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Review

How Can We Stabilize Soil Using Microbial Communities and Mitigate Desertification?

Faten Dhawi

Agricultural Biotechnology Department, College of Agricultural and Food Sciences, King Faisal University, Al Ahsa 31982, Saudi Arabia; falmuhanna@kfu.edu.sa

Abstract: The desert, which covers around one-third of Earth's continental surface, is defined as the harshest terrestrial environment and comprises a highly extensive biome of the terrestrial ecosystem. Microorganisms are key drivers that maintain the integrity of desert terrestrial ecosystems. Over the past few decades, desertification has increased owing to changes in rainfall patterns and global warming, characterized by land degradation, loss of microbial diversity (biocrust diversity), and multifunctionality with time. Soil stabilization is a geotechnical modality that improves the physiochemical properties of the soil. Biological modality is an emerging method that attracts the scientific community for soil stabilization. Enriching the soil with microorganisms such as some bacteria geniuses (*Cystobacter, Archangium, Polyangium, Myxococcus, Stigmatella and Sorangium, Bacillus, Acinetobacter, Proteus, Micrococcus*, and *Pseudom)* or Cyanobacteria (*Oscillatoria pseudogeminata, Chroococcus minutus, Phormidium Tenue*, and *Nostoc species*), and Lichens *(Collema sps.*, *Stellarangia sps., and Buellia species*) might contribute to stabilizing the soil and mitigating desertification. In this timeline review article, we summarize the biological method of soil stabilization, especially focusing on the role of microorganisms in soil stabilization in the desert.

Keywords: desert; soil stabilization; plants and microbes interaction

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1. Introduction

The surface of the Earth is covered with 29% land and 71% water. A large portion of the terrestrial ecosystem (41% of the Earth's surface) consists of hyperarid, semiarid, and arid lands [1], characterized by low/inconsistent rainfall, limited resources of water, high temperatures, damaging UV radiation, and rapid evaporation [2,3]. Desert is the harshest terrestrial environment on the Earth, basically defined as arid regions that receive less than 250 mL rainfall/year. The soil composition of deserts varies from rocky to sandy with low amounts of organic matter [4,5]. Deserts are also characterized by the availability of low nutrients, an excessive incidence of UV radiation, strong winds, and high temperatures [6–8] (Table 1). Globally, aridity is continually expanding owing to alterations in rainfall patterns and global warming [9,10]. Due to this, the desert may undergo degradation and expansion, reaching 56% of the Earth's terrestrial surface by 2100 [9,10]. Biocrust plays a crucial role in maintaining the integrity of desert ecosystems [11,12] where it regulates the functionality of soil to sustain productivity, maintain the quality of the desert environment, and promote the conservation of biodiversity. Expansion and deterioration of deserts can be explained by land degradation, loss of microbial diversity (biocrust diversity), and multi-functionality with time [13–16] which may affect the lives of millions of people, particularly in developing countries [17]. Hence, it is essential to protect these areas to confirm the resilience and dynamic of their natural resources [18]. Maintenance of the integrity of physical soil coherence and abundant community structure is a crucial factor to prevent the degradation and expansion of desert [19–21]. Soil stabilization is a technique for the irreversible alteration of the physiochemical properties of the soil that increases the efficacy of the physical properties of the soil [22]. The soil stabilization method is categorized into mechanical, chemical, and biological methods, or a combination of these. Mechanical stabilization depends on vibration or compaction, while chemical stabilization depends on the cohesive properties of the material employed for soil stabilization [23,24]. The biological method depends upon a biochemical reaction that occurs in soil mass and leads to calcite precipitation. This method provides promising outcomes and better structural stability to soil [25].

Table 1. Basic characteristics of different deserts around the world *.

Desert	Area (km^2)	Temperature (°C)	Precipitation (mm/year)	Topography
Karoo	395,000	2–40	50–200	Bush lands & savannah, Gravel Plains
Namib	81,000	5–45	5–100	Sand plains & dunes, Gravel Plains
Sahara	9,100,000	−5–45	5–150	Sand, dunes, gravel plains, Desert & rock pavements
Kalahari	520,000	−10–45	100–250	Longitudinal dunes & sand sheets
Sonoran	312,000	−10–50	70–400	Plains and basins bounded by ridges
Atacama	105,000	−5–40	0–20	Lava fields & sand dunes, Salt basins
Mojave	152,000	−10–50	30–300	Calcium carbonate dunes, Mountain chains, Dry alkaline lake beds
Chihuahuan	455,000	10–40	70–400	Numerous mountain ranges and with shrubs & covered flat basins
Thar	2,00,000	4–50	200–300	Dunes & saline soil, Rocky mountains
Arabian	2,300,000	5–40	25–230	Rocky highlands & gravel plains, Sands
Gobi	53,000	−20–30	30–100	Gravel plains & rocky outcrops, Grasslands
Tamami	185,000	10–40	300–500	Shrubs & grasslands, Sandy plains
Gibson	156,000	6–40	200–400	Grasslands & rocky highlands, Sandy plains
Simpson	180,000	5–40	50–400	Extensive dune fields
Nagev	13,000	5–40	100–300	Rocky highlands & sandy soils, Dunes

* Note: This table is quoted from Makhalanyane et al. [26].

Although some drought-tolerant plants, such as cacti, have been extensively studied and recommended to mitigate desertification, we still have to emphasize the role of the microorganism in transforming the soil community and enriching plant growth. Hence, we summarize the role of biological methods, especially focusing on different microorganisms, in the stabilization of desert soil.

2. Biological Method—Soil Stabilization

Recent studies on biological methods proved that it was more important to ensure the sustainability of the terrestrial ecosystem. Biological method-mediated soil improvement is defined as a novel approach in geotechnical engineering, especially employed to inhibit soil erosion [26,27]. Several lines of evidence demonstrated that the biomediated method improved the shear strength and reduced the permeability of soil [26–29]. Basically, it refers to a biochemical reaction that occurs within the mass of soil resulting in calcite precipitation through modifying the physiochemical properties of soil [30]. Naturally, the desert consists of microorganisms and biocrust that reside between plants and colonize the rhizosphere in several forms (Figure 1). The formation of a biological soil crust occurs when bryophytes and prokaryotic life forms (fungi, lichen, algae, and cyanobacteria) inhabit the soil surface of the desert. The rooting structures of these life forms intertwine the soil particles, resulting in the stability of desert soil [31]. The soil particles are further amalgamated by polysaccharides (glue-like substances) secreted by fungi, cyanobacteria, and algae [32]. It is well reported that every desert consists of a biological soil crust with a thickness from 2 mm to 2 cm [33]. Some of the microorganisms of the biological soil crust, especially cyanobacteria, have been found in the world's deadliest desert, i.e., the Atacama Desert of Northern Chile [34]. The biological soil crust is negatively correlated with vascular plants; hence, they occupy the open areas between scattered vascular plants. Plants are other biofactors that lessen the loss of nutrients, water, and sediments in the desert ecosystem [35], as well as enhance vegetation coverage and productivity [36]. Desert plants, especially cacti, are considered wonderful topsoil stabilizers [37].

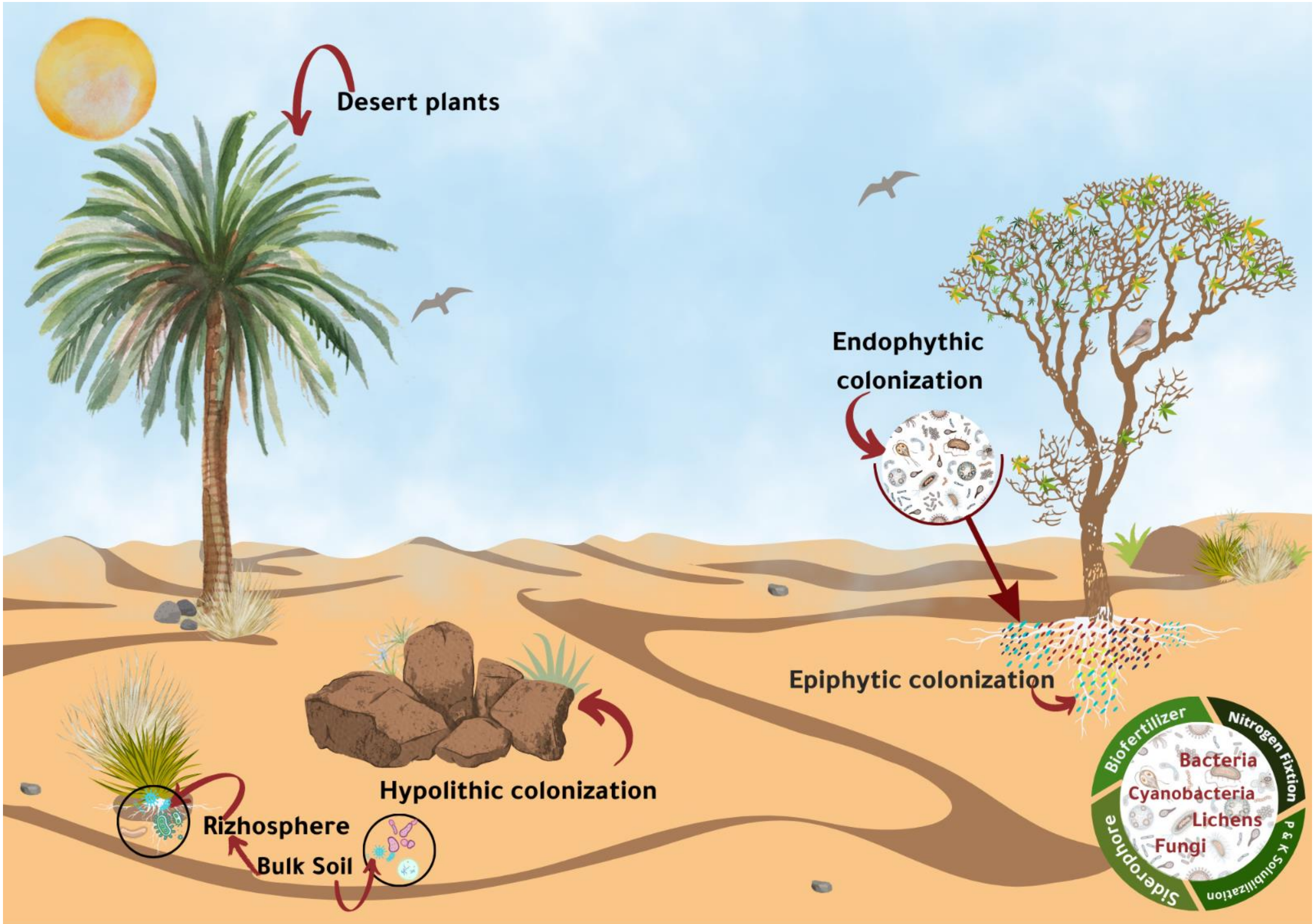

Figure 1. Microorganisms' niches in desert landscapes and their benefits. Arrows show the colonization location.

The detailed discussion about the role of microorganisms in soil stabilization is as follows.

2.1. Soil Stabilizing Microorganisms

Microorganisms are a crucial constituent of soil and play an important role in geochemical cycling [38]. The activity of microorganisms in desert soil depends upon moisture, temperature, and the availability of organic carbon [39–41]. Moisture availability is one of the key constraints that affects microbial activity, community structure, and diversity. The aerobic bacterial population varies from <10 (Atacama) to 1.6×10^7 g^{-1} (Nevada) of desert soil [42], while the sand dunes of Thar possess about 1.5×10^2–5×10^4 g^{-1} soil [43,44]. Spore-forming Gram-positive bacteria are a dominant population among bacteria, and their populations do not decrease even during the summer [45]. Actinomycetes contribute approximately 50% of the total microorganism's population of desert soil [44]. The dominant form of microflora in desert soil consists of coryneforms, i.e., *Cystobacter, Archangium*, *Polyan-gium*, *Myxococcus*, *Stigmatella*, and *Sorangium*, followed by *Bacillus*, *Acinetobacter*, *Proteus*, *Micrococcus*, and *Pseudonym.* Cyanobacteria also contribute significantly to the desert soil ecosystem, especially in terms of the fixation of nitrogen and productivity [44]. The biological soil crust is the hallmark of desert lands dominated by several forms of microorganisms (Table 2), such as cyanobacteria of the Thar Desert are *Oscillatoria pseudogeminata*, *Chroococcus minu-tus*, *Phormidium tenue*, and *Nostoc species.* Additionally, the fungal population ranges from nil to 6.3×10^3 in the desert of Uzboi Taky [46,47], with dominant genera that include *Curvularia*, *Aspergillus*, *Mucor*, *Fusarium*, *Pénicillium*, *Paecilomyces*, *Stemphyli*, and *Phoma*. Xeric mushrooms have also been observed in desert soil that includes *Coprinus, Fomes, Terfezia,* and *Terman* [48]. Microorganisms play a key role in the formation and maintenance of soil structure integrity through the secretion of exopolysaccharides, bioenzymes, and various beneficial organic acids. Fungal hyphae promote the formation of macroaggregates in soils and strengthen the macroaggregates' stability through the secretion of exopolysaccharides. Mycorrhizal hyphae form a network within the soil that connects the soil and plant roots to gain nutrients. Glomalin (a recalcitrant glycoprotein) is secreted by mycorrhizal fungi that increase the stability of aggregates [49,50].

Table 2. Dominant forms of microorganisms in desert soil.

Microorganisms	Members	Ref.
Lichens	*Collema sps., Stellarangia sps., Buellia sps.*	[11]
Cyanobacteria	*Oscillatoria pseudogeminata, Chroococcus minutus, Phormidium Tenue and Nostoc species*	[46,47]
Fungi	*Curvularia, Asperrgillus, Mucor, Fusarium, Pénicillium, Paecilomyces, Stemphyli and Phoma*	[48]
Xeric Mushroom	*Coprinus, Fomes, Terfezia, and Terman*	[48]

In spite of increasing the stability of soil aggregates, extracellular polysaccharides also protect the bacterial colonies by forming a protective layer around the outer layer (capsule) of bacteria. The clay particles, together with decomposed organic matter and minerals, are precipitated on the polysaccharide layer that serves as a biological glue to form soil aggregates. Microorganisms residing in soil effectively convert organic matter into humus. Soil aggregates enhance the availability of nutrients for uptake by plants because they provide the surface area for the adsorption of nutrients. Soil microorganisms also induce the formation of soil structure and fertility. Hence, soil microorganisms are a crucial component of the terrestrial ecosystem, especially in drylands.

2.2. Soil Stabilization via Bacteria

Bio-cementation is a biological process of soil-binding gel formation by bacteria. MICP (microbial-induced calcite precipitation) is a promising biocementation process that improves the physical properties of soil through calcium carbonate ($CaCO_3$) precipitation. MICP is very demanding in desert soil because desert soil contains very low amounts of carbon and bacterial populations [51]. However, it is well noted that MICP is a versatile and green modality employed for the improvement of desert soil. In this procedure, a soil sample is first mixed with substrate solution to induce bacteria, then mixed with cementation solution to precipitate $CaCO_3$. Ureolytic bacteria (such as *Bacillus. pasteruii*) produce carbonate and ammonium ions by hydrolyzing the urea. Further, the addition of calcium ions leads to the precipitation of $CaCO_3$ on the cell wall of bacteria [52].

$$CO(NH_2)_2 + 2\,H_2O \rightarrow 2\,NH_4{}^{+} + CO_2{}^{-3} \quad (1)$$

$$Ca^{2+} + CO_2{}^{-3} \rightarrow CaCO_3 \quad (2)$$

The precipitation of $CaCO_3$ during the MICP process interconnects adjoining soil particles, followed by gluing the soil particles together [53,54]. The precipitation of $CaCO_3$ decreases compressibility and permeability while increasing the strength of soil [52–54]. There are two approaches for employing MICP to improve soil strength: biostimulation and bioaugmentation. Biostimulated MICP refers to increasing the quantity of indigenous urea-hydrolyzing bacteria by providing suitable precipitation and enrichment medium. A recent study showed that MICP-mediated precipitation of $CaCO_3$ reduces soil erosion in desert soil [54]. Another report found that biostimulated MICP is beneficial to prevent soil erosion in desert soil [55]. Zhou et al. [56] showed that MICP increases the unconfined compressive strength of biosolidified sands. Bioaugmentation is the introduction of a large volume of an exogenous bacterial population into the soil. Several lines of evidence report that bioaugmentation is effective in improving silty and sandy soils [57–61]. Bio-augmentation successfully enhanced the durability and concrete strength, decreased the permeability of sand, and reduced sand liquefaction [62–64].

2.3. Soil Stabilization via Fungi

Fungi are another group of soil microorganisms that decompose organic materials and provide nutrients to plants for their growth. In spite of this, they also shield the plants from harmful microorganisms that influence the health of the soil [65]. Arbuscular mycorrhizal (AM) fungi help plants to tolerate harsh environments such as pathogens and abiotic stress [66]. AM fungi stabilize the desert soil through the following mechanisms:

(i) The external hyphae of AM fungi serve as skeletal structures that grasp the soil particles together;
(ii) The extracardinal hyphae bridge the organic debris with mineral particles through mechanical entanglement that leads to the formation of microaggregates;
(iii) Finally, these particles are cemented together through a physiochemical process involving different kinds of glued agents, such as an extracellular polysaccharide.

Numerous previous studies showed that AM fungi helped the desert plant cope with stressful conditions [57,58]. AM fungi promote the drought resistance capability of plants as they access the small soil pores through hyphae, thereby increasing the water uptake capacity of plants from belowground [59]. AM fungi have the ability to change the moisture retention property of soil by increasing soil aggregates [60–62]. A recent study reported that inoculation of AM fungi with biocrust is helpful in soil stabilization in desert soil in contrast to inoculation of mere AM fungi. Inoculation of AM fungi with *Azospirillum brasilense* enhances soil stabilization in the desert and prevents soil erosion [63,64].

2.4. Soil Stabilization via Plant Growth-Promoting Rhizobacteria (PGPR)

A group of free-living bacteria that colonize the plant roots and promote the growth of plants is considered PGPR. PGPR acts through two mechanisms: an indirect mechanism and a direct mechanism. The indirect mechanism includes the protection of plants from pathogens by inhibiting their growth by secreting molecules with antagonistic activity [65]. Direct mechanisms include the mobilization of nutrients such as potassium and phosphate solubilization, the fixation of nitrogen, the regulation of plant hormones, and the sequestration of iron in the soil. PGPR increases the physiological processes of plants and their resistance to pathogens [66]. A meta-analysis conducted by Worchel et al. [67] showed that grasses in drought conditions with AM fungi tend to grow larger in contrast to grasses without AM fungi symbiosis. Another report found that inoculation of enriched microorganisms in the rhizosphere of poor soil enhanced the availability of base elements [68]. A study based on the proteomic analysis found that a combination of plant growth-promoting bacteria (PGPB) with mycorrhiza or alone upregulates the level of specific proteins, culminating in enhanced biomass and nutrient uptake, Shi et al. [69] showed that AM fungi improve the growth of plants in desert conditions. They also reported that AM fungi improve the water attainment capability of ephemeral plants in deserts under variable water conditions. Desert PGPR is very suitable for excessively stressful environmental conditions like high salinity and heat and enhances the fertility of the soil in contrast to microorganisms found in non-arid regions [70–74] A recent study showed that PGPR regulates the phytobeneficial traits via reciprocal induction of protein both during the colonization process and post-colonization [71]. Another study showed that PGPR associated with native plants of the Atacama Desert helps the plants to tolerate high salinity conditions [75]. Bashan et al. [40] performed a study in the Sonoran Desert and found that inoculation of native PGPR is effective in the revegetation and restoration of degraded soil. They also reported that inoculating PGPR on degraded soil after isolating native PGPR has multiple positive impacts on plants and soils. Another study carried out in the Sonoran Desert demonstrated that inoculation of native PGPR on degraded soil restored soil fertility [76]. Aseri et al. [77] performed a study on a native strain (*Azotobacter chroococcum*) of the Thar desert and found that it improved the plant's growth by enhancing soil fertility. They also reported that the *Azotobacter chroococcum* strain shows more promising outcomes with AM fungi in contrast to AM-free inoculation. The *Serratia marcescens* PGPR strain extracted from *Capparis deciduas* (a native plant of the Thar Desert) acts as a promising biofertilizer for degraded soil [78]. Pseudomonas strains extracted from native plants of the Saharan desert act as biocontrol agents as well as biofertilizers; hence, they are beneficial in improving soil health [79].

2.5. Soil Stabilization via Cyanobacteria

Cyanobacteria are photosynthetic Gram-negative bacteria and the largest proportion of the biocrust community. They are considered the first colonizer of the terrestrial ecosystem. Cyanobacteria enhance the fertility, structural stability, and water retention properties of soil by fixing N and C and secreting exopolysaccharides [80,81]. In Asia, cyanobacteria are employed as biofertilizers in rice paddy fields [82–84]. Numerous studies have shown that cyanobacterial inoculation promotes the formation of biocrust, which corresponds to clusters of soil particles containing various microorganisms of biocrust [85,86]. Both exopolysaccharides and filaments of cyanobacteria serve as adhesive agents that bind the soil particles to form the aggregates, hence promoting the stability of desert soil [87]. They also reported that cyanobacteria also enhance water retention and protect the microorganisms. Several lines of evidence demonstrate that cyanobacteria increase soil fertility in dryland regions [83,88,89]. Inoculation experimental studies on sandy desert soil demonstrated that cyanobacteria improve soil stability and fertility [90–92]. Inoculation of the *Phormidium ambiguum* and the *Scytonema javanicum* strains shows a positive impact on desert soil [93–96]. A recent study showed that the application of cyanobacterial solution rapidly establishes the cyanobacterial crust and significantly improves the physicochemical properties of the Ulan Buh Desert soil [97]. The artificial cultivation of *Scytonema javanicumin* desert soil showed that *Scytonema javanicumin* is a favorable desert species for transferring nutrients from wastewater to the desert [98].

2.6. Soil Stabilization via Plants

Plants are immobile organisms of the terrestrial ecosystem, continuously exposed to alterations in environmental conditions. Plants play a crucial role in the stabilization of soil in various ecosystems around the world [99]. The physical roots of plants bind the soil particles and organic root exudates that support the rhizome around the roots [100–102]. In spite of this, plants also secrete the elements that enhance the cohesion property of soil [103]. Desert plants must grow in extremely hostile conditions such as the low availability of water, heat, and drought conditions [104].

Desert plants are classified into three classes:

(i) Succulents, with unique morphological and physiological characteristics suitable for dry conditions;
(ii) Perennial, survival of these plants depends upon dormancy, especially during the dry season;
(iii) Annual, these plants have rapid growth and a short life cycle.

Cacti plants are the best adaptable plant in the desert environment and act as the best soil stabilizer [40], such as *Pachycereus pringlei* (Giant Cardon cactus), which is an excellent topsoil stabilizer, especially in the Sonoran Desert and is able to stabilize the soil for up to one hundred years [105,106]. Previous studies showed that the application of cacti plants improved the desert soil [107–109]. Bhasan et al. [40] demonstrated that inoculation of cacti plants (*Pachycereus pringlei*) with *Azospirillum brasilense* increased the stabilization of the Sonoran Desert soil. Inoculation of three native plants with cacti restores the desert as it improves soil fertility by enhancing N fixation [110]. Another study reported that inoculation of cacti plants with plant growth bacterium restored the degraded desert soil [111]. Akinwumi et al. [112] demonstrated that the mucilage of *Opuntia ficusindica* enhances the UCS soil strength and decreases the permeability of the soil. Several lines of evidence showed that plants restore degraded soil by decreasing soil salinity, improving the microorganisms' environment, and overcoming the poverty trap [113–116]. Xu et al. [117] showed that planting Miscanthus in high-salinity soil improves the soil by decreasing salinity and electrical conductivity and increasing the organic materials in the soil. They also reported that Miscanthus also improves the microbial composition of the soil.

A recent study found that *Pelargonium graveolens* decreased the salinity of soil and increase the diversity of soil bacteria after plantation [118]. Plantations of *psammophytes* (*Haloxylon ammodendron*) and haloparastic species (*Cistanche deserticola*) restore the ecological degradation and poverty in the desert area of Alashan by improving the vegetation [119].

3. Conclusions

The desert constitutes around 33% of the landscape of the Earth's surface and is characterized by low nutrients, high UV irradiation, and strong winds. Microorganisms that form the biocrust communities of the desert are the key factors responsible for soil stabilization. Biological factors, including microbes and plants, affect the structural stability and fertility of soil; hence, it is necessary to understand the inoculation of microbes from different conditions of the desert into degraded areas of the desert. Biostimulated MICP is an effective process to mitigate soil erosion that may be affected by different conditions in various deserts. Sustainable development factors are achieved not only by protecting the soil from erosion but also by rehabilitating the desert environment for the vital community by taking advantage of the different types of microorganisms that are able to withstand the desert soil environment, which, in turn, will increase soil fertility factors, stimulate plant growth, and encourage the presence of other organisms, thus preserving biodiversity. Hence, studies are needed to explore the effect of different conditions on multiple deserts while preserving indigenous nature.

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