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Microbial synergies in phytoremediation: A comprehensive review

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Abstract

Phytoremediation is an environmentally friendly and economical method where plants and the microorganisms around the plants are used to eliminate, stabilize, or decompose the pollutants in the contaminated soils, water, and air. Microbial synergies are also very important in improving the effectiveness of phyto-remediation through improvement of plant growth, ability to withstand stress, and change of contaminants. Plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and endophytic microbes coexist mutually with plant roots and promote nutrient uptake as well as synthesize phytohormones such as auxins, gibberellins, and cytokinins, which enhance root development and biomass gain. These microorganisms also release their enzymes and chelating agents that increase the bioavailability and degradation of heavy metals, hydrocarbons, and organic pollutants. Further, microbial consortia are able to cause systemic tolerance to the plants against oxidative and metal stress, thereby ensuring physiological and biochemical stability during contaminated environments. Specificity and efficiency of phytoremediation are further enhanced through the integration of innovative microbial biotechnology, including those that are genetically engineered and microbial consortia. The mechanisms of plant-microbe-pollutant interactions and the optimization of microbial association are a sustainable way of recovering the polluted ecosystem through understanding the mechanisms of interaction between the microbes and plants, and pollutants.

Keywords: Phytoremediation, micro-synergy, plant-microbe interaction, rhizobacteria, mycorrhiza, endophytes, heavy metal remediation, biodegradation, restoration of environment, sustainable technology.

Introduction

Plants have also been used to clean up the environment through a process known as phyto remediation, where the plants eliminate, degrade, or stabilize the pollution in the environment instead of using expensive conventional ways of remediation. The key to the success of phytoremediation is the complexity of the interaction of plants and microbial communities, especially the rhizosphere and the plant tissues. There is nothing accidental about these plant-microbe associations; rather, they are a consequence of co-evolutionary changes that allow plants and microbes to become adapted to and survive in polluted environments. Microbes, including bacteria, fungi, are important in improving the phytoremediation activity by stimulating plant growth, enhancing stress and tolerance, as well as transforming, mobilizing, or immobilizing pollutants such as heavy metals and organic pollution. As an example, plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi can adjust the amount of phytohormones, enhance the nutrient uptake, and release siderophores and organic acids that increase the bioavailability and uptake of pollutants by plants, as well as directly degrade or transform pollutants into enzymatic processes (Raklami *et al*., 2022; Khalid *et al*., 2021) [29, 19]. The rhizosphere is a dynamic interface that is influenced by root exudates and microbial action, forming a hot spot of biochemical interaction that leads to rhizodegradation processes, phytoextraction, and phytostabilization. The presence of endophytic microorganisms (living organisms in the plant tissues) also adds to the process of controlling plant metabolism, relieving stress, and increasing the detoxification of organic and inorganic pollutants (He *et al*., 2020). Recent breakthroughs in molecular biology and omics technologies have also provided a greater insight into such complex plant-microbe interactions, showing that they entail complex genetic, biochemical, and metabolic networks that underlie successful phytoremediation (Raklami *et al*., 2022; Khalid *et al*., 2021) [29, 19]. The combination of the approaches of microbial consortia, bioaugmentation, and biostimulants into the phytoremediation process has demonstrated potential in addressing the limitations of low pollutant bioavailability, slow plant growth, and environmental variability of the process, making it stronger and more adaptive to the environment (Raklami *et al*., 2022; Khalid *et al*., 2021) [29, 19]. Since the environmental pollution caused by industrial, agricultural, and urban activities continues to endanger the health of plant and animal ecosystems, the prospective use of plant-microbial synergies to remediate polluted environments and maintain ecological stability has become a promising prospect (Raklami *et al*., 2022; He *et al*., 2020; Khalid *et al*., 2021) [29, 19, 17].

Mechanisms of Microbial-Assisted Phytoremediation

Microbial-assisted phytoremediation involves utilizing the interactions between plants and the microbial communities that live on them to greater effect, to stimulate the growth of plants to remove, transform, or stabilize contaminants of the soil and water, especially toxic metals and organic toxins, present in the soil and water. This is a multi-faceted strategy that incorporates a number of prominent mechanisms, which include: rhizodegradation, phytoextraction and microbial mobilization, phytostabilization, phytovolatilization, and microbial transformation that play a distinct role in the overall remediation process and results. Phytostimulation or rhizodegradation is the degradation of organic pollutants in the rhizosphere, which is the portion of the soil that is in contact with plant roots, mainly through the action of rhizosphere microorganisms. Root exudates include amino acids, sugars, and organic acids, which encourage microbial populations that have the capacity to break down complex pollutants like polycyclic aromatic hydrocarbons (PAHs) and pesticides, among other xenobiotics, which makes them less toxic and persistent in the environment (Figure 1). The plant species, soil properties, and diversity and activity of the microbial community determine the efficiency of rhizodegradation, and the outcomes of the experiment indicate a significant decrease in the level of contaminants and a higher well-being of the soil (Khan *et al*., 2023; Raklami *et al*., 2022) [20-21, 29]. Phytoextraction and microbial mobilisation are concerned with plant uptake and accumulation of inorganic contaminants, particularly heavy metals, by plants, which is highly facilitated by plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi. These microorganisms enhance the bioavailability of metals by the release of organic acids, siderophores, and biosurfactants that chelate or solubilize metal ions, causing them to become absorbed by plant roots and then translocated to the above-ground parts of the plant. Microbial mobilization not only enhances the efficiency of phytoextraction but also helps plants to grow in the presence of metal stress due to changes in the levels of phytohormones and enhanced acquisition of nutrients. Laboratory and field experiments have revealed that it is possible to enhance the efficacy of contaminated site remediation through the inoculation of microorganisms, which can greatly enhance the accumulation of metals and the growth of biomass (Raklami *et al*., 2022; Yu *et al*., 2024) [29, 40]. Another important process is phytostabilization, which is related to immobilization of contaminants in the soil or in tissues of root plants, which makes them less mobile and bioavailable. Microorganisms are implicated in phytostabilization by enhancing metals to precipitate, adsorb, or complex, usually via synthesizing extracellular polymeric materials, organic acids, or by modifying soil pH. The process is especially useful in preventing the washing out of toxic elements into the groundwater and reducing their release into the food chain, and the anticipated consequences are a decrease in the contaminant migration and an increase in the stability of the ecosystem (Yu *et al*., 2024; Raklami *et al*., 2022) [29, 40].

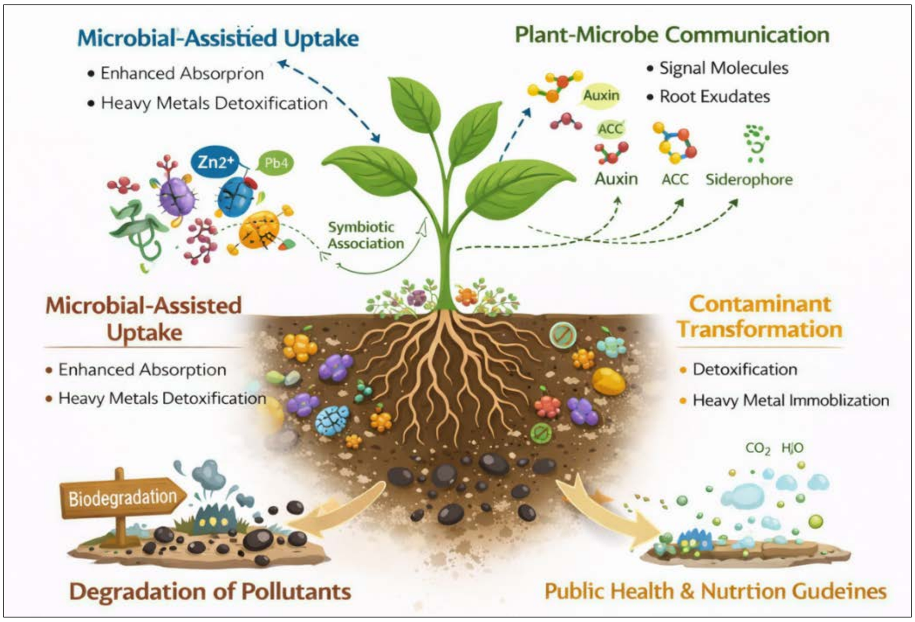

Fig 1: Unveiling Microbial-Assisted Phytoremediation Mechanisms

Phytovolatilization is defined as the intake of some pollutants by plants, their conversion to volatile compounds, and their release into the atmosphere. Microbial communities can also more effectively facilitate this process through catalyzing the transformation of non-volatile or less volatile contaminants into plant-absorbing and volatizing forms. As an example, special bacteria and fungi may methylate mercury or selenium, making it easier to absorb it and release it to the atmosphere by plants. Although phytovolatilization may be an effective method to eliminate the contaminants of soil and water, it has to be properly managed to prevent the secondary air pollution (Raklami *et al*., 2022) [29]. Microbial transformation is a range of microbial biochemical processes through which the chemical structure, oxidation state, or the toxicity of contaminants is changed by microbes. The redox reactions, methylation, demethylation, and enzymatic degradation are some of the transformations that are involved, which usually lead to the detoxification or immobilization of the pollutants. As an example, bacteria can decrease the toxicity of hexavalent chromium [Cr(VI)] to the less toxic trivalent form [Cr(III)], or decrease the toxicity of arsenite [As(III)] to arsenate [As(V)], which is less mobile and less harmful. Combined with microbial transformation, plant-based approaches graphically enhance the capacity of total remediation since the transformed contaminants can be taken up by plants, sequestered, or even volatilized (Kurniyawa *et al*., 2022; Raklami *et al*., 2022) [22, 29]. The joint action of these processes in the microbial-assisted phytoremediation has several significant outcomes and anticipated effects: the rates of contaminant removal are increased, the growth rate and stress tolerance of the plants, the soil structure and its fertility, and the environmental and health risks that are linked with the exposure to contaminants are minimized. The literature always speaks of increased biomass growth, enhanced contaminant absorption or sequestration, as well as more robust plant/microbe systems that can adapt to diverse and demanding environmental conditions with the co-inoculation of plants with beneficial microbes. In addition, phytoremediation can be enhanced to address these constraints through using microbial consortia and bioaugmentation approaches, which increase the bioavailability of contaminants, enhance the growth rate of plants, and address site heterogeneity, making it stronger and scalable to the field (Yu *et al*., 2024; Raklami *et al*., 2022; Kurniawan *et al*., 2022) [40, 29, 22]. Overall, microbial-assisted phytoremediation, by utilizing a collection of interconnected processes, rhizodegradation, phytoextraction and microbial mobilization, phytostabilization, phytovolatilization, and microbial transformation, is an effective, sustainable, ecologically sound remediation approach to contaminated water, soil, and air (Yu *et al*., 2024; Raklami *et al*., 2022; Kurniawan *et al*., 2022; Khan *et al*., 2023) [40, 29, 22, 20-21].

Plant-Microbe Interactions in Phytoremediation

The success of phytoremediation depends on the presence of plant-microbe interactions, and the rhizosphere, the small zone of soil around roots that is affected by root exudates, is a dynamic interface of interaction between plants and various microbial communities to promote more effective contaminant remediation and plant health. Bacteria, fungi, protozoa, and other microorganisms are highly concentrated in the rhizosphere, which is characterized by a high population density, which in turn can be 10 to 100 times that of bulk soil, where a high population density of microorganisms preconditions biochemical exchanges and nutrient cycling, resistance to stress, and the ability to transform pollutants (Giannelli *et al*., 2023; Fasusi *et al*., 2023) [13, 11] (Table 1). Plant growth-promoting rhizobacteria (PGPR) are major participants in this environment as they commonly colonize the root surface and rhizosphere environments to contribute to plant growth by fixing nitrogen, solubilizing phosphates, generating phytohormones, and eliciting systemic resistance to pathogens. PGPR additionally includes adaptation of plants to abiotic stress such as salinity and heavy metals through the regulation of antioxidant systems, osmotic adjustment, and hormonal balance, resulting in enhanced root architecture, nutrient uptake, as well as plant resilience (Giannelli *et al*., 2023; Fasusi *et al*., 2023; Al-Turki *et al*., 2023) [13, 11, 3]. They are mutualistic, mycorrhizal fungi, with particular species such as arbuscular mycorrhizal fungi (AMF), which associate themselves with the roots of the plant, penetrating their hyphae into the soil to enlarge the surface area on which water and nutrients (especially phosphorus and micronutrients) can be absorbed. Not only does this symbiosis lead to an improvement in nutrient uptake, but it also plants resistance to drought, salinity, and heavy metal stress, through the regulation of stress-responsive gene expression and strengthening of the plant defense system (Dagher *et al*., 2025; Fasusi *et al*., 2023) [7, 11]. Further contribution to phytoremediation is made by endophytic bacteria and fungi, which inhabit plant tissues without harming them, increasing plant tolerance to stressors, stimulating growth, and detoxifying or sequestering pollutants. Such endophytes can synthesize bioactive compounds, enhance water rates, and control plant metabolism, usually collaborating with rhizosphere microbes to enhance plant resistance to adversarial environments (Dagher *et al*., 2025) [7]. The difference between symbiotic and free-living microorganisms is also important: symbiotic microorganisms, including rhizobia and AMF are directly deposited into the plants, engaging in mutual exchange of nutrients and signaling molecules and the free-living microorganisms are independent in the rhizosphere, bringing benefits (i.e., nutrient cycling, pathogen suppression, and pathogen transformation) without being directly integrated into plant tissues (Fasusi *et al*., 2023; Munir *et al*., 2022) [11, 25]. The joint activity of these groups of microbes leads to a higher level of phytoremediation effects, such as increased plant biomass, better uptake or immobilization of the contaminant, tolerance to stress, and decreased dependence on chemical fertilizers and pesticides. Research regulated by consistent outcomes indicates that co-inoculation of endophytes, AMF, and the growth of contaminated environments through the introduction of the microorganism, the PGPR, leads to the rescue effect, including enhanced nutrient uptake, photosynthesis, and antioxidant defense, which eventually results in more effective and sustainable cleanup of contaminated environments (Dagher *et al*., 2025; Giannelli *et al*., 2023; Fasusi *et al*., 2023) [7, 11, 13]. The desirable components of the application of the plant-microbe interactions in phytoremediation are not only the effective removal or stabilization of pollutants but also the restoration of soil health, the enhancement of crop yield, and the advancement of long-term agricultural activities.

Table 1: Key Roles of Plant-Microbe Interactions in Phytoremediation

Mechanism/Component	Function in Phytoremediation	Expected Outcomes	Citations
Rhizosphere Structure & Function	Dense microbial activity, nutrient cycling, pollutant transformation	Enhanced soil fertility, pollutant breakdown	(Giannelli *et al*., 2023; Fasusi *et al*., 2023) [13, 11].
Plant Growth-Promoting Rhizobacteria (PGPR)	Nitrogen fixation, hormone production, stress tolerance, and pathogen suppression	Improved plant growth, stress resilience, and increased contaminant uptake	(Giannelli *et al*., 2023; Fasusi *et al*., 2023; Al-Turki *et al*., 2023) [13, 11, 3]
Mycorrhizal Fungi (AMF)	Enhanced nutrient/water uptake, stress gene modulation	Greater nutrient acquisition, stress tolerance, and heavy metal mitigation	(Dagher *et al*., 2025; Fasusi *et al*., 2023) [7, 11]
Endophytic Bacteria & Fungi	Internal stress tolerance, growth promotion, and contaminant detoxification	Increased plant resilience, pollutant sequestration	(Dagher *et al*., 2025) [7]
Symbiotic vs. Free-Living Microbes	Direct nutrient exchange vs. independent nutrient cycling and pathogen suppression	Synergistic effects, improved remediation efficiency	(Fasusi *et al*., 2023; Munir *et al*., 2022) [11, 25]

Microbial Functional Traits Enhancing Phytoremediation

Microbial functional characteristics are critical in improving phytoremediation through facilitating plant survival, elevating the contaminant bioavailability, and directly changing or immobilizing the pollutants. Among the major microbial characteristics is the ability to produce 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which aids vegetation to deal with stress by reducing the traces of ethylene, a hormone that, in excess, suppresses root development in case of stressful conditions, such as heavy metal poisoning or salinity. Plants grown in soils with ACC deaminase-producing microbes like some strains of Bacillus and Pseudomonas allow plants to sustain root growth and biomass acquisition despite the contamination of soil (Qureshi *et al*., 2024; Raklami *et al*., 2022) [28, 29] (Table 2). Another important characteristic is siderophore secretion, which not only allows the intake of iron by both microbes and plants but also chelates heavy metals such as cadmium, lead, and zinc and makes them more soluble and bioavailable to plant uptake or microbial processing. As an example, Pseudomonas and Azotobacter species have been demonstrated to improve the absorption of heavy metals and iron in crops such as Pennisetum glaucum and Sorghum bicolor, which results in an increase in phytoremediation efficiency (Raklami *et al*., 2022; Sharma, 2021) [29, 35]. Micro-producing biosurfactants like Bacillus and Pseudomonas additionally support phytoremediation by decreasing surface and interfacial tension, hence enhancing the solubility and mobility of both hydrophobic organic pollutants (e.g., hydrocarbons, pesticides) and heavy metals. This characteristic not only enhances the disintegration of pollutants and their absorption but also supports the growth of plants through better nutrient efficiency and less toxicity of pollutants, as reported in the literature where biosurfactant enrichment increased plant biomass and stress indicators in crops in contact with the heavy metals (Eras-Muñoz *et al*., 2022; Raklami *et al*., 2022) [10, 29]. Microbes can also decompose or convert organic pollutants (polycyclic aromatic hydrocarbons (PAHs), pesticides, and industrial chemicals) directly or into less toxic or more assimilable forms enzymatically through degradation pathways, including production of oxidoreductases, dehalogenases, and peroxidases. Rhizospheric and endophytic bacteria such as Pseudomonas putida and Achromobacter xylosoxidans have proven to break down herbicides and petroleum hydrocarbons and, as a result, eliminate the concentration of contaminants in soil and plant tissues (Anand *et al*., 2023) [4]. The other adaptive characteristic is biofilm formation, which improves microbe-assisted root colonization, providing a protective matrix to microbial communities, and can ensure close interaction of the plant and microbe. Biofilms on the roots enhance the persistence of microbes, degradation of pollutants, and exchange of nutrients, and eventually result in healthier and stronger phytoremediation systems (Shahid *et al*., 2020) [34]. The collective effect of these microbial qualities leads to greater plant growth, greater uptake or degradation of contaminants, better soil health, and more overall remediation effectiveness. As an example, when Brassica napus was inoculated with phosphate-solubilizing bacteria (PSB) with the characteristic of ACC deaminase and siderophore production, it resulted in a significant increase in biomass and heavy metal accumulation, whereas biosurfactant-producing microbes alleviated cadmium toxicity and stimulated shoot and root growth in Medicago sativa and Bidens pilosa (Wang *et al*., 2025; Eras-Muñoz *et al*., 2022) [37, 10]. These results demonstrate the possibility of exploiting some microbial functional characteristics to streamline phytoremediation operations towards different contaminants and environments.

Table 2: Microbial Functional Traits and Their Impact on Phytoremediation

Microbial Trait	Mechanism/Function	Example/Result	Citations
ACC deaminase production	Reduces stress ethylene, promotes root growth	Bacillus/Pseudomonas enhance plant growth under metal stress	(Qureshi *et al*., 2024; Raklami *et al*., 2022) [28, 29]
Siderophore secretion	Chelates heavy metals, increases bioavailability	Pseudomonas/Azotobacter boost Fe, Cd, Pb uptake	(Raklami *et al*., 2022; Sharma, 2021) [29, 35]
Biosurfactant production	Solubilizes organics/metals, reduces toxicity	Bacillus biosurfactants increase biomass, reduce Cd stress	(Eras-Muñoz *et al*., 2022; Raklami *et al*., 2022) [10, 29]
Enzymatic degradation	Breaks down organics (oxidoreductases, etc.)	Pseudomonas putida degrades herbicides, hydrocarbons	(Anand *et al*., 2023) [4]
Biofilm formation	Enhances root colonization, pollutant degradation	Biofilms on roots improve resilience and remediation	(Shahid *et al*., 2020) [34]

Factors Influencing Microbial Synergies

The development of microbial synergies during phytoremediation occurs as a result of intricate interactions between physicochemical properties of the soil, the nature of the contaminants, the characteristics of the plants, the microbial diversity, and the environmental stress factors, which together define the effectiveness and stability of the partnerships between plants and microbes in polluted soil. The basic characteristics of the soil, including PH, texture, and organic matter (OM), are important because they have a direct impact on the structure of microbial communities, nutrient cycling, and bioavailability of contaminants. An example is that the optimal pH (usually between 5.5-7.5) allows the growth of a wide range of diverse and active microbes, whereas extreme acidity or alkalinity can reduce the activity of microbes and change the composition of the community, consequently influencing the breakdown of organic matter and nutrient cycling (Wang and Kuzyakov, 2024; Dai *et al*., 2021) [36, 8] (Figure 2). The texture of soil, the percentage of sand, silt, and clay, influences aeration, water adsorption, and soil aggregates, which influence the mobility of microbes and organic substance stabilization. The presence of high clay content can, in turn, augment the formation of aggregates and stabilization of organic matter, sustaining an increase in microbial biomass and diversity, but sandy soils could limit the growth of microbes, because of reduced retention of water and nutrients (Dai *et al*., 2021; Rola *et al*., 2022) [8, 31]. Another important parameter is organic matter content, which is one of the main sources of energy for soil microorganisms and determines the presence of useful groups, including nitrogen-fixing lithogenic bacteria and mycorrhizal fungi, which play a crucial role in the development of plants and changing contaminants (Dai *et al*., 2021) [8]. Metal speciation and pollutant properties are also determinants in the determination of microbial synergies. The toxicity of the metals or organic pollutants and the ways in which they are converted or immobilized depend on the chemical form, solubility, and bioavailability of the chemical. To use an example, some heavy metals in their ionic forms may impair the microbial cell membrane, enzymatic activity, and microbial diversity, or less bioavailable forms may be less toxic yet less amenable to remediation (Raklami *et al*., 2022; Zheng *et al*., 2024) [29, 42]. Microbial consortia that are able to biosorb, redox convert, or chelate can change speciation of the metal and cause a decrease in toxicity and an increase in phytoextraction or phytostabilization. Complex organic pollutants can only be broken down in complex microbial enzyme pathways, and the interaction between these pathways in microbial communities is what makes complex pollutants break down (Zheng *et al*., 2024) [42].

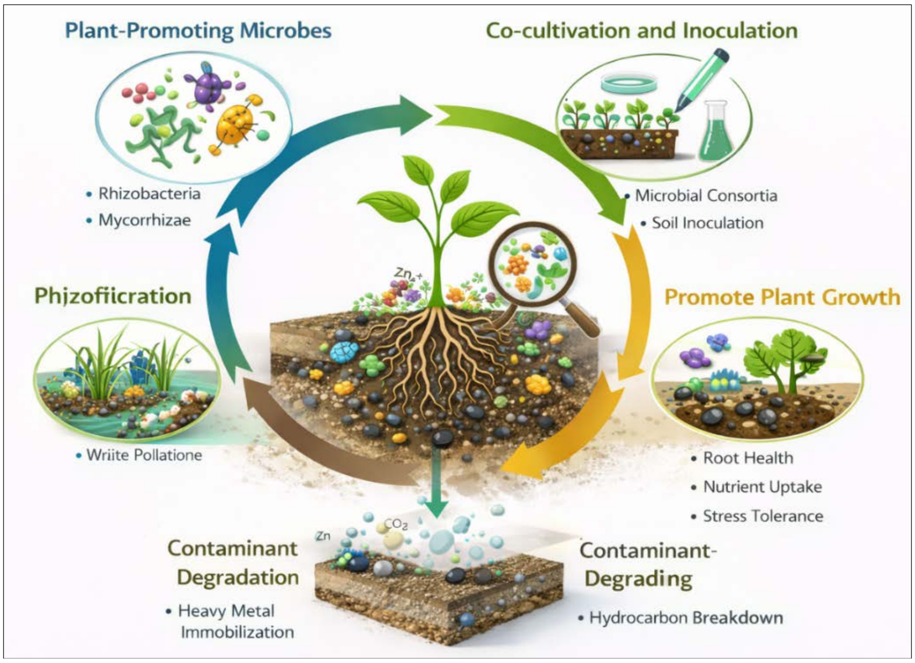

Fig 2: Optimizing Microbial Synergies for Phytoremediation

Plant species and root structure also play an important role because the various plants are capable of exuding various profiles of organic acids and sugars and secondary metabolites, which attract and maintain certain microbial communities within the rhizosphere. Extensive or highly branched root systems expand the quantity of soil searched, which boosts the acquisition of various microbes and mobilization of nutrients and contaminants (Zhakypbek *et al*., 2024; Adeniji *et al*., 2024) [41, 2]. Specific microbiome Hyperaccumulator plants, including can develop unique rhizosphere microbiomes, specifically well adapted to tolerate and transform heavy metals, and the composition and density of root exudates can regulate the abundance and activity of beneficial microbes, including plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi (Zhakypbek *et al*., 2024) [41]. Plant-microbiome compatibility is therefore the main determinant of phytoremediation success, as evidenced by observations whereby inoculating contaminated soils with particular microbial consortia enhanced plant growth, metal uptake, and stress tolerance (Raklami *et al*., 2022) [29]. The resilience and functional ability of phytoremediation systems are based on microbial diversity and abundance. Microbial diversity makes functional redundancy more likely to occur, as the key processes, including nutrient cycling, pollutant degradation, and stress mitigation, are maintained despite the changing environmental factors (Munyai *et al*., 2021; Dai *et al*., 2021) [26, 8]. Heterogeneous communities of microbes are well adapted to adjust to the variation in soil chemistry, load of pollutants, and profile of plant exudates to ensure stable and effective remediation processes. On the other hand, diversity can be limited by heavy metal toxicity or unfavorable soil conditions, limiting the effects of these functions and, therefore, reducing plant growth and cleaning capacity (Raklami *et al*., 2022; Munyai *et al*., 2021) [29, 26]. Specifically, the high occurrence of essential functional groups, including PGPR, mycorrhizal fungi, and metal-tolerant bacteria, is of great significance when it comes to maintaining the health of plants and contaminant transformation or sequestration (Raklami *et al*., 2022; Munyai *et al*., 2021) [29, 26]. Alteration of microbial synergies by environmental stressors such as salinity, drought, and extreme temperatures further exerts selective pressure on plants and microbes. Such stressors may decrease the biomass of microorganisms, change the composition of the community, and repress the beneficial interactions, yet they may also select stress-adapted taxa with improved transformative pollutant and plant growth-promoting abilities (Raklami *et al*., 2022; Munyai *et al*., 2021) [29, 26]. As an example, in salty or dry soils, the population of halotolerant or drought-resistant microbes can be enhanced to sustain the survival of plants and their remediation in unfavorable environments. Nonetheless, when these adaptations are overloaded or prolonged, they result in low remediation efficacy and the resilience of the ecosystem (Raklami *et al*., 2022; Munyai *et al*., 2021) [29, 26]. These interacting factors yield a dynamic and context-specific landscape of microbial synergies with optimal phytoremediation performance attained by optimally selecting plant species, microbial inoculants, and soil management practices depending on the site-specific factors. As an example, germination of Medicago sativa seed on soils with heavy metal contamination after inoculation with a consortia of Proteus, Pseudomonas, and Ensifer strains increased seed germination, early growth, and the reduction of metal in plant tissues, which proved that engineered microbial consortia have the potential to improve phytostabilization (Raklami *et al*., 2022) [29]. On the same note, maize and sunflower plant growth and heavy metal stress were improved with copper-resistant Pseudomonas strains, which underscores the need to align microbial phenotypes with plant and soil traits to be used in remediation (Munyai *et al*., 2021) [26]. Finally, it can be concluded that sustainable management of soils, plants, and environments can result in enhanced removal of contaminants, re-established soil health, and regeneration of sustainable ecosystems by enhancing microbial synergies.

Microbial Consortia and Engineered Systems

The creation and use of microbial consortia and engineered systems have transformed the research area of environmental remediation, and they provide strong answers to the degradation and elimination of various pollutants. Multi-strain microbial consortia may be microorganisms (bacteria, fungi, and cyanobacteria) that can be used to combine the complementary metabolic functions of individual microorganisms to more effectively and resiliently remediate the environment compared to single-strain methods. Such consortia are capable of degrading complex pollutants, increasing nutrient cycles, as well as the growth of plants, as was observed in the application of bacterial-fungal-algal combinations to treat wastewater and decontaminate soil. One can provide as an example the co-inoculation of microalgae by bacteria or fungi which is proven to be much more effective in wastewater systems, where microalgae -bacteria consortia can remove chemical oxygen demand and nutrients up to 90 percent and microalgae -fungi consortia can enhance yields of biomass and lipids to be used in bioenergy production (Mehra *et al*., 2025; Nagarajan *et al*., 2022) [23, 27]. Metabolic interactions that occur within these consortia include the algae generating oxygen, which promotes the survival of aerobic bacteria, and the relocation of bacteria to secrete growth-promoting compounds to improve the productivity of the algae. The possibility of these systems is further increased by synthetic biology and the engineering of microbial strains. Microbes can also be genetically modified to have more pollutant-degrading enzymes, metal-binding proteins, or other characteristics of stress resistance. Genome-editing technologies like CRISPR/Cas9 have made possible the development of designer microbes and consortia specific to a particular contaminant, i.e., heavy metals or persistent organic pollutants. Artificially engineered strains of Escherichia coli and Pseudomonas putida, such as those, have been shown to have better cadmium and lead capturing and transformation ability or be more effective in degrading complex hydrocarbons than their wild-type counterparts (Khan *et al*., 2023; Raklami *et al*., 2022) [20-21, 29]. The developments enable the site-specific optimization of microbial communities to help solve site-specific issues and enhance the remediation. Practical methods that can be used are bioaugmentation and biostimulation, which exploit natural and engineered microbial consortia. Bioaugmentation is the procedure of introducing into contaminated environments chosen or engineered microbes to increase the remediation capacity of the native community, whereas biostimulation is the process of increasing the activity of the native microbes by the addition of nutrients, electron donors, or other amendments. Such tactics have also been utilized effectively in the rehabilitation of the heavy metal-contaminated soils, where consortia of metal-tolerant bacteria and fungi bioaugmented soils have resulted in drastic decreases in soil metal and enhanced plant development. In particular, removal rates of lead and cadmium in polluted soils were up to 98 and 85 percent in the case of a four-bacterial consortium introduction, and fungal consortia have been applied in polluted landfill soils to eliminate arsenic, chromium, and copper (Chaudhary *et al*., 2023; Kurniawan *et al*., 2022) [6, 22]. Nevertheless, the effectiveness of bioaugmentation is determined by the compatibility of the introduced strains with the endogenous microbiome and the environmental factors, and their persistence and competition in the environment. Microbial consortia combined with nanotechnology development to form the microbial-nanotechnology hybrids is one of the most advanced methods of transforming pollutants. Nanoparticles may promote microbial action through an increase in the bioavailability of pollutants by acting as electron shuttles or by providing redox-active surfaces. Microbes engineered to coexist with metal or carbon-based nanomaterials have demonstrated potential in enhancing the rate of recalcitrant pollutant degradation (e.g., polycyclic aromatic hydrocarbons and heavy metals) and also in enhancing microbial fuel cell efficiency in the simultaneous treatment and conversion of waste to energy (Khan *et al*., 2023) [20]. An example of this is the application of microalgae-bacteria consortia with the aid of nanomaterials that have resulted in enhanced treatment of wastewater of nutrients and organic contaminants and the recovery of useful resources such as biofuels and fertilizers (Mehra *et al*., 2025; Abate *et al*., 2024) [23, 1]. The anticipated results of these superior systems are increased pollutant removal efficiencies, increased resistance to environmental changes, as well as the possibility of resource recovery and circular economy uses. Fluorid examples have shown that multi-strain consortia and engineered microbes can perform better than traditional single-strain or chemical remediation methods, which can be used as a sustainable and scalable approach to complex environmental problems. An example is artificial consortia of Chlorella and growth-promoting bacteria have been able to remove ammonium and up to 90% of nitrate and phenol in leachate treatment, and engineered consortia can treat soils contaminated with various heavy metals and achieve better soil fertility and crop productivity (Mehra *et al*., 2025; Chaudhary *et al*., 2023; Gonzalez-Gonzalez and De-Bashan, 2021) [23, 4, 14]. With the development of synthetic biology, bioaugmentation, and nanotechnology, the combination of all these methods is likely to improve the performance and usefulness of microbial remediation systems that will lead to a clean environment and sustainable use of resources.

Phytoremediation of Different Contaminants

Phytoremediation is a long-term, sustainable, vegetative bioremediation technology to remove, stabilize, or detoxify various environmental contaminants such as heavy metals, organic and new contaminants, pharmaceuticals, and microplastics. The synergistic effects of other microbes associated with phytoremediation significantly increase the efficacy of the system as it promotes plant tolerance and uptake and detoxification processes. In the case of heavy metals such as cadmium, lead, and arsenic, plants adopt phytoextraction, phytostabilization, and phytovolatilization among other mechanisms, which are usually through the aid of rhizospheric and endophytic microbes. Such microbes, such as bacteria and fungi, can be used to sequester metals by biosorption, bioaccumulation, and bioprecipitation, or by using enzymes to convert them into rather less toxic forms. As an example, arbuscular mycorrhizal fungi (AMF) and endophytic fungi invade plant roots and can extend their hyphae to the rhizosphere to increase the uptake of mineral nutrients and the regulation of the acquisition of heavy metals, in addition to increasing the resistance of the plant to stress caused by metal (Khalid *et al*., 2021; Raklami *et al*., 2022) [19, 29] (Figure 3). Plant growth-promoting bacteria (PGPB) also contribute to phytoremediation by secreting siderophores, phytohormones, and antioxidants, which not only make metals more soluble and taken up but also reduce oxidative stress in plants, resulting in enhanced growth and increased rates of contaminant uptake (Sharma, 2021) [35]. In the handling of organic pollutants, including hydrocarbons, pesticides, and industrial solvents, phytoremediation uses such processes as rhizodegradation and phytodegradation, whereby plant roots and exudates are used to stimulate the growth of populations that can metabolize complex organic compounds. Microbes in the rhizosphere have a wide range of metabolic pathways concerning their degradation of these pollutants, which are frequently augmented by root exudates, which act as a source of carbon or as a co-metabolite. Endophytes are useful contaminants since some directly degrade organic contaminants and some can also regulate plant metabolism to enhance tolerance and transformation capacity, thereby helping remediate mixed or recalcitrant contaminants (He *et al*., 2020) [17]. As an example, it was demonstrated that endophyte-assisted phytoremediation may be effective in both heavy metals and organic-contaminated soils because endophytes can stimulate plant growth and convert various pollutants to form or eliminate them (He *et al*., 2020) [17].

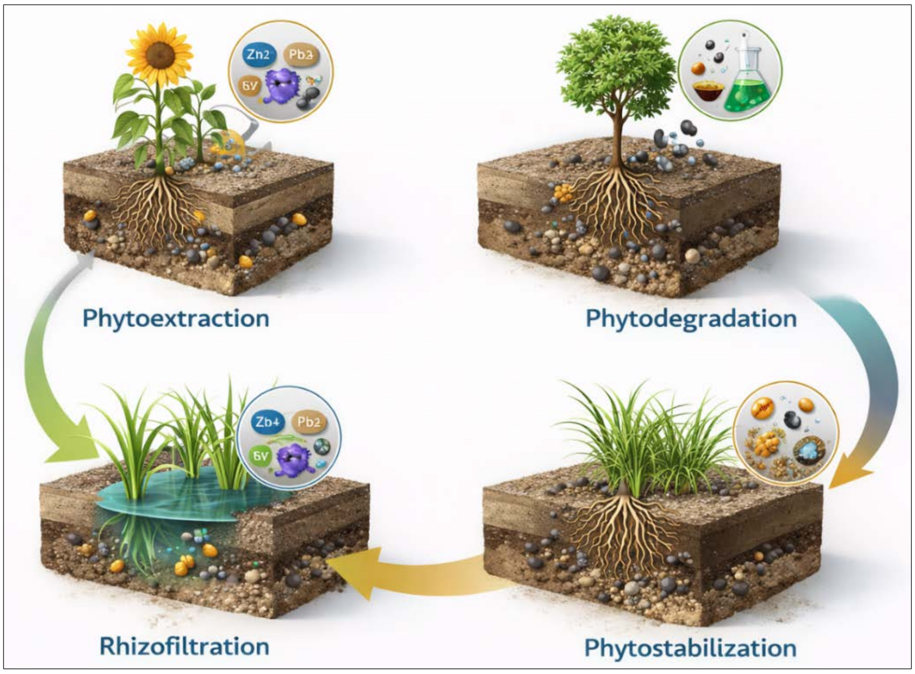

Fig 3: Phytoremediation Strategies

New challenges are brought about by emerging contaminants such as pharmaceuticals, personal care products, and microplastics that are persistent and interact in the environment in a complex manner. The strategies of phytoremediation of these contaminants are still in their developmental stage, although there is evidence that plants and the associated microbes can absorb, store, or convert a host of new pollutants. Microbial communities are important in the degradation of complex molecules, and plants can store or volatilize some of them, which lowers their impact on the environment (Raklami *et al*., 2022; Zhakypbek *et al*., 2024) [29, 41]. Additional biotechnological methods, including the application of genetically modified plants and microorganisms, are being considered to make phytoremediation more specific and efficient in dealing with these new contaminants. The anticipated results of phytoremediation, especially when reinforced by microbial colleagues, are substantial lowering of concentrations of contaminants, rebuilding of soil and water, and ecosystem recovery are possible. As an illustration, co-application of hyperaccumulator plants and metal-tolerant bacteria has led to up to 98 percent removal of lead and 85 percent removal of cadmium from polluted soils, with the co-application of endophyte-assisted phytoremediation process having facilitated successful remediation of sites that contained mixed organic and inorganic contaminants (Sharma, 2021; He *et al*., 2020) [35, 17]. Floating macrophytes with biofilters of microorganisms have been shown to have high removal efficiencies of heavy metals and organic contaminants in aquatic environments, and this technology has been shown to provide scalable solutions to water remediation (Demarco *et al*., 2023) [9]. Comprehensively, the combination of plant and microbial activities in the phytoremediation process not only improves the removal of contaminants, but also helps plants to be healthy, soils to be productive, and the long-term viability of sites that have received remediation.

Case Studies and Recent Advances

Microbe-assisted phytoremediation is another environmental technique that has been used extensively in the world, exploiting certain plant-microbe interactions to respond to diverse environmental pollutants through the use of omics technologies. It is established in both field and laboratory studies that plant growth-promoting bacteria (PGPB), arbuscular mycorrhizal fungi (AMF), or endophytes can greatly reinforce uptake, tolerance, and detoxification of heavy metals and organic pollutants when combined with hyperaccumulator plants. As an illustration, rhizospheric bacteria inoculation of Thlaspi caerulescens increased zinc concentration by three times and shoot accumulation by four times, and Bacillus subtilis increased nickel uptake in Brassica juncea, and phytoremediation with endophytes was successful in mixed organic and inorganic pollutants (Gayathiri *et al*., 2022; Sharma, 2021) [12, 35] (Table 3). Not only were heavy metal concentrations decreased by the use of long-term field-scale phytoremediation with white clover, ryegrass, and alfalfa on the abandoned mine lands in China, but the ecological restoration of the soil microbial diversity and activity was also proven (Raklami *et al*., 2022) [29]. Equally, microalgae like Chlorella vulgaris and *Scenedesmus almeriensis* have proven to be very efficient in laboratory and pilot-scale experiments on the removal of arsenic and cadmium in water systems, although in most cases they are restricted to aqueous environments (Kurniawan *et al*., 2022) [22]. The examples show that the choice of plants and microbial combinations, which are compatible and specific to particular contaminants and site conditions, is vital. The phytoremediation systems have been revolutionized in terms of understanding and optimization with the recent development of omics technologies, namely metagenomics, transcriptomics, proteomics, and metabolomics. Metagenomics can be used to discover unculturable microbial communities in the rhizosphere, which can identify important taxa and functional genes to work on degrading contaminants and plant-microbial interactions (Rane *et al*., 2021; Raklami *et al*., 2022) [30, 29]. Transcriptomics and proteomics give information on the changes in the expression of genes and proteins during contaminant stress in both plants and microbes that can be used as stress-responsive pathways and regulatory networks, and thus be used to enhance remediation. Metabolomics reveals the changes of small molecules in relation to the uptake and detoxification of the pollutants to provide biomarkers that can be used to monitor remediation and plant health (Hassan *et al*., 2025; Cembrowska-Lech *et al*., 2023) [16, 5]. These layers of omics, which are commonly aided by machine learning and artificial intelligence, enable the system to be holistically designed into high-performing phytoremediation consortia and predict the behavior of the system under varying conditions in the field (Sanches *et al*., 2024; Cembrowska-Lech *et al*., 2023) [32, 5]. Although there has been promise in laboratory and greenhouse work, there is a general failure to work out at the field scale because of variation in the environment and some of the microbes present there, and the varying burden of contaminants present. In laboratory experiments, removal efficiencies are usually higher and more reproducible, whereas field experiments have to deal with complex soil matrices and climatic interactions and have to be long-term (Kurniawan *et al*., 2022; Raklami *et al*., 2022) [22, 29]. An example is that bioaugmentation by engineered/selected microbes may improve remediation in laboratory-scale environments, but their survival and activity in the field may be hampered by competition and environmental limitations, and thus community assembly and resilience should be studied further (Raklami *et al*., 2022; Kurniawan *et al*., 2022) [29, 22]. However, the achievements with field-scale projects (like revegetation of mine tailings or restoration of microbial diversity in contaminated soils, etc.) indicate that the translation of laboratory developments into practice can be successful (Raklami *et al*., 2022) [29].

Table 3: Global Examples, Species-Microbe Combinations, and Omics Advances

Case Study/Advance	Species-Microbe Combination	Key Omics Tool(s) Used	Result/Outcome	Citations
Zinc and nickel remediation in contaminated soils	Thlaspi caerulescens + rhizobacteria; Brassica juncea + Bacillus subtilis	Metagenomics, transcriptomics	3-4x increase in metal uptake and accumulation	(Gayathiri *et al*., 2022; Sharma, 2021) [12, 35]
Long-term field remediation of mine tailings (China)	White clover, ryegrass, alfalfa + native microbes	Metagenomics	Reduced heavy metals, restored microbial diversity	(Raklami *et al*., 2022) [29]
Arsenic and cadmium removal from water	Chlorella vulgaris, Scenedesmus almeriensis + bacteria	Metagenomics, proteomics	High removal efficiency in lab/pilot studies	(Kurniawan *et al*., 2022) [22]
Multi-omics for stress response and system design	Various hyperaccumulators + PGPB/AMF/endophytes	Metagenomics, transcriptomics, proteomics, metabolomics	Identification of key genes, pathways, and biomarkers	(Rane *et al*., 2021; Hassan *et al*., 2025; Cembrowska-Lech *et al*., 2023) [30, 16, 5]

Constraints and Limitations

Although microbe-assisted phyto-remediation is a promising strategy as a green and cost-effective technique for remedying polluted soils and waters, it has several serious limitations and constraints that impact its application and overall effectiveness. The most common of the challenges is the great variation of field conditions, such as variations in temperature, pH, water availability, nutrient availability, and distribution of contaminants, which can severely affect plant growth, microbial activity, and contaminant bioavailability. The laboratory and greenhouse experiments usually acknowledge high remediation efficiencies because of the controlled environments, yet such values cannot be replicated in the field with the unpredictable weather conditions, heterogeneous soils, and multi-polluted mixtures, which result in inconsistent findings and slow improvement (Raklami *et al*., 2022; Kurniawan *et al*., 2022) [29, 22]. The other serious constraint is competition between native and introduced microbes. Although bioaugmentation can be used successfully to increase the phytoremediation process with plant growth-promoting bacteria (PGPB) or fungi, these introduced strains may not readily colonize the rhizosphere because they tend to be outcompeted by the already adapted native microbial populations. Native microbes are generally adapted to the specifics of the local environment, and exogenous strains might not survive or manifest their useful characteristics and lower the anticipated contamination removal benefits (Kurniawan *et al*., 2022; Hoang *et al*., 2020) [22, 18]. Another important obstacle is phytotoxicity caused by a large amount of contaminants. Most hyperaccumulator plants and their microbial associates are intolerant of high levels of heavy metals or organic contaminants, which may suppress seed germination, retard plant growth, and disrupt physiological functions. When the levels of contaminants are excessive, they also cause oxidative stress in plants, surpassing their ability to counter such stress, and resulting in low biomass production, which eventually restricts the overall quantity of contaminants that can be recovered or stabilized (Qureshi *et al*., 2024; Raklami *et al*., 2022) [28, 29]. This condition limits the use of phytoremediation in moderately contaminated sites, where too contaminated locations might not be able to sustain either plant or microbial life to effectively mediate the process (Wani *et al*., 2023) [38]. Moreover, the slow nature of the remediation process and the lengthy time interval in phytoremediation are serious disadvantages. Biological processes are not as fast as physical or chemical reactions to reduce contaminant levels, unlike other physical or chemical reactions that may occur through the development cycles of plants, seasonal changes, and gradual build-up or conversion of contaminants. Full site remediation can be several years or decades incompatible with the urgent land-use demands or the regulatory schedule (Raklami *et al*., 2022; Saxena *et al*., 2020) [29, 33]. The persistence and growth of useful microorganisms in polluted habitats are also a challenge. The process of microbial colonization and maintenance can be blocked by factors that include soil toxicity, nutrient restriction, and environmental stress factors. Despite the successful introduction of microbes, they can become less active over the course of time in the form of predation or competition, or inappropriate abiotic conditions, resulting in a low efficiency of remediation (Kurniawan *et al*., 2022; Hoang *et al*., 2020) [22, 18]. As an example, it has been demonstrated that although the initial effect of bioaugmentation with metal-resistant bacteria or consortia can increase the level of heavy metal removal, this effect can be overwhelmed by native populations or the strains would not adapt to the changing conditions in the field (Kurniawan *et al*., 2022) [22]. Also, there is a risk of ecological and regulatory issues, such as breaking the local microbial communities or bringing unwanted pathogens because of the use of non-native microbial strains (Hoang *et al*., 2020) [18]. Nevertheless, microbe-aided phyto-remediation has had significant achievements under favorable conditions. As an example, the controlled experiments on the inoculation of Medicago sativa (alfalfa) with Cellulosimicrobium sp. resulted in substantial growth of plants and accumulation of chromium, and Pseudomonas libanensis improved copper and zinc uptake in Brassica species (Kurniawan *et al*., 2022) [22]. Nevertheless, these outcomes are seldom replicated in field experiments, where the complexity of the environment and the competition of the introduced microbes minimize the effects of the introduced microbes. The anticipated results, consequently, tend to be less ambitious in the real world, where complete elimination of contaminants, slow, incremental changes in the well-being of soils, and sustained monitoring and control are the results. The solution to these challenges is to preserve the potential of microorganisms and their activity in the field by continuous research aimed at the selection of strong plant-microbe complexes, an optimal strategy of their inoculation, and the creation of amendments or immobilization methods (Qureshi *et al*., 2024; Kurniawan *et al*., 2022; Raklami *et al*., 2022) [28, 22, 29]. In conclusion, although microbe-assisted phytoremediation can still be an important tool in sustainable remediation, the practical use of this method needs to be considered thoroughly in combination with site-specific limitations, realistic schedules, and multifaceted management strategies to make the most out of this process and reduce the drawbacks.

Future Prospects and Research Needs

Microbe-assisted phytoremediation is set to undergo radical evolutionary changes in the future, led by the creation of climate-tolerant microbial inoculants, precision agrogeometric tools, genetic editing, and the merging of phytoremediation with more ecological restoration practices. With the increase in the environmental stresses of climate change, the development of resistant and stress-tolerant microbial consortia that can survive under varying temperature, drought, and salinity conditions will become very crucial in ensuring consistent remediation results. Recent studies point to the perspective of engineering or screening microbial strains, including phosphate-solubilising microorganisms or plant growth-promoting rhizobacteria, which not only increase the rate of contaminant removal but also increase the plant resistance to adverse abiotic factors, as observed in the successful drought mitigation of Australian and Californian agricultural systems (Wang *et al*., 2025; Mikiciuk *et al*., 2024) [37, 24]. These climate-tolerant inoculants will be beneficial in enhancing the predictability and applicability of phytoremediation in a wide and adverse environment. Remote sensing, soil sensors, and data analytics, which are collectively referred to as precision agriculture tools, are becoming popular in real-time monitoring of remediation progress. These technologies make it possible to manage each site separately, monitor the stress of plants or microbes early, and optimize the use of resources, making phytoremediation projects more efficient and predictable. As an example, ecological modeling can be used in conjunction with metagenomic monitoring to evaluate the dynamics of microbial communities and the ecological effects of the bioinoculants' use in the long-term, as well as to maintain the environmental safety and remediation efficiency (Wang *et al*., 2025) [37]. The application of such tools is likely to enable adaptive management, minimise the cost of operation, and enable compliance with the regulation. Genetic modification of plants and microorganisms is one of the leads in increasing phytoremediation. The progress that has been made in plant biotechnology has led to the creation of transgenic plants containing more biomass, deeper root systems, and more tolerance to high amounts of contaminants. As an example, genetically modified Brassica juncea and Helianthus annuus were shown to be more effective in terms of heavy metal uptake and stress tolerance, whereas the addition of particular transporter or detoxification genes has enhanced the contaminant sequestration and transformation (Wani *et al*., 2023; Zhakypbek *et al*., 2024) [38, 41]. Likewise, micro engineered microorganisms with enhanced metal resistance, biosorption, and degradation processes will be able to fast-track the beneficial removal of pollutants and will be able to adapt to the local site conditions. Nonetheless, genetically engineered organisms require stringent biosafety evaluations and regulatory controls to eliminate the occurrence of unanticipated environmental effects and gene escape to the wild populations (Wani *et al*., 2023) [38]. Combining phytoremediation with ecological restoration is becoming popular as a concept that is holistic in land rehabilitation. Instead of employing contaminant removal as the sole strategy, plans are meant to rehabilitate the ecosystem processes, biodiversity, and heal the soil. It incorporates the use of native or naturalized plant microbe assemblage, organic and inorganic amendments, and design of multifunctional landscapes that offer habitat, facilitate nutrient cycling, and make them more resilient to future disturbances (Yu *et al*., 2024; Hassan *et al*., 2024) [40, 15]. Indicatively, the treatment of mine tailings by a mixture of hyperaccumulator plants, useful microbes, and amendments to the soil has not only decreased the levels of contamination but also enhanced the regeneration of the native vegetation and microbial ecosystems to make them more sustainable and self-sustaining (Hassan *et al*., 2024) [15]. The future research and implementation are focused on the areas of policy development, scalability, and economic feasibility. Favorable regulatory and financial incentives, coupled with social acceptance, determine the extent to which phytoremediation can be successful at a large scale. The policymakers are advised to develop explicit regulations regarding bioinoculants and genetically modified organisms usage, standardize certification, and interdisciplinary cooperation between scientists, the industry, and stakeholders (Wang *et al*., 2025; Zhakypbek *et al*., 2024) [37, 41]. Economical studies are supposed to take into consideration not just the immediate expenditure of remedial work but also the advantages of the restoration of the ecosystem in the long run, which include enhanced soil fertility, water quality, and the value of land. Another option to improve the economic viability and sustainability is the integration of phytoremediation and bioenergy production or a circular economy model, whereby contaminated biomass is utilized to produce valuable products (Wijekoon *et al*., 2025) [39]. The future directions are expected to yield stronger, more flexible phytoremediation systems that can deal with more contaminants and site conditions, have shorter remediation periods, and bring about more ecological and economic co-benefits. As an illustration, the introduction of microbial consortia that are climate-resistant in drought-prone areas has already resulted in better planting and removal of contaminants, whereas more effective and open project management has become achievable with the help of precision monitoring tools (Wang *et al*., 2025; Mikiciuk *et al*., 2024) [37, 24]. It is predicted that the future of genetic engineering and combined restoration strategies will increase the extent and influence of phytoremediation, and it will become a foundation of the sustainable management of the environment in the context of the persistent global transformation.

Conclusion

Microbial interactions are very crucial in improving the performance, vigor, and ecological feasibility of phytoremediation in various polluted settings. The connections between plants and useful microorganisms, e.g., plant growth-promoting rhizobacteria, mycorrhizal fungi, and endophytes, play a significant part in enhancing the uptake, mobilization, degradation, and stabilization of pollutants. These microbes can be used to improve the growth of roots, alter rhizosphere chemistry, produce siderophores and organic acids, aid in the enzymatic degradation of toxic substances, and hence increase the capacity of plants to withstand and remediate heavy metals, organic contaminants, and emerging contaminants. Microbial consortia, particularly when they are a combination of bacteria and fungi, have synergies of benefits because they amplify the scope of degradable contaminants and enhance the rate of remedial action in stress-sensitive situations. The possibilities of architecting site-specific remediation of microbe-plant collaborations have been further increased by developments in omics instruments, genetic engineering, and synthetic biology. Nevertheless, issues like the lack of establishment of microorganisms in the field soils, competing with native microorganisms, and environmental heterogeneity continue to limit scalability. Irrespective of these limitations, microbe-assisted phytoremediation is an attractive, environmentally friendly, and viable approach. Further studies on the relationships between microbes and plants and engineering microbial inoculants will be critical in the creation of a strong, sustainable, and scalable phytoremediation system that can efficiently and sustainably clean up polluted environments.

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