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Review

Microbial Solutions in Agriculture: Enhancing Soil Health and Resilience Through Bio-Inoculants and Bioremediation

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Abstract

Soil microbes are important for maintaining agricultural ecosystems by promoting nutrient cycling, plant growth, and soil resilience. Microbial-based inoculants, such as bio-inoculants and bioremediation agents, have been identified as suitable means to promote soil health, reduce environmental deterioration, and achieve sustainable agriculture. Bio-inoculants, such as biofertilizers and biopesticides, promote nutrient availability, plant growth, and chemical input dependency reduction. Diverse microbial populations, especially plant growth-promoting bacteria (PGPB), enhance resistance by promoting a symbiotic association with plants and inducing natural resistance against insects. Bioremediation, the second significant microbial intervention, is the use of microorganisms for detoxifying and rehabilitating polluted soils. Methods effectively degrade organic pollutants, immobilize heavy metals, and mitigate the toxic effects of industrial and agricultural pollutants. Recent advances in microbial ecology and biotechnology, such as metagenomics, have transformed the knowledge of microbial soil communities, and tailor-made microbial formulations and monitoring equipment may be developed to maximize their activity. Though promising, environmental heterogeneity, scalability, and lack of field-based evidence constrain their widespread application. Multidimensional applications of microbial solutions in agroecology are explored in this review, with a focus on their potential in maintaining soil health, crop production, and environmental sustainability. It also addresses the application of bioremediation and microbial inoculants in agroecosystems and technological innovations with future research objectives. Microbial innovation to shape the soil microbiome offers a valid tool for addressing global challenges in agriculture, food security, and ecological resilience in the context of climate change.

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1. Introduction

The process of soil development, fertility, plant growth and development, resistance to stress, nutrient cycling, and carbon sequestration are all directly or indirectly affected by the soil microbiome [1]. Nonetheless, most knowledge regarding the soil microbiome originates from research into the surface top layers, discounting the subsurface layers or subsoils. Environmental impact, new additions of organic matter, levels of nutrients, amounts of gases and moisture, and physical properties all are affected by depth in soils [2]. These soil property changes influence the soil microbial community composition and modify the functional characteristics of microorganisms [3]. We can refine the precision of terrestrial C flow models and obtain a better perception of ecosystem function by understanding the variation in microbial processes with depth in the soil [4].

In the present review, the influence of soil health on the soil microbiome is reviewed, with a specific emphasis on disparities between the very top and the very bottom subsurface horizons. An inherent quality of soil is its health, which is a collection of attributes that determine and categorize the soil [5]. It is an external quality of soil that varies with the ways individuals intend to use it, e.g., to produce recreational goods or for wildlife sustainability, agricultural yields, or watershed conservation. Future harvests will have to be doubled through sustainable methods because of rising food demands and a lack of new agricultural land development since the population of the world is expected to grow at a fast pace [6]. Another integrated strategy that can responsibly address the intrinsic and pragmatic concerns about food production is sustainable agriculture. It develops new, environmentally friendly activities by combining ecological, chemical, physical, and biological concepts [7]. Sustainability may contribute to addressing global food agricultural demands. Crop development can be supplemented by the plant rhizosphere, the very small area of soil closest to the root system, with or even without balanced or minimized pesticide inputs. Evaluation of soil health is grounded in soil quality indicators that ensure a sustainable crop production for agricultural purposes [8].

The significance of soil biota elements, including the microbial community, abundance, diversity, activity, and stability, as soil quality indicators has been demonstrated in a few studies. Besides converting nitrogen into organic and inorganic forms and affecting the plant mineral consumption, structure, and yield, the soil biota facilitates mineralization of plant residues [9]. The basic processes that confer stability and production to agroecosystems are sustained by microbial communities. Soil microbial populations like beneficial nematodes, active bacteria, and arbuscular mycorrhizal fungus (AMF) are interrelated with the crop yield, fruit quality, water storage in the soil, and nutrient cycling for differentiating between improved plant health and fertility of the soil [10]. Organic farms contain greater microbial biomass carbon in the soil compared to conventionally farmed fields, as found in a seven-year study on vegetables and field crops [11]. In mold board ploughing under organic agriculture, the mean total earthworm population was higher than reduced tillage (297 m^{-2}) [12].

Global attention should be given to enhancing or rejuvenating soil health, and the evaluation of soil health indicators will enable us to gain a deeper understanding of the ingredients that form the basis of the systems that ensure sustainable agriculture [13]. Soil microorganisms, which can modify the soil structure and nutritional content, are adversely affected by climate change. Soil tillage, crop type, fertilizer transport, and water management are agronomic practices that alter the microclimate of agriculture and affect soil microorganisms. In agricultural environments, these practices also increase agrarian production [14]. Especially in agricultural environments, soil microorganisms play a key role in maintaining the ecological balance, promoting nutrient cycling, and supporting crop growth.

Tillage of the soil, the crop variety, transportation of fertilizer, and management of water are agronomic factors that alter agriculture's microclimate and influence agricultural soil microbes [15]. These procedures increase the agrarian yield in farm settings as well. Plant development, resistance against disease, and nutrition are promoted through bio-inoculants, which are compounds of microbes with beneficial properties increasing crop yields and soil health. They are essential to sustainable farming since they lower the use of artificial pesticides and fertilizers [16]. Legume plants and rhizobia bacteria, for example, enter symbiotic relationships that drastically lower the demand for nitrogen fertilizer by allowing nitrogen fixation. Bio-inoculants can increase the crop yield and enhance the soil structure and nutritional capacity. By enhancing the water quality and restoring the biological equilibrium, bioremediation is an environmentally sound and cost-saving approach to conventional cleanup. Microbial consortia in aquatic ecosystems break down oil spills, avoiding long-term environmental degradation and promoting marine biodiversity [17]. Bioremediation methods are increasingly being incorporated into industrial waste management programs because of their considerable reduction in pollutant levels and cleaning expenses compared to older methods [18]. Microbial solutions can revolutionize a variety of industries, spanning agricultural production, environmental cleansing, economic benefits, and sustainability over the long term, as per quantitative estimations [19]. Soil health, carbon capture, and enhanced resilience against climate change effects can be improved by farmers adopting microbially supported sustainable farming practices.

The soil microbiome refers to a sophisticated network of microbes in soils, comprising viruses, fungi, bacteria, archaea, and protozoa. Microbes are responsible for plant growth, soil fertility, nutrient cycling, and ecosystem functioning because they interact with the soil environment and among themselves [20]. Knowledge of the composition and function of the soil microbiome is vital for enhancing soil fertility, land management, and agriculture. The soil microbiome is rich in diversity, with parameters including the soil texture, water content, pH, temperature, organic matter, and vegetation influencing the soil's types of microorganisms [21]. Bacteria are the most frequent and ubiquitous microorganisms in soil, accounting for the maximum microbial biomass, with important functions like nutrient cycling, organic matter decomposition, and nitrogen fixation [22]. Fungi, archaea, and viruses also make a substantial contribution. Fungi, however, are less dominant compared to bacteria but are essential in the soil microbial community, making up most of the overall microbial biomass. Archaea play a central role in carbon and nitrogen cycling, particularly in soils with extreme characteristics such as high salinity, acidic pH values, and high temperatures. Archaea are implicated in ammonia oxidation and methanogenesis, which produce methane. Crenarchaeotes and Euryarcheotic represent some of the most prevalent phyla of archaea. Viruses are also prevalent among soil microbiomes, ranging up to 10:1 more virus particles than bacteria [23]. They can infect the bacterium and fungus, changing microbial numbers and the nutrient cycle. Protozoa and nematodes, which are two eukaryotic microbes, contribute to the soil microbiome through predation, affecting the microbial community structure and nutrient cycling.

2. Interactions Between Microorganisms and Plants in the Rhizosphere

To assist plants in receiving essential nutrients such as nitrogen, phosphate, and potassium, which are often not available due to soil limitations, rhizosphere bacteria are required [24]. Through the conversion of atmospheric nitrogen into usable ammonia, nitrogen fixation, facilitated by bacteria such as *Rhizobium* and *Frankia*, makes a nitrogen source required for growth available to the plant. Leguminous plants can gain from this process through the uptake of 50–100 kg of nitrogen per hectare per year, making the soil more fertile. The productivity of plants is enhanced when there are *Rhizobium* bacteria in the rhizosphere [25]. Phosphorus solubilization, facilitated by bacteria like *Pseudomonas* and *Bacillus*, boosts the phosphorus availability in soils where this nutrient is lacking. By producing organic acids that degrade insoluble phosphorus molecules, phosphorus-solubilizing bacteria facilitate the uptake of phosphorus by plants more efficiently. In potassium-deficient soils, in particular, rhizosphere bacteria like *Bacillus* and *Pseudomonas* facilitate the mobilization of potassium, enhancing plants' uptake of potassium.

Microorganisms present in the rhizosphere reduce disease by protecting plants from soil-borne diseases. The microbes produce antimicrobial compounds, induce systemic resistance in plants, and compete with harmful diseases for space and resources [26]. Through competition with pathogenic microorganisms for resources and space, helpful bacteria such as plant growth-promoting bacteria (PGPB) inhibit the growth and development of harmful diseases. If used on plants such as maize, wheat, and tomatoes, PGPB have the capability of reducing the incidence of diseases. PGPB also produce secondary metabolites, enzymes, and antibiotics among other antimicrobials. Fungi from the genus *Trichoderma* are capable of lowering pathogen-induced root diseases and protecting the plant against root rot diseases caused by fungi such as *Fusarium* and *Rhizoctonia* [27]. Another way in which certain rhizosphere bacteria and fungi condition the plant's immune system to respond more effectively to subsequent pathogen infections is referred to as induced systemic resistance (ISR). Quantitative studies indicate that ISR can reduce the severity of diseases such as graymold and powdery mildew in treated plants.

Through the production of vitamins, enzymes, and phytohormones, rhizosphere microorganisms, especially PGPB, play a crucial role in promoting plant growth [28]. Auxins, cytokinins, and gibberellins are some of the phytohormones that stimulate cell division, nutrient uptake, and root development. For example, indole-3-acetic acid (IAA), which is synthesized by *Azospirillum* species, increases nutrient and water uptake. In rice and maize crops, PGPB treatment can increase root biomass. Cellulases, chitinases, and phosphatases are a few enzymes that can assist in degrading organic compounds and improving nutrition availability [29]. During organic agriculture when microbial degradation makes soil nutrients accessible, it is particularly useful. Soil fertility improvement can occur with the enhancement of the decomposition of organic material by enzyme-secreting bacteria. Also, some of the rhizosphere microbes produce growth hormones and vitamins enhancing the health of plants, like folic acid and biotin, which are crucial for plant development and metabolic processes [30].

Fungi, especially arbuscular *Mycorrhizal fungi* (AMF), form symbiotic relationships with the roots of plants [31]. Some instances of the taxonomy of the AMF are *Amanita*, *Boletus*, and *Russula*, whereas *Glomus* is a well-known genus [32]. Orchid *Mycorrhizal fungi* are members of the *Rhizoctonia* genus, while ericoid *Mycorrhizal fungi* are members of the *Helotiales* genus [33]. This interaction has several outcomes. By extending fungal networks of hyphae over the soil around them, these microorganisms enable plants to take up minerals, especially phosphorus. The plant supplies the fungus with carbohydrates produced through photosynthesis and nutrient transfer by providing a greater surface area for nutrient uptake [34]. AMF allows plants to take up micronutrients such as copper and zinc as well as phosphorus, which otherwise are hard to obtain [35]. In several crop varieties, it is estimated that AMF enhances phosphorus uptake [36]. AMF also improves water and nitrogen uptake, which makes plants drought-resistant. Studies have shown that AMF symbiotic plants are more resistant to drought, with some crops showing increases in production when under water stress. The hyphal networks formed by AMF also contribute to soil aggregation, which improves the soil structure. Plant growth is facilitated by this aggregation, which boosts air penetration and water retention. AMF-inoculated soil aggregates are believed to enhance soil porosity, which will facilitate root development and soil aeration [37].

Beneficial fungi, bacteria, and other microbes are types of microbial inoculants increasingly widely recognized as a critical component of sustainable agriculture [38]. Soil, seeds, or crops are sprayed with these beneficial microbes to enhance soil fertility, promote plant growth, prevent disease, and enhance overall crop yield. With the growing demand for environmentally friendly farming methods that reduce chemical application, microbial inoculants offer an alternative that assists farmers in soil management, increasing yields and reducing the environmental impact [39]. The effectiveness of microbial inoculants, particularly when quantitatively measured, highlights their significance as an essential part of modern farming methods.

3. Roles and Benefits of Microbial Inoculants

3.1. Enhanced Nutrient Availability

Under less-nutrient-rich soils, where plant growth is often limited by the supply of essential elements such as nitrogen and phosphorus, microbial inoculants are beneficial in enhancing the availability of nutrients. *Rhizobium* and *Azospirillum* bacteria form symbiotic relationships with legumes, fixing nitrogen from the atmosphere and converting it into ammonium, which can be utilized by plants [40]. Moreover, they reduce the dependence on synthetic nitrogen fertilizers, which reduce costs and are environmentally friendly. Microorganisms that produce organic acids, including *Pseudomonas*, *Bacillus*, and *Penicillium*, solubilize phosphorus and make it available to plants [41]. Phosphorus-solubilizing bacteria in phosphorus-deficient soils can increase phosphorus availability, which can boost the crop yield. By releasing potassium from the insoluble minerals in the soil, microbial inoculants are capable of mobilizing potassium, yet another nutrient for plants. Through research, potassium-solubilizing microbes can enhance uptake in plants such as rice and maize up to the maximum level.

3.1.1. Nitrogen Fixation (Symbiotic and Free-Living)

In symbiotic relationships with legumes and non-leguminous plants, respectively, various bacteria, primarily *Rhizobium* and *Azospirillum*, convert atmospheric nitrogen (N_2) into ammonia (NH_3) or other forms that can be readily used by plants [42]. Because nitrogen is often the most limiting factor in soils, nitrogen fixing is a critical process. In agriculture, where there is excessive consumption of artificial nitrogen fertilizers and resultant adverse effects on the environment, such as acidification of soils and greenhouse gases, this becomes very crucial. *Rhizobium* bacteria induce the formation of nodules in legume root cells like peas and soybeans [43]. The bacteria in the nodules convert nitrogen in the atmosphere to ammonium ions, which are later absorbed by plants to develop proteins, amino acids, and other essential plant constituents. *Azospirillum* attaches itself to grasses like wheat and maize, fixing nitrogen in the rhizosphere, particularly in places where nitrogen is limited. *Rhizobium* inoculation can increase nitrogen fixation the most, which increases legume crop yields [44]. In nitrogen-deficient conditions, *Azospirillum* inoculation can increase the nitrogen uptake, boosting the plant biomass and favoring healthier development.

3.1.2. Phosphorus Solubilization

Phosphorus is often present in soils in forms that are unavailable to plants, particularly as insoluble phosphates. Microbial inoculants, particularly phosphorus-solubilizing bacteria (PSB) such as *Bacillus* and *Pseudomonas*, secrete organic acids, phosphatases, and other metabolites that hydrolyze these insoluble phosphorus compounds into plant-available forms [45]. Through the release of protons (H^+) or organic acids into the soil, these bacteria facilitate the breakdown of the bonds that phosphorus shares with other minerals, thus making it better available to the roots of plants. Phosphate ions are liberated when organic phosphorus molecules are hydrolyzed by the enzymatic synthesis of phosphatases. Under phosphorus-deficient conditions, use of phosphorus-solubilizing bacteria can increase the availability of phosphorus, and in many cases, this leads to an increase in crop yield [46]. These bacteria, through the conversion of bound phosphorus into a bioavailable form, could raise the phosphorus uptake in soils with high phosphorus.

3.1.3. Potassium Mobilization

Even though potassium is required for plant growth and health, it often occurs in soil in an insoluble state unavailable to plants. Through the formation of organic acids and other metabolites, some microbial inoculants, e.g., *Bacillus* and *Pseudomonas*, can make potassium soluble by mobilizing potassium from soil minerals and enhancing plant availability [47]. By dissolving insoluble potassium salts or potassium-bearing minerals in the soil, these microorganisms increase the amount of potassium that is available. In potassium-deficient soils, the application of microorganisms that solubilize potassium can increase absorption. Compared to non-inoculated plants, potassium solubilization can lead to the maximum increase in growth and yield in certain crops, like rice and maize [48].

Microbial inoculants not only enhance the pool of nutrients but also induce plant growth directly via the synthesis of growth-regulating substances like vitamins, enzymes, and phytohormones (auxins, cytokinins, and gibberellins).

3.2. Phytohormone Production

Auxins, cytokinins, and gibberellins are some of the plant growth hormones that are synthesized by many beneficial microorganisms, particularly PGPB, which act to directly stimulate growth in plants by influencing root initiation, cell division, and plant metabolism [49,50]. By promoting elongation and branching in roots, auxins such as indole-3-acetic acid (IAA) enhance a plant's ability to gain water and nutrients from the soil. Cytokinins induce faster plant growth by encouraging cell division and shoot development. Gibberellins facilitate stem elongation and overall plant growth by facilitating seed germination and growth. Auxin-producing PGPB inoculation has the potential to enhance the nutrient uptake to the maximum and raise the root biomass in crops such as rice, maize, and wheat [51]. Efficiency in nutrient uptake is increased by root surface area expansion, especially in conditions of stress such as drought. Auxins, which are synthesized by some bacteria like *Azospirillum*, *Bacillus*, and *Pseudomonas*, stimulate elongation and branching of roots, enhancing the uptake of water and nutrients [52]. Based on reviews, the application of these microbes can increase root biomass, enhancing plant growth and stress resistance. In addition, rhizosphere microorganisms produce gibberellins and cytokinins that stimulate cell division and shoot elongation, which further enhances plant growth.

3.3. Vitamin and Enzyme Production

Beneficial microbes also produce vitamins, including B vitamins, and enzymes that enhance plant metabolism. For instance, *Bacillus* species can synthesize folic acid and biotin, both of which are required for plant growth [53]. Soil fertility is also enhanced with enzymes such as cellulases and phosphatases, which degrade organic matter and make nutrients available for absorption into plants. Especially in cases where nutrients are scarce, the collective effect of these compounds can promote the overall health and energy of plants.

3.4. Disease Suppression and Plant Health

The management of plant diseases caused by soil-borne pathogens necessitates the application of microbial inoculants via antibiosis, systemic resistance elicitation, and competitive exclusion, they can restrain infections via competitive exclusion in crops such as tomatoes, potatoes, and wheat, meaning root rot, blight, and wilting diseases decrease [54]. This happens as beneficial fungi and bacteria block the space and nutrient occupation required by pathogens for development in the rhizosphere. In plants such as beans and cucumbers, antimicrobial production, e.g., *Trichoderma* spp., suppresses the root disease severity by inhibiting the development of soil-borne fungal infections [55]. Certain rhizobacteria, e.g., *Bacillus* and *Pseudomonas*, induce systemic resistance (ISR), which conditions plants' immune systems to resist infections. This form of resistance offers an environmentally friendly alternative to chemical pesticides and fungicides. Microbial inoculants can contribute to the suppression of soil-borne diseases through several processes. Pathogenic organisms have less chance to become established in the rhizosphere when helpful microorganisms such as *Bacillus* and *Pseudomonas* compete with pathogenic germs for resources and space [56]. Antimicrobial metabolites such as antibiotics and antifungal compounds are produced by the most beneficial bacteria, particularly *Trichoderma* species, and directly inhibit the development of pathogens. Some bacteria present in the rhizosphere induce plants to acquire systemic resistance, which conditions their immune systems to combat infection. The ability of the plant to resist many diseases is enhanced through this resistance. *Trichoderma* inoculation enhances plant health and yield by reducing the intensity of fungal infections such as root rot [57]. It has been proven that PGPB inoculants are able to reduce the incidence of damping-off diseases in vegetables such as tomatoes and cucumbers. *Bacillus* species can reduce the severity of disease, particularly in the case of bacterial and fungal diseases such as powdery mildew and fusarium wilt.

3.5. Soil Health and Structural Improvement

Through the stimulation of soil aggregation, enhancement of organic matter decomposition, and augmentation of soil diversity, microbial inoculants can enhance soil health and structure. *Mycorrhizal fungi*, for example, can enhance soil aggregation, enhancing porosity, infiltration of water, and root penetration, thereby diminishing the susceptibility to soil erosion and enhancing the water retention capacity, in turn enhancing plant growth [58]. Microbial inoculants also hasten the decomposition of organic residues, liberating nutrients that enhance soil fertility; cellulolytic bacteria can accelerate crop residue decomposition, enhancing soil health; and favorable microorganisms can enhance soil microbial diversity, facilitating a healthier and more stable soil ecosystem [59]. Complex microbial communities can adapt more readily to environmental change, resist disease outbreaks, and maintain soil fertility in the long term. This process, by facilitating the decomposition of organic matter, enhancing soil aggregation, and enhancing soil aeration and water-holding capacity, means microbial inoculants have the potential to enhance the structure and health of the soil. Soil aggregation extracellular polysaccharides from *Mycorrhizal fungi* and certain bacteria, including *Bacillus*, act to bind soil particles and form stable aggregates [60]. This reduces soil erosion, enhances water infiltration, and increases soil strength. Organic matter decomposition crop residues and other organic materials are decomposed into simple chemicals by microbes such as cellulolytic bacteria, which supply nutrients to the soil. More tolerant ecosystems, equipped to withstand environmental stress factors such as drought or disease, can be facilitated through enhanced microbial diversity in the soil, which is achieved by incorporating beneficial microbes [61]. Under arid conditions, *Mycorrhizal fungi* may enhance soil aggregation, enhancing root growth and water infiltration. Cellulolytic bacterial inoculation would enhance organic matter decomposition, enhancing soil fertility and speeding up nutrient cycling.

3.6. Stress Tolerance Enhancement

Microbial inoculants help plants to counteract a variety of environmental stresses, including salt, drought, and extreme temperatures. Many PGPB produce compounds such as osmo protectants, which help in the regulation of osmotic stress in plants or trigger the defense mechanisms of a plant itself [62]. Microbes produce osmo protectants, including proline and trehalose, which protect plant cells from dehydration during periods of excessive salt or drought. Microbial interactions yield heat shock proteins (HSPs) to enable plants to cope with temperature fluctuations and excessive heat stress. PGPB inoculation can enhance drought tolerance among crops, enabling them to survive prolonged water scarcity conditions [63]. Microbial inoculants have been shown to enhance the yield and water-use efficiency in salt-stressed crops through the mitigation of salinity effects on growth.

4. Types of Microbial Inoculants

Different types of microbial inoculants can be distinguished based on their composition and intended application. The following are the main categories of microbial inoculants (Table 1; Supplementary Table S1).

Table 1. Microbial inoculants' impact on agriculture, including their effects on nutrient availability, plant growth, disease suppression, and soil health.

Microbial Inoculum	Effect	Details of Effects	References
Rhizobium Nitrogen-Fixing Bacteria	Nitrogen fixation in legumes	Increase nitrogen fixation and crop yields	[64]
Azospirillum Nitrogen-Fixing Bacteria	Nitrogen fixation and plant growth	Increase nitrogen uptake and enhance root biomass	[65]
Pseudomonas (PGPB)	Phosphorus solubilization and plant growth	Increase phosphorus availability and yield	[66]
Bacillus (PGPB)	Phytohormone production and growth promotion	Increase root biomass and improve nutrient uptake	[67]
Trichoderma Fungal Inoculant	Disease suppression and growth promotion	Reduce root rot and other diseases by enhancing growth in stress conditions	[68]
Mycorrhizal fungi (AMF)	Phosphorus uptake and soil structure	Increase phosphorus uptake and improve soil aggregation	[69]
Bacillus (PGPB)	Disease suppression via ISR	Reduce disease severity and enhance resistance to fungal and bacterial diseases	[70]
Cellulolytic Bacteria	Organic matter decomposition	Accelerate decomposition and improve nutrient cycling and soil fertility	[71]
Potassium-Solubilizing Microbes	Potassium mobilization	Increase potassium uptake in potassium-deficient soils	[72]
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Potassium-Solubilizing Microbes	Potassium mobilization	Increase potassium uptake in potassium-deficient soils	[72]

5. Microbial Bioremediation: Restoring Soil Health

5.1. Degradation of Organic Pollutants

A very common bioremediation process is the degradation of organic pollutants, such as hydrocarbons, insecticides, and solvents. Enzymes in microorganisms such as bacteria, fungi, and actinomycetes can break down large organic molecules into simpler, less toxic forms. This can occur either aerobically (with oxygen) or anaerobically (without oxygen) depending on the contaminant and microbial species [73]. When organic pollutants such as petroleum hydrocarbons are aerobically degraded, oxygen is typically employed to oxidize the pollutants and convert them into water and carbon dioxide (CO_2). Reductive dichlorination is employed by specialized bacteria to degrade organic pollutants such as chlorinated solvents in anaerobic conditions, often producing non-toxic end products such as ethene. Quantitative data confirm the efficacy of bioremediation in the degradation of organic pollutants. For example, it has been reported that fungi such as *Phanerochaete chrysosporium* can degrade man-made colors and pesticides in contaminated soils [74], and that bacteria such as *Pseudomonas putida* and *Mycobacterium* species can degrade petroleum hydrocarbons within weeks [75]. By stimulating natural microbial activities to eliminate toxins from the environment, bioremediation not only reduces the toxicity of pollutants but can also potentially heal ecosystems [76].

5.2. Detoxification of Heavy Metals Through Biosorption and Bioaccumulation

Since heavy metals are environmentally persistent and toxic to living organisms, there is increasing concern about heavy metal contamination. The two major operations carried out under heavy metal bioremediation are biosorption and bioaccumulation. However, many other mechanisms of detoxification are possible in a microbial cell (Figure 1; Supplementary Table S2). The procedure by which bacteria and fungi adsorb metal ions on their cell wall or extracellular material is referred to as biosorption [77]. This process is often a passive accumulation process and does not require the bacteria to metabolize the metals. Bioaccumulation, in contrast, is where the heavy metals are actively taken in and concentrated inside microbial cells. Some species of *Bacillus* and *Pseudomonas* can bioaccumulate lead (Pb), cadmium (Cd), and mercury (Hg) from contaminated environments, storing them in non-toxic forms [78]. These transformations play a crucial role in microbial detoxification and bioremediation strategies. For example, mercury can be enzymatically reduced to elemental mercury, which is volatile and less reactive, or it can be precipitated as mercuric sulfide, an insoluble and stable compound. Cadmium may be sequestered intracellularly through binding with metallothionein, like proteins, or precipitated as cadmium phosphate, reducing its mobility and toxicity [78]. Similarly, lead can be immobilized through the formation of insoluble compounds, such as lead phosphate or lead sulfide. These biochemical conversions as highlighted in the review by Alotaibi et al., 2021, along with the functional versatility of these microbial genera in mitigating heavy metal contamination through bioinformation and bioaccumulation mechanisms [78]. Heavy metal amounts in polluted zones may be significantly reduced thanks to the ability of microorganisms to accumulate and detoxify them. For instance, it has been shown that *Sphingomonas* species can bioaccumulate as much as or at higher levels than chromium in industrial effluent, while *Pseudomonas putida* could accumulate as much dry weight as copper ions in contaminated water [79]. The concentration of heavy metals in contaminated areas is, at times, brought down by maximally using such microbes in the process of bioremediation, making the environment healthier for both flora and fauna.

5.3. Transformation of Persistent Organic Pollutants (POPs)

Toxic chemicals referred to as persistent organic pollutants (POPs) tend to accumulate in living organisms, are resistant to breakdown in the environment, and cause severe health risks [80]. Polychlorinated biphenyls (PCBs), dioxins, and pesticides like DDT are some examples of POPs. Microorganisms with the ability to change the chemical structure of POPs can modify them via bioremediation, reducing their toxicity and enhancing their biodegradability [80]. The stable, complex structures of POPs can be degraded into less toxic intermediates by enzymatic reactions called biotransformation, which is a function of certain bacteria and fungi. Reductive dichlorination, which converts chlorinated compounds such as PCBs and DDT into less chlorinated or non-chlorinated products, is another reaction that bacteria can sometimes carry out [81]. *Bacillus* and *Mycobacterium* species have been used to break down organochlorine pesticides, including DDT, in contaminated soils, whereas *Dehalococcoides* species have been shown to dechlorinate as much as PCB congeners in contaminated sediments [82]. Such types of bioremediation methods help reduce the long-term impacts of POPs on ecosystems and human health as well as reduce their persistence in the environment.

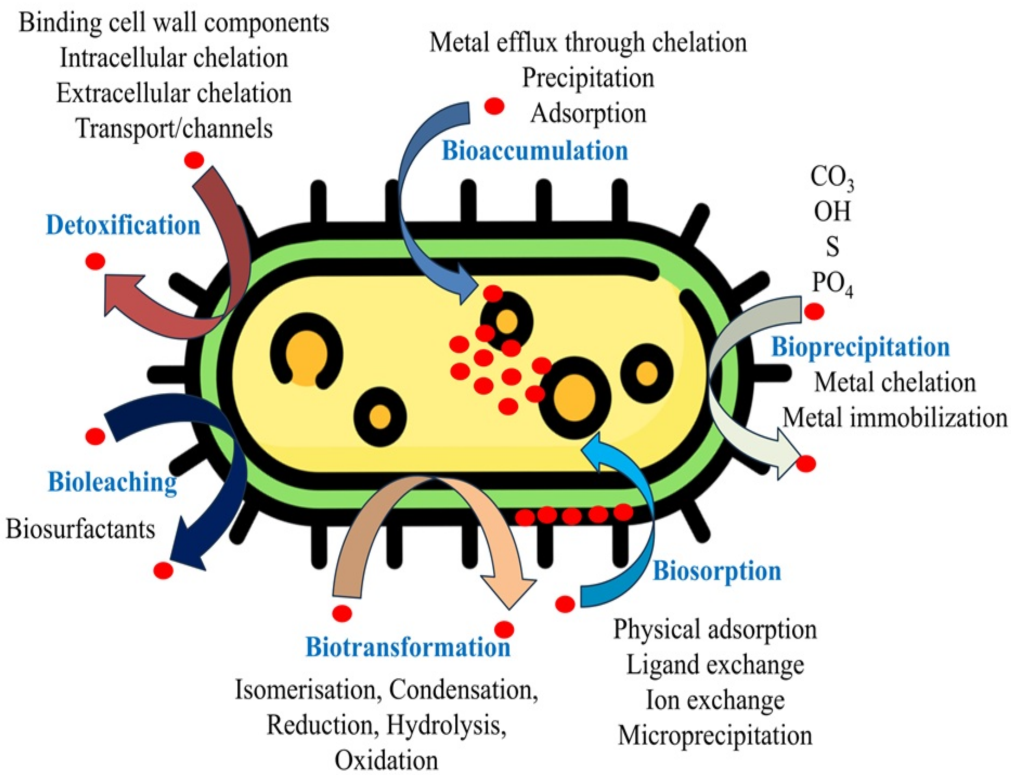

Figure 1. Heavy metal detoxification mechanisms by a bacterial cell (Supplementary Table S2).

6. Applications for Bioremediation in Agricultural Soils

6.1. Cleaning up Pesticide-Contaminated Soils

Though essential for crop pest management, the application of pesticides in agriculture often leads to the contamination of water and soil resources. Pesticides such as organochlorines (e.g., DDT), organophosphates, and carbamates are examples that can persist for many years in the soil, causing damage to soil microorganisms, reducing biodiversity, and affecting the crop yield [83]. Through the action of microorganisms that can degrade or transform pesticides into harmless byproducts, bioremediation offers a sustainable method for remediating pesticide-polluted soils. Microbial species such as *Pseudomonas*, *Bacillus*, and *Rhodococcus* are known to metabolize a wide range of pesticides by dissolving their complex chemical structures [84]. The microorganisms dechlorinate or hydrolyze pesticides, reducing their toxicity, through the action of enzymes such as esterases and dehalogenases. For instance, *Pseudomonas putida* can significantly reduce the concentration of organophosphate pesticides in the soil by degrading them within a few weeks [85]. Apart from detoxifying the toxins, bioremediation restores the microbiome of the soil, providing an environment that is more conducive to microbial diversity and plant growth (Table 2).

Table 2. Microbiomes and their functions and details.

Microbiomes	Functions/Details	References
Microbial Biomass	Soil contains between 10^7 and 10^9 microbial cells per gram of soil.	[86]
Bacterial Biomass	Bacteria make up most of the total microbial biomass in the soil.	[87]
Fungal Biomass	Microbial biomass.	[88]
Bacterial Phyla	Proteobacteria: Dominant in nutrient cycling and organic matter degradation. Firmicutes: Important for breaking down complex organic molecules. Actinobacteria: Significant in organic matter decomposition and antibiotic production. Acidobacteria: Key players in acidic soil environment and nutrient cycling. Bacteroidetes: Degrade complex organic compounds.	[89]
Fungal Phyla	Ascomycota: Important in decomposing plant material. Basidiomycota: Key in forming mycorrhizal associations and decaying complex materials. Zygomycota: Important for nutrient cycling and plant symbiosis.	[90]
Archaea	Archaea represent a smaller portion but are critical in methanogenesis and ammonia oxidation.	[91]
Viruses in Soil	Viruses can outnumber bacteria by a ratio of 10:1 and regulate microbial diversity.	[92]
Protozoa and Nematodes	Protozoa and nematodes are important predators of soil bacteria and fungi.	[93]
Microbial Contributions to Soil Health and Nutrient Cycling		
Microbial Role in Nitrogen Fixation	Nitrogen fixation bacteria, e.g., *Rhizobium*, *Frankia*, contribute most of total nitrogen input.	[94]
Organic Matter Decomposition Rate	Microbial decomposition rates in temperate soils.	[95]
Soil Carbon Storage	Total soil organic carbon.	[96]
Phosphorus Cycling	Phosphorus-solubilizing bacteria, e.g., *Pseudomonas*, help convert insoluble phosphorus into bioavailable forms.	[97]
Soil Aggregate Formation	Fungi produce extracellular polysaccharides to bind soil particles, improving soil aggregation.	[98]
Soil Disease Suppression	Beneficial microbes can produce antibiotics or enzymes that suppress soil-borne pathogens.	[99]
Plant Growth Promotion	Plant growth-promoting bacteria (PGPB) produce phytochromes, e.g., auxins, cytokinins, that enhance root growth.	[100]

6.2. Managing Industrial Effluents and Wastewater in Agroecosystems

Wastewater and toxic effluents are often discharged into the environment due to industrial activities, destroying nearby agricultural lands [101,102]. Heavy metals, oils, organic solvents, and other toxic substances that could harm plants and lower the soil quality could be contained in these effluents [103]. By utilizing microorganisms that could either degrade or immobilize the pollutants, bioremediation provides an effective means of managing such pollutants, minimizing their toxicity. Petroleum hydrocarbons, for example, can be degraded into simpler non-toxic compounds by hydrocarbon-degrading bacteria and fungi that act on hydrocarbon components of industrial waste [104,105]. Additionally, through a process such as biosorption and bioaccumulation, bacteria such as *Bacillus* and *Pseudomonas* efficiently remove heavy metals such as lead, mercury, and cadmium from polluted water and soil. Aside from sanitizing the effluents, microorganisms decrease the bioavailability of toxic metals so that plants and animals cannot take them up. Biological ecosystems in agriculture can benefit from reduced levels of chemical pollution by using bioremediation methods, which will lead to better soil and increased crop production [106].

6.3. Role in Reducing Greenhouse Gas Emissions

Methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) are the primary greenhouse gases (GHGs) emitted by the agricultural sector [107]. Rice paddies emit methane, but waste management and commercial fertilizers emit nitrous oxide. By increasing microbial processes that either oxidize or reduce GHGs, bioremediation can be instrumental in reducing these emissions. Denitrifying soil nitrates to nitrogen gas (N_2) in anaerobic conditions, for instance, certain soil microbes, including denitrifying bacteria, can effectively limit the release of this potent greenhouse gas [108]. Methane release in rice paddies may also be limited by using bioremediation methods involving methanotrophic bacteria, which utilize methane as a source of energy. Second, enhancing soil organic matter by adding organic amendments (e.g., compost) will stimulate carbon-sequestering microbial communities, decreasing atmospheric CO_2 levels [109]. As well as reducing GHG emissions, these microbial applications increase crop yields, fertility, and soil health.

6.4. Integration of Microbial Solutions into Agroecosystems

Agroecosystem incorporation of microbial solutions presents an integrated strategy to achieve profitable and sustainable agricultural practices [110]. Farmers may enhance crop growth, reduce environmental contamination, and enhance soil integrity by integrating bio-inoculants and bioremediation strategies. Apart from mitigating prevailing problems such as insect infestations, soil contamination, and nutrient shortages, this integrated strategy towards soil management enhances ecological sustainability in the long term [111].

6.5. Combining Bio-Inoculants and Bioremediation for Holistic Soil Management

There is substantial potential for enhancing soil fertility and productivity by using the dual approach of bio-inoculants and bioremediation. *Mycorrhizal fungi*, nitrogen-fixing bacteria, and plant-growth-promoting rhizobacteria are some examples of bio-inoculants that could promote the growth of plants, enhance nutrient uptake, and reduce the requirement for synthetic fertilizers [112]. But bioremediation techniques can eliminate toxins from the soil and re-establish its microbial equilibrium through the application of microorganisms to detoxify heavy metals and degrade organic pollutants. Practically, this could be achieved through the application of fungi such as Trichoderma, which degrades pesticide residues in polluted soils, in combination with *Rhizobium* or *Azospirillum* for nitrogen fixation, which can enhance soil fertility [113], promote healthier plant growth, and minimize the environmental impact of agricultural practices. When these two approaches are combined, they create a synergistic effect that not only stimulates plant growth but also purifies the soil of toxic chemicals, minimizes nutrient leaching, and revives the microbial ecosystem.

6.6. Strategies for Incorporating Microbial Products into Integrated Pest and Nutrient Management Systems

Through the successful integration of microbial solutions into nutrient management and integrated pest management (IPM) systems, agroecosystem issues can be handled in a sustainable way. Microbial products such as biopesticides *Bacillus thuringiensis*, *Beauveria bassiana*, and *Trichoderma* spp. represent a natural alternative to traditional pesticides in integrated pest control [114,115]. Without posing a threat to the ecosystem or beneficial organisms in the soil, these microbial bioagents eradicate or inhibit pest and disease development. For example, *Trichoderma* species are very effective in controlling fungal diseases in the soil, while *Bacillus thuringiensis* is widely used to control insect pests like caterpillars. These microbial biopesticides reduce the use of traditional pesticides, which can adversely affect biodiversity, soil quality, and human health [116]. Microbial inoculants play a significant role in enhancing the availability of essential nutrients such as potassium, phosphorus, and nitrogen in nutrient supply systems. Fertilization programs may utilize microorganisms that fix nitrogen such as *Rhizobium* and *Azotobacter* or phosphorus solubilizers such as *Pseudomonas* and *Bacillus* species to reduce nutrient runoff into adjacent ecosystems and reduce the need for chemical fertilizers [117–119]. These microbial metabolites help promote the sustainability of agroecosystems through enhanced soil aggregation, decomposition of organic matter, and water absorption as well as providing nutrition to plants.

6.7. Synergistic Effects of Diverse Microbial Communities over Single Strains

The synergistic effect that multiple strains can exert on the use of a single microbial strain is one of the primary benefits of adding various microbial communities to agroecosystems. While individual microbial species may offer specific benefits, e.g., disease control or nitrogen fixation, a diverse community of microorganisms can serve the environment more generally and strongly [120]. Collectively, these communities perform numerous functions that enhance the balance and functionality of the agroecosystem, including nutrient cycling, organic matter decomposition, disease suppression, and soil structural development. Applying a mixed inoculant that harbors both *Mycorrhizal fungi* and nitrogen-fixing bacteria might be more effective than the application of each organism separately [121]. The *Mycorrhizal fungi* enhance the water uptake and nutrient acquisition, especially phosphorus, and the nitrogen-fixing bacteria enhance the pool of available nitrogen. Bacteria also aid in maintaining ecosystem stability by protecting each other from abiotic stresses such as drought or temperature fluctuations. By stimulating competition among beneficial microorganisms and harmful pathogens, the combination of diverse microbial species further enhances disease suppression [122]. Soil diversity, plant resistance against pests and diseases, and total agricultural production may all be enhanced by richly diverse microbial populations.

7. Advances in Soil Microbiome Research and Technology

7.1. Metagenomics and Microbial Ecology

Metagenomics is transforming our comprehension of microbial diversity and the community composition, especially for soil communities. Metagenomics examines genetic material directly from environmental samples, which enables scientists to obtain a broad picture of microbial communities without the necessity of cultivating microorganisms [123]. Metagenomics enables the development of novel microbial inoculants by providing comprehensive insights into the diversity, structure, and functional potential of soil and rhizosphere microbiomes without the need for cultivation. Through high-throughput sequencing, it identifies genes responsible for beneficial plant traits such as nitrogen fixation, phosphate solubilization, hormone production, and stress tolerance. This allows researchers to discover unculturable or previously unknown microbial taxa and assess their functional roles, making it possible to select, design, or engineer microbial consortia with synergistic capabilities tailored to specific crops or environments. Consequentially, metagenomics facilities the formulation of targeted efficient and sustainable biofertilizers and soil inoculants that enhance the plant growth nutrient uptake and resilience to stress. Metagenomic analysis detects intricate interactions that form microbial communities, including bacteria, viruses, fungus, archaea, and protists. It also reveals the functional potential of such communities by discovering genes that are responsible for vital processes such as nutrient cycling, disease suppression, and plant growth promotion. The most fascinating use of metagenomics in microbial ecology is the identification of functional genes with possible agricultural uses [124]. Such genes, involved in nitrogen fixation, phosphate solubilization, and hormone production, can be utilized to enhance sustainable agriculture (Table 3). Metagenomics also holds the potential to create bio-based fertilizers and soil inoculants to allow microorganisms to exert beneficial processes. Discovery of stress tolerance or disease resistance genes in plants would result in more resilient crops, which would mitigate the environmental effects of traditional agriculture [125].

Table 3. Genes involved in nitrogen fixation, phosphate solubilization, and plant hormone production.

Gene	Full Name	Function	Notes	References
Nitrogen fixation genes				
nifH	Nitrogenase iron protein gene	Encodes dinitrogenase reductase, essential for nitrogen fixation	Common marker gene for diazotrophs (N_2-fixing bacteria); widely used in metagenomic studies	[126–128]
nifD	Nitrogenase alpha subunit gene	Encodes one of the catalytic components of nitrogenase	Works with *nifK* to form dinitrogenase	[129–131]
nifK	Nitrogenase beta subunit gene	Encodes another catalytic subunit of nitrogenase	Required for the full nitrogenase complex function	[130,132,133]
nifA	Nitrogen fixation regulatory protein A	Activates transcription of nitrogen fixation genes	Regulates *nif* gene cluster expression under low nitrogen	[134–136]
nifL	Nitrogen fixation regulatory protein L	Acts as a negative regulator of *nif* genes in the presence of oxygen or ammonia	Balances nitrogen fixation activity with environmental conditions	[134,137]
Phosphate solubilization genes				
gcd	Glucose dehydrogenase gene	Oxidizes glucose to gluconic acid	Gluconic acid solubilizes insoluble phosphates in the soil	[138–140]
phyA/appA	Phytase genes	Hydrolyze phytic acid to release inorganic phosphate	Important in mobilizing organic phosphorus	[141–143]
phoA	Alkaline phosphatase gene	Hydrolyzes organic phosphates under alkaline conditions	Enhances phosphate availability	[144–146]
phoD	Alkaline phosphatase D gene	Another alkaline phosphatase with high activity in soils	Frequently found in plant rhizospheres; good marker for phosphorus cycling potential	[147–149]
Hormone production genes				
ipdC	Indole-3-pyruvate decarboxylase gene	Catalyzes conversion of indole-3-pyruvate to indole-3-acetaldehyde in IAA biosynthesis	Key gene in the tryptophan-dependent IAA pathway in PGPR	[150–152]
iaaM	Tryptophan monooxygenase gene	Converts tryptophan to indole-3-acetamide	Part of the IAM (indole-3-acetamide) pathway in IAA synthesis	[153–155]
iaaH	Indole-3-acetamide hydrolase gene	Converts indole-3-acetamide to IAA	Works in tandem with *iaaM*	[153,156,157]
amiE	Amidase gene	Involved in auxin (IAA) biosynthesis	Associated with tryptophan metabolism	[158–161]
Ipt	Isopentenyl transferase gene	Involved in cytokinin biosynthesis	Catalyzes the first step in cytokinin formation; often found in endophytes	[162–164]
cps	Copalyl diphosphate synthase gene	Involved in gibberellin biosynthesis	Key enzyme in diterpenoid hormone production like GA	[165–167]
ks	ent-Kaurene synthase gene	Converts CPP to ent-kaurene, a GA precursor	Works with cps in GA biosynthetic pathway	[165,168]
ga20ox	Gibberellin 20-oxidase gene	Catalyzes formation of bioactive gibberellins	Important for growth regulation	[169–171]
acdS	1-Aminocyclopropane-1-carboxylate deaminase gene	Breaks down ACC, a precursor to ethylene	Reduces stress ethylene in plants, promoting root elongation and stress tolerance	[172–174]

7.2. Biotechnology in Microbial Product Development

Biotechnology has played a major role in the production of microbial products, most importantly stress-resistant strains and efficient delivery systems for microbial inoculants [175]. Genetic engineering techniques can increase microbial strains' tolerance to environmental stresses such as drought, salt, high temperatures, and changes in soil pH. Modified microorganisms can improve sustainable agricultural practices by reducing the negative effects on plant growth. Stress-tolerant strains of *Rhizobium* or *Azotobacter* have been bred to enhance nitrogen fixation in nutrient-poor soils [176]. To ensure the efficacy of these biotechnologically modified microorganisms, innovative formulation and delivery systems for microbial inoculants must be formulated in parallel. Traditional microbial inoculants tend to lack viability, shelf life, and soil environment establishment. Biotechnological advancements are directed towards encapsulating microbial strains within protective vehicles such as hydrogels, nanoparticles, or bio-based matrices [177]. Controlled-release methods are also in progress to facilitate effective delivery to the root zone. Such biotechnological advances are developing more robust and potent microbial products that are poised to substantially influence sustainable agriculture.

7.3. Monitoring and Assessment Tools

Monitoring and evaluation tools are essential for establishing soil health and microbial activity. Biomarkers and molecular tools, including qPCR, metagenomics, and DNA/RNA sequencing, are the leaders in this area [178]. These methods precisely detect and measure microbial abundance and functional genes and yield excellent information on microbial diversity, community composition, and potential functions. Biomarkers are molecules or genes that indicate microbial activity, health, and ecosystem functioning [179]. For example, particular functional genes such as nitrogenase or phosphatase genes are suitable as microbial activity biomarkers of essential processes in soil fertility and plant growth. The technology further enables microbial activity monitoring using gene expression assessment, meta transcriptomics, and enzymatic activity meta proteomics [180]. Molecular biosensors and probes are being created to detect microbial activities or species linked to the health of soil so that farmers and soil scientists can quickly diagnose. These new monitoring techniques can inform the creation of targeted plans for enhancing soil health and sustainability.

8. Challenges and Future Perspectives

Soil–microbe–plant interaction agriculture is confronted with various challenges because of an unawareness of the complex interactions between soil, microbes, plants, and the environment [181]. The specific mechanisms of these processes are under study, and the success of microbial treatments is soil- and crop-dependent locally. Standard protocols for applying and validating microbial treatments are another serious challenge. The scalability of microbial solutions to large-scale agricultural systems is still challenging owing to aspects like microbial viability upon storage, inconsistent performance between different environments, and variability in microbial product compositions [182]. Lack of proper regulations and lengthy approval procedures might discourage farmers from embracing microbial solutions. There is a need for interdisciplinary research to create more resilient, scalable, and locally applicable microbial products. Socioeconomic determinants must be taken into consideration, as knowledge of farmer conduct, economic viability, and effects of microbial solutions on yields and profitability is key to their uptake at the large scale [183]. Policy support for regulation and marketing of microbial products is required, with governments and intergovernmental organizations developing policies in favor of research and development on microbial biotechnology, offering fiscal incentives for eco-friendly agriculture operations, and putting regulations in place for the proper use of microbial inoculants in the field [184]. Microbial solutions have strong potential in climate-smart agriculture because they could counteract climate change-induced increases in droughts, floods, and temperature extremes. Nitrogen-fixing or phosphorus-solubilizing soil bacteria could minimize the use of chemical fertilizers, and drought-tolerant microbial isolates could enhance water-use efficiency in arid areas [185]. Soil microbes have the potential to mitigate climate change through carbon sequestration mechanisms. Regulatory frameworks and policy support are essential to streamline approval processes for microbial solutions, ensuring their safe and effective implementation in large-scale agriculture and production. Additionally, addressing stakeholder concerns, including farmer adoption and economic viability, will be key to accelerating the use of microbial innovations in sustainable farming.

9. Conclusions

Microbial technologies can enhance soil health and decrease the dependency on chemical fertilizers. Soil fertility can be increased by adding beneficial microbes such as *Mycorrhizal fungi*, phosphorus-solubilizing bacteria, and nitrogen-fixing bacteria, raising yields. Bio-inoculants can also elevate stress tolerance towards salinity and drought, while drought-resistant varieties can improve the efficiency of water use. Bacteria in soil have an important role to play in bioremediation, decontaminating toxins such as pesticides, heavy metals, and petroleum hydrocarbons, enriching the quality of soil, and lessening pollution. Certain bacteria have the capability of producing the maximum breakdown of residues from pesticides in polluted soils in weeks. Microbial solutions assist in the establishment of stable organic carbon in soils, which enriches the soil structure and water storage capacity. Yet, there are obstacles like standard application routes and a microbial efficiency difference that must be overcome prior to extensive application. Microbial solutions should become a central pillar of sustainable agricultural practices, as agriculture shifts towards more climate-responsible strategies.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/bacteria4030028/s1, Table S1: Comprehensive classification of microbial inoculants based on composition, species diversity, and functional purpose; Table S2: Quantitative Comparison Between Bioprecipitation and Biosorption in Heavy Metal Removal.

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Abbreviations

PGPB	Plant growth-promoting bacteria
C	Carbon
N	Nitrogen
P	Phosphorus
AMF	Arbuscular mycorrhizal fungus
ISR	Induced systemic resistance
IAA	Indole-3-acetic acid
NH_3	Ammonia
N_2	Nitrogen
PSB	Phosphorus-solubilizing bacteria
H^+	Protons
HSPs	Heat shock proteins
CO_2	Carbon dioxide
Pb	Lead
Cd	Cadmium
Hg	Mercury
POPs	Persistent organic pollutants
DDT	Dichloro-diphenyl-trichloroethane
CH_4	Methane
N_2O	Nitrous oxide
GHGs	Greenhouse gases
IPM	Integrated pest management

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