

The role of microbes in carbon sequestration: A hidden ally against climate change.

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Received: 09-Aug-2025, *Manuscript No.* AAMCR-25-171310; **Editor assigned:** 10-Aug-2025, *PreQC No.* AAMCR-25-171310 (PQ); **Reviewed:** 22-Aug-2025, *QC No.* AAMCR-25-171310; **Revised:** 24-Aug-2025, *Manuscript No.* AAMCR-25-171310 (R); **Published:** 30-Aug-2025, *DOI:* 10.35841/aamcr-9.3.271

Introduction

As the world grapples with the escalating impacts of climate change, carbon sequestration has emerged as a vital strategy to reduce atmospheric carbon dioxide (CO₂) levels. While forests and oceans are widely recognized as major carbon sinks, a less visible but equally powerful ally resides beneath our feet and within aquatic ecosystems—microbes. Moreover, the complexity of microbial ecosystems makes it difficult to predict outcomes of interventions. There is a need for site-specific strategies and long-term monitoring to ensure ecological stability and effectiveness. To harness microbial carbon sequestration at scale, supportive policies and incentives are essential. Integrating microbial strategies into climate frameworks like the Paris Agreement can amplify their impact. Governments and organizations must invest in research, soil health programs, and microbial-based technologies. Public-private partnerships can accelerate the deployment of microbial solutions in agriculture, forestry, and land restoration. Education and outreach are also vital to raise awareness about the role of microbes in climate resilience. These microscopic organisms play a pivotal role in capturing, transforming, and stabilizing carbon, offering promising avenues for climate mitigation. This article explores the mechanisms by which microbes contribute to carbon sequestration and their potential in shaping sustainable climate strategies [1].

Microbes sequester carbon through four primary biological pathways: photoautotrophy, chemoautotrophy, biomineralization, and soil organic matter stabilization. Photoautotrophic microbes, such as cyanobacteria and microalgae, fix atmospheric CO₂ using sunlight via

photosynthesis. These organisms form the base of aquatic food webs and contribute significantly to oceanic carbon sinks. Chemoautotrophic microbes, including nitrifying and sulfur-oxidizing bacteria, fix CO₂ in the absence of light, often in deep-sea or subsurface environments. Biomineralization involves microbes converting CO₂ into stable mineral forms like calcium carbonate, locking carbon away for centuries. Soil organic matter (SOM) stabilization is driven by microbial decomposition and transformation of plant residues into humus, a long-lasting carbon pool [2].

The future of microbial carbon sequestration lies in interdisciplinary collaboration. Combining microbiology, ecology, data science, and policy can unlock new pathways for climate mitigation. Emerging tools such as metagenomics, AI-driven modeling, and remote sensing will enhance our ability to monitor and optimize microbial carbon sinks. Innovative approaches like microbial carbon capture in industrial settings and engineered microbial biofilms for CO₂ absorption are also on the horizon. These technologies could complement natural systems and offer scalable solutions to reduce atmospheric carbon. Soil hosts one of the largest reservoirs of organic carbon on Earth, and microbes are its primary architects. Bacteria, fungi, archaea, and protists interact with plant roots, decompose organic matter, and regulate nutrient cycling. Through these processes, they influence the formation and persistence of SOM, which can store carbon for decades to millennia. Microbial communities also modulate the balance between carbon storage and release. For instance, fungi like mycorrhizae enhance carbon input by promoting plant growth, while bacteria involved in denitrification can release greenhouse gases if not properly managed [3].

In the oceans, microbial plankton such as *Prochlorococcus* and *Synechococcus* are responsible for nearly half of global photosynthetic activity. These microbes fix CO₂ and contribute to the biological pump—a process where organic carbon is transported from surface waters to the deep ocean, effectively sequestering it for centuries¹. Additionally, marine microbes facilitate the formation of particulate organic carbon (POC), which sinks to the ocean floor. This microbial-driven sedimentation is a critical component of long-term carbon storage in marine ecosystems. Advances in synthetic biology and microbial ecology have opened new possibilities for engineering microbes to boost carbon sequestration. Genetically modified strains of cyanobacteria and algae are being developed to increase photosynthetic efficiency and carbon fixation rates [4].

In soils, microbial consortia can be introduced to degraded lands to accelerate SOM formation. These interventions include inoculating soils with beneficial microbes, applying biochar to support microbial habitats, and manipulating soil conditions to favor carbon-storing species. Agriculture is both a source and potential sink for carbon emissions. Microbial strategies in agroecosystems can enhance carbon sequestration while improving soil health. Practices such as cover cropping, reduced tillage, and compost application stimulate microbial activity and increase carbon inputs. Rhizosphere microbes, particularly nitrogen-fixing bacteria and mycorrhizal fungi, play a key role in promoting plant growth and carbon allocation to roots. These interactions not only sequester carbon but also reduce the need for synthetic fertilizers, lowering emissions. Despite their potential, microbial carbon sequestration faces several challenges. Microbial communities are highly sensitive to environmental changes, and their carbon-storing functions can be disrupted by land-use change, pollution, and climate variability [5].

Conclusion

Microbes are silent but powerful allies in the fight against climate change. Through diverse metabolic pathways and ecological functions, they contribute significantly to carbon sequestration in soils, oceans, and engineered environments. Recognizing and leveraging their role offers a promising, sustainable, and scientifically grounded strategy for climate mitigation. As research advances and awareness grows, microbial carbon sequestration may become a cornerstone of global efforts to stabilize our climate.

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