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Biotechnological Approaches to Combat Desertification: Integrating Native Microbial Consortia and Drought-Resistant Legumes for Sustainable Ecosystem Restoration in Arid Iraqi Regions

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Abstract

This study was prepared to throw light on the role of some soil microorganisms in the restoration of natural deteriorated pastures in Iraq, by improving the stability of soil followed by stability and diversity of vegetation in pastures, as well as improve the ability of woody legumes to fix nitrogen through inoculation with symbiotic bacteria, such as *Rhizobium*. Inoculation with Mycorrhiza that infect the plant roots and extends their hyphae externally to the surrounding soil, helps to tighten the soil around the plant roots that improving the root stability ,absorption and helps plants to withstand environmental stress such as lack of nutrients, drought and soil degradation. Since the deterioration and erosion of soil is usually followed by lack of microbial activity specially effectiveness of nitrogen-fixing bacteria and Mycorrhiza, therefore, the restoration of those micro-organisms and increase abundance is considered as a key, and a strong evidence of improvement in deteriorated natural pastures.

Live crust of soil has a special significance to the ecosystem because they contain large numbers and a variety of microorganisms such as aggregates of bacteria, blue-green algae, fungi, molds and nitrogen- fixing bacteria. The crust is particularly important in the cohesion of the soil and avoiding land deterioration. Crust composition depends on falling dew, the abundance of microorganisms, strong winds and water flow. Best technique used in sustainable land use was to apply bio fertilizers, and formulation of mixed inoculation with many strains of Rhizobia and Mycorrhiza to cover a wide range of plants in order to restore vegetation in the deteriorated natural pasture lands.

Keywords: Biotechnology; Combat desertification; Microbial consortia; Sustainable ecosystem
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1. Introduction

Food security and Climate changes are closely linked, as the global population is expected to reach 9 billion by the end of 2050, with food demand projected to increase by 85% (FAO, 2017). The agricultural sector faces numerous major global challenges, including increasing droughts, heavy rainfall, temperature fluctuations, attacks by various pests on the most economical crops, and the emergence of soil salinization (Dhankher & Foyer, 2018; Hussain et al., 2019).

More than 831 million hectares of agricultural land worldwide are affected by salt. Due to improper practices such as irrigation with saline water, reduced rainfall, and increased evaporation caused by rising temperatures, saline-affected lands may constitute up to 50% of global agricultural land. Significant losses in the productivity of important food crops, such as maize, rice, and wheat, have been recorded [2].

Rapid developments in climate changes impact the most critical factors in agriculture: temperature, precipitation, and sunlight. Soil properties, including organic carbon content, are affected by reduced water availability, as well as decreased decomposition and mineralization rates of organic compounds. Changes in temperature and soil particle size also influence soil moisture and water retention capacity, increasing evaporation rates and restricting water movement in the soil, soil degradation and reduced plant productivity in moisture-deficient regions ultimately lead to desertification. Arid and semi-arid soils are known for their nutrient deficiencies, particularly in phosphorus and nitrogen

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[3] . It is widely accepted that the natural balance of an ecosystem can be disrupted when any natural (climatic or terrestrial) activity is disturbed. The composition and appearance of associated species and vegetation cover can deteriorate along with the biological, chemical, and physical degradation of the soil [4,5].

Desertification is known as one of the major global challenges, identified as a critical issue in the early 1970s. However, the international community did not prioritize it initially until it became severe [6]. Theoretically, ecosystem degradation and desertification are considered irreversible. However, in practical and experimental terms, appropriate restoration strategies based on ecological principles can be developed to rehabilitate vegetation cover.

The Green Revolution of the 20th century, which aimed to increase global food production and sustain vegetation, relied on two key agricultural strategies: chemicals treatment (commercial fertilizers and pesticides) and genetic modifications through targeted breeding and gene manipulation. Although these chemical treatments were beneficial, their prolonged use has caused significant environmental issues, including soil and water pollution and the emergence of resistant pest and fungal strains. This has prompted scientists to explore alternative technologies that can provide environmental sustainability, enhance crop yields, and reduce the negative impacts of excessive chemical use while combating desertification [7].

One of the most important strategies for rehabilitating environmentally degraded soils is the use of plant growth-promoting rhizobacteria (PGPR). These bacterial treatments are among the most eco-friendly solutions, with slow bacterial spread, long-lasting effects, and repeated growth cycles, along with interactive benefits with plant roots [8]. These bacteria offer numerous advantages, making them a key practice in agricultural land reclamation, including: a) Participation in C, N, P, and S cycling, b) Solubilization of essential nutrients and immobilization of heavy metals, C) Production of plant growth regulators, vitamins, amino acids, and secondary metabolites that enhance soil quality and nutrition [9], d) Enhancement of plant salt tolerance by modulating enzymatic activities [10].

The objective of this study is to propose a practical, applied approach to restoring natural pasture vegetation, based on proper regulatory methods for plant-microbe interactions. Accordingly, the study will focus on analyzing three important aspects: 1.The current state of ecosystem desertification in the Arab region, particularly Iraq, 2. The ecological importance of soil microorganisms as a vital solution for sustaining natural ecosystems, 3. General methods for vegetation restoration and relevant biotechnological techniques.

2. Desertification of Ecosystems

Desertified lands are characterized by the loss or disruption of vegetation cover, increased soil erosion, depletion of available nutrients and organic matter, and the absence of microbial growth and reproduction—essentially, a loss of microbial activity. This disrupts the cycling of essential nutrients required for plant growth. Neglecting these key characteristics and failing to address them as primary factors in combating desertification leads researchers into a vicious cycle, exacerbating degradation at both soil fertility and vegetation levels. Consequently, this results in reduced plant productivity and diminished soil resilience against erosion.

Ecosystems in the Arab region, particularly Iraq, are exposed to harsh climatic conditions, including scarce and irregular rainfall as a primary factor, leading to prolonged drought periods, especially in summer, which often extend for most of the year. High temperatures, sometimes exceeding 50°C, coupled with overgrazing, the cutting of shrubs for fuel during crises, the draining of marshes, and reduced water flow in the Tigris and Euphrates due to upstream dam construction by neighboring countries, have contributed to the progressive decline of vegetation cover and rapid topsoil erosion [11].

3. Microbial community of Natural Ecosystems

The sustainability of ecosystems—whether natural or artificial—largely depends on soil biological balance, which is fundamentally governed by the activity of soil microbial communities. These microorganisms, a natural component of soil, may adhere to soil particles, form soil aggregates, or specifically interact with the root systems of various plants [12] . Soil microorganisms play a crucial role in ecosystem functionality through various activities, particularly those of root-associated microbes known to enhance both soil and plant quality. These activities include:

1-Promoting plant growth, 2-Increasing nutrient availability, 3-Enhancing nutrient uptake, 4-Protecting plants from environmental stress and pathogens, 5-Improving soil structure [13]. Undoubtedly, plant productivity and health largely depend on soil quality, which in turn relies on the diversity and influence of its microbial content. In most ecosystems, the biological soil crust (the microbial- and nutrient-rich layer) is a key to soil stability, ranging in thickness from a few millimeters to over 12 inches. Field studies have confirmed that restoring this bio-crust is an extremely slow process, taking several years in semi-arid regions to millennia in hyper-arid deserts, highlighting the profound impact of these microorganisms on ecosystem integrity [14,15].

4. Classification of Soil Microorganisms

The Two main groups of microorganisms constitute the biological soil crust:
1- Saprophytic microorganisms, 2-Symbiotic microorganisms. Most microbes classified as Plant Growth-Promoting Rhizobacteria (PGPR) are saprophytic [16,12], whereas mycorrhizal fungi and nitrogen-fixing bacteria are among the most significant symbiotic organisms. Plants colonized by mycorrhizal fungi exhibit enhanced nutrient absorption compared to non-colonized plants, as mycorrhizae solubilize otherwise unavailable nutrients, making them more accessible. Nitrogen-fixing bacteria include species of *Rhizobium*, *Cyanobacteria*, and *Frankia*, along with vast populations of green algae, cyanobacteria, molds, and fungi—all of which play a vital role in ecosystem sustainability and restoration through diverse nutrient-providing mechanisms [17,18].

5. Mycorrhizal Symbiosis

Certain mycorrhizal fungi form symbiotic relationships with woody plants by growing between cortical cells, creating a Hartig net, and forming a fungal sheath around feeder roots. Extending from this sheath are rhizomorphs—hyphal bundles that spread several meters into the soil, enhancing nutrient acquisition for the host plant and improving soil particle cohesion, thereby mitigating desertification.

Some mycorrhizae develop arbuscules (tree-like structures within root cells), characteristic of Arbuscular Mycorrhizal Fungi (AMF). The most prominent and prevalent in both natural and agricultural ecosystems mycorrhizal type is Glomales (Zygomycetes) and are pivotal in vegetation restoration [19].

These structures of arbuscules serve as nutrient exchange sites: the plant supplies the fungus with photo-synthetically derived carbohydrates, while the fungus provides phosphorus, copper, zinc, and water, also enhancing the plant's tolerance to salinity, drought, and pathogens.

Additionally, the external fungal mycelium collaborates with other soil microbes to stabilize water aggregates and booster plant defenses against biotic and abiotic stresses. Most plant species naturally form this symbiotic relationship, wherein mycorrhizal hyphae extend from the root cortex into the surrounding soil, aiding the plant through:

1. Nutrient and water exploration via extensive mycelial networks that also bind soil particles, 2.Enhanced phosphorus uptake in deficient soils, where mycorrhizae dramatically increase absorption surface area, 3.Improved nitrogen and micronutrient (e.g., copper, zinc) acquisition in certain species [20].

Symbiosis phenomenon enhances plant adaptability to adverse conditions (nutrient scarcity, drought, micronutrient imbalances, soil disturbance), making it ideal for combating desertification. Figure 1 shown mycorrhizal spores, while Figure 2 illustrates the stark contrast between mycorrhizal-colonized and non-colonized roots

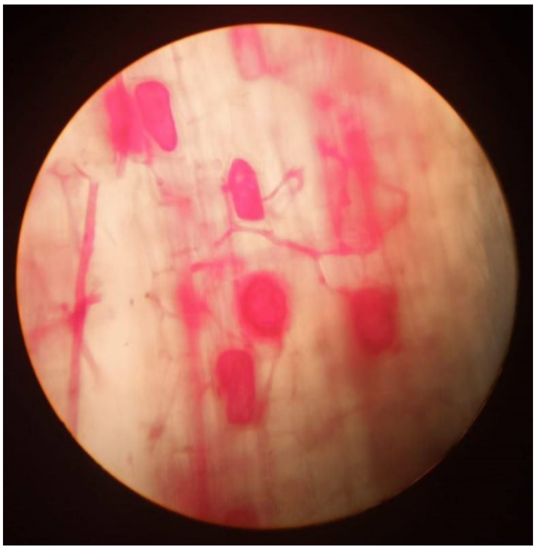

Fig. (1) Mycorhizal spores (mycorhiza laboratory in The Biological Control Department at the Agricultural Research Center / Scientific Research committee 2024)

Fig. (2) Mycorhizal colonization of plant root A and plant root without colonization B
http://www.appliedturf.com/organic-fertilizer/mycorrhiza

6. Strategies for Vegetation Restoration

As previously mentioned, while desertified ecosystems are theoretically irreversible, appropriate vegetation restoration techniques can be implemented to rehabilitate plant cover. Utilizing pre-existing native species (indigenous plants) can restore a degraded ecosystem to its peak ecological functionality (reclamation) [21]. In contrast,

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introducing non-native plants or locally alien species often yields suboptimal results.

A well-established vegetative cover enhances soil chemical, physical, and biological properties [5]. However, the scarcity of microbial populations in degraded soils [22,23] can hinder plant growth due to the absence of a functional rhizosphere, particularly in nutrient-poor environments. Studies [23] demonstrated the positive effects of mineral nutrient supplementation (zinc, iron, nitrogen) on the growth of mung bean (Vigna radiata) in degraded, desertified soils of Iraq's Anbar and Kut provinces [24]. Further investigated the role of Bradyrhizobium spp. in reducing environmental stress and minimizing mineral fertilizer requirements in mung bean cultivation. Later, study utilized *Rhizobium leguminosarum* to identify superior mung bean genotypes, finding that local varieties outperformed others in vegetative and yield traits while reducing nitrogen inputs by 50% [25].

7. Dominant Plant Species in the Arab Region

The region's dominant vegetation consists primarily of drought-resistant shrubs, forming woody plant communities in semi-arid zones. These species should be introduced into restoration programs. Most plants need and depend on adequate soil nitrogen content. In dry land ecosystems, nitrogen sources are limited to atmospheric deposition (0.5–2 kg ha^{-1} yr^{-1})[26] or biological nitrogen fixation (BNF) by symbiotic microbes mainly the *Rhizobium* spp as presented in figure 3.

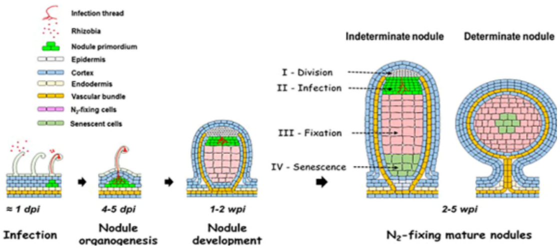

Fig. (3) Illustration of stages of *rhizobium* spp infection to woody plant

Leguminous shrubs are conceder as a cornerstone of vegetation restoration in water- and nutrient-deficient environments [27], because of their dual symbiosis with: Rhizobia the nitrogen-fixing bacteria that significantly improve Root elongation (by 36.2%) and Seed germination rates [27] as well as Mycorrhizal fungi that enhance phosphorus uptake. These symbiotic relationships enable legumes to thrive in nutrient-poor, arid soils, making them ideal for combating desertification

Soil erosion can significantly reduce the proliferation of mycorrhizal fungi [22], particularly under phosphorus-deficient conditions. Consequently, most plant species rely on symbiotic relationships with Arbuscular Mycorrhizal Fungi (AMF) to compensate for phosphorus scarcity [28]. On the other hand, in nitrogen-fertilizer-limited environments, soil phosphorus availability becomes a critical determinant of nitrogen content in leguminous crops [29]. Without AMF colonization, external phosphorus supplementation becomes essential to maintain nitrogen fixation rates by rhizobia and ensure economically viable legume yields (Fig. 4).

The main Mechanisms for restoration:

1. Nitrogenase Activity: Rhizobia employ the nitrogenase enzyme to fix atmospheric nitrogen within root nodules, 2.Mycorrhizal Phosphorus Mobilization: AMF hyphae (mycelium) enhance phosphate ion uptake from soil, facilitating root absorption. Mycorrhizal networks reduce dependency on synthetic P fertilizers, promoting sustainable agriculture in degraded soils [28].

Fig (4) Root nodules from a locally cultivated legume, demonstrating the symbiotic association of *Rhizobium* spp. (Microbiology lab in Agriculture Center/ Scientific Research Committee 2024)

Low soil P directly constrains N fixation efficiency in legumes [30] , many observation were ensured that relationship as: reduced number and size of nodules, lower nitrogenase activity, carbon limitation, impaired signal transduction that regulate symbiosis and nodule function.

Different scientific implications were recognized for Phosphorus-Nitrogen Linkage:

1-Energy Demand: Biological nitrogen fixation (BNF) by rhizobia in legume root nodules is highly energy-intensive, requiring large amounts of ATP (adenosine triphosphate), which depends on phosphorus availability [31]. 2-Nodule Formation and Function: P is essential for nodule development, legume root growth, and the synthesis of key molecules like leghaemoglobin (which maintains low oxygen conditions for nitrogenase activity), 3-Nitrogenase Enzyme: The nitrogenase enzyme complex (responsible for converting N_2 to NH_3) requires P for its synthesis and function [32].

8. Plant-Microbial Interactions for Vegetation Restoration

The multi-inoculation approach in degraded soils has been established as the most effective method for sustainable agriculture, leveraging natural environmental factors. Research has demonstrated that high organic matter application significantly enhances microbial biomass recovery [33]. A case study by Herrera et al. [34] that last four years of vegetation restoration biological strategies in a semi-arid, desertified ecosystem in southeastern Spain, selected for its representative Mediterranean conditions.

Study Site Characteristics for experiment: Sedimentary basin in Almería, Spain (600–800 m elevation) that has 230 mm annual rainfall (arid Mediterranean). Abandoned for 50 years, featuring a natural community of woody legumes, dominated by the shrub Anthyllis cytisoides (60% of vegetation cover, Figure 5). The team investigated the role of dual inoculation (mycorrhizal fungi + rhizobia) in accelerating vegetation recovery in this phosphorus-deficient region [35]. The finding of efforts was only native woody legumes successfully germinated and persisted under local environmental stresses. Co-inoculation with Rhizobia and Mycorrhizae caused to enhance plant resilience, Increase biomass production and improve survival rates. This confirmed that native shrubs within natural vegetation assemblages are optimal for restoring desertified areas.

The scientific implications were Organic matter enrichment reactivates microbial communities, aiding soil viability, Dual microbial inoculation (AMF + Rhizobia) outperforms single treatments in harsh environments and finally local adaptation is a critical because the exotic species often fail in extreme arid conditions.

9. Technical and applied perspective on Bio-fertilizer Production

a) The challenges of Microbial Inoculant Production

Rhizobial Inoculants were experimentally and relatively straightforward to produce. While, Mycorrhizal inoculants were Face significant production challenges , despite hurdles, mycorrhizal biotechnology can be incorporated into vegetative propagation systems to enhance ecosystem resilience [13]. Also, recent advances by researchers have improved scalability.

b) Role of Native Mycorrhizae

Serve as fertility islands, providing Nitrogen enrichment for non-legumes in semi-arid ecosystems. As well as, heavy metal filtration by Glomus spp. and Azotobacter chroococcum that reduced Ni, Fe, Mn, Zn, Cu, and Co in contaminated soils [36].

c) Direct Nutrient Acquisition

Through atmospheric N_2 fixation by Rhizobia, Azotobacter and other bacteria, Mineral solubilization as P, Zn, and Ca. Siderophore production such as iron chelation. Phytohormone synthesis the IAA and cytokinins.

d) Indirect Stress Tolerance

Mitigates different type of stresses such as biotic caused by pathogens and abiotic mainly drought, salinity stresses.

10. Commercial Bio-fertilizer Development

The most challenges for bio-fertilizer industry were recognized as: 1- Field Adaptation: Lab-to-field translation remains a major step due to: Microbial competition with native soil biota as well as abiotic factors such as pH, temperature, and salinity, 2-Formulation: the Carrier materials must chose very properly because some of them might extend shelf life but reduce bacterial viability as peat. On the other hand cost-effective media so many researcher screen agricultural waste as substrates for media.

11. Pioneering Work in Iraq

Many field trials were done at Institution of Agricultural Research Center/ Scientific Research Committee (formerly under Ministry of Science and Technology).

The achievements were: Wheat (2013–2014): 50% reduction in chemical fertilizers [37]. Implemented in Wasit, Diyala, and Salahuddin (100 hectares each), Rice (2013–2014): N-fixing and P-solubilizing strains reduced chemical use by 50%. Soybean: Introduced *Bradyrhizobium japonicum* that known to absent in Iraqi soils, reducing N-fertilizers by 60–70% [38], Peanuts: 70% less chemical fertilizers in Diyala (200 hectares), Legumes (Mung Bean): Mix bacterial- inoculant constitute of *Rhizobium leguminosarum*, *Bacillus megaterium*, and *Pseudomonas fluorescens* reduce inputs by 75%. Recently, added *Streptomyces* spp. to enhance N-fixation [39]. From above trials of bio-fertilizers (figures 5 and 6) we should focus on the knowledge of new sustainable technology by: a) Farmer Adoption: Training programs to promote bio-fertilizers as part of modern agro-technology, 2) Research Priorities: Isolation and introduction of stress-tolerant bacterial strains for open-field conditions and design low-cost carrier materials.

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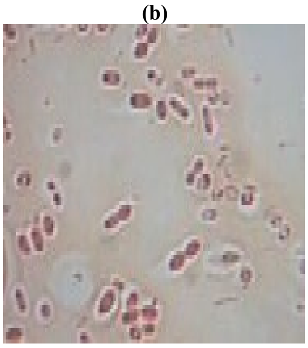
(a)

(b)



(c)

Fig. (5) Microscopic Examination for gram stained bacteria A= *Rhizobium* spp, B= Azosperillum spp and C= Azotobacter spp

Fig. (6) the experiment of bio-fertilizing effects on the mung bean in pots and tomatoes cultivated at field

12. Conclusion

In conclusions, vegetation restoration necessitates soil microbial rehabilitation, as these organisms are critical for soil structure rebuilding and plant growth. Drought-tolerant legumes should be prioritized due to their ability to fix atmospheric nitrogen when paired with compatible rhizobial bio-fertilizers. Soil quality improvement depends on arbuscular mycorrhizal fungi (AMF) and other soil microbes which enhance soil aggregation, aeration, and fertility. AMF inoculation boosts plant drought resilience and nutrient uptake (especially P, Zn, Cu), accelerating vegetation recovery for Iraqi deserts using native legumes could streamline restoration of ecologically similar areas.

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