



Potential Role of Microbes in Soil Fertility Restoration in Arid Zones

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Abstract: Arid lands are distributed across multiple climatic regions worldwide and play an important role in supporting communities by providing key ecosystem services and natural resources. However, the lands are constrained by chronic water scarcity, extreme temperatures, intense solar radiation, and high evapotranspiration, all of which severely limit biological productivity. Arid soils are typically poor in organic matter, weakly aggregated, often saline or alkaline, and nutrient-depleted, making them highly vulnerable to soil erosion and long-term degradation. Harsh conditions also alter soil microbial communities by reducing microbial abundance, shifting community composition toward stress-tolerant taxa, weakening enzymatic activity, and disrupting nutrient cycling processes essential for ecosystem functioning and vegetation establishment. Despite such constraints, arid soils harbour highly specialized microbial communities that exhibit diverse physiological and genomic adaptations enabling survival under extreme conditions. The current review discusses the challenges in arid environments, the understanding of microbial communities and their adaptive strategies in arid soils, and how these traits contribute to soil fertility restoration across diverse dryland ecosystems. It further evaluates key microbe-driven restoration mechanisms, including reactivation of biogeochemical cycles, the role of native microorganisms as ecological engineers, and plant-microbe-mediated interactions that enhance overall soil health. Finally, the review highlights key limitations of current restoration approaches, including limited long-term field validation, unpredictable microbial interactions, and insufficient functional understanding of introduced microbes. Based on the limitations, the review provides recommendations for future studies, emphasizing the integration of multi-omics approaches, trait-based microbial selection, and long-term ecosystem monitoring for developing effective and scalable microbial solutions for restoring degraded arid soils.

Key words: Arid soils, dryland microbiomes, microbial adaptations, microbe-based restoration, soil fertility.

Arid lands are among the most extensive terrestrial ecosystems, covering nearly 40-47% of the Earth's land surface, and they provide essential ecosystem services and livelihoods for millions of people worldwide (Gaur and Squires, 2017; Perez-Aguilar *et al.*, 2021). The ecosystem services include nutrient cycling, carbon sequestration, hydrological processes regulation, biodiversity conservation, and the provision of grazing land, fuelwood, and subsistence agriculture. The arid regions are characterized by low and irregular rainfall (<400 mm year⁻¹), strong winds, extreme temperatures, high solar radiation, and high evapotranspiration rates, all of which severely limit biological productivity (Quoreshi *et al.*, 2022). In addition to climatic challenges, arid soils are generally poor in organic matter and nutrients, have high salinity or acidity, which further restricts agricultural sustainability (Whitford, 2002; Rathore *et al.*, 2019). The degradation of arid lands is primarily driven by human activities, including deforestation, overgrazing, unsustainable agricultural practices, and urban expansion, which are increasingly intensified by climate change, leading to accelerated desertification, biodiversity loss, and reduced soil fertility (Yan *et al.*, 2024; Abdullahi *et al.*, 2023; Huang *et al.*, 2017). As a result, the ecological stability of arid regions is compromised, directly threatening the food security and economic well-being of communities that depend on these fragile ecosystems.

Soil microbial communities have a pivotal role in ecosystem functioning and recovery in the challenging environment of arid lands (Wang *et al.*, 2022c; Zhang *et al.*, 2021). However, water scarcity, land-use intensification, and climate stress lead to major alterations in microbial communities (Liu *et al.*, 2022; Coleine *et al.*, 2024). Microbial abundance often declines due to prolonged drought, which suppresses growth, reduces biomass, and shifts community composition toward highly stress-tolerant taxa (Castro *et al.*, 2019). The microbial shifts also reduce metabolic efficiency, as drought and salinity stress limit enzymatic activity, slow nutrient cycling, and other functions (Elhady and Hirt, 2025; Naorem *et al.*, 2023). As a result, arid soils experience disrupted microbial networks, reduced functional redundancy, and a loss of important species, making the ecosystem more

vulnerable to degradation and less capable of supporting vegetation recovery. Microbes are key drivers of nutrient cycling and ecosystem recovery in arid lands that enhance soil fertility by fixing nitrogen, solubilising nutrients, decomposing organic matter, and improving overall soil structure, thereby supporting plant growth in extreme environments (Zhao *et al.*, 2025; Nelson and Thompson, 2025). Additionally, microbial communities produce enzymes and bioactive compounds that help transform and detoxify toxic contaminants in degraded soils (Benabdellah *et al.*, 2011; Yadav and Hassanizadeh, 2011). Moreover, beneficial microbes, such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, enhance plant health and resilience, contributing to soil stability and ecosystem recovery (Nelson and Thompson, 2025; Du *et al.*, 2024; Kasana *et al.*, 2024). Therefore, protecting native microbial communities and promoting microbial-based restoration strategies are essential for restoring soil fertility in arid regions. Integration of microbial processes into land management and restoration practices can enhance ecosystem resilience, support sustainable agriculture, and improve the long-term productivity of arid and semiarid landscapes. The current review examines the role of diverse microbial communities in restoring various types of arid zones and discusses challenges in microbial-based soil restoration approaches, along with potential strategies to enhance their effectiveness and field applicability.

Arid zones are divided into four categories such as hyper-arid, arid, semiarid, and dry subhumid regions according to the aridity index (FAO, 1993; Gaur and Squires, 2017). The formation of arid zones is controlled by climatic and anthropogenic factors, including high pressure, continental winds, low rainfall, cold ocean currents, temperature extremes, deforestation, overgrazing, unsustainable irrigation, and poor land management (Maliva and Missimer, 2012; Perez-Aguilar *et al.*, 2021; Bashan *et al.*, 2012). In the arid ecosystems, plant growth and associated soil microorganisms are severely hampered due to stress imposed by water scarcity, which leads to cellular membrane damage, accumulation of reactive oxygen species, protein denaturation, and DNA injury (Coleine *et al.*, 2024; Cui *et al.*, 2018, 2024).

The soils of arid zones are typically hard and sandy, with poor water-holding capacity, low clay content, low organic matter, and deficiencies in essential nutrients such as nitrogen and phosphorus (Singer, 1991; Gaur and Squires, 2017; Lopez-Lozano *et al.*, 2016). The weakly aggregated soils of arid regions are highly vulnerable to wind and water erosion, that accelerates the breakdown of soil structure, removes nutrient-rich topsoil, intensifies land degradation, and reduces the long-term productive capacity of soil in dry ecosystems (Naorem *et al.*, 2023; Shahabinejad *et al.*, 2019). Land-use pressures, such as overgrazing and the conversion of forests to grazing lands, further exacerbate desertification (Araujo *et al.*, 2023; Yadava *et al.*, 2018). Land degradation processes directly disrupt microbial habitats, suppress microbial activity, and reduce the resilience of soil communities (Pedrinho *et al.*, 2024).

Arid soils typically contain less than 4% soil organic matter (SOM), severely constraining microbial growth and activity (Bekhit *et al.*, 2025). Low SOM is consistently observed in arid soils due to minimal litter inputs from sparse vegetation and rapid decomposition driven by high temperatures and low moisture availability (Naorem *et al.*, 2023; Dlamini *et al.*, 2014). As a result, microbial biomass declines, weakening soil biological functions in the fragile ecosystems (Bekhit *et al.*, 2025). Microbial communities in arid environments play an important role in nitrogen fixation and carbon cycling, and reductions in their biomass directly lead to deficiencies in nitrogen, phosphorus, and other essential nutrients (Bekhit *et al.*, 2025; Chauhan and Pandey, 2024; Ren *et al.*, 2018). As a result, soils in arid regions remain low in fertility, have poor structural stability, and show low buffering capacity against pH or salinity fluctuations (Sahrawat *et al.*, 2010; Taghizadeh-Mehrjardi *et al.*, 2020). Soil salinity and alkalinity are important constraints in arid and semiarid soils (Dierickx, 2009), which arise due to high evapotranspiration, limited rainfall leaching, and the rise of soluble salts (Taghizadeh-Mehrjardi *et al.*, 2020; Naorem *et al.*, 2023), leading to the accumulation of salts in the soil (Jordán *et al.*, 2004). Salt-affected soils alter soil physicochemical properties and impair plant root function due to sodium toxicity and high alkalinity (Jassal *et al.*, 2012).

At the microbial level, salinity stress reduces enzymatic activity, alters community structure, and disrupts functional networks essential for soil nutrient cycling (Elhady and Hirt, 2025; Naorem *et al.*, 2023). Overall, the harsh conditions of arid soils make microbial survival difficult, and understanding the specialized adaptations that help microbes survive in arid environments is crucial for restoring soil fertility in arid zones through microbial interventions.

Microbial Communities and their Adaptational Attributes in Arid Soils

Arid soils harbour diverse and highly specialized microbial communities, including bacteria, fungi, archaea, and biological soil crusts (biocrusts), that sustain essential ecosystem processes under extreme environmental stress (Csotonyi *et al.*, 2010; Yang *et al.*, 2024). Globally, arid soils are dominated by stress-tolerant bacterial phyla such as Actinobacteria, Proteobacteria, Chloroflexi, Bacteroidetes, Firmicutes, Acidobacteria, and Cyanobacteria, which are widely reported from drought-, heat-, and radiation-stressed environments due to their resilient cell structures and versatile metabolic strategies (Coleine *et al.*, 2024; Vásquez-Dean *et al.*, 2020; Naylor and Coleman-Derr, 2018). Similarly, among archaea, members of Euryarchaeota are dominant in arid hypersaline soils and halite deposits, reflecting strong osmotolerance and adaptation to extreme ionic conditions (Coleine *et al.*, 2024; Cowan *et al.*, 2019). While fungal communities in arid soils are dominated by stress-tolerant taxa belonging to the phyla Ascomycota, Basidiomycota, Glomeromycota, and Zygomycota, which are well known for their drought tolerance, spore-based persistence, and efficient nutrient acquisition under resource limitation (Manici *et al.*, 2025; Ameen *et al.*, 2021; Coleine *et al.*, 2024). Although many of these taxa occur globally, only microbial lineages with strong tolerance to chronic water scarcity and extreme temperatures tend to persist in arid soils, reflecting long-term adaptation to desert conditions (Coleine *et al.*, 2024). Co-occurrence network analysis further reveals substantial seasonal and geographic differences in microbial community composition and structure across arid zones (Zhang *et al.*, 2024).

To persist under polyextreme conditions characterized by low water availability, high salinity, temperature fluctuations, and intense radiation, microbes in arid soils exhibit a wide range of physiological and genomic adaptations. The important adaptational attributes include production of extracellular polymeric substances that improve water retention, accumulation of compatible solutes to counter osmotic stress, synthesis of UV-protective pigments such as carotenoids, scytonemin, and melanin, and membrane modifications that help maintain cellular integrity under stress conditions (Coleine *et al.*, 2024; Casero *et al.*, 2021; Leung *et al.*, 2020). Additionally, microbes employ specialized solute transport systems such as osmoprotectant uptake (Opu) proteins to acquire osmolytes that help maintain cellular hydration under water-limited conditions. While under extreme salinity, haloarchaea and certain bacteria adopt a potassium chloride accumulation strategy to balance external osmotic pressure and sustain metabolic activity (Teichmann *et al.*, 2018; Uritskiy *et al.*, 2019). Fungal communities further enhance desiccation tolerance by accumulating trehalose and intracellular glycerol, which protect cellular membranes from dehydration and freezing stress (Coleine *et al.*, 2022). Along aridity gradients, microbial communities are further enriched with stress-related genes associated with DNA repair, sporulation, osmolyte biosynthesis, and ion transport, often accompanied by reduced genome size, increased genomic GC content, and broad metabolic versatility, particularly among oligotrophic populations in nutrient-poor soils (Chen *et al.*, 2021; Li *et al.*, 2022).

In nutrient-limited hyperarid environments, microbial survivals are supported by specialized energy and nutrient acquisition strategies by cyanobacteria and algae, while heterotrophs utilize alternative energy-harvesting mechanisms such as light-driven proton pumps and atmospheric trace gas oxidation, including hydrogen oxidation and chemosynthesis, to meet their energy demands (Jordaan *et al.*, 2020; Ray *et al.*, 2020; Coleine *et al.*, 2024). Nitrogen availability is maintained through nitrogen-fixing cyanobacteria and efficient nitrate and ammonia assimilation pathways, sustaining nutrient cycling under resource scarcity (Coleine *et al.*, 2024). Additionally, cooperative interactions such as

metabolic interdependence and cross-feeding may further enhance community stability and functional resilience in arid soils (Cicarese *et al.*, 2022). Overall, the adaptive traits of arid-soil microbes demonstrate a remarkable capacity to survive under extreme aridity and support key functional processes that drive soil fertility restoration and long-term fertility enhancement.

Microbial Mechanisms Driving Soil Fertility Restoration in Arid Ecosystems

Microbial communities play a central role in restoring soil fertility by re-establishing key biogeochemical cycles that regulate nutrient availability and ecosystem functioning in arid ecosystems. Microbes help rebuild soil health in degraded drylands through carbon sequestration, nitrogen fixation, nutrient mobilization, and enzymatic transformations (Quoresh *et al.*, 2022; Kumar *et al.*, 2023). In arid soils, biological soil crusts (biocrusts), which are assemblages of cyanobacteria, fungi, and associated microorganisms, play a significant role in maintaining soil fertility under extreme conditions by promoting carbon and nitrogen fixation, soil stabilization, nutrient retention, and water regulation (Pointing and Belnap, 2012; Dacal *et al.*, 2022). In parallel, interactions between bacteria and fungi in the rhizosphere enhance nutrient cycling and improve soil physicochemical properties, facilitating vegetation establishment and ecosystem recovery (Lian *et al.*, 2025; Bencherif *et al.*, 2015a, b) (Fig. 1). Moreover, evidence synthesized across multiple studies indicates that soil restoration can be effectively achieved by transplanting native soil microbiomes from intact, undisturbed ecosystems into degraded lands, thereby reintroducing locally adapted microbial communities that enhance plant establishment and restore soil functionality (Averill *et al.*, 2022; Guo *et al.*, 2024; Pacheco *et al.*, 2025). With the shared goal of restoring soil fertility and microbial community in arid lands, Marasco *et al.* (2023) highlighted the growing research focus on manipulating soil microbiomes for restoration purposes by using either inoculation-based approaches involving beneficial microbial strains, their bio-products, or microbiome transplant strategies that transfer entire microbial communities from healthy reference sites to degraded soils. A field-based study on soil microbiome manipulation

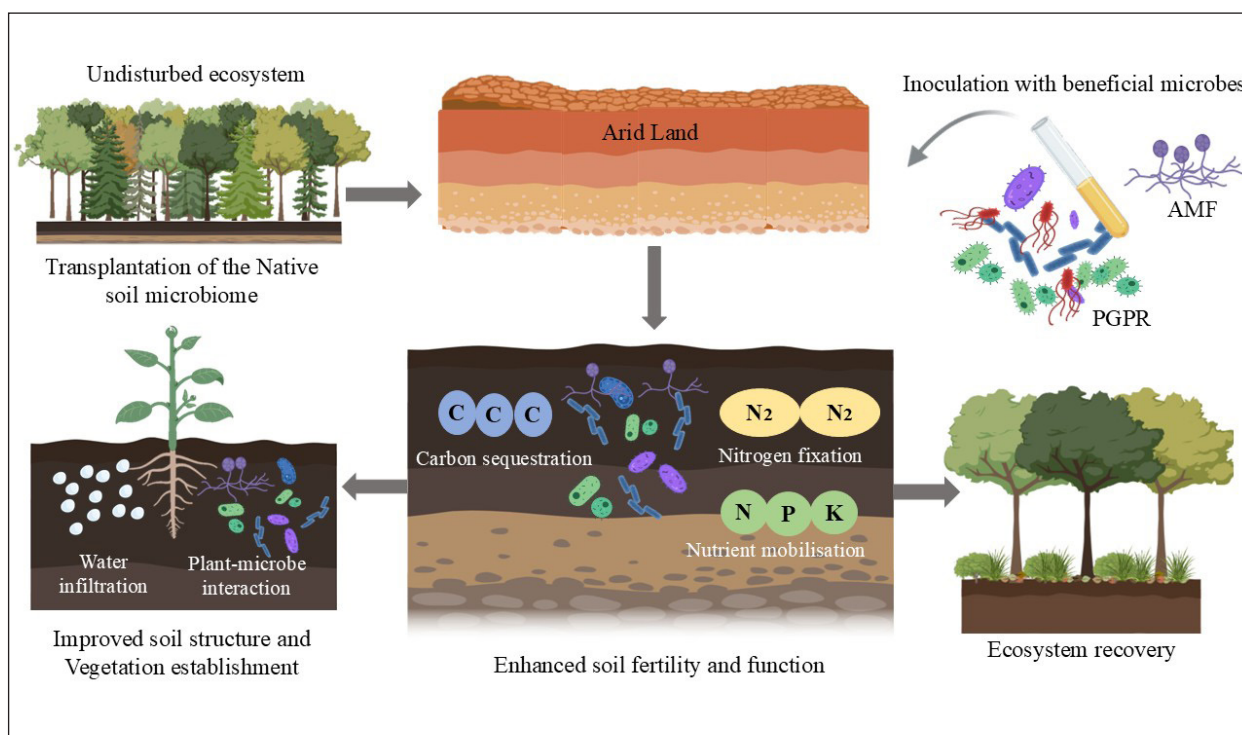


Fig. 1. Microbe-mediated mechanisms driving soil fertility restoration in arid ecosystems.

demonstrated that inoculation with locally sourced AMF and whole rhizosphere soil collected from nearby undisturbed prairie ecosystems in the Midwestern United States significantly improved native plant establishment and successional recovery in degraded restoration sites compared to non-inoculated soils (Kozioł *et al.*, 2022). Similarly, inoculation with native beneficial bacteria has shown improvement in plant survival, nutrient uptake, and rhizosphere restructuring in arid ecosystems (Solans *et al.*, 2021; Galaviz *et al.*, 2018). In addition, mixed microbial consortia-based treatment has also demonstrated rapid restoration potential by enhancing biocrust development, soil stability, and extracellular polysaccharide production in degraded arid soils (Reeve *et al.*, 2023). Vegetation restoration in arid ecosystems is closely linked to the recovery of native soil and plant-associated microbial communities that enhance soil health and fertility (Alsharif *et al.*, 2020; Bi *et al.*, 2024). Long-term studies have reported that the establishment of vegetation and associated plant-microbe interactions gradually reshape microbial community assembly, towards more stable and functionally organized structures (Wang *et al.*, 2022a; Wang *et al.*, 2022b). Furthermore, strong plant-microbe interactions have been shown to improve

soil physical properties by enhancing water infiltration, increasing moisture retention, and reducing soil hydrophobicity, thereby creating favorable conditions for vegetation growth and long-term ecosystem restoration (Coban *et al.*, 2022; Zhao *et al.*, 2024). Collectively, insights from recent studies highlight that soil restoration in arid ecosystems is largely driven by microbe-mediated recovery of biogeochemical cycling, soil structure, and plant-microbe interactions, emphasizing the central role of native microbial communities in reversing soil degradation.

Microbial communities contribute to the recovery of degraded arid lands. Restoration strategies include transplanting native soil microbiomes from undisturbed ecosystems and inoculating with beneficial microorganisms, such as arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR). These microbial interventions enhance key biogeochemical processes, including carbon sequestration, biological nitrogen fixation, and nutrient mobilization, thereby improving soil fertility and ecosystem function. Microbial activity also strengthens plant-microbe interactions, promotes water infiltration, and improves soil structure. Collectively, these processes facilitate vegetation establishment

and long-term ecosystem recovery in arid landscapes.

Challenges and Future Recommendations for Microbial Restoration Strategies

A major limitation of microbial restoration strategies is the inherent complexity of soil microbial communities, as introduced microorganisms often interact unpredictably with native microbiota, leading to variable or short-lived restoration outcomes (Marasco *et al.*, 2023). In addition, there is limited understanding of the physiological, ecological, and evolutionary mechanisms that drive microbial adaptation in arid environments, which restricts accurate prediction of microbial responses to restoration interventions (Coleine *et al.*, 2024). Many inoculation-based approaches have been evaluated primarily under controlled or short-term conditions, while long-term field-scale validation remains limited, particularly under the fluctuating climatic stresses characteristic of arid regions. Another critical challenge of arid ecosystem functioning is driven more by specific functional microbial groups than by overall species richness; therefore, the introduction of theoretically beneficial microbes may fail to provide sustained benefits or may even disrupt native community balance (Gufwan *et al.*, 2025a, b).

To overcome limitations and fully harness the potential of microbes in soil restoration, future research needs to move beyond isolated approaches and adopt more integrated strategies. Recent advances in environmental microbiology are exploring microbial functions, metabolic pathways, and interaction networks in greater detail, and explain how microbes drive nutrient cycling, improve soil structure, and support plant resilience in degraded ecosystems (Coleine *et al.*, 2024; Zhao *et al.*, 2025; Beshah *et al.*, 2024). Insights from the advances will guide the careful design of microbial consortia suited to local soil conditions and restorations. The growing use of artificial intelligence and machine learning is further strengthened by helping to analyse complex datasets, identify key microbial functions, and support site-specific, real-time decision-making (Zhao *et al.*, 2023). Further, genome editing and synthetic biology offer new ways to study and refine microbial traits associated with soil restoration, stress tolerance, and functional stability

(Singh and Ramakrishna, 2021). Together, the emerging tools offer a promising pathway to translate microbial ecological understanding into practical and effective restoration strategies for arid landscapes

Conclusions

Arid lands face extreme water scarcity, high temperatures, low organic matter, nutrient deficiencies, salinity, and anthropogenic pressures, which severely limit soil fertility and productivity. Despite these harsh conditions, arid-soil microorganisms possess adaptive traits, including stress tolerance, efficient nutrient-acquisition strategies, and metabolic versatility, that support essential biogeochemical processes and improve soil structure and plant-soil interactions. Emerging evidence demonstrates that restoration of degraded arid ecosystems is strongly linked to microbe-mediated recovery of nutrient cycling, soil aggregation, and plant-associated symbioses, highlighting the central role of native microbial communities in re-establishing soil functionality and long-term ecosystem stability. However, while microbial-based restoration strategies are increasingly recognized, limited understanding of microbial adaptation to arid environments constrains the accurate predictions of restoration outcomes. Many inoculation-based approaches also lack long-term field validation under fluctuating dryland climates. Moreover, ecosystem functioning in arid soils is driven by specific functional groups rather than overall diversity; as a result, introduced inoculants may fail to provide sustained benefits or disrupt native community balance. Future restoration efforts should therefore prioritize functional, context-specific approaches that integrate microbial ecology, plant-soil interactions, and long-term ecosystem monitoring. Advances in high-throughput sequencing, metagenomics, and systems-level ecological modelling offer promising tools for translating microbial ecological knowledge into practical, resilient, and scalable restoration strategies.

Competing Interests

The authors declare no competing interests.

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