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Soil Microbiome and Carbon Sequestration: Mechanisms, Processes and Climate Change Mitigation

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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Abstract

Soil microorganisms influence terrestrial carbon cycling by regulating the transformation, release and retention of plant-derived organic carbon. This review examines the biological and physicochemical mechanisms through which the soil microbiome contributes to soil organic carbon sequestration and considers their responses to climate change. Bacteria, fungi, archaea and other soil microorganisms decompose organic substrates, assimilate carbon into biomass and generate microbial residues that may become associated with mineral surfaces or protected within soil aggregates. Microbial carbon-use efficiency, extracellular polymeric substances, microbial necromass formation and rhizosphere interactions therefore influence the balance between carbon mineralisation and stabilisation. Temperature, drought, rewetting and altered oxygen availability can affect microbial community composition, enzyme activity and greenhouse gas fluxes, although their consequences for persistent carbon pools depend on soil and environmental conditions. The review also considers the roles of plant root exudates, mycorrhizal associations, nutrient availability

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and particulate and mineral-associated organic matter in carbon dynamics. Sustainable practices, including reduced tillage, cover cropping, organic amendments, biochar application and microbial inoculants, are discussed as possible approaches to improving carbon retention under suitable conditions. Metagenomics, other multi-omics methods and stable-isotope techniques offer complementary means of investigating microbial functions and carbon transformations. Overall, integrating microbial processes with soil mineralogy, climate responses and context-specific management may improve understanding of soil carbon persistence and inform climate change mitigation strategies.

Keywords: *Soil microbiome; soil organic carbon; carbon sequestration; microbial necromass; carbon-use efficiency; climate change mitigation; biochar; sustainable soil management.*

1. Introduction

Climate change represents one of the most pressing environmental challenges of the twenty-first century, with profound implications for terrestrial ecosystems, agricultural productivity, and global biogeochemical cycles. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2022) highlights the widespread and intensifying impacts of climate change on natural and human systems. In India, climate change is increasingly associated with altered seasonal patterns, rising sea levels, greater variability in rainfall, and an increasing frequency and intensity of extreme weather events, including droughts, floods, cyclones, heat waves, and episodes of intense precipitation (Krishnan *et al.*, 2020). These changes are primarily driven by rising atmospheric concentrations of greenhouse gases, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which influence global temperature regimes, precipitation patterns, and the occurrence of climatic extremes. Such climatic shifts have important implications for soil functioning, affecting soil moisture dynamics, vegetation productivity, organic matter decomposition, nutrient availability, and the formation and persistence of terrestrial carbon reservoirs.

Experimental evidence demonstrates that increasing temperatures can significantly alter soil carbon cycling by stimulating microbial respiration and organic matter decomposition. Zhou *et al.* (2016), through a meta-analysis of ecosystem-warming experiments, reported that a 2°C increase in temperature enhanced total soil respiration by approximately 12% during the early years of warming, while heterotrophic respiration increased by 21%. These findings indicate that warming can intensify microbially mediated carbon release from soils, although the magnitude of the response depends on ecosystem characteristics and the duration of exposure. Similarly, a global meta-analysis by Yan *et al.* (2022), published in Geoderma, reported that experimental warming increased soil CO_2 and N_2O emissions by 9.9% and 17.9%, respectively, highlighting the potential influence of rising temperatures on soil greenhouse-gas fluxes. However, increased respiration does not necessarily translate into an equivalent decline in soil organic carbon stocks, as carbon inputs from vegetation, microbial transformation, and organic matter stabilization also regulate the overall soil carbon balance.

In addition to temperature, climate-induced changes in precipitation and soil moisture can substantially modify microbial activity and nutrient cycling. Gao *et al.* (2020), in a meta-analysis of 79 studies, found that experimental soil drying reduced microbial biomass by approximately 21% and net nitrification by 39%, while also decreasing N_2O emissions. In contrast, ammonium and available phosphorus concentrations increased, demonstrating that drought can affect different soil nutrient pools in contrasting ways. Furthermore, drying–rewetting cycles can stimulate microbial activity following the reintroduction of moisture, leading to short-term pulses of carbon mineralization and greenhouse-gas emissions. Sang *et al.* (2022) reported that drying–rewetting cycles increased soil CO_2 emissions by 35.7% compared with constant soil-moisture conditions. Such fluctuations may influence the decomposition of organic matter, nitrogen transformations, and the temporal availability of nutrients for plant uptake.

The interaction between climate change and soil microorganisms is particularly important because microorganisms transform organic carbon into microbial biomass, CO_2, and microbial residues that may contribute to persistent soil organic matter (Liang *et al.*, 2017; Kallenbach *et al.*, 2016). Soil microbes both release CO_2 and contribute to soil organic matter through necromass formation and microaggregate development(Cotrufo *et al.*, 2015). Rising temperatures can accelerate microbial metabolism, enhancing organic matter decomposition and increasing greenhouse gas emissions from soil. Higher microbial carbon-use efficiency (CUE) may promote soil organic carbon accumulation, whereas lower CUE may increase respiratory CO_2 losses.

Although necromass is not inherently stable, it can persist through interactions with soil minerals, incorporation into aggregates, or protection within physically inaccessible microsites (Buckeridge *et al.*, 2020; Liang *et al.*, 2017; Witzgall *et al.*, 2021). Temperature and moisture control SOC mineralization and extracellular enzyme activity (Singh *et al.*, 2021; Wang *et al.*, 2023). POM in surface soils is more sensitive to warmer/wetter conditions, whereas MAOM has a longer residence time and is controlled more by soil properties (Benbi *et al.*, 2014; Lavallee *et al.*, 2020; Witzgall *et al.*, 2021). Occlusion of organic matter into aggregates and formation of organo-mineral associations are the two most prominent persistence mechanisms (Witzgall *et al.*, 2021). Microbial residues bind to reactive minerals, supporting long-term stabilization (Buckeridge *et al.*, 2020; Liang *et al.*, 2017; Witzgall *et al.*, 2021). Labile plant inputs are transformed by microbes into necromass that preferentially binds to reactive minerals (Buckeridge *et al.*, 2020; Liang *et al.*, 2017; Witzgall *et al.*, 2021) (Buckeridge *et al.*, 2022).

Recent evidence suggests that microbial carbon-use efficiency and necromass formation explain different aspects of soil organic carbon accumulation and should be considered together when interpreting carbon dynamics (Yang *et al.*, 2025).

Experimental studies also indicate that soil mineralogy and microbe–mineral interactions influence the formation of mineral-associated organic carbon and the retention of microbial residues (Elias *et al.*, 2024; Zhao *et al.*, 2025).

Changes in temperature and moisture can modify microbial community composition, extracellular enzyme activity, substrate utilization, and the balance between carbon mineralization and stabilization (Singh *et al.*, 2021; Wang *et al.*, 2023). Consequently, climate change may influence both labile carbon pools, which are readily decomposed, and more persistent carbon pools protected through mineral associations and soil aggregation (Lavallee *et al.*, 2020; Witzgall *et al.*, 2021; Zang *et al.*, 2024). These processes have direct implications for agricultural soils, where changes in carbon storage and nutrient availability can influence soil fertility, crop productivity, and ecosystem resilience (Abshiba *et al.*, 2025; Bünemann *et al.*, 2018)

In the Indian context, a meta-analysis by Patil *et al.* (2025) reported that regenerative agricultural practices, including biochar application and organic amendments, influenced soil organic carbon stocks across Indian agroecological regions, highlighting the importance of soil management in improving carbon retention. Nevertheless, management-related increases in soil carbon should be distinguished from direct climatic effects, as the two processes may interact but are not equivalent. Therefore, understanding the combined effects of climate variability, microbial functioning, soil properties, and nutrient management is essential for predicting soil carbon dynamics and developing climate-resilient and sustainable agricultural systems.

A recent review of plant–soil interactions likewise identifies microbial dynamics and nutrient cycling as relevant considerations for sustainable crop production (Kumar *et al.*, 2025).

In a two-year study of charland cropping systems, biochar and trichocompost treatments were associated with improvements in soil organic carbon, microbial biomass carbon and aggregate stability (Younus *et al.*, 2026).

Soil organic carbon (SOC) is a vital component of soil organic matter and plays an essential role in maintaining soil fertility, improving soil structure and water-holding capacity, regulating nutrient cycling, and supporting ecosystem functioning (FAO, 2017; Jackson *et al.*, 2017; Lal, 2004; Ngatia *et al.*, 2021). Globally, soils store approximately 2,000 petagrams of carbon (Pg C), making them one of the largest terrestrial carbon reservoirs (Lal, 2008; Ontl & Schulte, 2012). The size and stability of this carbon pool depend on the balance between carbon inputs, mainly from plant photosynthesis, root biomass, and organic residues, and carbon losses through microbial respiration, decomposition, erosion, leaching, and land-use changes (FAO, 2017; Nature Geoscience, 2020; Poudel & Ghimire, 2026). Climate change can influence this balance by altering plant productivity, root exudation, microbial activity, and the physical and chemical processes responsible for organic matter stabilization (FAO, 2017; Nature Geoscience, 2020; Poudel & Ghimire, 2026). Soil microbial communities play a crucial role in regulating carbon cycling and sequestration by transforming organic materials, contributing to the formation of stable soil organic matter, and enhancing nutrient availability (Liang *et al.*, 2017; Nature Geoscience, 2020; Poudel & Ghimire, 2026). These processes support plant growth and increase carbon inputs to the soil, thereby contributing to long-term carbon storage and climate change mitigation (FAO, 2017; Nature Geoscience, 2020; Poudel & Ghimire, 2026). Research explores methods to manipulate soil microbiomes, such as through bioaugmentation and biostimulation, to enhance their carbon sequestration capabilities. Understanding these processes aids in developing sustainable agricultural practices and land management strategies that maximize carbon storage as well as helping mitigate climate change (Freeman *et al.*, 2004).

Soil microorganisms are potent actors in climate-relevant processes via their influence on soil carbon turnover and sequestration, along with their consumption and production of greenhouse gases (GHGs) (Beattie *et al.*, 2025). Soil occupies a central position in the climate system because it functions simultaneously as a major carbon reservoir, a source of greenhouse gas emissions, and a potential sink for atmospheric carbon dioxide (Beattie *et al.*, 2025). Consequently, understanding the mechanisms governing soil carbon storage and turnover is essential for developing effective climate-change mitigation and adaptation strategies (Beattie *et al.*, 2025) (Jansson & Hofmockel, 2020).

The soil microbiome—the diverse community of bacteria, fungi, archaea, viruses, and protozoa living in the soil—plays a critical role in climate change mitigation. Viruses are extremely abundant in the soil (Williamson *et al.*, 2017). Thus, infection and lysis of microbial cells are major factors for microbial life and death in soils (Williamson *et al.*, 2017). After death, microbial cells begin to decay, and the integrity of the cell membrane is no longer maintained (Lengeler *et al.*, 1999). Because soils store roughly 2,000 billion tons of organic carbon, managing these underground microbial networks has become one of the most promising biological strategies to sequester carbon (Beattie *et al.*, 2025; Lal, 2008) (Jansson & Hofmockel, 2020).

Research gap: Although microbial transformation and soil carbon stabilization are discussed extensively, a more integrated account of how changes in temperature and moisture interact with microbial carbon allocation, mineral protection and soil management to influence carbon persistence remains necessary.

Objective: This review examines the mechanisms through which soil microorganisms regulate carbon transformation and stabilization under changing climatic conditions and considers the implications of rhizosphere processes, sustainable soil management and molecular approaches for soil carbon sequestration.

2. Soil Microorganisms Alter the Carbon Pool

Microorganisms alter the size, stability, and form of the soil carbon pool through several distinct biological processes:

2.1 Decomposition and Mineralisation (Carbon Loss)

Microbes, mainly bacteria and fungi, secrete extracellular enzymes to break down complex plant and animal compounds, including sugars, cellulose, and lignin, into smaller molecules that can be used for energy (Henry, 2012; Janusz *et al.*, 2017; Moorhead *et al.*,

2013). During this respiration process, a significant portion of the carbon is converted into carbon dioxide and released back into the atmosphere (Moorhead *et al.*, 2013; Moyano *et al.*, 2013; Wang *et al.*, 2023). This reduces the overall mass of active organic carbon if decomposition outpaces new plant inputs (Davidson & Janssens, 2006; Lathrop *et al.*, 2025; Moorhead *et al.*, 2013).

2.2 The "Microbial Filter" and Necromass Stabilisation (Carbon Sequestration)

Rather than solely decomposing organic matter, microbes also contribute to stable soil carbon formation. When microbes consume plant carbon, a fraction (roughly 3% to 33% or more) is converted into microbial biomass. When these microbes die, their cell walls and cellular debris—known as microbial necromass—bind strongly to clay and silt particles, transforming into long-lasting components of stable organic carbon. Importantly, microbial necromass may be partly recycled by microorganisms or persistently stabilized within the soil matrix by the "entombing effect", which is conceptualized as the soil "microbial carbon pump" (MCP), highlighting that microbes are active players in soil C storage (Liang *et al.*, 2017). The "MCP" theory has sparked a paradigm shift in soil C cycling: increasingly, SOC dynamics may be seen as a microbial consequence of employing diverse metabolisms (Kästner *et al.*, 2021).

2.3 Production of Extracellular Polymeric Substances (EPS)

Bacteria and fungi secrete EPS and polysaccharides that bind soil particles into aggregates, while arbuscular mycorrhizal fungi produce glomalin. These substances bind soil particles to form aggregates. Soil aggregation can physically shield organic carbon from decomposers by protecting it within soil aggregates (Costa *et al.*, 2018; Wright & Upadhyaya, 1998) (Nichols, 2008).

2.4 Nutrient Stoichiometry and Priming Effects

Microbes require balanced nutrients, including nitrogen, phosphorus, and sulfur, to assimilate added carbon efficiently. When fresh carbon inputs are nutrient-poor, microbes may accelerate the decomposition of older, more stable soil organic matter to obtain limiting nutrients—a positive priming effect (Kuzyakov *et al.*, 2000; Chen *et al.*, 2014; Mehnaz *et al.*, 2019). Consequently, the persistence of soil carbon cannot be predicted from plant-residue chemistry alone; microbial transformation of residues into microbial products and the capacity of soil minerals and aggregates to stabilize those products are also decisive (Cotrufo *et al.*, 2013; Kleber *et al.*, 2015).

2.5 Influence of Climate Change on Microbial Regulation of Soil Carbon Pools

Climate change alters microbial regulation of soil carbon by changing the physical conditions under which microbes decompose, transform, and stabilize organic matter. Warming, altered precipitation, oxygen shifts, and changes in plant inputs can shift both the size of carbon pools—such as particulate organic matter (POM) and mineral-associated organic matter (MAOM)—and their turnover rates.

Temperature: Higher temperatures generally increase microbial metabolism, extracellular-enzyme activity, and decomposition rates, especially for labile carbon pools. This can reduce the residence time of fast-cycling soil carbon and increase CO_2 release to the atmosphere. (Davidson & Janssens, 2006). However, temperature effects are not uniform. Labile POM often decomposes rapidly under warming, whereas MAOM can be more physically and chemically protected; its persistence depends more strongly on mineral surfaces, aggregation, texture, and nutrient availability. Warming may also change microbial community composition and enzyme production, potentially allowing microbes to access more recalcitrant substrates over time. (Kirschbaum, 1995).

Moisture: Moisture controls microbial access to substrates, oxygen and nutrient diffusion, and enzyme activity; drought limits water films, substrate diffusion, and microbial mobility, while rewetting after drought can produce a strong "Birch effect": a pulse of microbial activity and CO_2 release as previously protected organic matter becomes available again (Meisner *et al.*, 2013; Moyano *et al.*, 2013). Long-term drought can reduce plant productivity and carbon inputs while shifting microbial communities and carbon-degrading genes (de Nijs *et al.*, 2019; de Vries *et al.*, 2020) (Sanaullah *et al.*, 2012).

Oxygen Availability and Redox Conditions: Climate-driven changes in flooding, waterlogging, and soil saturation alter oxygen availability. Under aerobic conditions, fungi and aerobic bacteria efficiently decompose organic matter and release CO_2; under oxygen-limited conditions, decomposition slows, methane-producing archaea become more important, and carbon can accumulate in wetland or saturated soils (Davidson & Janssens, 2006; Conrad, 2009; Moomaw *et al.*, 2018). Thus, increased flooding may preserve carbon by slowing aerobic decomposition, but it can also increase methane emissions (Bridgham *et al.*, 2013; Mitsch *et al.*, 2015). Conversely, drainage or drought can expose previously protected organic matter to oxygen, accelerating its loss (Armentano & Menges, 1986; Leifeld & Menichetti, 2018).

Plant Productivity and Carbon Inputs: Elevated atmospheric CO_2 can increase plant photosynthesis, below-ground carbon allocation, root exudation, and litter inputs. These inputs can support microbial biomass and necromass formation that may contribute to stable soil carbon. (Phillips *et al.*, 2012; Cotrufo *et al.*, 2013). However, this "CO_2 fertilization" effect is often constrained by nitrogen, phosphorus, water, or other limiting resources. If nutrient supply does not keep pace with increased carbon inputs, microbial nutrient demand may stimulate decomposition of older soil organic matter—the priming effect—potentially offsetting carbon gains (Cheng *et al.*, 2014; Terrer *et al.*, 2016; Walker *et al.*, 2021) (Zhu *et al.*, 2021; see Fig. 1).

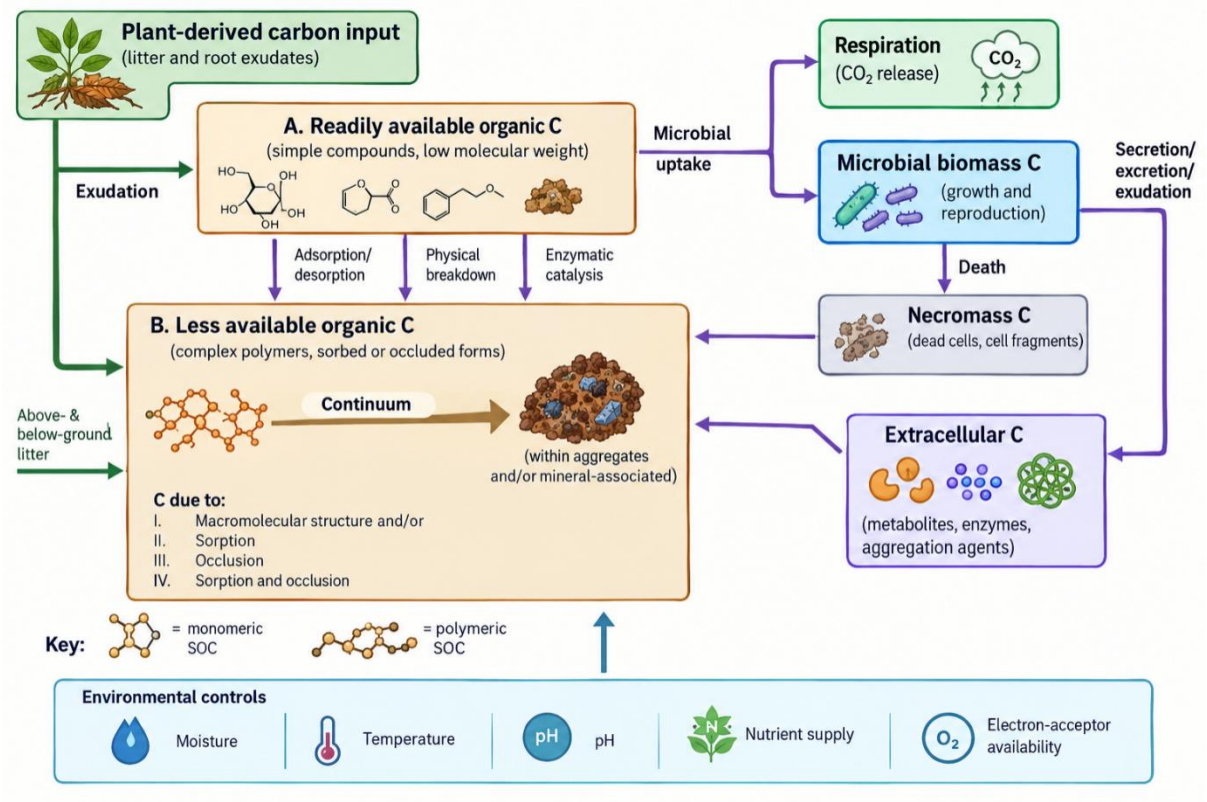


Fig. 1. Fate of primary production inputs to soil.Reproduced from Gougoulias *et al.* (2014)

The figure illustrates the fate of plant-derived carbon entering soil through plant litter and root exudates. Readily available organic carbon (A), consisting of simple compounds, is easily utilized by soil microorganisms. Some carbon is released as carbon dioxide (CO_2) through respiration, while the remainder supports microbial growth and biomass production. Less available organic carbon (B) includes complex compounds that are sorbed onto soil minerals or protected within soil aggregates. These compounds may become accessible through enzymatic breakdown, desorption, or physical exposure. Microbial biomass contributes to soil carbon cycling through the formation of microbial necromass following cell death and the release of extracellular substances, including metabolites, enzymes, and aggregation agents. These products can contribute to soil organic matter formation and carbon stabilization. Mineral association and aggregate formation may protect organic carbon from decomposition. The processes are regulated by environmental factors such as moisture, temperature, pH, nutrient availability, and electron-acceptor supply, which influence microbial activity and carbon persistence in soil.

3. Rhizosphere Microbial Interactions

A) **The Rhizosphere Effect**: Plant-derived carbon released through root exudates creates a nutrient-rich zone around roots, increasing microbial biomass and reshaping the abundance and composition of bacteria, fungi, protozoa, and algae near roots (Hiltner, 1904; Bais *et al.*, 2006; Philippot *et al.*, 2013; Sasse *et al.*, 2018) (Yadav *et al.*, 2014).

B) **Copiotrophic Bacterial Proliferation:** Rapidly growing bacteria, including members of Proteobacteria and Bacteroidetes, flourish on labile carbon compounds in root exudates, accelerating nutrient cycling and turnover (Fierer *et al.*, 2007; Shi *et al.*, 2011; Zhalnina *et al.*, 2018).

C) **Fungal Networks and Mycorrhizae**: Arbuscular mycorrhizal and saprotrophic fungi extend hyphal networks into soil; mycorrhizal fungi acquire relatively immobile nutrients, especially phosphorus and nitrogen, and exchange them with plants for photosynthetically derived carbon (Smith & Read, 2008; Bonfante & Genre, 2010; Jiang *et al.*, 2017; Keymer & Gutjahr, 2021).

4. Impact on Soil Organic Matter (SOM) Decomposition

Fresh plant-derived carbon stimulates microbial metabolism, stimulating or "priming" the decomposition of older, native soil organic matter as microbes seek limiting nutrients, especially nitrogen, locked in soil organic matter. While plants and microbes compete for available soil nutrients, this interaction can ultimately increase mineralization and release nutrients that sustain primary productivity. Furthermore, a significant portion of the decomposed plant carbon is incorporated into microbial biomass; when microbes die, their cellular residues—microbial necromass—can bind to soil minerals and aggregates, forming stable, longer-term soil carbon pools (Kuzyakov, 2010; Cheng *et al.*, 2014; Zhu *et al.*, 2014; Cotrufo *et al.*, 2013; Liang *et al.*, 2017).

5. Role of Microbiome in Climate Resilience and Carbon Sequestration

Soil microorganisms are central to climate change mitigation due to their role in carbon sequestration and reducing greenhouse gas emissions. Microbial processes like decomposition and nutrient cycling are essential for soil carbon storage, which helps regulate atmospheric carbon dioxide levels (Lehmann & Kleber, 2015).

5.1 Carbon Sequestration by Soil Microbes

Soil microbes, particularly fungi, play an important role in the formation of stable organic carbon compounds, which are stored in soil for long periods. This process enhances soil carbon sequestration, contributing to climate change mitigation (Liang *et al.*, 2019; Phillips *et al.*, 2012). It plays an important role in climate change mitigation, soil fertility, and sustainable agriculture. Plants absorb atmospheric carbon dioxide (CO_2) through photosynthesis and transfer carbon into the soil through root exudates, dead roots, fallen leaves, and crop residues.

5.2 Microbial Role in Greenhouse Gas Mitigation

Microorganisms are also involved in the reduction of greenhouse gas emissions, such as methane and nitrous oxide, from agricultural soils. Certain microbial communities can promote methane oxidation and denitrification processes that mitigate nitrous oxide emissions (Conrad, 2009; Mitsch *et al.*, 2015; Moomaw *et al.*, 2018; Sánchez-García *et al.*, 2015).

5.3 Microbial Carbon Assimilation and Carbon Use Efficiency (CUE)

Carbon Partitioning: Microbes absorb plant-derived organic compounds—root exudates, litter-derived monomers, and other soluble substrates—and partition assimilated carbon between biomass synthesis and respiration (Manzoni *et al.*, 2012; Geyer *et al.*, 2016).

Carbon Use Efficiency (CUE): CUE is the fraction of assimilated carbon allocated to microbial growth rather than lost as CO_2 through respiration. Higher CUE can increase microbial biomass production and, through necromass formation and mineral association, enhance stabilized soil-carbon pools (Liang *et al.*, 2017; Sinsabaugh *et al.*, 2013).

Metabolic Controls: CUE is regulated by substrate availability, temperature, moisture, and nutrient stoichiometry—especially C:N:P balance. Nutrient limitation generally lowers CUE, whereas adequate nitrogen and phosphorus supply can increase it. Positive biotic interactions, such as facilitation and cross-feeding, may also reduce metabolic or enzyme-production costs and thereby raise community-level CUE (Iven *et al.*, 2022; Kästner *et al.*, 2024; Manzoni *et al.*, 2012; Qiao *et al.*, 2019; Sinsabaugh *et al.*, 2013).

5.4 Soil Aggregation and Mineral-Associated Organic Carbon (MAOC)

Physical Protection: Microbial products, extracellular polymeric substances (EPS), and cell fragments glue mineral particles together to form micro- and macro-aggregates. These aggregates physically shield organic matter from extracellular enzymes and decomposers. (Totsche *et al.*, 2018; Costa *et al.*, 2018; Six *et al.*, 2004).

Mineral Association (MAOC): Microbial necromass and metabolic byproducts chemically bind to reactive mineral surfaces, including clay minerals and iron or aluminum oxides such as goethite, forming mineral-associated organic matter (Cotrufo *et al.*, 2019; Liang *et al.*, 2019).

Pool Distinction: Particulate organic carbon (POC) generally occurs in less protected spaces and turns over faster, whereas MAOC can persist much longer because strong mineral sorption and diffusion limitations reduce microbial and enzymatic access. However, MAOC is not uniformly inert; a portion can cycle relatively rapidly (Georgiou *et al.*, 2022; Jilling *et al.*, 2025; Jia & Feng, 2026; Lavallee *et al.*, 2020; Sokol *et al.*, 2022).

6. Microbial Interactions and Long-Term Carbon Stabilization

Microbial life-history strategies influence soil carbon cycling, with fast-growing, resource-acquisitive microorganisms promoting rapid carbon turnover, while slow-growing, resource-efficient communities may contribute to carbon retention (Malik *et al.*, 2020; Ho *et al.*, 2021). The Microbial Carbon Pump (MCP) describes how microbial processes, including growth, biosynthesis, cell death, and enzymatic decomposition of plant polymers, transform readily available carbon into more stable forms in the soil (Liang *et al.*, 2017; Qiao *et al.*, 2025). Long-term carbon sequestration depends on the balance between microbial growth, the formation of microbial necromass, the capacity of soil minerals to protect organic matter, and land management practices such as tillage, cover cropping, and targeted nutrient application (Liang *et al.*, 2019; Malik, 2026; Wang *et al.*, 2025; Zhou *et al.*, 2023).

7. Sustainable Agricultural Practices for Carbon Sequestration

Reduced Tillage & No-Till: Reducing tillage limits the physical disruption of aggregates and fungal hyphae and may slow the exposure of protected organic matter to oxygen and decomposers. Outcomes depend on soil type, climate, crop rotation, residue management, and the duration of adoption; changes in carbon concentration near the surface should not automatically be interpreted

as equivalent gains throughout the soil profile (Aguilar-Paredes *et al.*, 2026; Hussain *et al.*, 2021; Kumara *et al.*, 2023; Srivastava, 2025).

Cover Cropping & Polycultures: Continuous living roots release carbon-rich exudates and return residues, sustaining rhizosphere microbiomes and increasing below-ground carbon inputs. Diverse cover crops and polycultures can further increase rhizosphere carbon inputs and microbial biomass (Gentsch *et al.*, 2020; Griffiths *et al.*, 2022; Seitz *et al.*, 2024). The effect on persistent SOC depends on biomass production, water and nutrient competition, residue quality, and soil conditions

Organic Amendments & Biochar: Compost, manure, and biochar provide carbon substrates, improve microbial habitat, and can enhance microbial carbon-use efficiency and necromass formation; biochar can also promote mineral–organic associations that support longer-term carbon stabilization (Liang *et al.*, 2017; Shyam *et al.*, 2025; Singh *et al.*, 2022).

Microbial Inoculants & Transplants: Introducing plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi, or synthetic microbial consortia can strengthen plant–microbe interactions, improve nutrient acquisition, and promote aggregate formation in degraded soils (Barea *et al.*, 2013; Fierer & Walsh, 2023; Singh *et al.*, 2025; Vessey, 2003).

8. Microbiome-Based Strategies and Biochar Applications

Modern agriculture is shifting from chemical-heavy interventions to biological and structural enhancements that stabilize soil organic carbon (SOC) for the long term. Biochar is a carbon-rich material produced through the pyrolysis of biomass under limited oxygen conditions. It improves soil fertility and plant nutrition by influencing soil properties, microbial activity, and nutrient cycling through three major mechanisms:

1. **Structural Recalcitrance:** Biochar contains stable, condensed aromatic carbon structures formed during pyrolysis that resist microbial decomposition, allowing carbon to persist in soil for decades to centuries and thereby supporting long-term SOC stabilization. Its porous architecture, high specific surface area, surface charge, and cation exchange capacity also improve soil structure, aggregation, aeration, water retention, and the retention of essential nutrients, reducing leaching losses and enhancing nutrient availability to plants (Brassard *et al.*, 2016; Jaiswal *et al.*, 2018; Shyam *et al.*, 2025)
2. **Microbial Refugia:** Biochar's porous structure and large surface area provide microhabitats and protected colonization sites for beneficial bacteria and fungi, potentially shielding them from desiccation, predation, and other environmental stresses. These refugia can support microbial biomass, activity, and diversity, thereby promoting nutrient cycling, biological nitrogen fixation, and phosphorus mobilization through phosphate-solubilizing microorganisms (Gul *et al.*, 2015; Jaiswal *et al.*, 2018; Shyam *et al.*, 2025; Singh *et al.*, 2022; Waheed *et al.*, 2026).
3. **Synergistic Co-Composting:** Combining biochar with compost or manure can enrich the amendment with nutrients and organic compounds while biochar adsorbs ammonium and nitrate, potentially reducing gaseous and leaching losses of nitrogen. Biochar addition during co-composting can also increase bacterial and fungal populations, alter carbon and nitrogen dynamics, and produce a nutrient-enriched biochar–compost material that supports microbial activity and soil organic matter stabilization (Godlewska *et al.*, 2017; Sánchez-García *et al.*, 2015).

Overall significance: Biochar can strengthen rhizospheric plant–microbe interactions, improve nutrient-use efficiency, support root development, and contribute to long-term soil fertility and carbon sequestration. However, its effectiveness is highly context-dependent, varying with biochar feedstock, pyrolysis temperature, pH and ash content, application rate, soil texture and chemistry, climate, crop requirements, and application method (Bo *et al.*, 2023; Purakayastha *et al.*, 2019; Singh *et al.*, 2022).

9. Molecular Tools for Studying Soil Carbon Dynamics

Soil omics platforms provide complementary insights into microbial involvement in soil carbon cycling (Overy *et al.*, 2021). Metagenomics identifies the functional potential of microbial communities, metatranscriptomics reveals active gene expression, metaproteomics identifies functional proteins, and metabolomics characterizes small-molecule metabolites involved in microbial metabolism (Abram, 2015; Bastida *et al.*, 2009; Overy *et al.*, 2021).

When integrated, these tools help researchers investigate how microorganisms decompose organic matter, assimilate carbon, and contribute to soil carbon stabilization (Overy *et al.*, 2021; Baldrian, 2019). However, measuring actual carbon transformation rates often requires complementary approaches, such as stable-isotope probing, soil respiration measurements, and extracellular enzyme activity assays (Kuzyakov & Razavi, 2019; Baldrian, 2019).

Microbiome engineering holds promise for precisely manipulating microbial communities to enhance plant growth, nutrient acquisition, stress resilience, and soil health (Darriaut *et al.*, 2025; Fierer & Walsh, 2023; Kumar & Dubey, 2020; Wang & Li, 2019).

Metagenomics and Microbiome Profiling: Metagenomic techniques allow for the detailed analysis of soil microbial communities, providing insights into their functional roles in soil health. In India, several research groups are working on microbiome profiling to identify beneficial microbial consortia that can be used as biofertilizers (Singh *et al.*, 2025).

10. Future Directions and Innovations in Microbiome Research

Future research should combine soil fractionation, microbial biomass measurements, extracellular enzyme assays, microbial necromass biomarkers, stable-isotope tracing, and molecular profiling. Long-term field experiments across contrasting climates and

soil types will be particularly important for determining whether short-term increases in microbial activity translate into sustained carbon sequestration.

11. Conclusion

Soil microorganisms play a crucial role in carbon transformation and stabilization by decomposing organic matter, recycling nutrients, and converting plant-derived carbon into microbial biomass and residues that can contribute to stable soil organic matter. Through their metabolic activities, they regulate carbon mineralization, soil respiration, and carbon storage. These processes have significant implications for climate change mitigation, as well-managed soils can store substantial amounts of carbon and potentially reduce atmospheric CO_2 levels. However, microbial decomposition can also release CO_2, while certain soil conditions may promote greenhouse gas emissions such as methane and nitrous oxide.

Therefore, sustainable soil management practices—including the application of biochar and compost, cover cropping, crop rotation, reduced tillage, and minimising soil disturbance—are essential for maintaining microbial diversity, improving soil fertility, reducing carbon losses, and enhancing long-term carbon sequestration. Integrating microbial research with sustainable agricultural practices can help build resilient soils, support food security, and contribute to climate change mitigation.

12. Limitations

This narrative review draws on studies conducted across different ecosystems, soil types and experimental conditions, which may limit direct comparisons of microbial responses and carbon sequestration outcomes. Reported changes in microbial activity, respiration or carbon concentration do not necessarily demonstrate long-term increases in soil carbon stocks. The persistence of mineral-associated carbon and the effects of management interventions remain context-dependent. Long-term field observations combining microbial measurements with soil carbon fractionation are therefore needed to evaluate whether proposed mechanisms translate into durable carbon retention.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. ChatGPT, Claude and Perplexity were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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