahman, A., Veettil, A., Elhassan, M., & Niraj, K. C. (2025). Improving soil health through manure and biochar amendments under climate-smart agriculture. *Soil Science Society of America Journal*, 89(5), e70129.
- Toprak, T., & Kızılkaya, R. (2026). Effect of vermicomposts obtained from hazelnut husuk-farmyard manure mixtures on their chemical properties, wheat yield, and soil microbial biomass carbon. *Toprak Bilimi ve Bitki Besleme Dergisi*, 14(1), 25-34.
- Trivedi, P., Leach, J. E., Tringe, S. G., Sa, T., & Singh, B. K. (2020). Plant-microbiome interactions: From community assembly to plant health. *Nature Reviews Microbiology*, 18, 607-621.
- Xing, Y., Xie, Y., & Wang, X. (2025). Enhancing soil health through balanced fertilization: A pathway to sustainable agriculture and food security. *Frontiers in Microbiology*, 16, 1536524.
- Xu, J., Li, Y., & Li, L. (2025). A comprehensive review of the effects of organic amendments on soil health and fertility: Mechanisms, greenhouse gas emissions, and implications for sustainable agriculture. *Agronomy*, 15(12), 2705.