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REVIEW

Soil microbes: a natural solution for mitigating the impact of climate change

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Abstract Soil microbes are microscopic organisms that inhabit the soil and play a significant role in various ecological processes. They are essential for nutrient cycling, carbon sequestration, and maintaining soil health. Importantly, soil microbes have the potential to sequester carbon dioxide (CO_2) from the atmosphere through processes like carbon fixation and storage in organic matter. Unlocking the potential of microbial-driven carbon storage holds the key to revolutionizing climate-smart agricultural practices, paving the way for sustainable productivity and environmental conservation. A fascinating tale of nature's unsung heroes is revealed by delving into the realm of soil microbes. The guardians of the Earth are these tiny creatures that live beneath our feet and discreetly work their magic to fend off the effects of climate change. These microbes are also essential for plant growth enhancement through their roles in nutrient uptake, nitrogen fixation, and synthesis of growth-promoting chemicals. By understanding and managing soil microbial communities, it is possible to improve soil health, soil water-holding capacity, and promote plant growth in agricultural and natural ecosystems. Added to it, these microbes play an important role in biodegradation, bioremediation of heavy metals, and phytoremediation, which in turn helps in treating the contaminated soils. Unfortunately, climate change events affect the diversity, composition, and metabolism of these microbes. Unlocking the microbial potential demands an interdisciplinary endeavor spanning microbiology, ecology, agronomy, and climate science. It is a call to

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arms for the scientific community to recognize soil microbes as invaluable partners in the fight against climate change. By implementing data-driven land management strategies and pioneering interventions, we possess the means to harness their capabilities, paving the way for climate mitigation, sustainable agriculture, and promote ecosystem resilience in the imminent future.

Keywords Soil microbes · Climatic variables · Soil ecosystem · Carbon sequestration · Microbial diversity · Soil health

Introduction

Climate change is an issue of worldwide significance, having profound impacts on the planet and all those who inhabit it (IPCC, 2021; Kumari et al., 2022). We are already experiencing the consequences of climate change, such as the rise in global temperatures, sea levels, and extreme weather events. In addition, climate change is affecting ecosystems and biodiversity, agriculture, human health, and social and economic systems. Climate change significantly affects soil health through soil erosion, SOM (soil organic matter) depletion, soil compaction, and changes in microbial communities (Jagadesh, Selvi, et al., 2023). The degradation of unstable carbon pools has also raised concerns about the potential increase in CO_2 emissions (Jagadesh, Srinivasarao, et al., 2023). Thus, by understanding these impacts, we can develop strategies to mitigate the effects of climate change on soil health and promote ecosystem resilience (Fig. 1).

To combat the negative effects of climate change on soil health, soil microbes can serve as a solution. The role of soil microbes in balancing the Earth's carbon cycle is crucial as it helps to reduce the amount of greenhouse gases in the atmosphere. Additionally, these microbes play an important part in nutrient cycling, especially carbon, regulating methane, and maintaining soil health, all of which are essential in mitigating the impacts of climate change (Lehmann & Kleber, 2015). In this review, we explored the role of soil microbes in addressing the key question of climate change. We discussed how soil microbes can help decrease greenhouse gas emissions, enhance carbon sequestration and soil health, and increase plant growth and productivity (Gougoulias et al., 2014). We have also examined how soil microbial communities can be managed to improve their ability to mitigate climate change. Through a better understanding of the role of soil microbes in climate change, we can develop strategies to promote soil health and ecosystem resilience under climate change scenarios.

Effects of climate change on soil health and fertility

Climate change significantly impacts soil ecosystems, including accelerating soil erosion due to intense rainfall, shifts in microbial diversity affecting the nutrient cycle, and ultimately reducing soil fertility. Rising temperatures in turn can lower the water retention capacity, and induce drought stress on plants and soil organisms. Changes in rainfall patterns can alter available soil moisture, plant growth, and soil stability. Added to it climate-induced disturbances like wildfires can instigate soil carbon loss, which in turn enhances greenhouse gas emissions. The resilience and efficiency of soil ecosystems are in danger as a result of these changes, which will have a knock-on effect on agriculture and terrestrial biodiversity. Thus, climate change significantly affects soil health, ecosystem function, plant productivity, and food security. Here are a few ways that soil health is being impacted by climate change:

1. Soil erosion

The increasingly frequent and intense rainfall events caused by climate change can lead to greater soil erosion and loss of nutrients (Lal, 2009). This erosion can also raise the risk of landslides, mudslides, and flooding.

2. Soil organic matter depletion

Rising temperatures and changes in precipitation patterns can lead to decreased soil organic matter (SOM) levels (Paustian et al., 2016; Tiedje et al., 2022). SOM is critical for maintaining soil health and fertility, and its depletion can lead to decreased nutrient cycling, soil structure, and water-holding capacity.

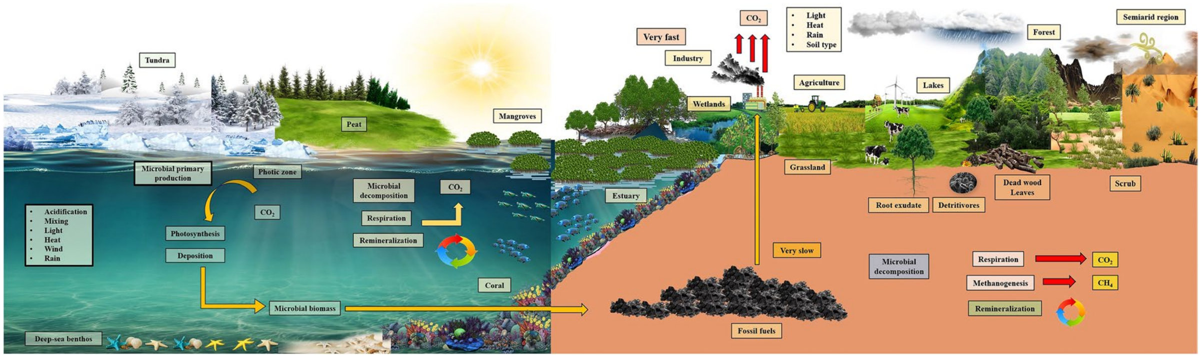

Fig. 1 Climate change and microbes in terrestrial and marine biomes (Cavicchioli et al., 2019). Oceans and seas span about 70% of our planet, extending from coastal areas like estuaries, mangroves, and coral reefs to the vast expanses of open waters. While microorganisms in the upper 200 meters of the ocean harness sunlight for energy, those in deeper regions rely on organic and inorganic compounds. Factors like the range of available energy sources and water temperatures, which can fluctuate from nearly −2 °C in icy waters to over 100 °C in hydrothermal vents, shape marine ecosystems. Elevated temperatures not only impact marine life processes but also alter the water's density, affecting stratification, circulation, species distribution, and nutrient movement. Elements like rainfall, salt content, and wind further influence these dynamics. Moreover, the composition and function of marine microbial communities are influenced by nutrients entering from the atmosphere, rivers, and estuaries. All these variables are being reshaped by the ongoing shifts in our climate. Marine microbes play a pivotal role in capturing CO_2 through primary production. Furthermore, they help in nutrient cycling within marine food chains, simultaneously emitting CO_2. On land, microorganisms act as the principal agents breaking down organic material, thereby making nutrients available for plants and releasing gases like CO_2 and CH_4. Over extended geological timescales, microbial biomass, along with other organic remnants, transforms into fossil fuels. However, in a relatively short span, the combustion of these fossil fuels releases significant amounts of greenhouse gases, disturbing the carbon equilibrium. The array of human-induced factors, encompassing sectors like agriculture, industry, and transportation, coupled with our increasing population and consumption habits, profoundly affects the intricate web of microbial interplay with their biotic surroundings. Such activities, combined with inherent environmental variables like soil composition and light intensity, determine how microbes both influence and react to climate change, such as through the emission of greenhouse gases. Additionally, changes in our climate, exemplified by rising CO_2 concentrations, temperature fluctuations, and alterations in rainfall, reciprocally shape microbial behavior

3. Soil compaction

Changes in rainfall patterns and increased use of heavy machinery in agriculture can lead to soil compaction, reducing plant productivity and soil health (Gursoy, 2021). Compacted soils have reduced water infiltration, air exchange, and root growth.

4. Acidity or alkalinity of soils

According to Chandra et al. (2013), most soil has a buffering capacity that prevents rapid changes in pH levels due to climate change. However, human activities that emit pollutants like sulfur dioxide and nitrogen oxides can cause increased acid rain, a possible consequence of climate change. But in the long run, specific types of soil acid rain can lower soil pH and affect soil nutrient availability and metal toxicity, leading to poor plant growth (Msimbira & Smith, 2020; Mueller, 2018). Changes in precipitation patterns due to climate change can also affect soil pH. For example, increased rainfall can leach basic cations, such as calcium and magnesium, from the soil, resulting in soil acidification (Nawaz et al., 2012; Rengel, 2011). Conversely, drought conditions can increase soil alkalinity due to the accumulation of basic cations (Msimbira & Smith, 2020).

5. Changes in microbial communities

Climate change can change soil microbial communities, affecting nutrient cycling, carbon sequestration, and plant productivity (Bardgett & van der Putten, 2014; Pugnaire et al., 2019). Alterations in soil moisture, temperature, and pH can select for different microbial species, which can have positive or negative effects on soil health.

Uses of soil microbes to address climate change and improve soil health

Soil microbes are part and parcel of the complex system of interactions between the atmosphere, plants, and soils that regulate the Earth's climate. By better understanding and managing soil microbial communities, we can help mitigate the impacts of climate change (Figs. 1 and 2).

Soil microbes perform a significant function in addressing the key question of climate change. Here are a few ways in which they are relevant:-

1. Use of soil microbes in Carbon sequestration

In the long run, capturing and storing atmospheric carbon dioxide in soil organic matter are known as carbon sequestration. Soil microbes are vital in addressing climate change issues. Microbes help in transforming the organic matter into humus and the glues like glomalin produced by them promote aggregate stability and thereby help in protecting the decomposition and further impart recalcitrant nature to the carbon (Rillig et al., 2019). By increasing the amount of carbon stored in the soil, soil microbes help mitigate climate change by reducing the amount of CO_2 in the atmosphere (Hu et al., 2018; Tiedje et al., 2022). Soil microbes, particularly fungi, are involved in forming stable carbon compounds, which help enhance plant growth and increase organic matter input to soil (Gougoulias et al., 2014; Lehmann & Kleber, 2015).

2. Use of soil microbes in Nutrient cycling

In terrestrial ecosystems, the cycling of nutrients is greatly influenced by soil microbes. They take part in the breakdown of organic materials, the mineralization of nutrients, and the development of symbiotic connections with plants, all of which increase the availability of nutrients. For instance, mycorrhizal fungi form advantageous relationships

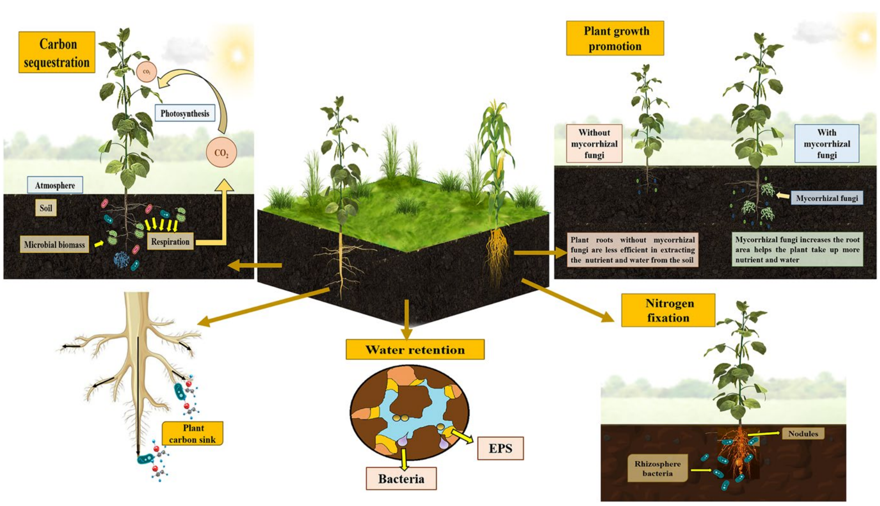

Fig. 2 Altering the soil microbiome to alleviate the deleterious effects of climate change (Jansson & Hofmockel, 2020). Leveraging the soil microbiome offers potential solutions to counteract the adverse effects of climate change. Here are some approaches that demonstrate how the soil microbiome can be used in this regard: Certain microorganisms can aid in moisture preservation in soils, especially during droughts. They achieve this by producing substances like extracellular polymeric substances (EPS) which fill the gaps in the soil, thereby helping retain water in dry periods. The soil microbiome can act as a repository for plant carbon. Microbes absorb the carbon released by plant roots and store it either as part of their cellular structure or as long-lasting metabolic byproducts. This carbon, when stored in the form of decreased microbial matter, is termed "necromass." Microbes that promote plant growth can be harnessed to bolster crop yields, especially in areas where climate change adversely affects soil health. A few mechanisms through which they achieve this include facilitating the conversion of atmospheric nitrogen to usable forms through bacteria that have nitrogen-fixing capabilities and enhancing nutrient absorption with the help of fungi like mycorrhizae, producing microbial hormones that promote plant growth, for instance, indole-3-acetic acid (IAA)

with plants that improve nutrient intake. Additionally, some soil bacteria participate in nitrogen fixation, which transforms atmospheric nitrogen into forms that plants can use. These microbial activities are necessary to preserve soil fertility and support plant growth. Thus, soil microbes are vital in nutrient cycling (Gougoulias et al., 2014; Prosser, 2007). They are also responsible for converting organic matter into nutrients that plants can use, which helps to support plant growth and productivity. This, in turn, helps to reduce atmospheric CO_2 levels by increasing plant biomass.

3. Use of soil microbes in Soil health

Through a variety of essential tasks, soil microorganisms play a crucial role in preserving soil health. They assist in the breakdown of organic matter, dissolving complex substances into vital nutrients that plants can absorb. By generating chemicals like glomalin, which encourage soil aggregation and stability, microbes also improve soil structure. Additionally, some microbes work to control soil-borne diseases, lowering the need for artificial pesticides. Microbes are essential in nutrient cycling because they recycle nutrients, making them available to plants and promoting overall soil fertility. Additionally, their metabolic processes can help maintain the pH balance of the soil and detoxify contaminants. A healthy microbial community is frequently a sign of a strong and fertile soil ecosystem. Soil microbes are important markers of soil health (Suman et al., 2022). Healthy soil can better support plant growth and productivity, which helps reduce atmospheric CO_2 levels. Therefore, protecting and improving soil health for sustainable agriculture and ecosystem stability requires knowledge of and promotion of the diversity and activity of soil microorganisms.

4. Use of soil microbes in methane emissions

Soil microbes play a significant role in the regulation of CH_4 emissions in relation to CO_2 in the atmosphere. CH_4 is a potent greenhouse gas, and its microbial cycling in soils can influence greenhouse gas dynamics. Methanotrophic bacteria, in particular, are key players in mitigating CH_4 emissions by converting CH_4 into CO_2. This process is a crucial component of the global carbon cycle (Conrad, 2020).

5. Use of soil microbes in water retention in soil

Soil plays a critical role in water retention, and soil microbes are essential in this process. They aid in the formation of soil aggregates, which enhance soil structure and increase the soil's water-holding capacity (Suman et al., 2022). Microbial exudates, such as polysaccharides and proteins, act as the adhesive that holds soil particles together to form stable aggregates (Costa et al. 2018). Also, soil microbes play a role in the biogeochemical processes affecting soil water retention. For example, they decompose organic matter, which releases nutrients that promote plant growth and increase plant water uptake (Gerba, 2005). Soil microbes also influence soil hydraulic properties, such as hydraulic conductivity, which affects the rate at which water moves through soil (Choudhury et al., 2018; Helliwell et al., 2014). Furthermore, soil microbes can produce extracellular enzymes that degrade organic matter and release water bound to the organic molecules (Lehmann & Kleber, 2015). This can increase water availability in soil, particularly in dry environments.

6. Use of soil microbes in enhancing plant growth and development

Soil microbes can help decrease the impact of climate change by increasing plant growth and development, which in turn can help to reduce atmospheric CO_2 levels by carbon sequestration (Naylor et al., 2020; Tiedje et al., 2022). Soil microbes are vital in promoting plant growth by facilitating nutrient uptake, suppressing plant pathogens, and producing growth-promoting substances (Teja et al. 2023). These benefits are often associated with specific groups of soil microbes, including mycorrhizal fungi, rhizobia, and plant growth-promoting bacteria (Mendes et al., 2013, Teja et al. 2023). Mycorrhizal fungi are mutualistic symbionts that form associations with plant roots. They improve plant nutrient uptake by enhancing the surface area of the root system and by releasing organic acids that solubilize nutrients from soil minerals (Begum et al., 2019; Huey et al. 2020). In return, the plant provides the fungi with carbohydrates (Kumari et al., 2023).

Rhizobia are soil bacteria that form nitrogen-fixing symbioses with legume plants. They convert atmospheric nitrogen into a form that the plant can use, thus increasing plant nitrogen availability and promoting growth (Broughton et al., 2003; Mahmud et al., 2020). Plant growth-promoting bacteria (PGPBs) are a diverse group of bacteria that colonize plant roots and stimulate plant growth through various mechanisms. Some PGPBs produce hormones that promote root growth, while others solubilize nutrients from soil minerals or produce antimicrobial compounds that suppress plant pathogens (Dutta & Bora, 2019; Glick, 2012).

7. Use of soil microbes in stress management

Climate change poses a variety of challenges for plants. Resilient crops, however, exhibit superior abilities to manage reactive oxygen species (ROS) balance and maintain cellular functions when compared to their more sensitive counterparts (Kumari et al., 2022). To combat the adverse effects of climate change and maximize plant growth under increasingly harsh conditions, beneficial microorganisms like PGPBs and fungi are being explored (Naylor & Coleman-Derr, 2018). These PGP microbes can be applied in various forms, including as liquid or granular probiotics or seed coatings, to field-grown plants. Traditionally, the use of PGP strains has been exemplified by rhizobium inoculants combined with legumes for biological nitrogen fixation (Compant et al., 2005). However, there is a growing interest in harnessing PGP microorganisms to mitigate the impacts of climate change, in addition to their conventional roles as biofertilizers and biopesticides. Scientists are actively investigating soil microbes associated with plants to enhance their ability to cope with drought stress (Lakshmanan et al., 2017) [see Table 1].

Some soil bacteria, for instance, have the capacity to produce extracellular polysaccharides (EPS) that create hydrophobic biofilms, providing plants with protection against desiccation (Naylor & Coleman-Derr, 2018). Consequently, there is a rising interest in utilizing soil bacteria that produce EPS to alleviate drought stress in plants, as EPS can retain water in the soil, making it more accessible to plant roots. Beneficial soil microbes can also enhance a plant's resistance to drought stress through various mechanisms, such as the production of phytohormones that promote plant growth, the accumulation of osmolytes or protective chemicals, or the detoxification of reactive oxygen species (Lakshmanan et al., 2017; Vurukonda et al., 2016). For example, specific Bacillus species in the rhizosphere produce indole-3-acetic acid (IAA), which stimulates root development (Armada et al., 2015) (Figs. 2 and 3).

IAA-producing soil bacteria can facilitate root initiation and elongation when introduced into the soil (Lakshmanan et al., 2017). This increased root biomass and length can aid in water uptake, reducing water stress for the plant and potentially contributing to the creation of soil organic matter. Additionally, the presence of rhizosphere bacteria has been associated with the accumulation of osmoprotectants in plant cells and the reduction of osmotic stress due to water imbalances (Pereyra et al., 2012). For instance, Azospirillum inoculation led to an increase in the osmoprotectant proline, helping maize plants withstand drought stress (Casanovas et al., 2002).

Furthermore, bacterial inoculants can directly influence the metabolome of plants. In a study by Schmidt et al. (2014), the composition of secondary metabolites in chamomile plants changed after inoculation with various bacterial strains, resulting in an increased production of bioactive metabolites. Bacteria equipped with 1-aminocyclopropane 1-carboxylate (ACC) deaminase can mitigate the effects of the plant stress hormone ethylene (Glick, 2014). Some endophytic Azospirillum strains have been shown to affect stomatal closure in maize by influencing gibberellin production via signal transduction pathways (Cohen et al., 2009).

Fungal interactions also play a crucial role in enhancing nutrient acquisition and resistance to drought stress. Many economically valuable plants form symbiotic relationships with beneficial arbuscular mycorrhizal (AM) fungi. These associations promote plant growth by improving the bioavailability of phosphorus in the soil to plants. Moreover, these symbiotic relationships can enhance a plant's ability to withstand environmental challenges such as climate change (Kumari et al., 2023). For example, AM fungi have been found to enhance maize plants' adaptation to drought stress by regulating the production of aquaporins, which are known to reduce water stress (Kapilan et al., 2018; Quiroga et al., 2017).

In addition to their effects on individual plants, some soil bacteria, like certain Geobacter species, have broader ecosystem-scale impacts by fixing atmospheric nitrogen into a bioavailable form (Bazylinski et al., 2000; Mouser et al., 2009).

Table 1 The roles of various soil microbes in addressing climate change

Soil microbe	Role in addressing climate change	References
Fungi	Formation of stable carbon compounds and carbon sequestration in soil	Lehmann and Kleber (2015)
Nitrogen-fixing bacteria	Fix nitrogen in the soil, improves soil health, promotes plant growth and increases biomass, leading to carbon sequestration	Mahmud et al. (2020)
Methanotrophic bacteria	Oxidize methane in soil, reducing greenhouse gas emissions	Cai et al. (2016)
Arbuscular mycorrhizal fungi	Improve plant growth and nutrient uptake, reducing the need for synthetic fertilizers	Begum et al. (2019); Veresoglou and Rillig (2012)
Actinobacteria	Degrade organic matter and promote soil health, leading to increased carbon sequestration	Bao et al. (2021)
Denitrifying bacteria	Convert nitrate to nitrogen gas, reducing nitrous oxide emissions	Vilar-Sanz et al. (2013)
Cyanobacteria	Fix nitrogen from the air and increase soil organic matter, leading to carbon sequestration	Sanyal et al. (2022)
Phosphate-solubilizing bacteria	Improve plant growth and nutrient especially phosphorus uptake, decreasing the requirement of synthetic fertilizers	Alori et al. (2017); Yadav et al. (2017)
Cellulose-degrading bacteria	Break down plant material and promote soil health, leading to increased carbon sequestration	Balamurugan et al. (2011)
Sulfur-oxidizing bacteria	Oxidize sulfur compounds and reduce soil acidification, which can improve plant growth and productivity	Rana et al. (2020)
VAM fungi	Improve plant growth and nutrient uptake, reducing the need for synthetic fertilizers and increasing carbon sequestration	Dar and Reshi (2017)
Acetogenic bacteria	Convert CO_2 to acetate, reducing greenhouse gas emissions	Bertsch and Muller (2015)
Methanogens	Convert CO_2 to methane, reducing greenhouse gas emissions	Conrad (2009)
Lactic acid bacteria	Improve soil structure and nutrient cycling, leading to increased carbon sequestration	Raman et al. (2022)
Nitrifying bacteria	Convert ammonium to nitrate, reducing nitrous oxide emissions	Hassan et al. (2022)
Bacillus subtilis	Reduce the negative impact of soil-borne plant pathogens while also enhancing plant growth, reducing the need for synthetic pesticides and fertilizers	Compant et al. (2005)
Actinomycetes	Produce antibiotics and promote soil health, leading to increased carbon sequestration	AbdElgawad et al. (2020)
Azotobacter	Fix atmospheric nitrogen and promote plant growth, reducing the need for synthetic fertilizers	Sumbul et al. (2020)

Understanding how microbial communities and metabolism respond to changes in CO_2:CH_4 production correlates with organic matter transformations can shed light on the control of methane production. Methanotrophic bacteria, which can consume a substantial portion of total wetland methane emissions (Megonigal et al., 2003), play a vital role in regulating the net emission of CH_4 to the atmosphere (Liebner et al., 2008; Wagner, 2008).

Furthermore, N_2O, a significant contributor to ozone depletion and a potent greenhouse gas in the stratosphere results from ammonia oxidation carried out by bacteria and ammonia-oxidizing archaea under aerobic conditions (Tiedje et al., 2022). These

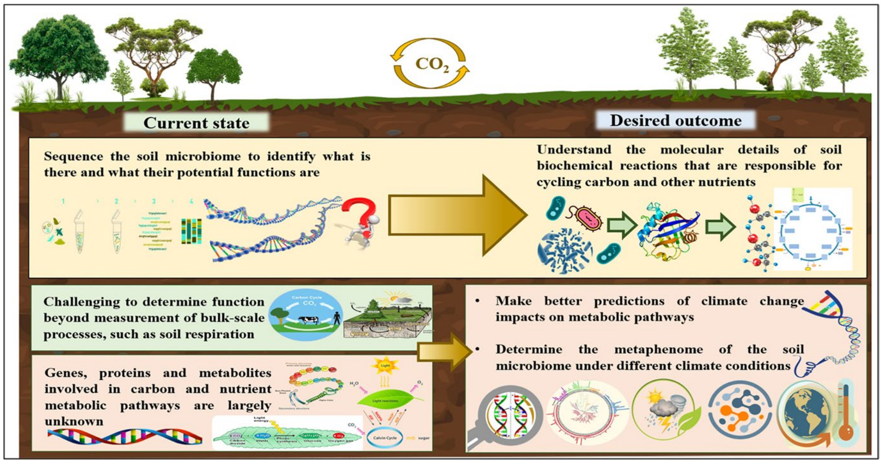

Fig. 3 Potential of soil microbiomes during different environmental variables (Jansson & Hofmockel, 2020). Due to progress in sequencing techniques, we can now identify the different species that make up soil microbial ecosystems and understand how these communities are affected by climate change. Gaining insights into the biochemical processes, like soil respiration, carried out by these interactive microbial members is critical. This understanding of core functions and their sensitivity to climate alterations can be achieved through comprehensive techniques like multi-omics and other state-of-the-art technologies

examples underscore the vast potential of understanding soil microbiomes in harnessing the adaptability of bacteria to address our changing environment and enhance ecosystem services.

8. Use of soil microbes in polluted environments

Soil microbes can degrade or detoxify hazardous pollutants in contaminated soils. Here are a few mechanisms in which soil microbes can be used in mitigating pollutants:

- Biodegradation: Microbial-driven degradation mechanisms can help in the detoxification and immobilization of organic pollutants, and heavy metals in the soil, and thereby preventing their movement (Zheng et al., 2023). Soil microbes can break down into less harmful substances. This process, known as biodegradation, involves specialized enzymes that break down pollutants (Bisht et al., 2015).
- Bioremediation: Soil microbes are harnessed to break down and transform heavy metal contaminants, reducing their bioavailability to plants and potential uptake (Zheng et al., 2023). Some soil microbes are capable of removing heavy metals, such as lead, cadmium, and mercury, from contaminated soils. This process, known as bioremediation of heavy metals, involves the use of microbes that can immobilize, transform, or volatilize the heavy metals (Tarfeen et al., 2022).
- Phytoremediation: Phytoremediation, a process that combines the capabilities of soil microbes and plants, holds promise in mitigating the risks associated with heavy metal contamination in crops (Zheng et al., 2023). In this approach, plants absorb and accumulate pollutants from the soil, while soil microbes work to break down these pollutants into less harmful substances, effectively reducing environmental contamination (Pilon-Smits, 2005; Salt et al., 1995).

As we grapple with the impacts of climate change on soil microbiomes, there is a growing need to harness the potential of soil microbes to counteract environmental disturbances. This encompasses direct manipulation of soil microbial populations, adjusting land management practices, or employing microbial inoculants as environmental probiotics. The soil microbiome emerges as a valuable tool in mitigating climate change's adverse effects. For instance, microbes can produce extracellular polymeric substances (EPS) that seal soil pores, enhancing soil water retention—a novel approach to alleviate drought stress. Microbes also act as carbon sinks by consuming plant-exported carbon and storing it as cellular biomass or stable metabolites.

Soil microorganisms contribute to the assimilation of carbon into stable, non-gaseous forms, either biotically or abiotically. Plants play a crucial role in transferring photosynthate to the rhizosphere, stimulating symbiotic and free-living soil organisms and dispersing carbon throughout the soil matrix. To further enhance carbon deposition into the soil, we can tap into the untapped biochemical potential of the soil microbiome, potentially altering carbon breakdown pathways to produce more resistant and stable end products.

Alternatively, we can introduce natural microbial species or consortia into soil ecosystems with desired metabolic pathways to capture carbon. Modifying soil microbiomes in situ by adding amendments that increase their carbon uptake and storage capacity is another viable approach. Encouraging the production of stable carbon from microbial products that can be preserved in deeper soil layers is a key strategy for climate change mitigation. Soil microbes contribute to the production of soil organic matter through the generation of stable metabolites or necromass (dead biomass).

Another avenue is amending soil with biochar to sequester soil carbon. The fate of biochar—whether it is respired or retained in the soil—is linked to the level of microbial activity, underscoring the indirect role of the soil microbiome in biochar's potential. Optimizing interactions between plants and the soil microbiome in the rhizosphere is gaining popularity as a means to promote soil carbon storage (Jansson et al., 2018; Wallenstein, 2017) (Table 1). These strategies showcase the evolving role of soil microbes in mitigating climate change and environmental challenges.

New insights from genomics data on climate change

The taxonomic makeup of soil microbial communities may now be determined, as well as how climatic change affects community membership, thanks to advancements in sequencing technologies. Important scientific research that can be focused on multi-omics approaches and other cutting-edge tools includes grasping the specifics of biochemical reactions, including the communications between soil respiration and the major functional members affected under the context of climate change. Different microbial cells are represented by colors in the left panel, while various biochemical process stages are described in the right panel (Jansson & Hofmockel, 2020) (Fig. 3).

Overall, soil microbes play critical roles in addressing the key question of climate change. They can help mitigate the effects of climate change by promoting carbon sequestration, reducing greenhouse gas emissions, and improving soil health and plant growth. By harnessing the power of these microbes, we can work towards a more sustainable and resilient future. It is important to note that while the research on the roles of soil microbes in addressing climate change is promising, there is still much to be learned about the complex interactions between soil microbes, plants, and the environment. Future research will help us better understand these interactions and how we can effectively utilize soil microbes to address the challenges of climate change.

Way forward

The future research directions for understanding and managing soil microbial communities and their potential applications in improving soil health, plant growth, and bioremediation can focus on the following areas:

- Microbial diversity and function: Further investigations are needed to explore the diversity of soil microbial communities and their functional roles in different ecosystems. This can involve advanced molecular techniques, such as metagenomics and meta transcriptomics, to identify and characterize specific microbial taxa and their active genes.
- Microbial interactions: It is crucial to understand the complex interactions among different microbial species and their influence on soil processes. Future research can explore microbial community dynamics, including competition, cooperation, and synergistic relationships, to uncover the mechanisms underlying microbial-mediated soil functions.
- Microbial bioinformatics and big data analysis: With the advancements in high-throughput sequencing technologies, bioinformatics tools, and computational models are needed to analyze and interpret large-scale microbial datasets effectively. Integrating

multi-omics data, machine learning algorithms, and network analysis can provide deeper insights into microbial communities and their functions.

- Microbial ecological engineering: Investigating novel strategies for manipulating soil microbial communities can improve soil health and plant growth. This can involve exploring specific microbial inoculants, amendments, and management practices to enhance the abundance and activity of beneficial microbial groups in different soil types and conditions.
- Microbes in bioremediation: Research should continue to investigate the potential of soil microbes for bioremediation purposes. This includes studying the microbial mechanisms involved in the degradation and detoxification of various contaminants and exploring the synergistic effects of microbial and plant-based remediation strategies for contaminated soil restoration.
- Application of microbial technologies: Translating research findings into practical applications requires the development of microbial-based technologies that can be readily applied in agricultural and environmental settings. Future research can focus on scaling up microbial interventions, optimizing delivery methods, and assessing their long-term effectiveness in diverse field conditions.
- Climate change impacts: Investigating the effects of climate change on soil microbial communities and their functions is essential for predicting the future resilience and stability of ecosystems. Research efforts should examine how shifts in temperature, precipitation patterns, and other climatic factors influence soil microbes, nutrient cycling, and overall soil health.
- Integrated approaches: A holistic and interdisciplinary approach is crucial for advancing research in this field. Collaborative studies integrating microbiology, ecology, agronomy, engineering, and environmental sciences can provide comprehensive insights into soil microbial communities and their applications.

Overall, future research should aim to deepen our understanding of soil microbial communities, their ecological functions, and their potential applications in improving soil health, plant growth, and bioremediation. This knowledge can contribute to sustainable agricultural practices, ecosystem restoration, and the development of innovative solutions for environmental challenges.

Conclusion

To maximize the favorable metabolic pathways of natural microbial communities that would direct them towards sequestration of soil C, for instance, better soil microbial inoculation and amendment procedures are required. To enhance climate impact assessments and develop effective microbial solutions to combat climate warming and soil degradation, it is crucial to gain a deeper understanding of how soil microbial processes are affected by climate change. Although it is commonly known that microorganisms perform critical function for plant health and the evolution of the plant environment, the bulk of the rhizosphere's microbial populations is still poorly understood. Insights into the soil microbiome have been gained by combining the traditional technique with metagenomic methodologies to evaluate the structure and function of the microbial population. By revealing numerous underutilized soil microorganisms, their processes, genes for different applications, increasing crop yield, nutrient cycling, and phytopathogen resistance has aided in the development of sustainable agriculture.

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Data availability Not applicable

Declarations

Competing interests The authors declare no competing interests.

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