https://journal.mdpip.com/index.php/oagmr

Open Access Organization and Management Review

Review Article

Exploring Anthropogenic Dark Earth Synthesis from Ancient Soil Wisdom to Modern Microbial Engineering to Restore Climate-Resilient Soil

Muhammad Arslan (BS Scholar)[1], Zain-ul-Abideen (BS Scholar)[2], Abida Ali (MPhil Scholar)[3], Dr. Fatima Ali (Assistant Professor)[4]

[1]Department of Bio-Science and Technology, Emerson University, Multan, Punjab, Pakistan. Email: muhammadarslanqureshi2005@gmail.com

[2]Department of Bio-Science and Technology, Emerson University, Multan, Punjab, Pakistan. Email: zainulabideen.2314@gmail.com

[3]Department of English, The Women University Multan, Punjab, Pakistan. Email: abidaali685@gmail.com

[4]Deakin University, Melbourne, Australia. Department of History and Pakistan Studies, The Women University, Multan, Punjab, Pakistan. Email: fatima.hps@wum.edu.pk

Corresponding author:

Muhammad Arsalan
Department of Bio-Science & Technology,
Emerson University, Multan,
Punjab, Pakistan.
Email: muhammadarslanqureshi2005@gmail.com

Received: 03 September 2026
Accepted: 17 September 2026
Published: 18 September 2026

DOI Prefix 10.59644

Quick Response Code:

ISSN (p): 2959-6211
ISSN (e): 2959-622X
Website: mdpip.com
Publisher: MDPIP

ABSTRACT

Anthropogenic activities, i.e. burning fossil fuels, biomass, and decomposition of organic matter, release climate pollutants such as carbon dioxide, nitrous oxide, and other greenhouse gases into the environment. Furthermore, this study aims to identify various carbon sequestration techniques to mitigate climate change and support soil productivity. Therefore, this qualitative research reviews fifty articles from (2022-26) to reflect the significance of ADE carbon-holding capacity from ancient to modern microbial engineering. Therefore, the findings reveal the Amazonian Dark Earth is a product of pre-Columbian human activities in central Amazonia. It holds an enormous portion of carbon, phosphorus, nitrogen, calcium, and other nutrients. Moreover, it explores the ways biosynthetic engineering can be used to produce Amazonian Dark Earth microbes' carbon-storing capacity in non-native soil to make it climate-change-resilient. It may improve microbial functionality to withstand climate conditions, restore degraded soil for sustainable agriculture, and improve plant growth and health. Hence, engineered microorganisms have a beneficial impact on agricultural growth and improve degraded soil for sustainable agriculture. However, direct microbial carbon-sequestration capacity, long-term persistence, field stability, native-community interactions, and ecological/biosafety risks remain insufficiently validated.

Keywords: Amazonian Dark Earth, Microbial Engineering, Carbon Sequestration, Synthetic Biology, Climate Resilience, Plant-Microbe Interactions, Degraded Soil Restoration.

How to cite this article: Arslan, M., Abideen, Z., Ul., Ali, A., & Ali, F. (2026). Exploring Anthropogenic Dark Earth Synthesis from Ancient Soil Wisdom to Modern Microbial Engineering to Restore Climate-Resilient Soil. *Open Access Organization and Management Review*, 4(2): 57-70. https://doi.org/10.59644/oagmr.4(2).304

INTRODUCTION

Anthropogenic activities have shifted Earth's natural cycles, leading to global warming. Moreover, the Industrial Revolution has warmed the Earth above pre-industrial levels. It affects not only the climate but also microbiological communities, and it is hard to predict whether soil becomes a source or a sink of greenhouse gases (Mukhtar *et al*., 2023). Furthermore, activities such as burning fossil fuels and biomass and the decomposition of organic matter release climate pollutants into the environment, and carbon dioxide is a major greenhouse gas. Therefore, carbon sequestration techniques are required to produce climate change-resilient soil for appropriate agricultural growth. Enhancing carbon reserves at the terrestrial level may reduce greenhouse gas emissions and improve soil fertility. However, microbes are hidden fighters (Pollo, 2025). Plant-associated microbes play an important role in retaining carbon for crop production purposes, changing soil composition and microbial communities (Sellappan *et al*., 2026).

Organic carbon is essential for improving soil structure and helps microbes to break down organic matter and release nutrients. It also plays a major role in combating climate change. Carbon sequestration is important not only for reducing greenhouse gases but also for improving soil function (Lamsili, 2025). Soil has the largest carbon reservoir and plays a crucial role in climate mitigation. Diverse soil microbial communities, such as bacteria and fungi, have varying potential to efficiently utilize carbon across ecosystems (Wang *et al*., 2026).

Soil stores a large amount of Carbon, almost 3.3 times the atmospheric pool. Soil organic matter is complex because of the metabolic and residual products of soil organisms and plants, and it emits CO2 into the atmosphere (Qiao *et al*., 2025). Moreover, proper management of soil may restore Soil Organic Matter and carbon. Adequate microbial inoculation and soil management enhance carbon sequestration while reducing greenhouse gases and climate change. Soil microbiome interventions could increase carbon stocks through plant inputs while reducing soil organic matter turnover. However, existing inoculant applications rarely monitor soil carbon outcomes (Beattie et al., 2024). Necromass (soil microorganisms) serves as a good source of natural carbon (Wang *et al*., 2023). Hence, Microbiomes are significant in carbon storage and restoring agricultural fertility of the soil (Rodrigues *et al*., 2023).

The anthropogenic Amazonian Dark Earth, formed by pre-Columbians in central Amazonia, laid the foundation for Terra Preta. Thereupon, the soil of this region is richer in nutrients and carbon than the surrounding earth. Another major source of this region's soil fertility is Biochar produced through pyrolysis (burning wood, plant residue, and other organic material to turn into coal in a controlled oxygen environment). Along with organic matter, it contains food remains like fish and animal bones, as well as archaeologically significant artefacts such as pottery shards left by past inhabitants (Ortega, 2023). These thermodynamically produced porous black substances served to store carbon for 2000 years in this region (Gross *et al*., 2025). Hence, pre-Columbian peoples played a vital role in producing this carbon-rich soil, a type of Black Carbon, on Earth (Lombardo *et al*., 2022).

Terra Preta is a carbon sink created by pre-indigenous communities thousands of years ago. Soil Organic Carbon and Biochar serve as a huge natural source of carbon deposits, and this is good for creating a balance between the environment and climate fluctuations. Furthermore, soil also assists archaeologists in connecting the ancient to the new, i.e. the old sites and the modern Xingu region and these areas show similarities in patterns, i.e. containing phosphorus, carbon, and other nutrients. Thus, these elements reduce aluminum toxicity and improve plant growth; common in animals, humans, and plants. The fertility of Amazon dark earth is beneficial for modern sustainable agriculture and can compete with climate change challenges (Schmidt *et al*., 2023).

Aims and Objectives

1. To explore biosynthetic engineering used to produce Amazonian Dark Earth microbes' carbon-storing capacity in non-native soil to make climate change resilient.
2. To identify the way engineered microbes, survive climate stress to restore degraded soil and boost agricultural productivity.

Research Questions

1. How can bio-synthetic engineering be used to produce Amazonian Dark Earth microbes' carbon-storing capacity in non-native soil to make climate change resilient?
2. How can engineered microbes survive climate stress to restore degraded soil and boost agricultural productivity?

Research Significance

This inquiry is significant at academic, theoretical and practical levels, i.e., Soil Science, Environmental Biotechnology, Microbial Biotechnology, Soil Ecology, Climate Science, Agricultural Biotechnology, and Synthetic Biology. Subsequently, it reflects the significance of Terra Preta and the scientists' role in utilizing the anthropogenic dark earth synthesis from ancient soil to modern microbial engineering. Thereupon, food, agricultural production, soil fertility, climate change, and population growth are real challenges in the modern era. Science, ancient wisdom, and biotechnological knowledge combined may prove fruitful in combating these prevalent threats. Hence, the improvement in the proper functioning of microorganisms may enhance climate change resilience in the soil and improve fertility.

Research Problem

The biggest cause of climate change is the release of greenhouse gases. In this regard, plants play a crucial role, but microbes are also essential. Plants store carbon and use it for their own benefit, using sunlight and water to convert carbon dioxide into sugar. However, microbes also help remove this carbon dioxide. Terra Preta is one of the best examples of a vast network of soil ecosystems because it held millions of tons of carbon dioxide for centuries without leakage. Climate change has significantly affected soil agricultural productivity, and extreme temperature fluctuations are also causing problems in agriculture. Subsequently, microbes act as a buffer to enhance agricultural production. Hence, microbial engineering of Terra Preta microbes is needed to restore climate-resilient soil, incorporate it into larger commercial agricultural fields to enhance crop productivity and soil durability, and hold carbon dioxide for a longer period. However, bioengineering Amazonian Dark Earth microorganisms is difficult in the lab, and their commercial-scale use remains underexplored because of non-native soil conditions and competition with resident microorganisms.

LITERATURE REVIEW

Machine learning and remote sensing approaches are used to locate Terra Preta across the Xingu Indigenous territory. Thereupon, the maximum storage of carbon in and around this area is 4%, and it is approximately 9 million Metric Tons of carbon from the ancient activities of humans, specifically in the Xingu Indigenous territory. This percentage of carbon storage is confined to this region, except for the entire Amazonian Dark Earth Basin (Goldberg *et al*., 2024). Furthermore, microorganisms in soil can regulate the turnover of carbon by decomposing plant residue and assimilating carbon into microbial biomass. Thus, microbes also play a significant role in carbon storage in the soil (Mason *et al*., 2023; Wu *et al*., 2024).

Microbial inoculants are beneficial for sustainable agricultural growth, and field experiments also show good results in this regard (Callaghan *et al*., 2022). Furthermore, microbial inoculants have commonly been developed for plant health and yield, with minimal direct attention to soil carbon sequestration. However, biological inputs such as plant growth-promoting bacteria and mycorrhizal fungi are great tools for influencing soil carbon sequestration processes (Mason *et al*., 2023).

Microbial engineering has developed many routes, including identifying useful microbes, assembling microbial communities, and genetically modifying microorganisms (Chemla *et al*., 2025). Moreover, genetic engineering has the potential to produce soil microbiomes through lab experiments to achieve the desired goals. Thereupon, genetic modifications in the microorganisms may enhance the performance of these microbes, and ultimately it leads to restoring soil resiliency (Jansson *et al*., 2023). Thus, incorporating engineered biological systems from controlled lab experiments to complex natural soil systems remains difficult because of stability, scale, environmental interactions, safety and regulatory constraints (Lea-Smith *et al*., 2025).

Microorganisms play an important role in restoring degraded biosphere habitats through nutrient cycling, nitrogen fixation, organic matter degradation, soil health maintenance, and pollutant degradation. However, naturally occurring indigenous microorganisms have limited potential for soil remediation. Furthermore, bioengineered microorganisms can enhance targeted environmental functions. Thus, engineered microbes may serve as a promising restoration tool, but this does not mean they have already restored degraded soils. Microbial engineering has improved worn-out soil conditions by directly inoculating microorganisms into the soil ecosystem (Basumatary *et al*., 2024).

A fifteen-member synthetic community was derived from the rhizosphere of Brachypodium distachyon (purple false brome, a small wild grass and a research model for cereal crops) using network analysis. The bacteria possessed various plant growth-promoting functions, including osmoprotectant (compatible solute) production, sodium or potassium transport, IAA production, ACC deaminase, phosphate-related functions, and gibberellin production; strain 11 showed higher median abundance in planta. Thus, under drought, SynCOM-inoculated plants recovered better than un-inoculated plants (Yadav *et al*., 2025).

The critical literature review from (2022-26) addresses the direct impact of synthetic microbial communities on degraded soil. However, it highlights key points from studies showing strong evidence: microbial engineering indirectly improves soil conditions for sustainable agriculture, supports plant growth, and improves the soil ecosystem through plant-microbe interactions.

RESEARCH METHODOLOGY

Data Collection

The research paradigm of this research is qualitative, and it uses the literature review method with an approach called critical review. Furthermore, the data are collected through searches across five types of databases, i.e. PubMed, ScienceDirect, Springer-Link, Multi-Disciplinary Digital Publishing Institute (MDPI) and Frontiers. The data selected are from the timeframe (2022-26) to maintain current relevance, and these databases were selected to remain relevant to the field of biotechnology. Moreover, the total number of research papers selected for this inquiry is fifty, based on concepts such as soil ecology. Amazonian Dark Earth Microbes, climate change, microbial engineering, and sustainable agriculture.

Data Analysis

This critical review uses qualitative thematic synthesis to compare and integrate the findings across the above-mentioned concepts in the data collection section (3.1) to explore the possible implications of native microbes' role in non-native soil. The data is selected from these databases through a purposive sampling technique and then through a critical review represented in the form of a table and narrative text.

FINDINGS AND DISCUSSION

Microbial Engineering and Carbon Sequestration

Amazonian Dark Earth microbial resources, properties, microbial inoculation persistence, synthetic microbial communities, and microbiome-based approaches to soil carbon sequestration management. However, modern microbial engineering may utilize the characteristics of ADE microbes in non-native microbes to enhance soil productivity. Hence, synthetic biology, ancient soil wisdom and modern microbial engineering may produce desired results in various fields, i.e., agriculture, soil sciences and microbial genetic engineering.

Terra Preta draws on archaeological, ethnographic, geomorphological, stratigraphic, and soil evidence. Furthermore, Amazonian Dark Earth, including the Caldeirão (cauldron), was largely formed by indigenous human activities of pre-Columbians. Thereupon, nutrient- and carbon-rich properties result from the accumulation and reworking of human-associated material, i.e., ash, food debris, fish bones, charcoal and ceramics. Thus, the rejection of alluvial deposition was

the primary explanation for Caldeirão. This leads to geomorphic and pyrogenic processes shaping the Terra Preta profile and its preservation (Lombardo *et al*., 2022). These inquiries reflect the significance of Amazonian Dark Earth as a reference system and its links to fertility and soil carbon. Microbial necromass is a crucial contributor to soil carbon; it does not classify ADE-native microorganisms as persistent carbon storage (Camenzind *et al*., 2023).
Furthermore, there is a need to extract the biological functions related to ADE and experimentally be transferred to microbial inoculants. Moreover, the target experimental unit includes plant establishment, plant-microbe interactions, and changes in soil microbial community composition and interactions. This will eventually increase plant-derived carbon inputs, affecting the overall carbon turnover and SOM formation.

Genome sequences of bacterial strains, i.e., Paenibacillus polymyxa, Bacillus cereus, Fictibacillus sp., and Brevibacillus agri. obtained from Terra Preta showed antagonistic activity against Fusarium oxysporum (a common soil-borne fungus that causes vascular wilt disease in a wide range of important crops) (Pelligrinetti, 2023). Moreover, mixing 20% ADE soil with unfertile soil changed microbial richness and increased soil carbon stocks (Freitas *et al*., 2023).

There are twenty-seven metagenomes of bacterial genomes present in the litter of a secondary forest in Brazil, above the Terra Preta pool. The genomes comprise several bacterial phyla. The authors presented the data resources to prospect microorganisms with biotechnological potential not only for agriculture but also for ecological restoration (Freitas *et al*., 2024). Therefore, ADE can be treated as a native microbial resource, but its importance for carbon sequestration still demands laboratory experimental verification.

A greenhouse experiment was conducted by a team of researchers utilizing a small portion about 2% of ADE soil and mixing it with degraded soil, along with the use of the plant species named Urochloa Brizantha, also known as signal-grass. Furthermore, it is not only resistant to harsh environments but also increases soil organic matter and plays a crucial role in nutrient cycling and carbon sequestration. It is widely used in pastures in the Brazilian Amazon Rainforest. Hence, the researchers find the significance of this plant in worn-out soil: its roots aggregate the soil, improve fertility, and support beneficial microbial activity, rehabilitating the soil for future plant growth (Freitas *et al*., 2025).

In a degraded Oxisol pasture (an area of grazing land consisting of highly weathered, acidic, and nutrient-poor tropical soils), Terra Preta and Urochloa brizantha (a tropical perennial grass native to Africa as high-yield livestock pasture and forage) altered soil microbial community structure and network properties. Furthermore, the outcome was a 70% decline in β-glucosidase activity in Acacia mangium (a fast-growing evergreen tree in the pea family). However, native microbiota resisted Terra Preta treatments. Thus, transferring native Amazonian Dark Earth material to degraded soil may yield good results (Freitas *et al*., 2026). Microbial inoculation for carbon accumulation is biologically feasible, but it demands a specific inoculant, soil, timescale and mechanism. Furthermore, the prominent component found in Terra Preta soil is biochar because it plays a significant role in sustaining microbes, sequestering carbon, and enhancing soil fertility. Moreover, its ability to store carbon depends on its physical and chemical properties. Sponginess, size, and surface area reflect biochar's physical properties. However, thermochemical conditions, feedstock, and post-treatment processes, i.e., recalcitrance, high carbon content, and thermal stability, reflect its ability to store carbon long-term in soil (Rani *et al*., 2026).

Biochar reduces emissions of harmful gases, i.e., nitrous oxide, methane, and ammonia. It contains large amounts of nutrients such as potassium, phosphorus, and nitrogen. These nutrients transfer to the soil and feed the microbial community. It is composed of carbon, hydrogen, and oxygen, and it reduces greenhouse gas emissions, benefiting the climate (Shoudho *et al*., 2024). Therefore, biochar-mineral interactions affect carbon absorption, changes in microbial carbon mineralization, aggregate formation, and microbial necromass. Its characteristics and properties highlight the importance of interactions among the physical, chemical, and biological components of the soil system (Enebe *et al*., 2025). Thus, the physicochemical environment influences microbial functions in soil. Biochar provides a microbial habitat while improving soil carbon dynamics, moisture, nutrient availability, pH and structure, influencing microbial activity and community composition. Currently, its effects are context-dependent, and its long-term stability still needs to be understood (Hayat *et al*., 2026).

It is hypothesized about Amazonian Dark Earth cannot be recreated by mixing nutrients, biochar, and organic matter. Furthermore, the carbon-rich, long-term soil-fertility characteristics reflect a path-dependent emergent ecological state produced by various historical co-developmental factors. Briefly, black carbon is a significant component, but it is not enough to produce a full Terra Preta system. It uses the language of attractor dynamics, hysteresis, thresholds, resistance to change, and dependence on ecosystem assembly. The superficial modern tactics may not yield the same long-term sustaining results. Broadly, the research needs to focus on interaction, long-term history, and assembly rather than just the ingredients themselves. It provides a hypothesis for testing but no empirical data. Therefore, the meta-stability of soil is not experimentally proven (Wilkins, 2026). Meta-analyses of biochar reveal the impacts on soil, prokaryotic, and microbial biomass diversity (Deshoux *et al*., 2023).

Amazonian Dark Earth native microorganisms may struggle to survive in non-native soil conditions. However, there are four barriers: cultivability biases, mismatch between production and field environments, competition from resident communities, and soil specificity (McGuire, 2026). Thus, without altering native soil structure, Amazonian Dark Earth native microorganisms may be outcompeted by native microbial strains, resulting in rapid population collapse.

Synthetic biology combines engineering principles with biological systems to create unique solutions for environmental stability, health, and agriculture, highlighting its significant advancement. The potential of developing synthetic genetic circuits and metabolic engineering tools has revolutionized medicine and enhanced crop resilience (Karatas & Ayaz, 2025). Furthermore, it is vital in the engineering of microorganisms to perform environmental functions more efficiently, such as carbon capture and pollutant removal. Therefore, researchers can engineer microbial metabolic pathways for carbon fixation, pollutant degradation, and environmental responsiveness using approaches such as CRISPR-based genome engineering and synthetic promoter regulation. Moreover, engineered cyanobacteria, algae and bacterial strains showed improved performance compared to non-engineered strains. The reported results showed a 64% increase in carbon capture and a 52% improvement in pollutant degradation. The future implications of this research predict the environmental applications could benefit from combining synthetic biology with computational modelling and precision bioengineering. This approach could help researchers design microorganisms with more targeted functions, such as improved carbon capture and environmental restoration (Thiruchenduran *et al*., 2026).

Carbon dioxide fixation and valorization, pollutant degradation, waste conversion, bio-mining, and bioplastic-related processes are investigated. Furthermore, successful environmentally disposition remains challenging because microbial metabolism depends on environmental conditions, as current models have limited ability to predict microbial behaviour in complex environmental conditions (Panagiotidou & Theodosiou, 2026). Therefore, soil microorganisms should be used as interacting communities rather than as single strains. In soil, they interact with each other, as well as with plants, nutrients, and the physics--style environment. Thus, synthetic microbial communities (SynComs) serve as a sandbox to identify the interactions between microbes and hosts. Moreover, SynComs showed division of labor, metabolic complementarity, resource exchange, and interactions among microorganisms.

Microorganisms selected based on good traits may perform better in a community because work is divided, but a single microorganism may face many difficulties in this regard, and this is beneficial for soil health. It also proposes the design-build-test-learn cycle approach to predict the ways microbe interactions in a community can improve soil function (Li *et al*., 2024). Thus, Amazonian Dark Earth native microorganisms may function in natural soil systems and require critical system development and community interactions, but single-strain inoculation may not provide authentic results.

ADE-native microbial strain genera like Bacillus, Paenibacillus, and Pseudomonas were isolated and grew in vitro, showing they can actively solubilize phosphate, produce indole acetic acid for root growth, and suppress plant pathogens. However, it does not support any ADE-native bacterial strain isolated and specifically functioning for carbon sequestration but demands further research. Thus, these advances provide a strong conceptual basis for whether synthetic biology can overcome the limitations of ADE-derived microbial interventions by enabling non-native microorganisms to sequester carbon, because this mystery remains unresolved.

Microbial Engineering: Climate Resilient Soil

Degradation occurs when soil fails or struggles to perform its productive and ecological functions because its physical, chemical, and biological properties change. Alterations in properties such as physical structure, nutrients, organic matter and water-related characteristics may weaken the soil's agricultural capacity and make it vulnerable to environmental pressure (Maula, 2026). Furthermore, grassland restoration requires building and understanding microbial communities, including their functions. Thus, degradation can disrupt microbial diversity, interactions, and ecosystem functions (Qiao *et al*., 2026). Genetic engineering may modify microorganisms to enhance specific environmental functions, such as improving contaminant transformation and removal in the environment. However, ecological and biosafety concerns still constrain their deployment (Rafeeq *et al*., 2023). Moreover, synthetic microbial communities, formed from functionally useful microorganisms, could be used to develop climate-smart bio-fertilizers, utilizing plant microbiomes and the photobiont concept to improve crop resilience to climate change. However, it requires solving major problems such as microbial colonization, environmental interactions, community stability, and persistence under field conditions (Liu *et al*., 2026).

Advances in multi-omics (combining data from two or more different "omic" layers such as the genome, proteome, or transcriptome to study life in a complete way), systems biology, and artificial intelligence have expanded plant-associated soil microbiome engineering for sustainable and climate-resilient agriculture. It has identified microbial inoculation, synthetic communities, and microbiome engineering strategies as promising approaches for improving not only plant health but also climate resilience, nutrient management, and ecosystem restoration (Sadanov *et al*., 2026).

Synthetic engineering no doubt plays an evolutionary role in this regard. However, challenges to persistent long-term stability hinder progress. Furthermore, microbial engineering offers various strategies to improve plant-associated microbial functions related to bioremediation and sustainable agriculture. Therefore, engineered microbial communities can contribute to the recovery of worn-out soils or environments, but they need greater stability and field-level validation (Flores *et al*., 2026). Thus, bioengineered microorganisms may help restore soil health by improving nutrient cycling and promoting plant growth. However, they also emphasize barriers to environmental deployment, such as stability, efficiency, horizontal gene transfer, and interactions with native microbial communities (Sharma *et al*., 2024).

One important study highlighting the role of microbes in degraded agricultural soil focused mainly on naturally occurring Jeevamrit. This naturally fermented microbial consortium restores degraded soil. Metagenome analysis identified diverse microbial communities containing genes associated with nitrogen fixation, phosphorus-related functions, potassium transport, siderophore (a small, specialized molecule produced and secreted by bacteria, fungi, and some plants to bind and scavenge iron from the surrounding environment) production, plant growth, and organic substrate transformation. It was a two-session field experiment focusing on Himalayan rice soil. After applying Jeevamrit, the authors interpreted the results as evidence of microbial ecological intensification and soil fertility restoration (Walia *et al.*, 2025).

Microbiome engineering could help address dysbiosis in stressed agroecosystems by enabling more targeted manipulation of microorganisms and their functions. It could potentially restore functions of microorganisms associated with soil fertility, but their deployment and long-term effects need further validation (Darriaut *et al*., 2025). Furthermore, plant-microbe interactions can help crops tolerate drought conditions and integrating plant-microbe mechanisms with genetic engineering, synthetic communities and microbiome approaches could enable manipulation of target functions for crop drought resilience and support sustainable agriculture (Haider *et al*., 2026).

A synthetic biology microbial-assisted system engineered bacteria facilitated rhizosphere colonization by a functional Trichoderma antiviride strain. In soil, the fungus-assembled beads reduced rhizosphere salinity, altered the microbiome, and improved crop growth. This highlights the potential of microbial engineering to overcome microbial colonization under climate fluctuations (Ji *et al*., 2025). Moreover, introducing the ACC-deaminase gene into BL-EF results in an engineered strain with ACC-deaminase activity is linked to improved plant physiological responses, photosynthesis, osmotic regulation, and antioxidant activity. It not only increases the enzyme activity measured in soil but also increases soil nutrient levels. Thus, microorganisms engineered for these functions could help mitigate changes in soil biological properties under saline conditions (Jia *et al*., 2025).

Engineered E. coli EcCMC (a glucan-binding protein) to display a polysaccharide-recognizing protein associated with plant roots and to facilitate the recruitment of exogenous nitrogen-fixing bacteria. It was a 28-day experiment. The treatment showed increased nitrogenase activity, soil nitrogen, SOM, and plant yield. Furthermore, it can enhance the functionality of beneficial bacteria in the rhizosphere. Although it was a short-term experiment, its significance cannot be ignored (Liu *et al*., 2025).

A synthetic microbial consortium dominated by Serendipita indica improved tartary buckwheat growth and drought tolerance, promoting photosynthesis and biomass accumulation; under drought conditions, it promoted root development and was also linked to reduced transpiration. H_2O_2 and Malondialdehyde (MDA: a reactive organic compound produced as a breakdown product during lipid peroxidation—the oxidative degradation of fats in cell membranes) levels. The treatment also altered the root-associated microbial community and improved measured soil structure and fertility (Zhong *et al*., 2025).

Metabolic engineering of the nitrogen-fixing bacterium Pseudomonas stutzeri for improving ammonium excretion improved nitrogen fixation-related performance and biomass of maize. Furthermore, field inoculation increased maize grain yield by 5.6% to 5.9%, and it was comparable to the wild-type strain under the tested conditions (Jiang *et al*., 2022). Bio-inoculants, i.e. plant growth-promoting bacteria, can improve plant health and soil fertility in dryland agriculture. Moreover, microbial functions such as IAA production and ACC (1-aminocyclopropane-1-carboxylate) deaminase activity, as well as nitrogen fixation and pathogen suppression, are relevant to crop performance under climate change (Mataranyika *et al*., 2022). Synthetic communities can improve drought tolerance in tree seedlings, suggesting their application in climate-resilient forest restoration. They used microorganisms with traits such as exopolysaccharide production and hormone-related activities. Thus, they selected Quercus pubescens and Sorbus domestica seedlings for drought-tolerance communities (Aleksieienko *et al*., 2025).

Synthesis of Major Findings

Table 1

Microbial Engineering: Carbon Sequestration to Restore Climate-Resilient Soil

Key Major Finding	Overall Implication	Author–Year Citation(s)
Amazonian Dark Earth (ADE/Terra Preta) is a valuable microbial and soil resource, but its carbon-sequestration potential is not yet experimentally established.	ADE provides a strong biological model and microbial resource, but its direct role in long-term microbial carbon sequestration remains unresolved.	Lombardo *et al*. (2022); Camenzind *et al*. (2023); Freitas *et al*. (2024)
ADE-derived microbial resources can improve soil properties and carbon stocks under some experimental conditions.	ADE has demonstrated potential for soil rehabilitation and carbon-related benefits, although effects are context-dependent.	Freitas *et al*. (2023, 2025, 2026)
Biochar is a major component associated with carbon storage, microbial habitat, and soil fertility, but its effectiveness depends on its properties and environmental context.	Carbon sequestration through biochar cannot be treated as a uniform process; biochar characteristics and soil–microbe interactions matter.	Rani *et al*. (2026); Enebe *et al*. (2025); Hayat *et al*. (2026)
Biochar can influence multiple dimensions of soil functioning beyond carbon storage.	Biochar operates as a multifunctional soil intervention rather than merely a carbon-storage material.	Shoudho *et al*. (2024); Enebe *et al*. (2025); Hayat *et al*. (2026)

Recreating Terra Preta by simply combining biochar, nutrients, and organic matter may not reproduce the original system.	Effective replication may require attention to microbial interactions, ecosystem history, and community assembly rather than ingredients alone.	Wilkins (2026); Deshoux *et al*. (2023)
ADE-native microorganisms face substantial barriers when transferred into non-native soils.	Successful microbial inoculation requires ecological compatibility and persistence, not simply selection of beneficial strains.	McGuire (2026)
Synthetic microbial communities (SynComs) offer an alternative to single-strain inoculation.	Community-based engineering may better represent the complexity of real soil ecosystems than single-microbe approaches.	Panagiotidou & Theodosiou (2026); Li *et al*. (2024)
Microbial engineering has demonstrated measurable potential for environmental functions, including carbon capture.	Synthetic biology provides a promising technological route for targeted environmental functions, including carbon capture.	Karataş & Ayaz (2025); Thiruchenduran *et al*. (2026)
ADE-derived bacteria possess useful agricultural traits, but direct evidence for ADE-native microbial carbon sequestration remains lacking.	The evidence supports agricultural and soil-health functions, while the specific carbon-sequestration function remains a research gap.	Pelligrinetti (2023); Freitas *et al*. (2024); Freitas *et al*. (2026)
Microbial engineering can contribute to climate-resilient soil management.	Microbial engineering has potential as a climate-resilience strategy, particularly in degraded or stressed soils.	Sadanov *et al*. (2026); Flores *et al*. (2026); Sharma *et al*. (2024)
Experimental studies demonstrate Improvements in plant and soil functions through engineered microorganisms and microbial consortia	Engineered microbes and microbial communities can affect both plant performance and soil functioning.	Ji *et al*. (2025); Jia *et al*. (2025); Liu *et al*. (2025); Zhong *et al*. (2025); Jiang *et al*. (2022)
Field-scale validation and long-term stability remain the central limitations.	The major challenge is moving from laboratory and greenhouse proof-of-concept to stable, predictable field applications.	Liu *et al*. (2026); Flores *et al*. (2026); Sharma *et al*. (2024); Darriaut et al. (2025)
Microbial engineering is most promising when microorganisms are treated as interacting communities rather than isolated strains.	Future approaches should focus on microbiome/community engineering rather than single-strain interventions alone.	Li *et al*. (2024); Panagiotidou & Theodosiou (2026); Aleksieienko *et al*. (2025)
Existing evidence supports a research pathway combining ADE microbial resources, synthetic biology, SynComs, and advanced biological analysis.	A combined approach could investigate which microbial functions can be identified, engineered, assembled, and maintained for soil carbon and climate resilience.	Freitas *et al*. (2024); Thiruchenduran *et al*. (2026); Sadanov *et al*. (2026)

Note: This table no. 1 represents the synthetic findings from the critical review of the data from (2022-26) and shows the overall implications along with references.

CONCLUSION

This review shows the importance of Terra Preta. It highlights the role of microbial engineering in this area, reducing climate change and the role of plants and microbes in holding carbon, especially the ADE soil microorganisms. It aims to determine whether any study has shown whether these microbes were isolated or engineered for carbon sequestration. Because climate change degrades soil and reduces fertility, microbial engineering plays an important role by improving microorganisms so they can function with or within plants to improve soil fertility, reduce carbon in the environment, and make crops more climate-change-resistant and improve plant life.

Engineered or isolated microbial strains from Terra Preta using different techniques. They assessed their effects on tree growth; another study examined soil restoration alongside plant responses. However, the direct inoculation of microbial strains from Terra Preta for targeted functions like carbon sequestration. Microbial engineering has potential benefits for soil health; many studies have found improved nitrogen fixation, yield, growth, and resistance to climate fluctuations when engineered microorganisms were inoculated into soil, improving not only plant health but also soil fertility. However, this review did not address whether microbial engineering can improve worn-out soil conditions by directly inoculating microorganisms into soil; any line or claim related to this statement should be considered a research gap.

FUTURE IMPLICATIONS

Microbial strains from Amazonian Dark Earth could be specifically isolated and grown in the lab and inoculated into natural soil for long-term carbon sequestration. Furthermore, identify why the microorganisms cannot be directly inoculated into soil to improve soil. Thereupon, Amazonian Dark Earth-associated microbial studies have not shown an experimental approach to engineering microbes for carbon sequestration. Moreover, synthetic microbes improve plant performance in controlled experiments, but long-term and multi-field studies are necessary before claiming they improve degraded soil. Future framework includes (1) identify Terra Preta-associated functions; (2) identify genes and candidate organisms; (3) experimentally verify its integrity; (4) check if it can persist and reduce climate change by stocking carbon; (5) analyze the functions of microorganisms in degraded soil; (5) challenge the system with salinity, drought and heat; (6) check carbon pools and fluxes using isotope approaches; (7) evaluate plant health, growth and resilience.

DECLARATIONS

Ethical Considerations: This study strictly adhered to the Declaration of Helsinki and relevant national and institutional ethical guidelines. Informed consent was obtained. All procedures performed in this study were in accordance with the ethical standards of the Helsinki Declaration.

Consent for Publication: Not Applicable.

Availability of Data and Material: Data for this study will be made available upon a request from the corresponding author.

Competing Interest: The authors declare that there is no competing interest.

Funding: Not Applicable.

Authors' Contribution: All authors have actively contributed from conception of the idea to conduct of study, writing, and until the submission for publication.

Originality, Plagiarism, and Similarity Statement: This manuscript is original and free from plagiarism. All sources have been appropriately cited and acknowledged. The manuscript was screened using the journal-approved similarity-checking system to ensure an overall similarity index below 19% and compliance with the journal's source-level similarity limit.

Acknowledgement: The authors acknowledge the support and assistance of colleagues.

Declaration on the Use of Generative AI: Generative AI was used solely to assist with language editing, restructuring, and addressing reviewer comments. The authors reviewed and verified the final manuscript and took full responsibility for its content, accuracy, and integrity.

Similarity Index/ Plagiarism: The similarity index was checked, and it is well below the threshold value of 19%, whereas each source is less > 5%.

REFERENCES

Aleksieienko, I., Fernandes Hertel, M., Reilhan, J., de Castro, M., Légeret, B., Caixeta Oliveira, H., Reiter, I. M., & Santaella, C. (2025). *Soil-Gradient-Derived Bacterial Synthetic Communities Enhance Drought Tolerance in Quercus pubescens and Sorbus d omestica* seedlings. *Plants, 14*(11), 1659. https://doi.org/10.3390/plants14111659

Basumatary, T., Parthipan, P., & Sarma, H. (2024). Chapter 7 - *Microbial contributions in restoring degraded biosphere habitats: Comparing natural and engineered approaches*. In H. Sarma & S. J. Joshi (Eds.), Biotechnology of Emerging Microbes (pp. 107–125). Academic Press. https://doi.org/10.1016/B978-0-443-15397-6.00008-5

Beattie, G. A., Edlund, A., Esiobu, N., Gilbert, J., Nicolaisen, M. H., Jansson, J. K., Jensen, P., Keiluweit, M., Lennon, J. T., Martiny, J., Minnis, V. R., Newman, D., Peixoto, R., Schadt, C., & van der Meer, J. R. (2024). Soil microbiome interventions for carbon sequestration and climate mitigation. *mSystems, 10*(1), e01129-24. https://doi.org/10.1128/msystems.01129-24

Camenzind, T., Mason-Jones, K., Mansour, I., Rillig, M. C., & Lehmann, J. (2023). Formation of necromass-derived soil organic carbon determined by microbial death pathways. *Nature Geoscience*, *16*(2), 115–122. https://doi.org/10.1038/s41561-022-01100-3

Chemla, Y., Sweeney, C. J., Wozniak, C. A., & Voigt, C. A. (2025). Design and regulation of engineered bacteria for environmental release. *Nature Microbiology*, *10*(2), 281–300. https://doi.org/10.1038/s41564-024-01918-0

Darriaut, R., Roose-Amsaleg, C., Vanhove, M., & Monard, C. (2025). Microbiome engineering to palliate microbial dysbiosis occurring in agroecosystems. *Microbiological Research*, *297*, 128178. https://doi.org/10.1016/j.micres.2025.128178

de Freitas, A. S., & Pellegrinette, T. A. (2024, June 4). *Bacterial genomes recovered from litter's metagenomes in Amazonian Dark Earths.* Microbiology Resource Announcements. https://doi.org/https://doi.org/10.1128/mra.00422-24

de Freitas, A. S., Hanada, R. E., Muniz, A. W., & Tsai, S. M. (2026). Urochloa brizantha and Amazonian Dark Earths reshape soil microbiota without affecting tree growth in degraded Central Amazon Oxisols. *Soil Ecology Letters, 8*(5), 260453. https://doi.org/10.1007/s42832-026-0453-0

de Freitas, A. S., Zagatto, L. F. G., Rocha, G. S., Muchalak, F., Martins, G. L., Silva-Zagatto, S. dos S., Hanada, R. E., Muniz, A. W., & Tsai, S. M. (2025). Harnessing the synergy of Urochloa brizantha and Amazonian Dark Earth microbiomes for enhanced pasture recovery. *BMC Microbiology*, *25*(1), 27. https://doi.org/10.1186/s12866-024-03741-3

Deshoux, M., Sadet-Burgeteau, S., & Gentil, S. (2023, January). (PDF) *Effects of Biochar on Soil Microbial Communities: A Meta-Analysis*. https://doi.org/DOI:10.2139/ssrn.4399308

Enebe, M. C., Ray, R. L., & Griffin, R. W. (2025). The impacts of biochar on carbon sequestration, soil processes, and microbial communities: A review. *Biochar, 7*(1), 107. https://doi.org/10.1007/s42773-025-00499-3

Flores, A. I., Morales-Cedeño, L. R., Loeza-Lara, P. D., Schoebitz, M., Orozco-Mosqueda, M. del C., & Santoyo, G. (2026). Engineering Plant-Associated Microorganisms for Bioremediation and Sustainable Agriculture. *Microorganisms, 14*(6), 1203. https://doi.org/10.3390/microorganisms14061203

Freitas, A. S. de, Zagatto, L. F. G., Rocha, G. S., Muchalak, F., Silva, S. dos S., Muniz, A. W., Hanada, R. E., & Tsai, S. M. (2023). Amazonian dark earths enhance the establishment of tree species in forest ecological restoration. *Frontiers in Soil Science, 3*. https://doi.org/10.3389/fsoil.2023.1161627

Goldberg, S. L., Schmidt, M. J., Himmelstein, J. D., Heckenberger, M., Franchetto, B., Lima, H., Watling, J., Moraes, B., Dorshow, W. B., Fausto, C., Waura, K., Kuikuro, H., Kuikuro, T. W., Kuikuro, A., & Perron, J. T. (2024). Widespread Amazonian dark earth in the Xingu Indigenous Territory. *Nature Sustainability*, *7*(10), 1304–1312. https://doi.org/10.1038/s41893-024-01399-3

Gross, A., Tahery, S., Joseph, S., & Glaser, B. (2025). Towards understanding the long-term fate of biochar in Terra Preta. *Carbon Management*, *16*(1), 2560126. https://doi.org/10.1080/17583004.2025.2560126

Haider, S., Munyaneza, V., Zhang, W., Ren, L., Song, H., Ahmad, I. A., Mehran, M., Liu, S., Xu, F., Kant, S., Yang, J., Yang, C., & Ding, G. (2026). Plant-microbe interactions under drought stress: Unlocking new pathways for sustainable agricultural resilience. *Microbiological Research, 309*, 128516. https://doi.org/10.1016/j.micres.2026.128516

Hayat, M. K., Mahmud, M. N., Muniza, N. T., Batool, R., Ullah, Q., Al Kafi, A., & Haider, W. (2026). Biochar-based strategies for improving soil fertility and mitigating environmental pollution. *Discover Environment, 4*(1), 222. https://doi.org/10.1007/s44274-026-00730-3

Jansson, J. K., McClure, R., & Egbert, R. G. (2023). Soil microbiome engineering for sustainability in a changing environment. *Nature Biotechnology, 41*(12), 1716–1728. https://doi.org/10.1038/s41587-023-01932-3

Ji, Y., Liu, S., Zhao, Z., Gu, F., Wang, F., Li, M., & Yu, Q. (2025). Synthetic biology-assisted fungus-assembling beads for regulating rhizosphere microbiome and improving plant growth in saline soil. *Environmental Technology & Innovation, 40*, 104343. https://doi.org/10.1016/j.eti.2025.104343

Jia, X., Sun, L., Yue, J., Zhou, X., Deng, Z., Liu, X., & Wu, Z. (2025). Developed BL-EF to acquire plant growth-promoting functions under salt stress by introducing the ACC deaminase gene. *Plant Physiology and Biochemistry, 222*, 109764. https://doi.org/10.1016/j.plaphy.2025.109764

Jiang, S., Li, J., Wang, Q., Yin, C., Zhan, Y., Yan, Y., Lin, M., & Ke, X. (2022). Maize Growth Promotion by Inoculation with an Engineered Ammonium-Excreting Strain of Nitrogen-Fixing Pseudomonas stutzeri. *Microorganisms, 10*(10), 1986. https://doi.org/10.3390/microorganisms10101986

Karataş, P., & Ayaz, F. (2025). Synthetic biology and application areas. *Discover Biotechnology, 2*(1), 3. https://doi.org/10.1007/s44340-025-00010-5

Lea-Smith, D. J., Hassard, F., Coulon, F., Partridge, N., Horsfall, L., Parker, K. D. J., Smith, R. D. J., McCarthy, R. R., McKew, B., Gutierrez, T., Kumar, V., Dotro, G., Yang, Z., EBIC partners, & Krasnogor, N. (2025). Engineering biology applications for environmental solutions: Potential and challenges. *Nature Communications, 16*(1), 3538. https://doi.org/10.1038/s41467-025-58492-0

Li, M., Wei, Z., & Jousset, A. (2024, February 11). *Synthetic microbial communities: Sandbox and blueprint for soil health enhancement*—Li—2024—iMeta—Wiley Online Library. https://doi.org/https://doi.org/10.1002/imt2.172Digital Object Identifier (DOI)

Liu, S., Zhao, Z., Ji, Y., Zhu, H., Sun, Y., Li, M., & Yu, Q. (2025). Synthetic bacterium-facilitated colonization of nitrogen-fixing bacteria for remodeling the rhizosphere microbiome and improving plant yield. *Microbiome, 14*(1), 7. https://doi.org/10.1186/s40168-025-02189-5

Liu, Y., Chen, Y., Yu, Y., Jeon, C. O., Bahram, M., Zhai, J., Wei, H., Wang, F., Cao, X., & Jia, B. (2026). *Synthetic microbial communities for engineering climate-smart biofertilizers*. https://doi.org/10.1002/imt2.70140

Lombardo, U., Arroyo-Kalin, M., Schmidt, M., Huisman, H., Lima, H. P., de Paula Moraes, C., Neves, E. G., Clement, C. R., Aires da Fonseca, J., de Almeida, F. O., Vieira Alho, C. F. B., Bronk Ramsey, C., Brown, G. G., Cavallini, M. S., Lima da Costa, M., Cunha, L., dos Anjos, L. H. C., Denevan, W. M., Fausto, C., … Teixeira, W. G. (2022). Evidence confirms the anthropic origin of Amazonian Dark Earths. *Nature Communications, 13*(1), 3444. https://doi.org/10.1038/s41467-022-31064-2

Mariana Pezzatte Pollo. (n.d.). *The Power of Soil Microorganisms in Carbon Sequestration*—Centre for Carbon Research in Tropical Agriculture at the University of São Paulo (CCARBON/USP). 2025-06-18. Retrieved August 10, 2026, from https://ccarbon.usp.br/the-power-of-soil-microorganisms-in-carbon-sequestration/

Mason, A. R. G., Salomon, M. J., Lowe, A. J., & Cavagnaro, T. R. (2023). Microbial solutions to soil carbon sequestration. *Journal of Cleaner Production, 417*, 137993. https://doi.org/10.1016/j.jclepro.2023.137993

Mataranyika, P. N., Chimwamurombe, P. M., Venturi, V., & Uzabakiriho, J. D. (2022). Bacterial bioinoculants adapted for sustainable plant health and soil fertility enhancement in Namibia. *Frontiers in Sustainable Food Systems, 6*. https://doi.org/10.3389/fsufs.2022.1002797

Maula, I. M. (2026). (PDF) *Soil Degradation and its Challenges to Agricultural Production Resilience: An Overview from a Soil Traits*

Perspective. ResearchGate. https://doi.org/10.58344/jws.v5i1.1620

McGuire, A. (2026, March 16). *Why Soil Inoculants Fail*. Centre for Sustaining Agriculture and Natural Resources. https://csanr.wsu.edu/why-soil-inoculants-fail/

Mukhtar, H., Wunderlich, R. F., Muzaffar, A., Ansari, A., Shipin, O. V., Cao, T. N.-D., & Lin, Y. P. (2023). Soil microbiome feedback to climate change and options for mitigation. *Science of The Total Environment*, *882*, 163412. https://doi.org/10.1016/j.scitotenv.2023.163412

O'Callaghan, M., A.Ballard, R., & Wright, D. (2022). *Soil microbial inoculants for sustainable agriculture: Limitations and opportunities* | Request PDF. ResearchGate. https://doi.org/10.1111/sum.12811

Panagiotidou, E., & Theodosiou, E. (2026). Systems metabolic engineering: An integrated approach for future environmental biotechnology. *Biotechnology for the Environment*, *3*(1), 8. https://doi.org/10.1186/s44314-026-00042-z

Pelligrinetti, T. A. (2023, October 9*). Draft genome sequences of representative Paenibacillus polymyxa, Bacillus cereus, Fictibacillus sp., and Brevibacillus Agri strains are isolated from Amazonian dark earth*. Microbiology Resource Announcements. https://doi.org/https://doi.org/10.1128/MRA.00574-23

Perez Ortega, R. (2023, September 20). *Ancient Amazonians created mysterious 'dark earth' on purpose*. https://doi.org/10.1126/science.adk9667

Qiao, L., Wang, J., Wei, S., Ren, Y., Lichtfouse, E., & Han, J. (2025). The soil microbial carbon pump for carbon sequestration. *Environmental Chemistry Letters*, *23*(5), 1145–1151. https://doi.org/10.1007/s10311-025-01861-4

Qiao, X., Yan, X., Dong, C., Tao, L., Aili, A., & Waheed, A. (2026). From microbiome collapse to recovery: A roadmap for microbiome-informed grassland restoration under global change. *Frontiers in Microbiology, 17*. https://doi.org/10.3389/fmicb.2026.1741287

Rafeeq, H., Afsheen, N., Rafique, S., Arshad, A., Intisar, M., Hussain, A., Bilal, M., & Iqbal, H. M. N. (2023). Genetically engineered microorganisms for environmental remediation. *Chemosphere*, *310*, 136751. https://doi.org/10.1016/j.chemosphere.2022.136751

Rani, M., Abideen, Z., Munir, N., Hasnain, M., Mehdizadeh, M., Qasim, M., & Radicetti, E. (2026). Enhancing soil fertility, nutrient recovery and carbon sequestration: The role of biochar, composted biochar, and biochar-compost mixtures in sustainable agriculture. *Journal of Trace Elements and Minerals*, *15*, 100276. https://doi.org/10.1016/j.jtemin.2025.100276

Ranjith Sellappan, K.Aswini, & Thangal Kalaiselvi. (2026). (PDF) *Role of Plant Microbiome in Carbon Sequestration for Sustainable Agriculture.* In ResearchGate. https://www.researchgate.net/publication/360765433_Role_of_Plant_Microbiome_in_Carbon_Sequestration_for_Sustainable_Agriculture

Rodrigues, C. I. D., Brito, L. M., & Nunes, L. J. R. (2023). Soil Carbon Sequestration in the Context of Climate Change Mitigation: A Review. *Soil Systems, 7*(3), 64. https://doi.org/10.3390/soilsystems7030064

Sadanov, A. K., Baimakhanova, G., Baimakhanova, B. B., Orazymbet, S., Ratnikova, I., Smirnova, I., Mamytova, N., Sydykbekova, R., Kossalbayev, B. D., Aitkaliyeva, G. S., & Belkozhayev, A. M. (2026). Engineering Plant-Associated Soil Microbiomes for Sustainable and Climate-Resilient Agriculture: Mechanisms, Technologies, and Applications. *Microorganisms, 14*(8), 1648. https://doi.org/10.3390/microorganisms14081648

Sara Lamsili. (2025, December 8). *From Soil to Sustenance: The Critical Role of Carbon in Agriculture – African Plant Nutrition Institute* (APNI). https://www.apni.net/2025/08/12/from-soil-to-sustenance-the-critical-role-of-carbon-in-agriculture/

Schmidt, M. J., Goldberg, S. L., Heckenberger, M., Fausto, C., Franchetto, B., Watling, J., Lima, H., Moraes, B., Dorshow, W. B., Toney, J., Kuikuro, Y., Waura, K., Kuikuro, H., Kuikuro, T. W., Kuikuro, T., Kuikuro, Y., Kuikuro, A., Teixeira, W., Rocha, B., … Perron, J. T. (2023). Intentional creation of carbon-rich dark earth soils in the Amazon. *Science Advances*, *9*(38), eadh8499. https://doi.org/10.1126/sciadv.adh8499

Sharma, S., Kesharwani, A. K., & Kulshreshtha, A. (2024). Correction to: Bioengineered Microbes for Restoration of Soil Health.

In R. K. Bhatia & A. Walia (Eds.), Advancements in Microbial Biotechnology for Soil Health (pp. C1–C1). *Springer Nature*. https://doi.org/10.1007/978-981-99-9482-3_16

Shoudho, K. N., Khan, T. H., & Ara, U. R. (2024). Biochar in global carbon cycle: Towards sustainable development goals—*ScienceDirec*t. https://doi.org/https://doi.org/10.1016/j.crgsc.2024.100409

Thiruchenduran, D. M., M, M. D., K, M. S., Purushothaman, I., & N, M. (2026). Engineering Microbial Synthetic Biology Systems for Carbon Capture and Environmental Restoration. *Genetics and Molecular Research*. https://doi.org/10.4238/s7xg5y78

Walia, A., Selvarajan, R., Ogola, H. J. O., Chauhan, R., Bala, J., Verma, S. K., & Kumar, R. (2025). Genome-resolved analysis of traditional fermented biofertilizers as scalable solutions for soil restoration. *Frontiers in Microbiology*, *16*. https://doi.org/10.3389/fmicb.2025.1725475

Wang, C., Wang, X., Zhang, Y., Morrissey, E., Liu, Y., Sun, L., Qu, L., Sang, C., Zhang, H., Li, G., Zhang, L., & Fang, Y. (2023). Integrating microbial community properties, biomass and necromass to predict cropland soil organic carbon. *ISME Communications*, *3*(1), 86. https://doi.org/10.1038/s43705-023-00300-1

Wang, Y., Wang, S., Zhang, X., Peng, Z., Chen, S., Pan, H., Chen, B., Qi, J., Liang, C., Liu, J., Ren, C., Wei, G., & Jiao, S. (2026). Soil microbial taxonomic traits control the biogeography of carbon use efficiently. *Agriculture, Ecosystems & Environment*, *404*, 110341. https://doi.org/10.1016/j.agee.2026.110341

Wilkins, S. L. (2026). *Terra Preta de Indio as an Emergent Ecological State: Reclassifying a Path-Dependent Attractor from Constructible Substrate*. https://doi.org/https://doi.org/10.31223/X5FN2R

Wu, H., Cui, H., Fu, C., Li, R., Qi, F., Liu, Z., Yang, G., Xiao, K., & Qiao, M. (2024). Unveiling the crucial role of soil microorganisms in carbon cycling: A review. *Science of The Total Environment*, *909*, 168627. https://doi.org/10.1016/j.scitotenv.2023.168627

Yadav, A., Chen, M., Acharya, S. M., Kim, G., Yang, Y., Zhao, T. Z., Tsang, E., & Chakraborty, R. (2025). A stable 15-member bacterial SynCom promotes Brachypodium growth under drought stress. Frontiers in Microbiology, 16. https://doi.org/10.3389/fmicb.2025.1649750 Zhong, S., Wang, W., Tang, W., Zhou, X., Bu, T., Tang, Z., & Li, Q. (2025). Serendipita indica-dominated synthetic microbial consortia enhanced tartary buckwheat growth and improved its tolerance to drought stress. *Frontiers in Microbiology*, *16*, 1562341. https://doi.org/10.3389/fmicb.2025.1562341

Note: Open Access Organization and Management Review is recognized by the Higher Education Commission of Pakistan in the Y category for 2026-2027. The journal is under evaluation by the ISI Web of Science and CNKI.