



CARBON FARMING AND MICROBIAL TECHNOLOGIES FOR SOIL CARBON SEQUESTRATION

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Abstract:

Climate change and rising levels of carbon dioxide (CO₂) in the atmosphere are among the major environmental challenges the world is facing today. Agriculture can be a potential solution for this problem by promoting sequestration and long term storage of atmospheric carbon in the soil. The soil is a significant carbon reservoir and improved carbon storage can contribute to reduced atmospheric CO₂ while enhancing soil health and crop growth. Carbon farming practices such as crop residue management, reduced tillage, manure application, cover crops, and biochar can improve carbon inputs to the soil and help in retaining carbon for longer periods. Soil microorganisms, especially bacteria and fungi, are important because they decompose organic matter and convert carbon into microbial biomass and residues that may contribute to soil organic carbon. However, the success of these approaches depends on factors like soil type, climate, crop type, availability of organic matter, microbial communities, etc. In this review, the role of carbon farming and microbial technologies in soil carbon sequestration and their potential, challenges and knowledge gaps at present are elaborated.

Keywords Carbon Farming, Soil Carbon Sequestration, Soil Organic Carbon, Microbial Technologies, Sustainable Agriculture.

1. Introduction

The increasing greenhouse gas emissions and climate change are important environmental concerns that have resulted in the need of agricultural methods that can produce sufficient food as well as protect the environment. Agriculture is intimately connected to the carbon cycle because soil is rich in carbon. Soil organic carbon (SOC) is mainly derived from plant material that is deposited on the soil and then decomposed. Proper soil management can enhance carbon storage, which can reduce atmospheric CO₂ and improve soil health [1, 2].

Traditional farming methods such as intensive tillage, excessive use of chemical inputs, and the loss of organic matter can reduce SOC and affect soil quality over time [3]. Carbon farming consists of a series of practices to

reduce emissions of greenhouse gases and increase the storage of carbon in soil and plants. Practices include the addition of organic matter, the maintenance of crop residues, reduced tillage, crop rotation, proper nutrient management and the use of biochar. But carbon farming isn't only about how much carbon is put into the soil. The amount of carbon that remains stored also depends on the activities of microorganisms in the soil. These microorganisms can determine whether carbon is released back into the atmosphere as CO₂ or becomes part of more stable forms of soil carbon [1, 2].

Soil microorganisms are significant drivers of the carbon cycle. They decompose plant residues and other organic matter, converting carbon into different forms. Some carbon is released as CO₂ during respiration, and some is converted into microbial biomass and residues that may be retained in the soil for longer time periods. Carbon use efficiency (CUE) is a term describing how microorganisms use carbon for their growth, rather than releasing it via respiration. Microbial CUE differs among agricultural, forest and grassland soils and is affected by factors like temperature and nutrient availability [4]. Therefore, it is important to understand these microbial processes to develop effective approaches for long-term soil carbon sequestration [1, 5].

Understanding how soil microbial communities behave is arguably as important to carbon farming as the farming practices themselves. Microbial responses are highly variable across soil types and environmental conditions, and further field-based studies are required to understand the processes under real farming conditions [6, 7].

New research suggests that microbial technologies may be an important approach to carbon farming. According to Beattie *et al.* (2024) such interventions typically involve the direct addition of microbial inoculants, the transfer of whole soil communities between sites, and the use of management practices that change the activity of resident soil microbiota. These approaches together could increase plant-mediated carbon input into soil, favor the formation of soil organic matter, and reduce the rate of decomposition of stored carbon. However, the efficacy of microbial technologies is not uniform across the board, as microbial community composition and environmental conditions differ significantly between locations [6].

One of the most promising technologies for carbon farming is biochar, a carbon-rich material produced by the pyrolysis of plant biomass in low-oxygen conditions. Since a large part of biochar carbon is recalcitrant to microbial decomposition, the addition of biochar to soil can cause two changes: a direct input of carbon and a change in the physicochemical properties of the soil. Soil structure has been shown to improve with biochar amendment, water holding capacity has been increased and nutrient availability has been enhanced, alongside providing a habitat for microbial colonization. Recent evidence suggests that the interaction of biochar with soil microorganisms, rather than the carbon content of biochar alone, is an important determinant of long-term carbon retention. Zhang *et al.* (2026) summarized data from 76 studies, and found the application of biochar increased organic carbon in soil by an average of 52.4%, but the magnitude of the effect was strongly affected by the structure of the microbial community present [8,9,10].

The interaction has brought about increasing interest in co-application of biochar with beneficial microorganisms. The porous structure of biochar can serve as a safe haven for microorganisms to survive and stay metabolically active, and these microbes can help cycle nutrients and transform organic carbon. Biochar can also be used as a carrier matrix for microbial inoculants. According to Li *et al.* (2026), immobilization of microbes in biochar integrates the physical benefits of biochar with functional activity of the associated microorganisms. Such co-

application strategy may prolong the survival of the introduced microbes after inoculation with consequent benefits to the soil health and crop productivity [9,11].

Another crucial microbial technology for soil carbon storage is arbuscular mycorrhizal fungi (AMF). AMF establish mutualistic relationships with plant roots that facilitate nutrient acquisition and plant growth, and fungal biomass and plant-derived carbon transferred via this symbiosis can play a role in soil carbon storage. Tao and Liu (2024) reported that AMF inoculation increased soil C content and plant growth in general, but the results were mediated through soil pH, pre-existing C stocks, root architecture and general soil conditions. In the same way, Mason *et al.* (2025) reported that AMF inoculation increased carbon accumulation in wheat systems and suggested that combined AMF–biochar application may improve the long-term stability of sequestered carbon.

Table 1: Combined findings of studies related with carbon farming and microbial technologies for soil carbon sequestration.

Aspect	Combined findings
Carbon farming practices	Crop residues, manure, reduced tillage, crop rotation, cover crops, and biochar can increase carbon inputs and reduce carbon losses from soil.
Biochar	Adds relatively stable carbon to soil, improves soil properties, and can provide suitable microsites for microbial activity.
Microbial activity	Bacteria and fungi decompose organic matter and convert part of the carbon into microbial biomass and residues that contribute to soil organic matter.
AMF	Supports plant growth, nutrient uptake, and transfer of plant-derived carbon into soil, increasing belowground carbon inputs.
Fungal endophytes	Can improve plant growth and soil functioning and may contribute to greater carbon inputs and retention.
Microbial inoculants & consortia	Introduce beneficial microorganisms that may improve plant growth, nutrient cycling, and carbon-related processes.
Integrated approaches	Combining carbon farming practices with microbial technologies may provide more effective and consistent carbon sequestration than using a single approach.
Influencing factors	Soil type, pH, climate, crop species, nutrient availability, and native microbial communities strongly influence effectiveness.
Overall outcome	Integrated strategies have potential to increase soil carbon sequestration while improving soil health and plant productivity.
Research gap	More long-term field studies are needed to evaluate carbon stability, microbial interactions, and performance under different agricultural conditions.

Endophytic fungi have also been explored for enhanced carbon storage. These organisms colonize internal plant tissues and can influence plant growth, root architecture, and carbon allocation to soil. A soybean field study demonstrated an increase in select soil organic matter fractions and, in some instances, grain yield with fungal endophyte inoculation [14]. Similar findings from fungal inoculant studies in wheat suggest that selected fungal inoculants can influence soil carbon fractions and microbial properties [15]. These results point to the potential

for microbial technologies to provide co-benefits beyond carbon sequestration, such as enhanced plant productivity which in turn affects long-term soil carbon dynamics.

The formation of microbial necromass, the leftover biomass of dead microorganisms, is also tightly coupled with microbial activity and can make a large contribution to soil organic matter and long-term carbon stabilization. Yang *et al.* (2025) pointed out that microbial carbon use efficiency (CUE) and necromass accumulation are the keys to understanding long-term soil organic matter (SOM) formation. This stresses the importance of efficient carbon farming to not only consider simple carbon inputs but also to design soil conditions that foster microbial carbon transformation and stabilization [15].

But the performance of carbon farming and related microbial technologies has been proven to be inconsistent in field settings. The degree of carbon storage can be modulated by climatic conditions, soil texture, pH, nutrient status, resident microbial communities, crop type and management practices [2, 4, 6].

The combination of carbon farming practices with microbial technologies is a promising approach to improve carbon sequestration and soil health, when taken together. Carbon farming is the land management system, and soil microbes are the biological agents that convert and stabilize carbon inputs. Technologies such as biochar, microbial inoculants, AMF and fungal endophytes can help with carbon input to soil, improve microbial carbon use efficiency and support the formation of stable soil organic matter. However, there is still a gap in long-term, field-scale research to understand the performance of these interventions across a range of farming systems and over the long-term [2, 6, 16]. Thus, this review investigates the interface of carbon farming and microbial technologies, with an emphasis on the processes by which soil microorganisms capture, convert, and stabilize carbon in agricultural soils.

2. Carbon farming and soil carbon sequestration

Carbon farming is being increasingly considered as a sustainable approach to agricultural management as it can both improve soil carbon storage and support crop production. Soils are one of the largest carbon reservoirs in terrestrial ecosystems, and agricultural methods can influence whether carbon remains in the soil or is released to the atmosphere [1, 2]. Under suitable conditions, reduced tillage, crop rotation, cover cropping, retention of crop residues, application of organic manure and biochar amendment can increase soil organic carbon [2, 10, 17]. However, the effectiveness of these practices could vary depending on the soil characteristics, climatic conditions and their application [1, 2].

Soil carbon sequestration refers to the process of capturing and storing atmospheric CO₂ in plant biomass and soil. Organic inputs, such as plant roots, root exudates, crop residues, and other carbon sources, contribute carbon to the soil system. Soil microorganisms decompose these materials and convert the carbon into microbial biomass and different forms of soil organic matter [1, 4, 5]. During this process, some carbon is lost as CO₂ through microbial respiration, while another fraction can persist in the soil for longer periods through microbial necromass formation and stabilization within soil organic matter [4, 5]. Thus, carbon sequestration is a function of both the amount of carbon entering the soil and the processes controlling its stabilization and decomposition [1, 16].

3. Soil carbon cycle and role of microorganisms

Microorganisms are intimately involved in the soil carbon cycle and have an important role in determining the fate of organic carbon in the soil. Bacteria and fungi break down plant residues and other organic matter, releasing

carbon as CO₂ through respiration. Simultaneously, part of the carbon is utilized by microorganisms as a source of energy and nutrients for their growth, contributing to microbial biomass formation [1, 4].

Therefore, microbial community composition and activity can affect the decomposition and retention of carbon in the soil. Microbial processes are involved in the degradation of organic matter and the transformation of plant-derived carbon into different soil organic carbon pools, Bhattacharyya *et al.* (2022) highlighted the close relationship between soil microbial communities and soil organic matter, particularly their role in carbon cycling, decomposition and soil carbon sequestration. Understanding these microbial processes is therefore important for evaluating the impact of agricultural practices on long-term soil carbon storage [1, 4, 5].

The effect of microorganisms is also dependent upon soil conditions. Factors such as temperature, moisture, pH, nutrient availability and the quality of organic substrates can influence microbial activity and carbon use efficiency [4, 7]. Therefore, the same carbon farming practice can produce different outcomes in different soils depending on environmental conditions and soil characteristics [7].

4. Microbial carbon use efficiency

Microbial carbon use efficiency (CUE) is a central parameter for understanding the fate of carbon in soil. It is the portion of the carbon assimilated by the microorganisms that goes to microbial growth and biomass production. The rest of the carbon is lost mostly through respiration (CO₂). Hence, CUE is the distribution of available carbon to microbial growth and respiratory processes [4, 5].

Dead microbial cell residues are named microbial necromass and can be incorporated into soil organic matter, thus contributing to soil organic carbon pools and microbial biomass can contribute to soil carbon storage. However, the persistence of these residues is determined by their interaction with soil minerals, availability of nutrients, environmental conditions and other soil properties [1, 5]. Thus, higher CUE does not necessarily imply that all extra carbon will be stored in soil, as the relationship between microbial carbon processing and long-term carbon storage is controlled by the stabilization and persistence of microbial-derived carbon [5, 16].

Microbial CUE is heterogeneous among ecosystems and is regulated by environmental conditions and resource availability [4]. This supports the idea that CUE is not an inherent property of soil microorganisms but a flexible trait that adjusts to changing environmental conditions. Microbial metabolism and the partitioning of carbon between growth and respiration can be affected by temperature, moisture, carbon availability and nutrient supply, among other factors [4, 7]. The composition and functional diversity of the soil microbiome can also affect carbon cycling and sequestration, suggesting that microbial communities themselves can be important targets for improving soil carbon retention [7, 16].

Microorganisms are involved in the sequestration of carbon in the soil through various pathways such as transformation of plant-derived carbon, formation of microbial biomass and necromass, interactions with soil minerals, and stabilization of carbon in soil aggregates [16]. Therefore, microbial CUE together with microbial community composition and soil environmental conditions is important for assessing the potential of microorganisms in increasing long-term soil carbon sequestration.

Table 2: Major mechanisms involved in soil carbon sequestration

Carbon sequestration mechanism	What happens	Contribution to soil carbon
Plant carbon input	Plants add carbon to soil through roots, root exudates and crop residues	Provides the main source of carbon entering soil
Decomposition	Microorganisms break down plant residues and organic matter	Converts complex organic matter into simpler forms
Microbial biomass formation	Microorganisms use part of the available carbon for their growth	Transfers plant carbon into microbial biomass
Microbial necromass formation	Dead microbial cells and their residues remain in soil	Can contribute to stable soil organic carbon
Mineral association	Organic compounds become associated with soil minerals	Helps protect carbon from rapid decomposition
Aggregate formation	Organic matter becomes physically protected inside soil aggregates	Reduces carbon loss and decomposition
Biochar addition	Stable carbon from biomass is added directly to soil	Increases relatively stable soil carbon
Root-microbe interactions	Microorganisms interact with plant roots and receive plant-derived carbon	Can increase carbon movement into soil

5. Microbial necromass and long-term carbon storage

Microbial necromass refers to the dead cells and cellular remains of microorganisms that accumulate in soil and contribute to soil organic matter formation and stabilization. Earlier approaches to understanding soil carbon storage mainly emphasized plant residues as important sources of soil organic matter; however, increasing evidence indicates that microbial-derived residues can make a substantial contribution to persistent soil carbon pools [1, 5]. Soil microorganisms transform plant-derived carbon into microbial biomass, and following microbial death, the resulting residues can contribute to particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) pools [5]. The contribution of microbial necromass to soil carbon storage can therefore depend on the type of microbial residue and the soil environment. Yang *et al.* found that fungal necromass was more strongly associated with POC, whereas bacterial necromass was associated with MAOC, highlighting that different microbial groups can contribute differently to soil carbon accumulation.

The persistence of microbial necromass is strongly influenced by interactions with the soil matrix. Microbial-derived compounds can interact with soil minerals and become physically or chemically protected within soil aggregates and mineral-associated organic matter, reducing their accessibility to decomposition [1, 5]. Soil physicochemical properties, mineral composition, aggregate formation, nutrient availability and microbial community characteristics can therefore influence the formation, stabilization and persistence of microbial necromass [1, 11]. This indicates that microbial residues do not automatically become permanently stored carbon; rather, their contribution to long-term sequestration depends on the mechanisms that control their stabilization and turnover.

Agricultural management can influence the formation and accumulation of microbial necromass by altering the quantity and quality of carbon inputs and the conditions experienced by soil microorganisms. Practices such as organic matter addition, crop-residue retention, crop rotation, conservation tillage and other carbon-farming practices can modify microbial activity, substrate availability and soil carbon dynamics [2, 10, 11]. Increased availability of organic substrates can stimulate microbial growth and carbon transformation, potentially increasing the formation of microbial residues. However, the extent to which these residues are retained in soil depends on soil characteristics, microbial community composition, nutrient availability, climatic conditions and interactions with minerals and soil aggregates [1, 5, 11].

Microbial necromass therefore provides an important connection between microbial activity and longer-term soil carbon storage. It demonstrates that microorganisms are involved not only in carbon decomposition and CO₂ release but also in the transformation, accumulation and stabilization of carbon within soil organic matter [1, 5, 16]. Understanding microbial necromass formation and its stabilization is therefore important for evaluating how agricultural practices can enhance persistent soil carbon storage and improve the long-term effectiveness of carbon farming [2, 16].

6. Biochar for soil carbon sequestration

Biochar is a carbon-rich material produced through the pyrolysis of biomass, in which organic materials are heated under oxygen-limited conditions. It has gained considerable attention in carbon farming because a substantial proportion of its carbon occurs in relatively stable forms that can persist in soil for long periods. This makes biochar a promising strategy for increasing soil carbon storage while also providing a productive use for agricultural and plant residues [8, 10]. The persistence and stability of biochar-derived carbon, however, can vary depending on the characteristics of the biochar, feedstock and soil environment [8, 10].

Biochar benefits extend beyond carbon sequestration. Its application can modify several physical and chemical properties of soil, including water-holding capacity, soil structure, nutrient retention and pH. These changes can improve the soil environment for plant growth and can also influence the abundance, composition and activity of soil microbial communities [8, 10]. Field studies and meta-analyses have also reported increases in soil microbial biomass carbon following biochar amendment, although the magnitude of the response varies with soil conditions, biochar characteristics and management practices [17].

The interaction between biochar and soil microorganisms is especially important for understanding its effects on soil carbon dynamics. The porous structure and surface properties of biochar can provide microsites that support microbial colonisation, while changes in soil pH, moisture and nutrient availability can further modify microbial activity [8, 11]. Biochar can also influence the decomposition and transformation of surrounding organic matter and interact with both soil minerals and microbial communities, thereby affecting the stabilization and cycling of soil carbon [10, 11]. Therefore, the contribution of biochar to soil carbon storage is not determined solely by the stability of its own carbon; it also depends on its interactions with soil organic matter, minerals and microorganisms and on the resulting changes in soil carbon cycling [8, 11].

7. Biochar and microbial technologies

The use of biochar in combination with microorganisms is gaining attention as a potential approach to improve soil quality, microbial activity and carbon management. Biochar has a porous structure and a large surface area that can provide sites for microbial attachment and colonization. Its physical and chemical properties may also

help create a more favorable microenvironment for microorganisms and, in some applications, improve the survival and activity of introduced microbial inoculants after their application to soil [9, 11]. The effectiveness of biochar as a microbial carrier, however, depends on its feedstock, production conditions, surface characteristics and compatibility with the microorganisms being introduced [8, 9].

Biochar-associated microorganisms can influence nutrient cycling and other soil processes and may promote plant growth by improving nutrient availability and plant-microbe interactions [9, 10]. Enhanced plant growth can increase carbon inputs to the soil through roots, root exudates and plant residues. At the same time, biochar provides a relatively stable form of carbon that can persist in soil. Therefore, the combination of biochar and microorganisms may contribute to soil carbon storage through both the persistence of biochar-derived carbon and increased inputs of plant-derived carbon [8, 11].

Li *et al.* (2026) discussed biochar as a potential carrier for microbial inoculants and highlighted the potential benefits of combining biochar with beneficial microorganisms. However, the outcomes of such treatments may vary depending on biochar properties, microbial species or strains, soil characteristics and interactions between the introduced microorganisms and the native soil microbiome. This implies that a biochar-microbial treatment that is effective under one set of soil and environmental conditions may not necessarily produce the same effects under different conditions.[9,11]

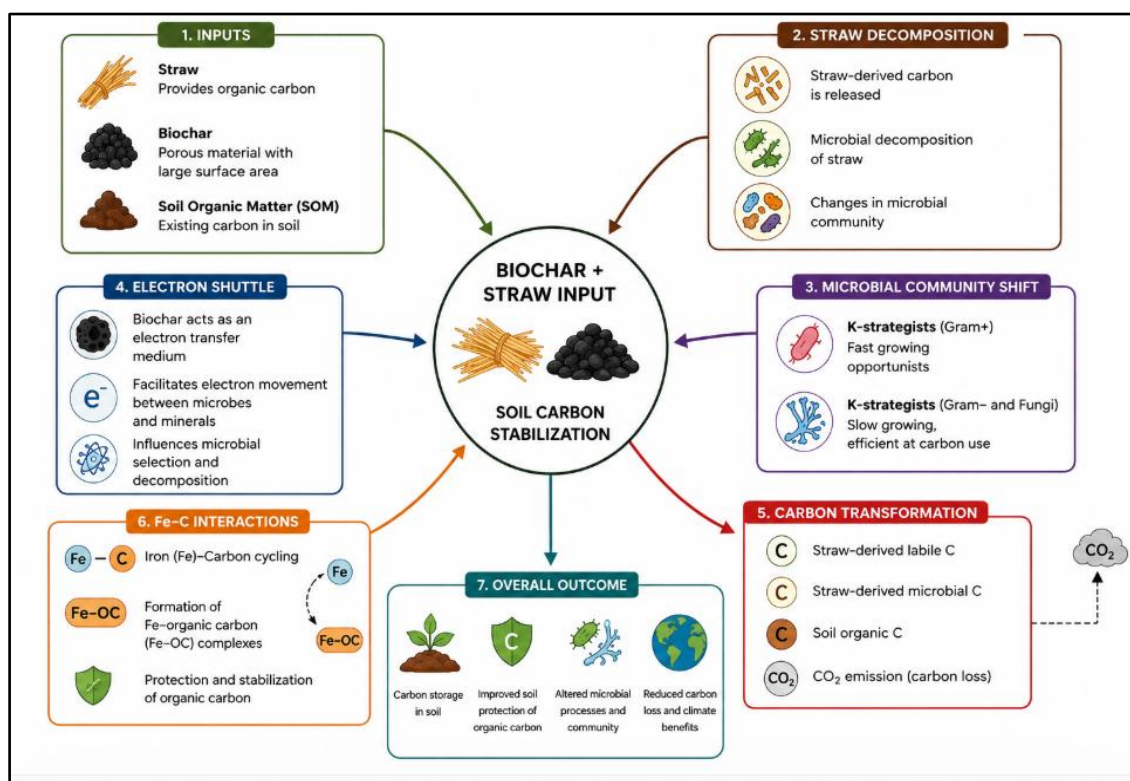


Figure 1: Effect of straw-biochar amendment on microbial activity and soil carbon dynamics in agricultural soil

8. Arbuscular mycorrhizal fungi and carbon sequestration

Arbuscular mycorrhizal fungi (AMF) are symbiotic with roots of a wide range of plant species. The fungi permeate the surrounding soil in return for carbon compounds produced by photosynthesis and help the plant acquire

nutrients and water [12, 16]. Such exchange is not without consequence for soil carbon cycling. Some plant-derived carbon is transferred to AMF, and these fungi are one of the more important pathways for carbon transfer from plants to soil. Fungal structures grow in and around the roots, and upon turnover of this biomass the residues can enter the pool of soil organic matter. Some compounds generated during microbial degradation are adsorbed to soil minerals, and can persist there, contributing to carbon storage over the longer term [12, 16, 18].

Tao and Liu (2024) reviewed the literature and explored that application of AMF tended to increase both soil carbon and plant biomass. But the strength of this effect was anything but stable. The outcomes were influenced strongly by AMF inoculation, which was determined by soil pH, pre-existing carbon content, plant species, and other environmental conditions [12].

AMF, thus, seems to be able to contribute to soil carbon storage – but not reliably, and not equally under all conditions. Because soil and crop responses vary, any evaluation of AMF as a carbon sequestration strategy must consider the specific soil properties and plant species involved [12, 13, 18].

9. AMF and biochar combination

The synergistic effect of arbuscular mycorrhizal fungi (AMF) and biochar is being increasingly studied as a promising strategy to improve soil carbon sequestration. Biochar has a porous structure that could harbor microorganisms. Meanwhile, AMF associates with plant roots and often enhances water and nutrient uptake. These two effects are not just additive, but potentially synergistic, affecting both plant growth and the amount of carbon transferred from plants to soil.

This combination was directly tested in wheat by Mason *et al.* (2025) where both AMF inoculation and biochar were applied. AMF treatment enhanced the soil carbon. However, a second, more surprising observation was that AMF x biochar interaction also affected the distribution of carbon deeper in the soil profile. To summarize, it's not just the amount of carbon that the soil gets, but where that carbon is, and the combination of the two approaches seems to change both.

So where does this leave the AMF-biochar approach? Looks promising but untested. Biochar's role is pretty straightforward. It adds carbon that tends to stick around. AMF works differently, by nudging how plants allocate carbon belowground in the first place. The key question is whether these combined effects are robust under real field conditions, and that is where the evidence is thin. Different soils, different crops, different climates, each could tip the balance and data for long-term variables has not been collected yet [8,11,13].

10. Fungal endophytes

Fungal endophytes take up residence inside plant tissues, quietly, without triggering disease. From that position, they can shape how a plant grows, how well it takes up nutrients, and how it copes with stress. And because they're altering plant growth in the first place, there's a reasonable case that they're also altering how much carbon makes its way into the soil. More root growth, more biomass, and the result is often more carbon entering the soil, whether through the roots themselves, root turnover, or the plant material left behind [14, 19].

Singh *et al.* (2025) researched at soybean and found that fungal endophyte inoculation shifted several fractions of soil organic matter, with some treatments even bumping up crop yield. Buss *et al.* (2025) reviewed something comparable in wheat: fungal inoculation changed aggregate-associated and mineral-associated organic matter, along with soil microbial properties more broadly. Neither study was looking specifically at carbon cycling, but

the pattern that emerges points that way; endophyte-plant relationships seem to reach further than plant performance alone [14,15].

All of this makes a reasonable case for including fungal endophytes in carbon farming and microbial soil management strategies. What's missing is certainty about the long game. Whether these effects hold up over years, in different soils, with different crops, under different endophyte strains, is still an open question. Getting a clearer answer will take sustained field research, not just controlled trials [14, 15, 19].

11. Microbial inoculants and microbial consortia

Microbial inoculants are manufactured products that contain selected microorganisms and are added to soil or applied to plants. Depending on the purpose of their application they can contain single strains of bacteria or fungi or mixtures of different microorganisms [6, 9].

Microbial inoculation is mainly used for promoting plant growth, improving nutrient availability and increasing plant tolerance against environmental stress. These organisms can also impact soil carbon cycling by changing decomposition, root growth and activity of native soil microbial communities. For instance, changes in root growth can alter the quantity of carbon entering the soil from roots and associated organic inputs [6, 7, 16].

The application of microbial consortia, where different microorganisms are mixed, might provide complementary functions that are not achieved from one microbial strain. But introduced microbes need to establish and remain active in the soil, and interact with the existing microbial community. Their performance may vary with soil properties, climate, crop type and other local conditions. This variability is an important consideration in the evaluation of microbial inoculants for agricultural applications and soil carbon management [6, 9].

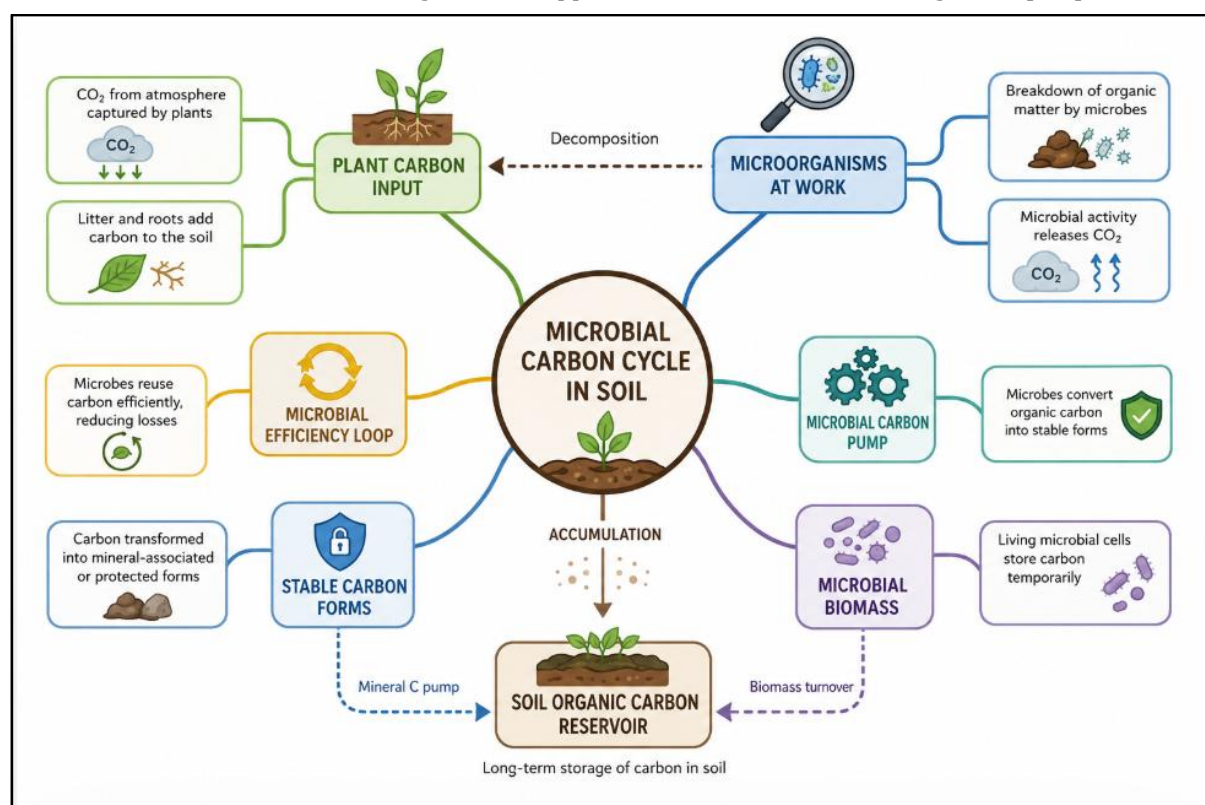


Figure 2: Role of microbial inoculants and microbial consortia in soil carbon cycling and carbon storage

12. Effect of agricultural practices on microbial carbon

Agricultural management practices can strongly affect soil microbial communities and, therefore, the cycling and storage of carbon in soil. Intensive and continuous cropping, frequent tillage and removal of crop residues can reduce organic carbon inputs and disturb the physical conditions under which soil microorganisms operate. These changes may affect the microbial biomass, decomposition processes and soil organic carbon retention [1, 2].

By contrast, microbial growth and activity can be supported by organic carbon and nutrients from manure, crop residues and green manure. Reduced and conservation tillage can also help, by reducing soil disturbance and maintaining soil structure, which may favor the retention of organic carbon in the soil [1, 2, 10].

He *et al.* (2023) reviewed that mineral fertilizers combined with organic inputs could increase microbial biomass and microbial necromass. Other practices including straw incorporation, manure application, crop rotation and conservation-based management have also been associated with increases in soil carbon storage. These effects emphasize the link between agricultural inputs, microbial processes and soil carbon dynamics [2, 4, 18].

Generally, effective carbon farming is unlikely to depend on a single practice or technology. Proper management practices in combination may lead to better conditions in maintaining soil organic carbon and microbial communities. However, the best combination will depend on the soil characteristics, climate, crop type and the specific management system used [1, 2, 4].

13. Challenges in microbial carbon sequestration

There is much potential for microbial technologies to improve soil carbon storage but their performance can be very different in different soil conditions. Soil pH, temperature, moisture, nutrient availability, and the composition of the existing microbial community affect microbial growth and activity. Therefore, a microbial treatment that works well under one set of conditions may produce a different response under a different soil environment [1, 4, 6].

Another important limitation is the establishment and survival of introduced microorganisms. Microbial strains selected under controlled laboratory conditions may not perform similarly after introduction into agricultural soils. They are required to adapt to the soil environment already present and to compete or interact with native microbial populations for available resources. These interactions can influence their survival, establishment, and efficiency to perform their intended functions [6, 9].

Microbial approaches to carbon sequestration should also consider the persistence of the stored carbon. An initial increase in soil carbon is not a guarantee that it will be stored long-term. Changes in environmental conditions and microbial activity could result in the carbon being decomposed and released in the future. Long-term field experiments are needed to assess whether carbon accumulated through microbial and management interventions stabilizes over several years. The significance of such studies is to assess the actual contribution of microbial technologies to sustained soil carbon sequestration [2, 4, 6].

14. Research gap

The studies showed that microorganisms play an important role in the cycling and sequestration of carbon in soils. However, many studies have primarily focused on individual approaches such as biochar application, AMF inoculation or microbial inoculants, rather than the performance of such approaches in combination with each other or with other carbon farming practices [6, 16].

Also, there is little information concerning the performance of combined microbial technologies in real agricultural conditions. Interactions of microbial communities with biochar, plant roots, soil organic matter, and soil minerals are complex and can influence both carbon inputs and carbon stabilization. Therefore, further work is needed to understand how these components interact and whether the combined use of these components can provide more benefits than the individual treatments [6, 10, 11].

Another big gap in research is the absence of long-term field studies. Many of the existing experiments have been conducted over relatively short periods or under controlled conditions and may not be representative of changes occurring in agricultural soils over time. Long-term field experiments are needed to determine if carbon sequestered by microbial and carbon farming practices can be stable for several years and to assess the consistency of these practices under different soil, climate and cropping conditions [2, 6].

One important research gap is the limited integration of different microbial and carbon management approaches within the same agricultural system. Microbial solutions for soil carbon sequestration have been investigated, but the evidence base is scattered across single interventions [16, 17]. Long-term nutrient-management studies also show links between soil carbon storage and arbuscular mycorrhizal fungal biomass, suggesting that microbial responses need to be considered in conjunction with sustained agricultural management and not as isolated treatments [18]. Potentially, edaphic microalgae may also serve as an agricultural inoculant for climate-change mitigation, which would mean that the range of microorganisms that are considered in carbon-sequestration research may need to be expanded [20].

Another major gap is how microbial technologies perform under changing environmental conditions and in combination with established farming practices. Microbially mediated processes have been shown to affect soil carbon accrual under long-term warming in conservation agriculture, but these responses need to be understood under realistic environmental conditions [21]. Likewise, the straw-biochar amendments might influence microbial activity and soil carbon dynamics. It is important to study the amendment and microbial response in combination [22]. Also, soil microbiome research indicates that microbial communities are an integral part of climate-smart agriculture. Metagenomic and fractionation approaches are beginning to provide ways to link microbial communities to stable soil carbon and to evaluate fungal inoculants more directly [7, 15].

Another research need is to determine whether various carbon-input strategies can result in consistent and durable sequestration benefits when paired with microbial interventions. Anaerobic microbial pretreatment of straw prior to returning it to the soil has been studied to affect both carbon sequestration and emission reduction. Reviews of carbon farming indicate that the effects of practices such as residue management, reduced tillage, manure use and related interventions can be variable among agricultural systems [2, 23]. Meanwhile, the tripartite interaction between biochar, microbes and soil and the wider effects of biochar on soil processes and microbial communities still remain an important area for further investigation [10, 11]. Collectively, these studies indicate a need for long-term, field-scale experiments that test combinations of practices, track microbial establishment and activity, and assess whether increases in soil carbon persist over time.

15. Conclusion

The soil carbon sequestration is not a simple function of the quantity of carbon added to soil, but rather a function of the effectiveness of conventional agricultural methods and of microbial communities in transforming, stabilizing, and retaining that carbon over time. Carbon farming practices, including retention of crop residues,

application of manure, reduced tillage, crop rotation, cover cropping, and biochar, can increase carbon inputs and create conditions conducive to carbon retention. At the same time, soil microorganisms are key biological regulators of carbon fate through decomposition, microbial carbon use efficiency, biomass formation, necromass production, and interactions with soil minerals.

The review also discusses the potential of microbial technologies to shift carbon farming from a simple carbon-input approach to a biologically driven strategy for carbon stabilization. AMF, endophytic fungi, microbial inoculants and microbial consortia can stimulate plant growth, nutrient uptake, root-derived carbon inputs and microbial transformation of organic matter. Biochar is especially relevant because it has the potential to produce a relatively stable pool of carbon and micro-sites conducive for microbial colonization, such that biochar-microbe combinations offer a promising avenue for increasing carbon retention.

Importantly, the studies suggest that no carbon farming practice or microbial technology can be considered universally effective. Their performance is highly dependent on soil type and pH, climate, crop species, nutrient availability, existing microbial community, and management practices. Thus, the future of soil carbon sequestration lies in integrated, site-specific approaches that combine appropriate carbon inputs with microbial processes that can transform and stabilize that carbon in the soil.

Nonetheless, a key limitation remains the lack of sufficient long-term, field-scale evidence that increases in soil carbon are stable and durable under real agricultural conditions. Future research should include multi-year field experiments comparing different combinations of biochar, organic amendments, conservation practices, AMF, fungal endophytes, microbial consortia and other emerging microbial interventions across various soils and cropping systems. The use of advanced tools such as metagenomics, microbial community profiling, and carbon fractionation can help to further identify the microorganisms and mechanisms that are responsible for persistent carbon storage.

Pairing carbon farming with microbial technologies offers a promising route to climate-smart agriculture ultimately, not only by increasing the amount of carbon that flows into soil but also by improving the biological processes that determine if that carbon stays there or returns to the air. Robust, site-specific and scalable combinations of these approaches have the potential to reinforce long-term soil carbon storage while providing the co-benefits of enhanced soil health, nutrient cycling, crop productivity and resilience of agricultural systems to changing environmental conditions.

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