Book Title: **Advancements in Arid Agriculture for the 21st Century: Emerging Paradigms, Innovations, and Future Prospects**

Chapter Topic-7: "Arid Soil Microbiome Dynamics: Unraveling the Role of Microorganisms in Nutrient Cycling and Soil Health"

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ABSTRACT

Arid regions extend to approximately 40 percent of the total land surface area. They are in threats with the expansion of area, increasing temperature, wind erosion of soil, and drastic drought occurrence projecting to the global climate change since the past decades. The alleviation of the arid regions from the grassroot level is a promising approach. The nurturing of soil microbiomes in this region is required to be more prioritized to sustain biodiversity. They function for the betterment of soil health (physical, chemical, and biological properties) that could lead the arid regions into a full-vegetated region and increase the food security, reduce the environmental risks, and provide the employment opportunities for an economy's prosperity of the region. The soil microbiome decomposes organic residues, direct involvement in soil nutrients cycling, increase the soil fertility, sequester the atmospheric carbon dioxide (CO_2), symbiotic association with plant roots, and help to develop an ecosystem. Varietal adoption of soil microbes relative to the crop species to grow in the region is also an important to be considered. Not a single soil microbe can growth without plant support and *vice versa*. However, the proliferation of soil microbiomes demands soil moisture, and the optimum maintenance of soil moisture is a perilous task in the minimum precipitated (annually <200mm) arid region. Many findings are forwarded into the screening of soil microbial species that are little sensitive to soil moisture scarcity. The improvement of soil health begins when a single soil microbe starts adapting without any negative impacts in their growth and proliferation. The termination of the arid region's expansion with the soil microbiome and recovered into a soil with proper nutrient cycling for a better soil health could be a global solution for a vegetated arid region.

Keywords: Arid regions; Climate change; Soil microbiomes; Soil health; Nutrients cycling; Biodiversity

I. INTRODUCTION

The global climate change caused by various anthropogenic activities in the past years led the arid regions that held 40 percent of the world's land surface area under threats. Arid regions are mainly characterized by the insufficiency of evapo-transpiration (ET) with the natural precipitation, received <250 mL of precipitation per year, and have a fragile environment with scarce vegetations and less soil microbial diversity. These led to a sensitive for desertification, areal expansion upto 56 percent of the total land area by 2100, atmospheric warming, and natural disasters [1], [2], [3] which more triggering for climate change in the upcoming decades. Moreover, the arid regions cover almost half of the Earth's total surface area, and less confinement of human populations became a scope for reclaiming to help in reducing the ongoing climate change. The resilience of arid regions for a hotspot of biodiversity is the promising approach. Various ways of resiliency existed, however, improving the adaptation potential of soil microbial communities in the arid regions would be a prime solution. Even though a hard to exercise in the beginning, many natural resources such as energy, food, and water for the soil microbes are limited for the soil microbiome to survive and proliferate in this arid region. However, we must take the risk as a repent for the curse we had made in the past years with our anthropogenic activities for a healthy future generation. Many success stories have been made which turned the arid regions into vegetated landscapes from a few years back and many more are under exercising. But the huge investments that needed and time and labour that required pulled down the progress to reclaim in wider area of the arid regions into a vegetated region. The potential of arid regions that can turn into a healthy soil condition and help in mitigating climate change are left to be understood well.

The development of soil microbial diversity demands optimum maintenance of soil water, soil air, soil available nutrients, soil temperature, and soil pH under a vegetation which is contrast to the arid environment. The major limitation is precipitation rather than high temperature in this region. However, soil microbiome can be existed in all the environments from extreme conditions to plenty of resources conditions even though differences in population and activity [4], [5]. It is a tedious and time-consuming task to isolate and screen out of the most aridity resistant soil microbial species to introduce in the aridic soil for the development of an arid biodiversity. The characteristics such as resistance to temperature, extreme pH, salinity/alkalinity, humidity, radiation, pressure, contaminants, and O_2/CO_2 concentration are looking forward for the soil microbiome to adapt under the aridity [6]. The strongly adaptable soil microbial species are the future to reclaim this region and depicts a scope for developing biodiversity under the arid environment. Soil microbiomes that are adaptable in an arid environment indirectly indicate that can play a pivotal role in various soil functions such as nutrient cycling and maintenance of soil qualities such as physical, chemical, and biological properties. The soil with proliferated soil microbiomes can have good soil health. Besides, the soil microbiomes that possess plant growth promoting (PGP) bacteria are responsive for atmospheric N-fixation, siderophore production, phosphorous solubilization, potassium solubilization, and scavenging of soil micronutrients that can directly maintain the soil nutrient cycles. The utilization of soil microbiomes as a weapon to improve the poor soil conditions of the arid region is a promising approach for enhancing biodiversity in the arid region.

II. CONSTRAINTS OF ARID ECOLOGY

Higher evaporation than precipitation, recurrent droughts, considerable climatic fluctuation, and strong winds are characteristics of arid areas. Loss of biodiversity can result from desertification, the process that converts non-arid regions into arid ones. The ratio of water utilized to available water determines aridity; arid locations usually have chilly winters and less precipitation than evapotranspiration. These conditions are caused in part by dry, stable air masses and a dearth of storm systems. Because of low soil absorption, precipitation in

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hot deserts typically falls in short, strong showers, with most of the rainfall evaporating fast or generating runoff, resulting in xeric and aridic soil moisture regimes [7].

The soil quality and, by extension, agricultural productivity are severely hampered in dry ecologies. Limited vegetation, low organic matter, quick decomposition, salinization, extreme erosion, compacted soils, low nutrient retention, and poor moisture retention are all factors that limit the sustainability and growth of plants in arid ecosystems (Figure 1) [8]. Agriculture is limited by these problems because they have a positive impact on soil fertility, structure, and plant development support.

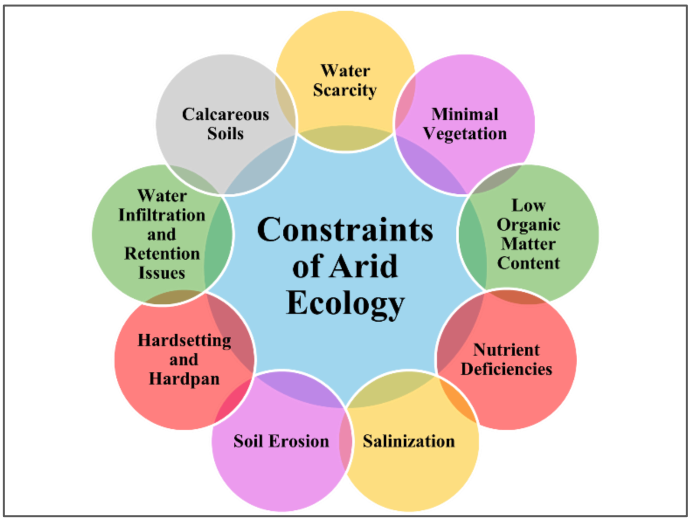

Figure 1: Constraints of arid ecology

III. REHABILITATION METHODS OF ARID REGIONS THROUGH SOIL MICROBIAL INTERVENTION

The establishment of relation between soil microbial community and soil physical, chemical, and microbiological properties is very crucial for terminating the areal expansion of arid regions [9]. This can be achieved through soil stabilization involving physical, chemical, and biological methods, or a union of these. Among the above methods, biological methods emphasizing on the soil microbial communities that depend on soil biochemical reactions and enhance the soil physico-chemical properties can stabilize the arid soil [10].

Naturally, the arid regions consist of soil microbiomes that form biocrust (2mm to 2cm) that can withstand extreme environment and colonize the rhizosphere. They include bryophytes and prokaryotic organisms *i.e.*, bacteria, fungi, lichen, algae, and cyanobacteria and possess them specific functions in strengthening aridic soil's physico-chemical properties (Table 1). They play an important role in geo-chemical cycling which depends on the moisture, nutrients, temperature, and soil organic carbon (SOC) that are limited in arid soils [11]. Among them moisture is the key to success natural resources for their survival. Various scientific novelties have documented that biomediated methods reduce soil erosion and water permeability and increased the shear strength of the arid regions [12]. The rooting behavior of the biocrust intertwines the soil primary particles and they secrete

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polysaccharides that bind the particles leading to a stable arid soil [13], [14]. Generally, scarce vegetations of arid regions provide less shelter for the soil microbiomes. However, arid biocrust has negative correlation with the vascular plants so they exist in the scarce vegetated arid regions. It is not like xerophytes like cacti has minimum role in the reclamation of arid regions, they do help in stabilizing the topsoil of the arid regions. Importance of soil microbiomes on arid soil stabilization are discussed briefly below:

A. Bacterial soil stabilization

In arid soil, actinomycetes contribute 50 percent of the total microbiomes' population and predominant bacteria are the gram positive such as *Bacillus*, *Micrococcus*, *Cystobacter*, *Proteus*, *Pseudonym*, *Polyan-gium*, *Myxococcus*, *Sorangium*, *Archangium, and Stignatella*. In soil, the aerobic bacterial population ranges from <10 to 1.6×10^7 g^{-1} soil. Biological cementation with the formation of precipitated calcite ($CaCO_3$) is the promising process under bacterial soil stabilization improving the physical condition of the arid soils. This process is demanding in arid regions as it contains low soil carbon and less bacterial population. It involves the procedure of adding soil bacterial substrate and cementation solution for a precipitated $CaCO_3$. Ureolytic bacteria are the most effective microbe for this cementation process and this $CaCO_3$ plays an important role as a gluing agent between the soil particles [15] and increase the soil aggregation under the two approaches such as biostimulation and bioaugmentation. The former biostimulation approach refers to as increasing the proliferation of indigenous ureolytic soil bacteria under the provision of suitable substrate and cementation solution. Whereas the later bioaugmentation approach involves the implementation of large quantity of exotic bacterial population in the arid soil. Various scientific results have documented that reduction of soil erosion, increases the soil strength, improving the skeletal soil particles (silt and sand), reducing sandy soil permeability and liquefaction under the bacterial soil stabilization strategies in aridic regions [16], [17], [18].

B. Cyanobacterial soil stabilization

Cyanobacteria are the first colonizer of the land ecosystem possessing the photosynthetic gram-negative contributing the largest microbial inhabitants in the biocrust. The cyanobacterial microbes which are dominant in arid soils includes *Oscillatoria sp.*, *Chroococcus sp.*, *Phormidium sp.*, *Scytonema sp.*, and *Nostoc sp*., are contributing to the fixation of atmospheric N and productivity. They also increase the soil fertility status, structural strength, and water holding properties owing to the ability of fixing nitrogen (N) and carbon (C) and releasing exoplysaccharides. Various studies reported that the oligosaccharides that are released by them can act as an adhesive agent for soil aggregation thereby promoting soil stability and increasing the soil fertility in desert soils [19], [20]. A stable soil structure facilitates water to be retained and improves the physico-chemical properties of

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desert soil [21]. Most common desert species of cyanobacteria is *Scytonema javanicumin* that help in supporting availability of soil nutrients from the wastewater in a desert soil [22].

C. Fungal soil stabilization

The eukaryotic soil microorganism, fungi, degrades soil organic materials, supply soil nutrient for plant, prevent harmful microorganisms to soil health [23]. Arbuscular mycorrhizal (AM) fungi are the most common ones which protects the host plants from infectious agents (pathogens) and abiotic stresses [24]. Besides, the AM fungi help in stabilizing the desertic soils under three mechanisms such as: the skeletal structure of the external hyphae aggregate the soil particles, the organic debris and soil minerals are aggregated with its extra-cardinal hyphae leading to micro-aggregation; and the released extracellular polysaccharides as glueing agent cement the soil particles through various physico-chemical properties. They create small soil pores that help the plants to water uptake from the ground water allowing the plants to drought tolerance, enhances soil aggregation thereby increasing the water accumulation capacity [25]. It was reported that *Azospirillium brasilense* as AM fungi stabilizes the desertic soil and reduced the soil erosion [26].

D. Plant Growth-Promoting Rhizobacteria (PGPR) soil stabilization

Plant Growth-Promoting Rhizobacteria (PGPR) are a consortia of beneficial soil rhizospheric microorganisms that can enhance the plant's growth and development. Various meta and proteomic analysis were conducted that resulted in the inoculation of PGPR with AM fungi showing positive response under desertic soil condition. Besides, some PGPR tolerate harsh environments such as soil salinity, alkalinity, extreme temperature, and enhances the soil health for an improved plant growth of arid soil conditions [27]. Some PGPR such as *Azotobacter chroococcum*, and *Serratia marcescens* are the promising PGPR that can function as a biofertilizer in arid soil condition [28]. Moreover, as a new approach the PGPR possessing ACC (1-aminocyclopropane 1-carboxylate) -deaminase activity indirectly help in tolerating the aridity stress by reducing the ethylene stress produced under this stress condition by the plants itself as self-protection, however, which is still lack to research and explore more.

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Table 1: Various soil microbial species responsible for improving aridic soil's physico-chemical properties

Soil microorganisms	Species	References
Fungi	*Asperrgillus, Fusarium, Curvularia, Penicillium, Phoma, Paecilomyces, Stemphyli*	[29]
Lichens	*Stellarangia, Buellia, Collema*	[30]
Cyanobacteria	*Chroococcus, Oscillatoria, Phormidium, Nostoc*	[31], [32]
Xeric mushroom	*Coprinus, Terman, Fomes, Terfezia*	[33]

IV. FUNCTIONS OF SOIL MICROBIOMES IN ENHANCING SOIL QUALITIES OF ARID CLIMATES

Arid climatic conditions are home to diverse soil microbiomes which perform a pivotal role in the soil health management to sustain productivity as well as to maintain quality. [34] had a survey on 10 unique genomes that were only found in soils of arid climatic conditions showed that they consist of more gene encoding functions for tolerance to alkaline conditions and more resilience to drought as compared to the genomes collected from other locations. Soil microbiomes are considered as one of the indicators of soil quality because of their sensitivity to biotic and abiotic stresses. They play an important role in nutrient cycling, carbon sequestration, soil water retention and maintenance of soil health, restore degraded land, alleviate plant stress.

A. Soil aggregation

Microbial activities influence the physical and chemical properties of soil. Soil aggregation improves porosity of soil, water infiltration and root penetration. Exopolysaccharides producing microorganisms alleviate drought stress thus improve soil structure. Their hygroscopic nature enhances the water holding capacity of soil, regulates the hydraulic conductivity. They also form organo-mineral complexes promoting soil aggregation [35]. The anionic nature of exopolysaccharides makes them bind free cations such as Na^+ and prevent their uptake by plants [36]. The hyphal networks of fungi play a prominent role in dry conditions to promote nutrient and water acquisition over long distance [37].

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B. Nutrient cycling

It maintains the ecosystem's functions and improves soil quality mainly for C and N cycle. Nutrients like phosphorus (P), potassium (K), and sulphur (S) are limited in arid climatic conditions. Microbiomes facilitate the bioavailability of nutrients in soil, produce organic acids for nutrient mobilization in soil and make nutrients available for plant uptake. They take part in N-fixation, P and Zn solubilization, siderophore, IAA (indole acetic acid), HCN and SA (salicylic acid) production. [38] conducted field survey across the different sites of Tibetan plateau reported that there is a reduce in C cycling index however with the increment of aridity the C decomposition gene abundance increased. AM fungi enhance C cycling under arid conditions. Free-living diazotrophs maintain the functions of soil under stressed environments by reducing gaseous nitrogen to bioavailable ammonium [39], [40].

C. Organic matter decomposition

During the period of decomposition of organic matter to humus, microbes feed on organic matter and release organic acids in soil which act as chelating agents. Microbiomes of drier habitats have abundant of genes required for degradation of celluloses and polysaccharides [41].

D. Carbon sequestration

Soil microorganisms contribute to the carbon cycle by breaking down organic matter and preserving carbon in soil organic material, essential for sustaining soil health and reducing the effects of climate change. Bacterial species viz. *Arthrobacter sp.*, *Microbacterium sp.*, *Planococcus sp.*, *Rhodococcus sp.*, *Streptomyces sp.* fix atmospheric CO_2 into $CaCO_3$ precipitates as vaterite and calcite [42]. Similarly bacterial genera like *Achromobacter sp.*, *Bacillus sp.*, *Ensifer sp.*, and archeal phyla *Thaumarchaeota sp.* and *Euryarchaeota sp.* from dryland soil convert atmospheric CO_2 to inorganic carbon and store it as carbonates & bicarbonates through microbial processes [43].

E. Degradation of pollutants

Pollution in dry lands has been increasing due to anthropogenic activities. It can be controlled through bioremediation. Soil microbes use their own degradative capabilities to degrade pollutants by enzymatically converting xenobiotic and non-halogenated compounds to either catechol or protocatechuate [44].

V. ASSOCIATION OF NUTRIENT CYCLING WITH SOIL WELL-BEING IN ARID CONDITIONS

Drylands store more than 30 percent of the world's soil organic carbon, making them essential to the worldwide cycle of nutrients. However, their lack of access to phosphorus and nitrogen affects the diversity of species and the functioning of ecosystems. Plant and microbial communities, including biological soil crusts and hypoliths, are essential to the cycling of nutrients in arid environments. Due to desertification, climate change, and human activity, drylands are more susceptible to degradation. These factors can limit carbon storage,

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phosphorus cycling, and disturb nutrient cycles [45]. To carbon sequestration, greenhouse gas emissions, biodiversity, and human habitation, it is essential to comprehend and respond to these changes.

Ecosystem health depends critically on the health of the soil, especially in dry regions with limited resources and high environmental stressors. By controlling the availability of vital nutrients, nutrient cycling—a basic ecological process—plays a crucial part in preserving soil health [46]. Low organic matter content, high temperatures, and restricted water supply can all upset the delicate balance of nutrient cycling in arid environments. In dry environments, the link between soil health and nutrient cycling is intricate and multidimensional, impacted by a range of biotic and abiotic variables [47]. It is essential to comprehend this relationship in these difficult settings to create sustainable land management strategies and lessen the negative consequences of desertification and climate change.

A. The Role of Nutrient Cycling in Maintaining Soil Vitality

Essential elements including C, N, P, and S are moved and transformed through a variety of biotic and abiotic activities in a process known as nutrient cycling. For the soil's fertility, structure, and general health, this cycling is essential. Because there is less microbial activity in arid soils, organic matter decomposition proceeds slowly, making nutrient cycling an essential mechanism for preserving nutrient availability. Because there is little rainfall and little nutrients available in arid settings, keeping the soil healthy is essential. Plant life depends on effective nutrient cycling, which guarantees the conversion of organic materials and nutrient availability. While reduced leaching in these areas keeps nutrients from being lost, it can concentrate nutrients in the top layers, reducing their availability. A reservoir of nutrients is created when bacteria break down organic stuff.

In delicate dry ecosystems, efficient nutrient cycling fosters long-term soil health, improves water retention, and supports plant development. According to research, decomposition rates can be lower in drier locations than in more humid ones, which might influence the fertility and productivity of the soil [48]. For instance, plant development and production are restricted by the lesser availability of nutrients in arid soils compared to more fertile soils. Plant development and microbial activity depend on soil physical qualities including water retention and aggregation, which are directly impacted by the effectiveness of nutrient cycling [49].

B. Microbe-Driven Nutrient Cycling

Nutrient cycling mediated by microbes is essential to ecosystem health and productivity. Organic matter is broken down by microorganisms such as bacteria, fungus, and archaea into simpler forms that are useful to plants. According to a study, microorganisms on Earth break down up to 90 percent of organic matter, returning vital nutrients like P, S, and N to the soil [50]. Because they mediate processes including N-fixation, nitrification, denitrification, and mineralization, microorganisms are essential to the cycle of nutrients. While denitrifying bacteria return surplus N to the environment to prevent N overload, N-fixing bacteria transform atmospheric N into a form that plants can use. Microbial communities have evolved to survive harsh environments in arid soils, but their ability to function is frequently restricted by the availability of moisture. [51] state that certain bacteria and archaea have evolved defense mechanisms against arid environments, including the production of extracellular polysaccharides that aid in moisture retention and the development of symbiotic partnerships with plants that promote nutrient exchange. In dry settings, these microbial actions are essential for sustaining nutrient

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availability and promoting plant growth. It is essential for soil fertility, sustainable agriculture, and ecosystem health to support a diversified microbial community.

C. Influence of Arid Environments on Nutrient Cycling

Arid areas present unique challenges for the cycling of nutrients, which is essential for the transformation and recycling of components within an ecosystem, because of their intense heat and lack of precipitation. Water scarcity inhibits the breakdown of organic matter and microbial activity, which lowers the amount of nutrients that become mineralized. Numerous investigations revealed that arid soils have noticeably decreased rates of microbial respiration [52], [53]. Microbial communities that are shifted in arid areas might be less effective in cycling nutrients. Because nutrient-rich soil particles are blown away by wind erosion, nutrient loss is made worse. Elevated temperatures may hasten the process of ammonia and other nitrogenous chemicals volatilization, thereby reducing the amount of nitrogen in the atmosphere [54].

Furthermore, the intake of organic matter is decreased when there is a deficiency in vegetation cover. Organic matter is necessary for the creation of soil organic carbon (SOC) and the maintenance of nutrient cycles. SOC levels are generally lower in arid locations than in more temperate regions, according to data, which has a major impact on soil resilience and productivity [55]. When combined, these elements upset the equilibrium of N cycling, making it challenging to preserve soil health in arid areas. Notwithstanding these obstacles, nutrient cycling is maintained by adaptations such as deep-rooted plants and symbiotic partnerships with N-fixing bacteria. In these delicate conditions, effective soil health measures are critical to sustaining plant growth and ecosystem function.

D. Plant-Soil Interactions and Nutrient Cycling

Through root exudation, litter deposition, and symbiotic partnerships with N-fixing bacteria and mycorrhizal fungus, plants have a considerable impact on the cycling of nutrients. Drought-resistant plant species aid in the cycling of nutrients in dry environments by supplying organic matter inputs and promoting nutrient uptake. A hotspot for microbial activity and nutrient conversions is the rhizosphere, the small area of soil affected by root secretions. Arid-adapted plants frequently have deep root systems that allow them to reach deeper soil layers for nutrients, which improves soil fertility and nutrient cycling [56]. Due to its ability to add organic matter to the soil and to facilitate nutrient uptake and release through root systems, vegetation is essential to the cycle of nutrients. Minimal vegetation cover in arid environments results in fewer organic inputs, which impairs soil fertility and the nitrogen cycle process [57].

E. Organic Matter and Soil Structure

The health of the soil is essential for ecosystem function in dry regions, and organic matter is essential to this process. As a nutritional reservoir, organic matter releases important nutrients like K, P, and N gradually. The limited organic matter buildup in arid soils has an impact on soil aggregation and water retention ability. It also strengthens the structure of the soil, facilitating aeration and water infiltration—both of which are essential for microbial activity and root respiration. By offering substrates for microbial activity, organic amendments like compost and manure can increase the amount of organic matter present and improve the cycling of nutrients. Numerous research studies have verified that soils with increased organic matter exhibit superior rates of

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infiltration [58], [59]. By boosting soil porosity and offering a home for helpful microbes, biochar, a type of charcoal made from plant biomass, has demonstrated potential in enhancing soil structure and nutrient retention in arid soils [60]. In dry areas, techniques such as cover cropping encourage the build-up of organic matter, which supports long-term plant development.

F. Contribution of Soil Fauna to Nutrient Cycling

By decomposing organic debris and promoting nutrient release, soil fauna—which includes earthworms, insects, mites, springtails, and nematodes—contributes to the cycling of nutrients. Although dry conditions in arid environments frequently limit the activity of soil fauna, some species have adapted to live and thrive in these circumstances [61]. These organisms facilitate nutrient cycling and improve soil structure by aiding in the breakdown of organic wastes, aerating the soil, and boosting microbial activity. In dry habitats, the existence and activity of soil fauna serve as markers of the resilience and health of the soil.

According to [62], earthworm activity speeds up the breakdown of trash and the release of nutrients. Grazing by nematodes and other soil fauna increases microbial activity, which improves the availability of nutrients. Furthermore, earthworm and termite burrowing enhance soil aeration and nutrient mixing through bioturbation, which encourages positive microbial activity [63]. The diversity of soil fauna is restricted by arid environments, but they have a major effect on the cycling of nutrients. In these delicate environments, actions like lowering tillage and applying organic amendments help sustain soil fauna and preserve a robust nutrient cycle.

G. Anthropogenic Influences and Land Use Strategies

In dry environments, human activities like agriculture, deforestation, and urbanization have a big impact on soil health and nutrient cycling. Unsustainable grazing methods can cause wind erosion, a decrease in organic matter and topsoil, which can impede soil fertility and nutrient cycling. Salinization can result from changes in land use, such as turning grasslands into cropland, rendering the area unusable for farming. It is imperative to implement sustainable methods such as conservation agriculture, effective irrigation, and rotational grazing. Effective irrigation reduces water usage, rotational grazing avoids overgrazing, no-till farming preserves soil moisture, and cover crops lessen erosion [64]. A study conducted in China found that drip irrigation decreased water usage while maintaining productivity, while a study conducted in Mongolia revealed that rotational grazing enhanced vegetation and soil organic matter [65]. By putting these sustainable strategies into reality, we can maintain ecological health while managing the usage of arid lands for human needs.

H. Climate Change and Future Challenges

In arid places, climate change presents more difficulties for soil health and nutrient cycling. According to [66], elevating temperatures have altered the patterns of precipitation, and an increase in the aberrant weather condition might worsen soil erosion and upset nutrient cycles. A thorough grasp of the relationships between the climate, soil, and biotic components is necessary to adapt to these changes. Maintaining nutrient cycling and soil

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58 Danny Dwi Saputra et al., "Recovery after Volcanic Ash Deposition: Vegetation Effects on Soil Organic Carbon, Soil Structure and Infiltration Rates," *Plant and Soil* 474, no. 1–2 (2022): 163–79, https://doi.org/10.1007/s11104-022-05322-7.

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64 Noelia Garcia-Franco et al., "Climate-Smart Soil Management in Semiarid Regions," *Soil Management and Climate Change: Effects on Organic Carbon, Nitrogen Dynamics, and Greenhouse Gas Emissions*, 2017, 349–68, https://doi.org/10.1016/B978-0-12-812128-3.00023-9.

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health in the face of climate change will need research on robust crop varieties, soil amendments, and water-efficient techniques.

VI. SOIL MICROBIOMES PARTICIPATING IN NUTRIENT CYCLING AND SOIL QUALITIES IN ARID CLIMATES

Biogeochemical cycling of soil nutrients in arid climate is microbially mediated and participates in ecosystem functioning. Biogeochemical cycling of nutrients is vital for survival of plant and animal life. [67] observed a significant relationship between soil multinutrient cycling in all natural environments except the desert and grassland environment. N is added to the soil through biological N-fixation and lost through denitrification. Leaching losses are not predominant in the case of arid regions. Specialized fungal and prokaryotic taxa participate in N cycling under arid climates. Free living diazotrophs are specific group of prokaryotic microorganisms, present in various domains (*Cyanobacteria*, *Actinimycetota*, *Bacillota*, *Pseudomonadota*, *Euryarchaeota)* maintain the functions of soil under stressed environments by reducing gaseous nitrogen to bioavailable ammonium [68], [69]. [70] study revealed that free living and symbiotic N-fixers are colonized in cryptic and productive desert niches, *Nostoc* spp. (Table 2). Of heterocyst cyanobacteria is ubiquitous in desert niche globally, Antarctic Beacon sandstone is dominated by cyanobacteria, the quartz rock of Mc Murdo dry valleys (East Antarctica) shows extensive hypolithic biomass.

Table 2: Different ecosystems with biological N fixation through free living diazotrophs

Ecosystem	Biological N fixation (kg ha^{-1} $year^{-1}$)
Desert	4.8 to 10.8
Arid shrubland	9.4 to 33.9
Cold boreal forest	1.5 to 2.0

Source: [71]

Aridity is negatively related to plant cover but favors rock weathering, a major source of P to ecosystems. AM fungi are in mutual symbiosis with 80 percent of land plants acting as P absorbers by extending plant roots deep into the soil. It helps plants to absorb nutrients, especially P, from deeper layers of soil. It shows assistance with plant N acquisition and diminishing N_2O production. In times of low moisture, P builds up on the top layer of the soil because of increased microbial death from drying out and radiation damage, the accumulation of dust, and the breakdown of organic matter by UV rays. [72] Biocrust communities of dryland soil surfaces are prime determinant of available P in arid soil, it improves the capture of P containing dust and prevents the loss of P by wind or water [73]. [74] reviewed that there is a relationship between the mycorrhizal infections of aridic plants and biocrusted surfaces from SE Utah have up to 3 times higher mycorrhizal infection rates as compared to the bare soil. The dark septic fungi form ectophytic and endophytic association with plant, colonizes the root cortex and

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surfaces, stem and shoot surfaces and vascular cylinder [75], fungal network dominated by dark septate fungi participate in C, N cycles and probably in P cycle.

Fe, Cu, Mn, Zn, Co are indispensable for almost all aspects of metabolism. Iron cycling drives the biogeochemical cycles of other elements. [76] surveyed the BSC microbial functional genes involved in Fe cycling along a revegetation chronosequences on the so the eastern edge of the Tengger desert, China. He used Geochip 5.0 microarray based metagene for this. At the phylum level of all metal metabolic genes, the actinobacteria and proteobacteria are the prominent sources and maximum genes function as redox catalyzer. Various functions of soil microbiomes under desertic soil are presented in Table 3.

Table 3: Role of microbiomes in deserts.

Deserts	Diversity of microbiomes	Functional role	References
Colorado plateau	*Nostoc* spp., *Tolypothrix* spp. and *Scytonema* spp.	Nitrogen cycling	77
Omani desert	*Microcoleus vaginatus, Nostoc* spp.	Nitrogen cycling	78
Arid soils of western Rajasthan (India)	*Aspergillus* spp., *Penicillium* spp. and *Acrophialophora* spp.	Release of bioavailabale P from organic phosphorus compounds	79
Sonaran desert region (USA), rock varnish from the Negev and Sinai deserts (Israel)	N.D.	Iron and manganese precipitation	80
Tengger desert, China	Proteobacteria and actinobacteria	Fe cycling	81

VII. SIGNIFICANCE OF IMPROVING SOIL HEALTH IN ARID REGIONS

Improving soil health in dry areas is essential because soil quality and ecosystem sustainability are closely related. Maintaining soil health in arid places is a particular problem due to their high temperatures, scarce vegetation, and inadequate rainfall. It is imperative to improve soil health in these regions to sustain agricultural output, stop desertification, and lessen the effects of climate change.

A. Boosting Agricultural Productivity

With better soil health, arid areas—which are frequently thought of as sterile and unproductive—can become surprisingly fruitful. Agricultural productivity is significantly influenced by the condition of the soil, particularly in dry areas where the supply of water and nutrients is limited. Techniques that increase microbial activity and organic matter, such as cover crops, increase crop yields and vital nutrients. Water retention and nutrient cycling are essential for crop growth, and they can be improved by healthy soils with enough structure,

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organic matter content, and microbial activity. For instance, adding organic amendments like compost and manure greatly increased soil fertility and crop yields, according to research done in the Sahel region of Africa [82]. Another example is the adoption of conservation agricultural techniques by farmers in dry regions of India, which has increased crop productivity by 20–30% [83].

B. Combating Desertification

Human livelihoods and the health of the soil are seriously threatened by desertification, the process of land degradation that occurs in dry sub-humid, semi-arid, and arid regions. Vital nutrients are retained in healthy soil, promoting plant growth and averting desolate areas vulnerable to wind erosion [84]. Reducing soil erosion is crucial to stopping desertification. Additionally, it enhances water management by facilitating improved precipitation infiltration and retention, which lessens the consequences of drought. Reforestation, cover crops, and the application of biochar are a few techniques that can improve soil organic matter, lessen erosion, and repair degraded areas. For instance, extensive reforestation and soil conservation initiatives on China's Loess Plateau have effectively enhanced agricultural productivity and ecosystem health by restoring damaged soils, increasing vegetation cover, and reducing soil erosion [85].

C. Promoting Water Sustainability

Although water is always scarce in arid areas, enhancing soil health can increase water efficiency. A high proportion of organic matter and a well-structured soil promote infiltration, which minimizes runoff and maximizes the absorption of rainwater. Additionally, it increases water retention, lowering the requirement for irrigation by retaining moisture like a sponge. Furthermore, vegetation grows in healthy soil, shading it and lowering evaporation. Research has demonstrated that organic matter-enriched soils can retain up to 20 times their weight in water [86]. Farmers in Australia's arid regions that use soil conservation methods, like organic mulching and no-till farming, have noted notable increases in soil moisture levels and crop resilience during dry spells [87]. A focus on soil health in dry areas increases the amount of rainfall and decreases the need for irrigation, increasing the sustainability of agriculture.

D. Biodiversity and Ecosystem Services

A unique biodiversity that depends on healthy soil is supported in dry environments despite their harsh surrounds. Encouraging the health of the soil encourages plant growth, which produces a variety of wildlife habitats. Numerous soil creatures, such as bacteria, fungus, insects, and earthworms, need healthy soil to thrive. These species support soil structure, nutrient cycling, and plant health. Robust food webs are sustained by healthy soil ecosystems due to elevated microbial activity. In nutrient-poor soils, for example, mycorrhizal fungi develop symbiotic associations with plant roots to enhance nutrient uptake and plant growth. Increased biodiversity and better ecosystem services, like carbon sequestration and erosion management, have resulted from the restoration of native vegetation and healthy soil in the desert ecosystems of the Southwestern United States [88]. Furthermore, better soil health attracts pollinators, which benefits plant reproduction and increases pollination. Moreover, carbon is sequestered by healthy soils, which slows down global warming. Therefore, in arid areas, healthy soil is essential to maintaining biodiversity and ecosystem services.

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E. Climate Change Management: Mitigation and Adaptation Initiatives

As a result of climate change, arid regions experience unpredictable rainfall, increased frequency of droughts, and rising temperatures. But by concentrating on soil health, these arid regions might become friends against climate change. Because they increase resistance to extreme weather events and absorb carbon, healthy soils are essential for mitigating the effects of climate change and facilitating adaptation. Increased soil organic carbon storage can be achieved by soil health-improving techniques including agroforestry, cover crops, and less tillage. Soil is a major sink of carbon. For instance, the "4 per 1000" programme, which was introduced at the 2015 Paris Climate Conference, intends to use sustainable soil management techniques to raise global soil carbon stocks by 0.4 percent annually, a significant amount of which can be offset by CO_2 emissions [89]. By enhancing soil health in arid settings, these techniques not only increase soil tolerance to temperature extremes and fluctuating precipitation patterns, but they also trap carbon. According to [90], improved soil structure increases water infiltration and retention, lowering the requirement for irrigation and the associated greenhouse gas emissions.

F. Economic and Social Benefits

People living in arid areas frequently struggle with hunger, poverty, and a lack of job options. On the other hand, enhancing soil health can yield major socioeconomic advantages. For communities residing in these difficult conditions, increased soil fertility and agricultural output can enhance food security, livelihoods, and economic stability. By generating new revenue streams, this enhanced productivity can stimulate the economy and lower poverty. For instance, sustainable land management techniques like agroforestry and soil conservation have been connected to higher household income and food security in the arid parts of Sub-Saharan Africa [91]. Furthermore, crops with healthy soil are more resilient to climate change, which guarantees a steady supply of food even during droughts. Furthermore, the requirement for chemical pesticides and fertilizers is decreased by healthier soils, which lowers production costs and has a positive environmental impact.

G. The Great Green Wall Initiative

The importance of enhancing soil health in arid areas is exemplified by the Great Green Wall project. The African Union started the massive Great Green Wall project in 2007 with the goal of halting desertification and improving millions of lives in the Sahel. By 2030, this 8,000 km long initiative in Africa hopes to sequester 250 million tonnes of carbon, repair 100 million hectares of degraded land, and generate 10 million green employments. It aims to restore fertile land, create economic opportunities for Africa's youth, guarantee food security, and improve climate resilience in one of the fastest-warming regions on Earth. It is being implemented across 22 nations with funding totaling over USD 8 billion. This enormous endeavor is a representation of sustainability and hope. With more than 15 percent of the project's target area recovered, the initiative has already achieved great strides towards increasing soil fertility, boosting agricultural output, and strengthening agricultural resilience to climate change [92]. This programme serves as an example of the significant economic, social, and environmental advantages that can result from extensive efforts to enhance soil health.

VIII. ROLE OF IMPROVED SOIL HEALTH IN FACILITATING ARID REGIONS INTO A VEGETATED LANDSCAPE

Some strategies of soil health management that can promote arid regions into a vegetated landscape are depicted in Fig. 2. that Arid regions include several aberrations such as high evaporation rates due to high temperatures, low rainfall and sparse vegetation which leads to challenges in terms of very low water retention capacity and low soil fertility ultimately affecting the soil to degrade which approximately covers 40 percent of the Earth's land surface. This degradation is mainly due to desertification, soil loss through erosion and salinization leading to annual universal losses in agricultural productivity of about 42 billion dollars. Salinization

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accounts for nearly 6 percent of the total world's land area, desertification affects the livelihoods of around 1 billion people and in some regions soil erosion rates can exceed 100 tons per hectare per year. Therefore, improving soil health indicators plays a pivotal role in enhancing the arid regions into vegetated landscapes by applying soil health management strategies for socio-economic development and ecological stability. These indicators were organic matter content, soil structure, nutrient availability, and microbial activity, water holding capacity, carbon sequestration, soil stability and erosion control measures.

Soil structure is crucial in determining water and nutrient availability in arid regions. This can be managed with crop residues and manures which stabilizes the soil aggregates. Green manuring and cover crops as a good organic matter sources can be incorporated in arid soils to enhance water retention. Further, crop rotation with legumes coupled with phosphatic fertilizers can manage soil structures with their extensive root systems that bind the soils and reduce erosion. A diversified microbial population found in healthy soils not only improves nutrient cycling and increases the availability of nutrients for plants but also acts as disease suppression in rhizosphere regions. Soil fertility and plant resilience may also be improved by adding beneficial microorganisms and using microbial diversity-promoting measures like crop rotation and covering crops. Healthy soils can sequester more carbon than arid soils, which helps to mitigate climate change. Healthy soils can sequester 0.5-2.0 metric tons of CO_2 per hectare per year compared to arid soils which is often less than 0.1 metric tons of carbon per hectare per year. Apart from these vegetated landscapes provide habitat for variety of organisms to enhance biodiversity and also attracts pollinators and natural pest predators ultimately supporting the overall ecosystem.

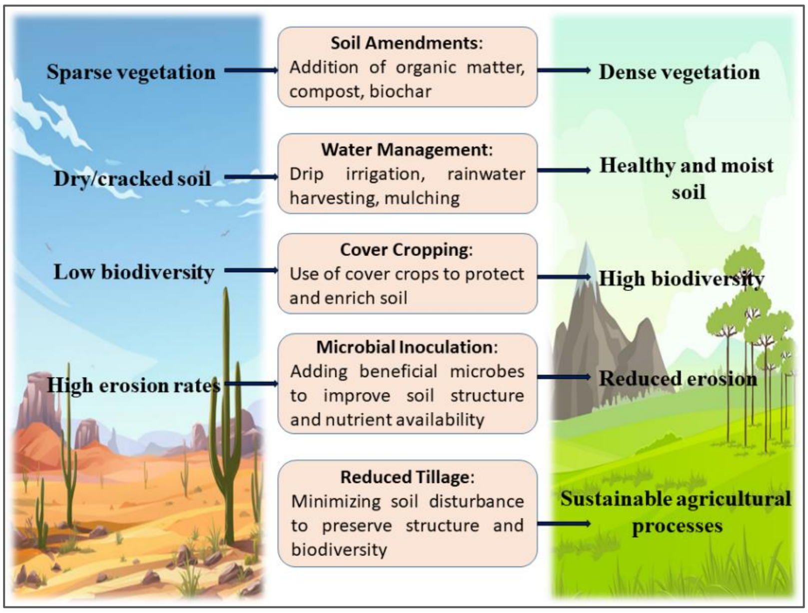

Fig. 2: Different soil health management strategies in facilitating arid regions into a vegetated landscape

IX. DIVERSE ROLE OF SOIL MICROBIOTA CONTRIBUTING TO THE ADOPTION OF SUSTAINABLE BIODIVERSITY IN ARID REGIONS

Maintaining soil health and ecosystem performance depends strongly on the soil microbiota, which consists of bacteria, fungus, viruses, archaea, and protozoa. These microbes play an important function in arid regions, where the climate is harsh. These soil microbiotas are not only involved in N-fixation but also facilitate inorganic transformations from sulphur to sulphates or ammonia to nitrate aiding plant nutrition. Further, they decompose soil organic matter reduces it to humus by producing phytohormones namely auxins, cytokines and gibberellins and facilitate the process of nutrient release for enhance plant growth and development. They facilitate the production of microbial exudates, such as polysaccharides to enhance the soil structure and stability. They also act as an important agent in solubilization of P and S compounds for nutrient availability. This will help in enhancing the soil structure and stability by producing microbial exudates, such as polysaccharides that help in binding soil particles into aggregates and enhances the water retention capacity of arid soils. Soil microorganisms like cyanobacteria, lichens, and mosses form biocrusts on the soil surface, which also reduce erosion, enhance water retention, and contribute to nutrient cycling.

In arid regions, AM fungi are particularly important for helping plants access water and nutrients in deep soil layers because they produce exopolysaccharides that improve soil water retention and help plants withstand drought conditions. These soil microorganisms are also adapted to extreme conditions and contribute to carbon sequestration by decomposing organic matter and protect plant roots from invasion by soil parasites and pathogens through the production of antibiotics, siderophores, and other bioactive compounds. Further, microorganisms degrade pollutants during the bioremediation process to produce chemical energy and helps in detoxification of arid soils for this procedure it involves certain bacteria and fungi species that affect the microorganisms and their metabolic pathways (enzymes) to break down pollutants like hydrocarbons, heavy metals, and pesticides, improving soil health and safety. These soil microfauna and microflora enhances the ecosystem resilience and stability by ensuring ecosystem functions were maintained even under stress conditions. For instance, the mechanism by which halophilic and halotolerant microbes help plants cope with saline conditions is by modifying the rhizosphere environment or through symbiotic relationships. This stability governs by complex interactions among plants, soil fauna and microbes that support overall soil health and productivity.

X. CONCLUSION

Soil microbiomes became familiar for reclaiming the aridic soil conditions. As the existence of living organisms began from a microbial cell, all the environmental functions are expected to be responsible by them. Adopting soil microbiomes in aridic soil conditions for improving soil health and flourishing in a vegetated environment is a crucial task. However, the current researchers are slightly deviating from utilizing the soil microbiomes as a tool for reclaiming aridic soil and that hinders the reclaiming pace. Understanding the role of soil microbiomes to reclaim aridic soil through enhancing nutrient cycling and that relate in improving soil health can only convert the aridic soil into a vegetated land. The relationship between soil microbiomes, nutrient cycling and soil health are needed to be explored more. Targeting soil microbiomes that can resist under little soil moisture and proliferate them is the only way to alleviate the areal expansion of aridic soil due to climate change and for a sustainable environment.

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