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PHYTOREMEDIATION: LEVERAGING PLANT-MICROBE INTERACTIONS FOR ENVIRONMENTAL CLEANUP

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ABSTRACT

Plant and microbe-based bioremediation is a realizable, cost effective and green approach to remove pollutants in soil and water. This review assesses major strategies where they focus on stimulation of soil microbial activity in the rhizosphere, application of plants by steadying, absorption, degrading, and metabolizing hazardous contaminants; in addition, the roles of plant growth-promoting rhizobacteria (PGPR) and endophytes within the plant, conferring stress tolerance and nutrient acquisition. Metagenomics and CRISPR/Cas9 genome engineering have enhanced the prospects of molecular tools for engineering plant microbe interactions improving remediation potential. For proper functionality, there is a need to integrate two or more functions as shown by the interaction of phytoremediation and bioenergy production. However, the effort in phytoremediation still has limitations in terms of implementation at field level such as site heterogeneity, longer time required for remediation, and high cost. Some of the solutions to these challenges include precision agriculture, bioengineering, plant microbe interactions, and integrated green technologies. This review indicates that plant-microbe interactions have the ability to be a cheaper, and eco-friendly remediation technology, and serves as a basis for phytoremediation systems' research work and application.

INTRODUCTION

A. Phytoremediation: Definition and Importance

Pollution in land, water, and air by toxic wastes including metals, hydrocarbons, and pesticides in particular, is a growing issue for the world as it threatens generic habitats, human lives, and food production (Weldeslassie et al., 2017; Kolawole & Iyiola, 2023). Traditional treatment processes include chemical or physical processes, most of which are expensive, energy consumptive and ecologically unsuitable (Farraji et al., 2016; Patra et al., 2020). However, phytoremediation referred to as a green and sustainable technology employ the natural ability of plants and their associated microorganisms to remove, stabilize or eliminate contaminants in soil and water. This has made this approach cheap, more so environmentally friendly when it comes to restoration of polluted areas hence an essential tool for sustainable development.

B. Plant-microbe interactions in bioremediation

Phytoremediation technologies are based on the complex and mutually dependent relationships between plants, microorganisms and soil particles. Plant microbe interactions in the rhizosphere are critical for improving contaminant bioavailability, plant growth and combating stress by mechanisms including nutrient cycling, signal transduction and enzyme formation and phytohormones. Despite the advances on these topic notable gaps remain, including the molecular mechanisms of the interactions and the metabolisms associated with pollutant biodegradation.

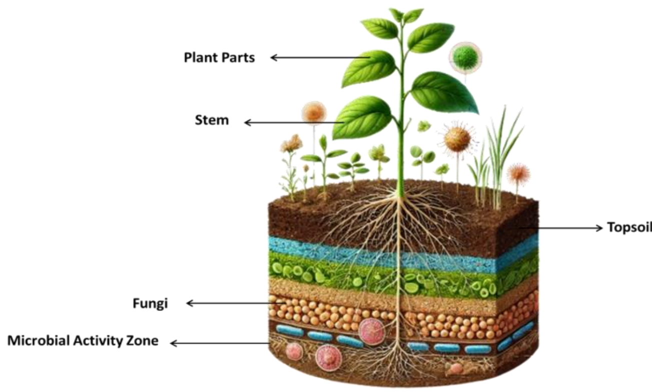

Fig 1: An example, mainly showing how it works, is a plant with its roots within the contaminated ground. The image show contamination uptake and degradation within the rhizosphere which refers to the region of soil surrounding the plant root.

C. Review, scope, and purpose

The techniques involved in phytoremediation are the rhizosphere stimulation, phytostability, phytoexcretion, and phytodegradation which are discusses in this review. It emphasizes that post-transformation, target plants can better tolerate stress and assemble more efficiently contaminants with the help of the plant growth-promoting rhizobacteria (PGPR) and endophytes. The present molecular biology advances including metagenomics and genome editing are examined for their applicability in optimizing plant-microbe symbiosis and enhancing the remediation performance. Additionally, the review defines certain concerns affecting phytoremediation development for field application, which include; heterogeneity, long period required for phytoremediation, and cost factors. In these respects, this work seeks to contribute to filling these gaps, toward the general goal of building a proper foundation for the further development of phytoremediation as a science and technology that holds great potential for properly remediating the environment on a large scale.

Methodology

1. Conceptual Framework

This study emphasizes the role of plant-microbe interactions in improving phytoremediation efficiency. The methodology investigates key mechanisms such as rhizosphere stimulation, phytostabilization, phytoextraction, and phytodegradation, which are crucial for understanding and optimizing the phytoremediation process (Ali et al., 2013; Ahemad & Kibret, 2014).

2. Experimental Processes

Rhizosphere Stimulation: Root exudates, including organic acids, sugars, and amino acids, enhance microbial activity, promoting contaminant transformation in the rhizosphere. This microbial proliferation creates favorable conditions for contaminant bioavailability and uptake (Ali et al., 2013; Akhtar et al., 2020).

Phytostabilization: This mechanism employs metallophytes to immobilize contaminants within their root systems or rhizosphere. Processes such as sorption to root surfaces, precipitation, and rhizosphere chemical modifications limit contaminant mobility and prevent environmental spread (Ali et al., 2013; Midhat et al. 2019).
Phytoextraction: Hyperaccumulator plants are used to absorb and store contaminants in their above-ground biomass. Key to this mechanism is the ability of certain plants, enhanced through microbial associations, to accumulate high levels of metals such as nickel or zinc (Abou-Shanab et al., 2003a; Akhtar et al., 2020).

Phytodegradation: Plants and their associated microbes degrade organic pollutants into less toxic compounds. This process involves enzymes secreted by plants and microorganisms that work synergistically to detoxify contaminants in the rhizosphere and plant tissues (Barac et al., 2004; Ali et al., 2013).

3. Tools and Techniques

The study employs the following tools and techniques: Biochemical Analysis: Measurement of root exudates, microbial diversity, and contaminant concentrations in plant tissues and rhizospheric soil ((Barac et al., 2004; Ali et al., 2013). Genetic Engineering: Use of genetic modifications to enhance the phytoremediation capabilities of plants, including traits for improved contaminant uptake and stress tolerance (Ali et al., 2013; Midhat et al. 2019). Metagenomics and Metabolomics: Profiling microbial communities and metabolic pathways in the rhizosphere to identify key players in contaminant transformation (Ahemad & Kibret, 2014; Ma et al., 2016).

4. Evaluation and Analysis

The effectiveness of phytoremediation is evaluated through: Quantitative analysis of contaminant reduction in soil and plant tissues (Glick, 1995; Ali et al., 2013). Monitoring plant growth and stress tolerance under contaminated conditions (Mukhopadhyay et al., 2017; Midhat et al. 2019). Assessing microbial community composition and functionality using high throughput sequencing and metabolomics profiling (Barac et al., 2004; Ahemad & Kibret, 2014).

Plant-microbe interaction mechanisms in phytoremediation

A. Rhizosphere stimulation

The rhizosphere, the active environment immediately surrounding plant roots, is key in phytoremediation. Plant-microbe interactions in this region play a crucial role in promoting more effective contaminant removal mechanisms:

Root exudates: A large variety of organic compounds such as sugars, amino acids, organic acids, and phenolics are released by plants to the rhizosphere (Moe, 2013). These exudates are carbon and energy sources that fuel the growth and activity of microorganisms in the rhizosphere (Neumann & Romheld, 2000; Vives-Peris et al., 2020).

Microbial proliferation: High levels of microbial biomass are sustained from the increase of available nutrients from root exudates in the rhizosphere compared to bulk soil (Landi et al., 2006; Nannipieri et al., 2008).). The term for this is the "rhizosphere effect," and it produces an exceptional hub for microbial activity and diversity (Gupta et al., 2024).

Increased bioavailability: Microbial processes in the rhizosphere may change chemical parameters of the soil that can increase or decrease the bioavailability of the contaminant for plant uptake (Wenzel, 2009; Dotaniya & Meena, 2015). This occurred mostly via pH changes, chelation and redox transformations (Seshadri et al., 2015).

Interaction synergy: The complex interactions occurring during plant and microbe interactions in the rhizosphere can generate synergistic effects in contaminant degradation and plant growth promotion (Anderson et al., 1993; Mohanram & Kumar, 2019). In particular, plant growth-promoting rhizobacteria (PGPR) can not only increase plant tolerance to the hazardous materials, but also improve degradation of these pollutants (Zhuang et al., 2007; Gupta et al., 2024).

Nutrient cycling: Rhizosphere microorganisms are involved in nutrient cycling: they solubilize many of the essential elements, making them more available for plant uptake (Dotaniya & Meena, 2015; Mimmo et al., 2017). It can indirectly aid phytoremediation by enhancing the growth and health of the plants. Plants play an important role in creating the suitable conditions for enhanced contaminant degradation and uptake, which leads to an improvement of the overall efficiency of the phytoremediation processes, by stimulating microbial activity and diversity in the rhizosphere (Anderson et al., 1993).

Table 1: Mechanisms of Phytoremediation and Associated Microbial Interactions

Mechanism	Description	Key Microbial Interaction	Examples (Plants)	Contaminants Targeted
Rhizosphere Stimulation	Plants release root exudates that stimulate microbial growth, enhancing contaminant degradation.	PGPR release siderophores, chelating heavy metals and increasing solubility.	*Brassica napus*, *Pteris vittata*	Heavy metals (Pb, Zn, Ni), hydrocarbons
Phytostabilization	Plants immobilize contaminants in roots, reducing mobility and bioavailability in soil.	Metallophytes promote root surface sorption and rhizosphere pH changes.	*Populus spp.*, *Vetiveria zizanioides*	Arsenic, lead, cadmium, zinc
Phytoextraction	Plants uptake contaminants and store them in above-ground biomass for harvesting.	Rhizobacteria enhance root uptake through biosurfactants and organic acids.	*Helianthus annuus*, *Thlaspi caerulescens*	Lead, nickel, cadmium, arsenic
Phytodegradation	Plants and microbes break down organic contaminants into less toxic compounds.	Endophytes produce enzymes like dehalogenases and oxygenases to degrade pollutants.	*Populus spp.*, *Arabidopsis thaliana*	Petroleum hydrocarbons, TCE, PCBs
Phytovolatilization	Contaminants are transformed and released as volatile compounds through plant leaves.	Microbes assist in converting heavy metals to volatile forms.	*Arabidopsis thaliana*, *Triticum aestivum*	Selenium, mercury, organic pollutants

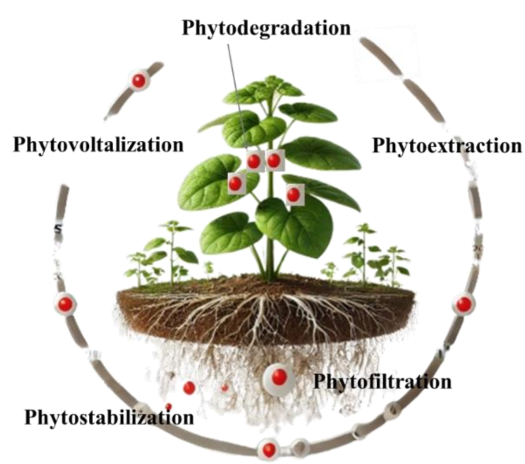

Fig 2: Mechanisms of Phytoremediation targeting heavy metal

B. Phytostabilization

Phytostabilization is a new green phytoremediation technology which employs plants to immobilize contaminants in the soil or within the root system, thereby limiting their transfer to the environment and their bioavailability, especially heavy metals (Shackira & Puthur, 2019; Sharma et al., 2023). Phytostabilization involves promoting a natural vegetative cover of metal-tolerant plants (metallophytes) on contaminated substrates (mine tailings) to physically stabilize pollutants and minimize the risk of their dispersal through different environmental pathways (Akhtar et al., 2020). The mechanisms are: (1) plants uptake and accumulate contaminants in their roots; (2) plants sorb contaminants to root surfaces (to form a solution); and (3) plants alter the chemistry in the rhizosphere which induces the precipitation of contaminants into less soluble phases (Ali et al., 2013). In contrast to phytoextraction, phytostabilization seeks to bind contaminants in the root zone, rather than transporting them into removable plant tissues (Egendorf et al., 2020). Especially for the large-scaled remediation of metal-polluted sites where contaminant removal is impractical or expensive (Ahemad & Kibret, 2014). Phytostabilization is successful when metal tolerant species are chosen with deep root systems that change soil chemistry (Alkorta et al., 2010). Besides, this method has advantages like soil erosion contraction, less leaching of contaminants and better ecosystem restoration (Alkorta et al., 2010; Shackira & Puthur, 2019). However, recovery of contaminants is not achieved since drastically contrasts to others, phytostabilization reduces contaminant mobility and consequently their bioavailability, requiring a long-term site management and monitoring (Robinson, 2006).

C. Phytoextraction

One of the mechanisms of phytoremediation is called phytoextraction, where plants absorb contaminants from the soil with their roots and translocate them into harvestable above-ground tissues (Chandra et al., 2019). Soil washing primarily works against metals and some organics in contaminated soils (Becerra-Castro et al., 2013). So, phytoextraction technique is successful when the following conditions are fulfilled the contaminants are more bioavailable, the plant is capable of accumulating high concentration of the pollutant in her aerial biomasses (de Souza et al., 1999a; de Souza et al., 1999b). In phytoextraction, hyperaccumulator plants are mainly used because they can accumulate the excessive amount of specific metals in their tissue (up to milligrams / gram tissue) (de Souza et al., 1999b; de Lima et al., 2019). New insights into the molecular basis of plant metal uptake, translocation and sequestration have made it possible to develop genetically modified plants having higher phytoextraction potential (Ma et al., 2009; Venegas-Rioseco et al., 2021). Preparing the treatment and option with the maximum potential of phytoextraction are increased contamination bioavailability and plant growth data on chelating agents and plant growth-promoting bacteria (Barac et al., 2004; Kamran et al., 2017). Although promising, this approach suffers from yet-to-be-resolved limitations in terms of long cleanup duration and plant biomass requiring disposal to avoid contamination (Kidd et al., 2015). Further exploration seeks to maximize plant-microbe associations, maximize metal movement through a plant, and achieve the sustainable handling of plant biomass after harvesting (Glick, 1995; Weyens et al., 2009)

D. Phytodegradation

Phytodegradation or phytotransformation, one of the most important mechanisms of phytoremediation, is a process where certain contaminants are biotransformed by plants and the microbes that live on and within them. Typically, it takes place in either plant tissues or rhizosphere where plant-excreted enzymes decompose organic pollutants to smaller and less toxic compounds (de Souza et al., 1999a; de Souza et al., 1999b). The efficiency of phytodegradation varies with the plant, and the type, as well as concentration of the contaminant, and the environmental conditions (Abhilash et al., 2009; Tripathi et al., 2020). Phytodegradation is a unique process of degradation of large complex organic molecules into a simpler structure by action of specific enzymes like dehalogenases, oxygenases and reductases (Spaczynski et al., 2012; Kumar et al., 2019; Pathak et al., 2024). It works especially well for organic contaminants such as herbicides, trichloroethylene, and petroleum hydrocarbons. Although phytodegradation can only act with the assistance of rhizospheric microorganisms that are known to consume those metals through intracellular and extracellular enzymes, this is often the case and the two are acted synergistically (de Lima et al., 2019). Genetic engineering has recently advanced into what are termed transgenic plants with improved phytodegradation capacity, (Ma et al., 2009; Abhilash et al., 2009) and thus provides hope for the treatment of these difficult pollutants. Nonetheless, difficulties still exist in maximizing plant-microbe interactions and in the full mineralization of contaminants to avoid the production of potentially toxic intermediates.

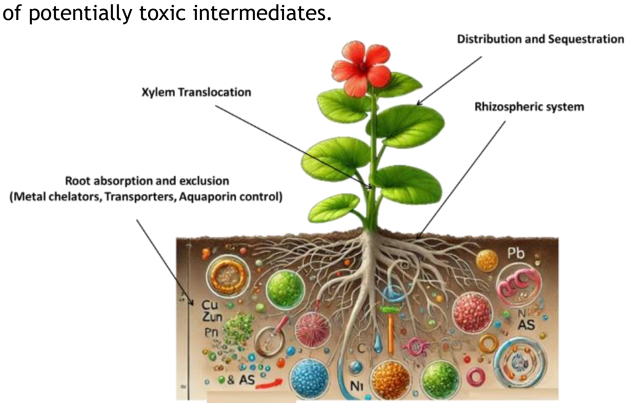

Fig 3: Plants uptake, transport, and detoxication of heavy metals, through multiple mechanisms, which are essential for phytoremediation strategies

FUNCTIONS OF PLANT GROWTH PROMOTING RHIZOBACTERIA (PGPR) AND ENDOPHYTES.

A. Introduction to Plant growth-promoting rhizobacteria (PGPR) and endophytes

Plant growth-promoting rhizobacteria (PGPR) and endophytes are important in improving contaminant uptake in phytoremediation. The beneficial microorganisms use several ways to enhance bioavailability and plant uptake of contaminants. Among them, one of the most important pathways is the secretion of siderophores to chelate with metal ions and increase their solubility (de Lima et al., 2019), thereby enhancing plant supplementation. Furthermore, both PGPR and endophytes synthesize organic acids ditto in the reduction of soil pH, allowing increased metal solubility and bioavailability (Etesami & Adl, 2020). Certain strains have been proven to express certain genes associated with metal transporters, which enable the uptake of heavy metals within plants (Ma et al., 2009; Das et al., 2016). For example, regarding organic contaminants, a few PGPR and endophytes are able to produce biosurfactant that can enhance the solubility and bioavailability of hydrophobic pollutants which favors its uptake by plants (Ali et al., 2022). In addition to changing root architecture by increasing root length and branching, these microorganisms can further increase the plant capacity to explore the contaminated soil and uptake the pollutants (de Souza et al., 1999a; de Souza et al., 1999b). These synergistic effects produced by several mechanisms utilized by PGPR and endophytes would help achieve a higher effectiveness in the contaminant uptake in phytoremediation systems, thus making them useful agents for bioremediation strategies (Chandra et al., 2019).

B. Improvement of stress tolerance in plants

PGPR and endophytes are important organisms in the enhancement of plant stress tolerance, particularly in phytoremediation. These beneficial microorganisms enhance plant tolerance against abiotic stresses resulting from soil contamination using different mechanisms. Osmotic pressure that is usually caused due to increasing concentrations of contaminants in soil, has been alleviated by using PGPR and endophytes (Vaishnav et al., 2019; Vocciante et al., 2022). This is done through osmolytes, antioxidants, and exopolysaccharides (EPS), all substances that allow the plants to maintain its water balance and protect its cellular structure (Ahemad & Kibret, 2014). Moreover, these microorganisms may alter plant hormone concentration specifically through 1-aminocyclopropane-1-carboxylate (ACC) deaminase enzyme activity that results in reduced ethylene production, thereby abolishing stress mediated growth suppression (Gallego et al., 2016). PGPR as well as endophytes increases nutrient uptake and availability that result in improvement of plant vigor and stress tolerance (Ullah et al., 2019; Akhter et al., 2020). They can also solubilize phosphates and produce siderophores that can enhance the bioavailability of nutrients needed by plants in polluted soils (Anderson et al., 1993; Etesami & Adl, 2020; Gupta et al., 2024). Alternatively, these beneficial microorganisms are able to elicit plant systemic resistance by pre-conditioning the plant against biotic and abiotic stresses (Janmeja, 2021). Some PGPR strains have also been applied in heavy metal-contaminated soils to either change metal speciation, reducing metal toxicity, or inducing plant metal binding mechanism and facilitating metal sequestration (Arzanesh et al., 2011; Wang et al., 2022; Gupta et al., 2024). These various stress tolerance mechanisms provided by PGPR and endophytes ultimately enhance the prospects of successful phytoremediation under stressful circumstances.

C. Enhanced uptake of contaminant

Rhizobacteria and endophytes contribute to the improvement of the phytoremediation process by promoting the uptake of contaminated organic matters by plants, enhancing photosynthetic efficiency of plants, and changing the pH levels of the rhizosphere. Siderophore production is known to be one of the most effective mechanisms. Siderophores are iron-acquiring substances produced by rhizobacteria, which package the metals in the soil, enhancing their generation and becoming quickly soluble to be absorbed by the plants. For example, the interaction of *Pseudomonas fluorescens* has been cited to increase iron, zinc, and nickel uptake in plants and basically raise biomass and metal uptake from contaminated zone through cyclic siderophores synthesis (Syed et al., 2023). In lead-contaminated soils, *Pseudomonas putida* facilitates the adsorption of lead in *Brassica napus* by secreting siderophores and indole-3-acetic acid (IAA), a plant growth hormone (Poursattari & Hadi, 2022).
The second important regulation mechanism entails the synthesis of ACC (1-aminocyclopropane-1-carboxylate) deaminase by plant microbes for instance; *Azospirillum brasilense* (Nascimento et al., 2014). This hormone, ethylene, is produced in large quantities by plants under stress conditions and is known to have a growth inhibiting effect. It synthesizes ethylene precursor ACC deaminase to reduce the ethylene level and relieve plant growth inhibition. According to this mechanism, plants develop tolerance not only to heavy metals, which are the main contaminant in these soils, but also to drought stress. Also, rhizobacteria like Bacillus subtilis produce biosurfactants that antagonise the water surface tension thus enhancing the availability of non-polar pollutants like the petroleum hydrocarbons (Selva Filho et al., 2023). This makes it possible for *Solanum nigrum* and other plants that are identified to bioaccumulate cadmium to break down and assimilate the contaminants (Khalid et al., 2019).

The combination of microbial quorum sensing (QS) with phytoremediation is enhanced by the ability of QS to negotiate gene expression and communication triggered by specific signals (Mangwani et al., 2016). Specifically, quorum sensing molecules like AHLs help bacteria and their associated activities like biofilm formation and root colonization (Harjai & Sabharwal, 2017). This interaction enhances plant-microbe mutualism, enhancing modes through which contaminants are taken up and degraded. Current research suggests that QS signaling can be manipulated in a way that enhances the release of metal resistance genes and thus improve efficiency of rhizoremediation in sites with very high levels of contamination.

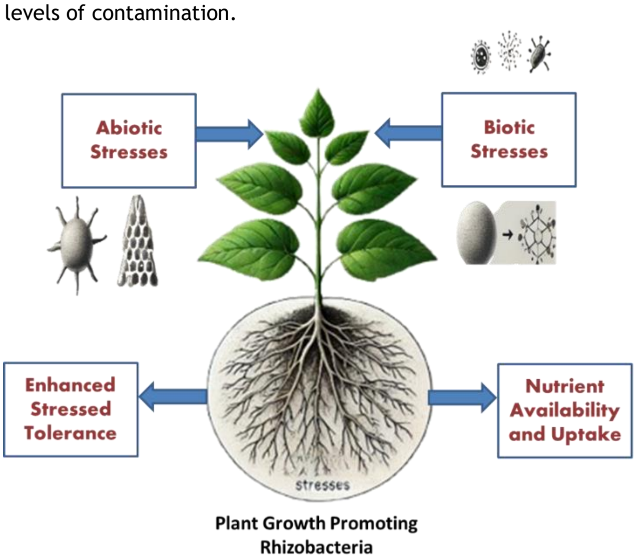

Fig 4: PGPR (Plant Growth Promoting Rhizobacteria) in Stress Tolerance and Nutrient Uptake

D. Examples of PGPR and endophytes in phytoremediation

The ability of specific PGPR and endophytes have shown great promise in furthering the usefulness of phytoremediation. For example, the use of Pseudomonas putida, a well-studied PGPR, increases the phytoremediation of lead-contaminated soils by enhancing the uptake of lead in *Brassica napus* with the production of indole-3-acetic acid (IAA) and siderophores (de Lima et al., 2019; Kumar & Chandra, 2019).

Bacillus subtilis, a well-known PGPR, has also been found to promote cadmium bioaccumulation in *Solanum nigrum* by regulating the expression of metal transporters and ameliorating antioxidant enzymes activities (Ullah et al. 2019). For example, *Burkholderia cepacia* is one of the endophytes able to promote the phytoremediation by poplar trees of trichloroethylene, increasing plant biomass and degradation of contaminants (Ma et al., 2009; Doty et al., 2017). *Enterobacter cloacae* may be a promising biocontrol agent for the maximation of phytoremediation of petroleum hydrocarbon, as previous studies demonstrated that its introduction could enhance plant growth of ryegrass and stimulate the biodegradation of hydrocarbons in the rhizosphere (Glick, 1995; Ejaz et al., 2021). In media spiked with arsenic, endophyte *Pseudomonas fluorescens* is known to promote arsenic uptake and translocation to shoots in the arsenic hyperaccumulator *Pteris vittata* (Tiwari et al., 2016; Vandana et al., 2020). These examples show the various genera of PGPR and endophytes which can be utilized to enhance differences aspects of phytoremediation including improving plant growth, tolerance to stress and uptake and degradation of contaminants.

MOLECULAR, BIOCHEMICAL AND PLANT MOLECULAR MICROBIOLOGY

A. Signaling pathways between plants and microbes

Signaling pathways between plants and microbes have important functions in the establishment and maintenance of beneficial interactions that facilitate phytoremediation. These include multifaceted molecular cross-talks between plants and their commensal/mutualistic microorganisms. Flavonoids and Nod factors exchange mediated by legumes and rhizobia is one of the key signaling pathways that triggers nodule development and nitrogen fixation (Garg & Geetanjali, 2009; Skorupska et al., 2017). In a similar fashion, strigolactones secreted by plants induce hyphal branching of arbuscular mycorrhizal fungi to generate symbiosis (Akiyama et al., 2005; Kowalczyk & Hrynkiewicz, 2018). Specifically, under heavy metal stress, plants affect the composition of root exudates and release certain signaling molecules to attract metal-tolerant microbes from soil in the framework of phytoremediation (Upadhyay, 2025). Here, these microbes are capable of synthesizing phytohormones such as indole-3-acetic acid (IAA) and cytokinins, which promote plant growth and tolerance to various stresses (Egamberdieva et al., 2017). Moreover, some bacteria can also synthesize ACC (1-aminocyclopropane-1-carboxylate) deaminase, which contributes to lower ethylene concentrations in the plants, thus reducing stress and enhancing function and growth of the plants under contamination conditions (Singh et al., 2015; Gamalero et al., 2023). Elucidation of these signaling pathways lays the foundation for engineering more effective plant-microbe partnerships for phytoremediation.

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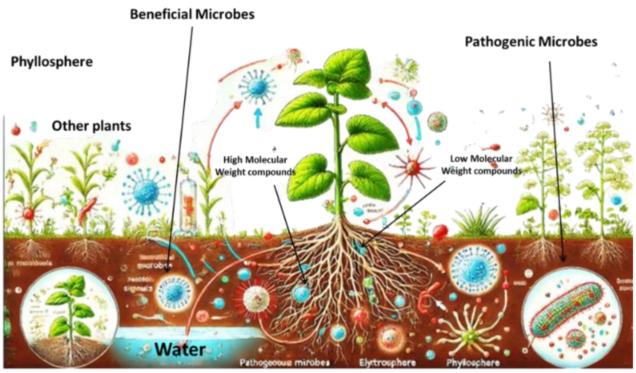

Fig 5: Interactions of beneficial and pathogenic microbes in the rhizosphere with emphasis on root exudates and chemical signaling.

B. Rhizosphere quorum sensing

Quorum sensing (QS), a type of cell-to-cell communication that regulates many types of microbial behaviours in the rhizosphere, can be particularly relevant for phytoremediation (Fig. 1). Many Gram-negative bacteria produce N-acyl homoserine lactones (AHLs) as key QS molecules, and AHL perception in plants can elicit a range of responses (Hartmann, 2020). Quorum sensing in the context of phytoremediation is also involved in regulating the biofilm that is an important prerequisite for the beneficial bacteria colonizing plant roots and forming a stable rhizosphere community (Ali et al., 2013; Harjai & Sabharwal, 2017; Mondal et al., 2025). Several AHLs have been demonstrated to promote plant growth and activate systemic resistance, which may benefit plant health in polluted soils (Hartmann, 2020; Shrestha & Schikora, 2020). Furthermore, QS can modulate the expression of metal resistance genes and organic pollutant-degrading genes in bacteria, thus increasing their phytoremediation capabilities (Arzanesh et al., 2011). In a fascinating development, plants can synthesize compounds that imitate or disrupt QS molecules of bacteria (Bais et al., 2008; Majdura et al., 2023), thereby modulating the behavior of microbes within the rhizosphere. By harnessing the QS mechanisms in the rhizosphere, phytoremediation can be optimized to be more effective in breaking down or sequestering contaminants through plant-microbe interactions (Arzanesh et al., 2011).

C. Between Plants and Microbial Metabolic Interactions

Plant-microbe metabolic interactions are at the basis of many phytoremediation processes. However, the application of plant growth-promoting rhizobacteria (PGPR) in heavy metal contaminated soils can improve the solubility of metals by producing siderophores, organic acids, and biosurfactants to increase metal bioavailability for plant uptake (Akhter et al., 2020). On the other hand, biotoxicity of metals would be avoided by immobilization of metals by biosorption or precipitation by some rhizobacteria (Gupta et al., 2024). For example, rhizospheric microbes are often equipped with the appropriate enzymatic pathways for degrading organic pollutants while the detoxification mechanisms for plants have been documented as well (Arzanesh et al., 2011). In exchange, collectively the carbon sources from plants via root exudates aid to enhance the growth and activities of the microbes (Ahemad & Kibret, 2014; Huang et al., 2014; Ma et al., 2022). Other microbes are capable of enhancing the metabolic potential of the plants themselves; for example, specific endophytic bacteria were found to increase the activity of plant enzymes responsible for degrading pollutants, such as dehalogenases and peroxidases (Anderson et al., 1993; Karaś et al., 2021). Such function can also provide nutrient cycling and availability of nutrients to plants in soil contaminated by heavy metals to help plant growth in stressful condition (Akhter et al., 2020). Phytoremediation, the use of plants to remove contaminants from the environment, may be a more efficient process if the rhizosphere and the complex interactions between plant and microbes that take place in it, become optimized as additional unique compartments of the plant matrix being utilized for environmental cleanup (Khan, 2005; Wenzel, 2009; Agarwal et al., 2020).

NEW INNOVATIONS IN PHYTOREMEDIATION

A. Genome editing techniques

Genome editing technologies have developed, and especially the modification of plant and microbial genomes using genome editing techniques has made it as a powerful tool for the improvement of phytoremediation. One of the areas where the CRISPR/Cas9 technology has proved especially significant is in plant metal hyperaccumulation and tolerance studies, which have allowed precision editing of the genes involved in metal uptake, translocation and tolerance. See, for example, the use of CRISPR/Cas9 to upregulate the expression of various metal transporter genes, resulting in higher metal accumulation and tolerance in plants (Ma et al., 2009; Belykh et al., 2019; Pandita, 2021). The overexpression of the AtHMA3 gene in *Arabidopsis thaliana* increased cadmium accumulation and tolerance in one study (Liu et al., 2017; Jiang et al., 2023). Likewise, genome-editing has been implemented on rhizobacteria to optimize their benefits for plant growth promotion and metal degradation (Akoijam & Joshi, 2024). For instance, bacterial strains have been genetically engineered with altered genes related to siderophore production or stress tolerance, and tested in phytoremediation scenarios (Barac et al., 2004). These approaches have the promise to achieve tailored "designer" plants and microbes for effective phytoremediation of targeted pollutants or environmental settings.

B. Applications of synthetic biology

Synthetic biology is paving the way for advanced phytoremediation through the design and assembly of new biological systems. One of the most evident applications is the creation of synthetic pathways that will allow plants to degrade or sequester certain contaminants. Experts have, for example, made plants express genes from bacteria for enzymes that permit breaking down of organic pollutants – like trichloroethylene (Kumari & Das, 2023) or polychlorinated biphenyls (Munawar et al., 2021). For heavy metal remediation, synthetic biology has been utilized to improve metal chelation and transport mechanisms to develop enhanced chelator-producing plants (Hofmann et al., 2020). By incorporating synthetic phytochelatin genes or altering existing metal transporter proteins, it has been possible to create plants that accumulate and tolerate greater amounts of metals (Koźmińska et al., 2018). Finally, the approaches of synthetic biology were also used for rhizosphere microorganisms to engineer and produce consortia with complementary functions so that metal-mobilizing bacteria are combined with plant growth-promoting strains to optimize the overall phytoremediation strategy (de Lima et al., 2019; Gupta et al., 2024).

Further development of genome editing and synthetic biology are the ultimate breakthroughs in phytoremediation due to the ability to make targeted changes to the DNA of both plants and microorganisms to increase contaminant accumulation and resistance. For example, gene regulation by CRISPR/Cas9 to control metal transport and accumulation genes in algae and other plants including Arabidopsis thaliana (Bhattacharyya et al., 2023). Large amounts of cadmium has been accumulated through studies that upregulated metal transporter genes such as AtHMA3 to enhance expressions of cadmium in plants that can be used to bio-accumulate (Liu et al., 2017). However, as said before, genome editing is not without constraints. Realization of genetically modified crops in open fields is still a contentious issue because of the legal traps and impacts on other species or environment like gene transfer to wild relatives or any other unintended impact on non-target organisms.

Synthetic biology goes a step further by building brand new biological circuits from the ground up inside plants, and microbes. One case is the use of genetic manipulation to cause plants to produce bacterial genes that encode for enzymes that may break down organic chemicals such as trichloroethylene (TCE) (Abhilash et al., 2009; Fazeli-Nasab & Rahmani, 2021). This (move) has been successfully done, for instance, by modifying poplar trees to produce poplar trees with bacterial dehalogenase enzymes capable of acting upon TCE water in the ground (Legault et al., 2017). The applications of synthetic biology are enormous, but there are difficulties for expressing synthetic pathways and sustainable existence as well as functionality in the field (Khalil & Collins, 2010; Katz et al., 2018). Furthermore, the development and implementation cost of synthetic biology solutions are high and, therefore, not feasible for most organizations.

Nevertheless, challenges in the implementation of genomic editing and synthetic biology into phytoremediation to meet the complexity of solutions are quite promising. The future research needs to work for reduction of ecological impacts, enhancement of the applicability of genetically modified systems, and gaining acceptance among people to realize the full use of such systems.

C. Fostering of plant-beneficial microbes

Progresses in molecular mechanisms of plant–microbe interactions offer novel strategies to redefine these interactions for optimized phytoremediation outcomes. The identification of the best plant-microbe combinations for use with specific contaminants and environmental conditions has only been made possible through high-throughput screening methods alongside metagenomic and metabolomic analysis (Gao et al., 2024; Srikanth et al., 2025). In response to this, researchers have started to design "designer rhizospheres" blanket term for selective inoculation of specific plants with summarized microbial consortia curated to boost plant growth and also rhizoremediation. Synergistic effects of co-inoculation with metal-resistant PGPR and arbuscular mycorrhizal fungi have been reported for plant growth and metal uptake in contaminated soils (Ju et al., 2019). In addition, the inoculation of "helper bacteria", which promote the colonization and activity of essential symbiotic microorganisms (e.g., rhizobia or mycorrhizal fungi), is a new tool to enhance the establishment and functionality of plant-microbe associations in phytoremediation systems (Ma et al., 2009; Rigamonte et al., 2010; Sangwan & Prasanna, 2022). In addition, the use of advanced bioinformatics tools and machine learning algorithms for prediction and optimization of plant microbiome interactions resulting in enhanced phytoremediation, facilitates more targeted and efficient remediation (Liu et al., 2017).

PHYTOREMEDIATION IN CONJUNCTION WITH BIOENERGY GENERATION

A. Possible synergies and gains

Combining phytoremediation with bioenergy production provides opportunities to obtain major synergies and advantages in terms of environmental remediation and renewable energy. This strategy, known as phytotechnology, integrates the soil remediation power of phytoremediation with the production of biomass that can serve valuable energy pots (Chandra, et al., 2015). These synergies involve remediation of contaminated land while producing renewable energy feedstock, which could make phytoremediation projects more cost-effective (Witters et al., 2012; Grifoni et al., 2021). The plants identified through this integrated strategy can accumulate the contaminants from the soil or water, and produce biomass that can be thereafter transformed into different bioenergy sources like bioethanol, biodiesel or biogas (Ochieng et al., 2022). Additionally, growing bioenergy crops on contaminated land can mitigate food security and competition between food and fuel crops for arable land (Barbosa et al., 2018). This integration also plays its part in carbon sequestration and greenhouse gas emissions mitigation, conforming to global climate change mitigation strategies (Ussiri & Lal, 2017). Furthermore, over time it can also improve soil quality and biodiversity and restore degraded ecosystems while delivering renewable energy.

B. Case studies and examples

There are many case studies where phytoremediation and bioenergy production have been combined successfully. One specific case is with Miscanthus a high-yielding perennial grass is used for its phytoremediation and bioenergy production ability in arable lands polluted with metals in Europe (Singh & Pandey, 2020). Results from this study demonstrated the ability of Miscanthus to preferentially accumulate cadmium and zinc while also generating substantial biomass for bioenergy production. Another case study based in the USA examined Phytoremediation of trichloroethylene contaminated groundwater using hybrid poplar trees while simultaneously producing woody biomass for bioenergy (Longley, 2007; Legault, 2013). This project showed not only successful contaminant removal but also the ability to produce biomass at an economical rate. *Jatropha curcas* has also been grown on mine tailings in China for phytoremediation and biodiesel production from the oil-rich seeds (Kumar et al., 2017; Malabadi et al., 2023). Note that these examples illustrate the wide range of contaminants and geographical regions where integrated phytoremediation and bioenergy production have been or could be applied.

Table 2: Large-Scale Phytoremediation Projects and Key Outcomes

Project Location	Plant Species	Contaminant	Scale	Outcome/Observations	References
California, USA	Hybrid poplar	Trichloroethylene (TCE)	10-year project	Significant TCE reduction in groundwater; biomass processed for bioenergy.	Strycharz & Newman, 2009
Europe (Germany, Poland)	*Miscanthus x giganteus*	Cadmium, Zinc	5 hectares	Reduced metal concentration in soil; bioenergy production offset costs.	Romantschuk et al., 2024; Zgorelec et al., 2025
China (Guangxi Province)	*Jatropha curcas*	Heavy Metals (Cd, Pb, As)	20 hectares	Mine tailings remediated; biodiesel produced from harvested seeds.	Kumar et al., 2017; Malabadi et al., 2023
Brazil (Minas Gerais)	*Vetiveria zizanioides*	Arsenic, Mercury	15 hectares	Stabilized mercury; erosion control improved soil health and structure.	Bernardino et al., 2016; Naz et al., 2022
India (Jharkhand Mining Belt)	*Helianthus annuus*	Lead, Nickel	12 hectares	Lead levels reduced by 40%; harvested biomass safely disposed.	Lothe et al., 2016; Chauhan & Mathur, 2020
Italy (Industrial Site)	*Pteris vittata*	Arsenic	8 hectares	Arsenic extracted from contaminated farmland; biochar produced from biomass.	Bettiol et al., 2012;Cantamessa et al., 2020

All these case studies show that even though phytoremediation is a very effective method for cleaning up the environment, it relies on some key factors like plant species, site characteristics and compatibility of other technologies. To implement phytoremediation at a larger scale, innovative approaches that balance remediation goals, environmental processes, and social contexts for each site need to be adopted along with an ongoing control and data sharing among foresters, engineers, and inhabitants.

C. The Challenges and Opportunities

Phytoremediation combined with bioenergy production has several advantages while facing many challenges. This can occur if mishandled, causing byproducts to potentially introduce contaminants into the food chain or energy production cycle (Gomes, 2012; Prabha, 2021). It is thus important to correctly monitor and process the biomass to ensure it can be used safely. Choosing plant species that can effectively remove contaminants, produce sufficient biomass, and generate high-quality fuels also remains a hurdle. It often involves some trade-off between phytoremediation efficiency and biomass production. In addition, there is still a need for studies on the ecological sustainability of land use even when it consists on the long-term cultivation of energy crops grown on contaminated lands (Abhilash et al., 2016; Barbosa et al., 2018).

Even so, a great deal of room still exists to promote this blended framework with the challenges posed. New plant breeding and genetic engineering techniques could be used to produce next-generation plant varieties that are optimized for enhanced phytoremediation and high-quality biomass production for energy (Yadav et al., 2010; Shah & Pathak, 2019). There are also future perspectives that are presented in relation to novel biomass conversion technologies that could tolerate contaminated and/or low biomass–energy conversion feedstocks (Callegari et al. 2020). Moreover, enabling policies and economic incentives can promote the widespread adoption of this approach leading to further implementation at scale and substantial environmental and economic benefits (Opschoor & Turner, (Eds.) 1994). Future research in this field opens the opportunity to develop specific and more efficient and sustainable systems that can enhance both remediation and energy generation with a circular economy outlook, in land remediation and energy generation.

FIELD APPLICATIONS FOR SCALED UP PHYTOREMEDIATION

A. Existing obstacles in Large Scale Implementation

Phytoremediation scaling up from lab or small-scale field trials to field-scale applications, retains several important challenges. The heterogeneity of contaminated sites is one of the major challenges consisting of diverse soils, the properties of soils, contaminant distribution, and environmental conditions (Tao et al., 2022). Such variability makes it challenging to predict and optimize performance of plant across wide long distances. Finally, the excessive time necessary for adequate remediation often takes several growing seasons or years, which can deter stakeholders looking for expedited responses (Hull et al., 2015; Chandra et al. 2019). Choosing the correct plant species able to grow in the given contaminated environment and perform the remediation of the pollutant on a larger scale continues being a crucial problem. In addition, the cultivation of large-scale plant- soil system that comes as in vitro remediation, requires considerable indirect expenses, including periodic cultivation, examination, and re-plantation making this process logistically challenging and expensive (Martin & Ruby, 2004). Another issue is the possibility that contaminants will enter the food chain by being taken up by the plants; thus, the biomass must be carefully managed and disposed of. In addition, regulatory frameworks and societal acceptance of phytoremediation as a large-scale remediation technology can constrain its implementation in certain areas (Phang et al., 2024).

B. Ways to work through drawbacks

Several strategies have been developed to overcome the challenges of phytoremediation scalability. One way is through the application of advanced site characterization approaches such as geospatial mapping and predictive modeling to inform decision-making that accounts for site heterogeneity (Siddique, 2024). Thus, these plants can be used for selective and cost-effective application of phytoremediation (Becerra-Castro et al., 2013). Another potential approach is to develop genetically modified or selectively bred plant varieties with improved remediation capacity and greater tolerance to a wide range of environmental conditions (KhokharVoytas et al., 2023). Phytoremediation can be combined with other remediation technologies, including bio-stimulation and soil amendments, to increase cleanup rates and efficiency (Zaghloul, 2020). In order to overcome time limitations, high-biomass, rapidly growing plants are gaining popularity. Precision agriculture methods in addition to drone-based monitoring and irrigation-based methods may allow us to have more efficient processing and cost-effective management of large scale projects (Khare, 2025). Addressing concerns about the transfer of contaminants, research is moving toward designing plants that either sequester contaminants in non-harvestable fractions or convert them into less toxic forms. At the same time, third, contaminated biomass remains accessible for exploitation of its value-added end-uses such as bioenergy production or phytomining, which may help to balance the cost of remediation with short- and long-term economic advantages that may improve the cost-effectiveness of large- scale projects (Phang et al., 2024).

DISCUSSION

This review underscores the unprecedented complexity of phytoremediation in which plant-microbe interactions drive processes, including rhizosphere stimulation, phytostabilization, phytoextraction, and phytodegradation. These fundamental processes are greatly improved by some of the latest technologies in genome editing and synthetic biology have expanded and accelerated phytoremediation technologies. For example genetically engineered plants using CRISPR/Cas9 systems for increased metal accumulation or microbial endophyte with biosurfactant synthesis potential show that innovation is helping overcome the challenges associated with phytoremediation. However, field applications show that although laboratory results are encouraging and innovative biotechnology solutions are effective when tested, implementing them at the field level involves the thoughtful interaction of biotechnological solutions and practical, site-specific solutions.

One lesson learned from case studies includes relationship between the use of *Miscanthus* x *giganteus* in Europe and hybrid poplar to remove trichloroethylene (TCE) in California, specifically the relationship between plants, microbes, and environment. Such projects show the importance of identifying the right plants to use and overall conditions within the rhizosphere for enhancing uptake and removal of contaminants. The combination of bioenergy production with phytoremediation shows that these technologies not only have economic benefits, but also allow for turning numerous environmental problems into economically beneficial processes. However, there are challenges, which include; slow plant growth, availability of the contaminants, and regulatory issues which limits its production. Overcoming these challenges will involve the use of plant biology, microbiology environmental engineering, policy to among other disciplines.

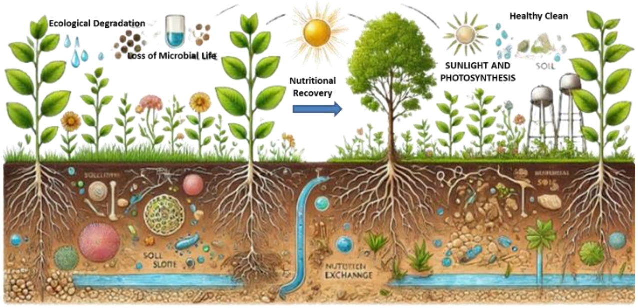

Fig 6: Figure illustrating ecological recovery and environmental restoration

Practical Implication

Thus, the derived efficiency of the phytoremediation research has further applications in environmental science, agriculture and industry rehabilitations. One of the most prospective areas is utilization of contaminated agricultural lands for using hyper-accumulator plants and plant growth-promoting rhizobacteria (PGPR) to rehabilitate the soil and ensure safe food production. Likewise, quicker clean-up of oil and petroleum hydrocarbon slicks, organic pollution and other hydrocarbons may also be achieved through the help of bio-surfactant producing bacteria and GM plants capable of degrading complex organic materials.

For industrial stakeholders, integrating phytoremediation with bioenergy production provides a dual benefit: In the area of sustainable development, it is involved in land remediation as well as the generation of renewable energy resources. This model can be an opportunity to ensure the brownfield contaminated lands become again productive land in order to improve the economic balance of the remediation costs with the additional value as actuators of carbon sequestration. Governments and policymakers too can benefit from implementing phytoremediation technologies in their municipality by reclaiming contaminated urban soils and for construction of new green infrastructures all to enhance cleanliness and public health.

In addition, phytoremediation is cheaper than other standard remediation techniques like excavation and chemical treatment, it is in a position to reach out to the needy people in the low income streams and the developing world. However, success in deployment depends on the choice of plant species, proper site characterization, and the use of microbial inoculants when developing the remediation capacity.

Future Research Directions

A. New frontiers in plant-microbe interactions

Phytoremediation research is in full expansion mode, with some new emerging trends promising even improved efficiency. A particular area of attention is the signaling networks on complexity between plants and microbial network associated with them, in contaminated environments. Techniques such as meta-omics (i.e., meta-genomics, meta-transcriptomics and meta-bolomics) are revealing the astonishing functional dynamics of plant-microbe interactions at unprecedented detail within the context of phytoremediation processes (Jaffri & Ahmad, 2024). The plant holobiont, an emerging field in plant biology that examines plants and their microbiome as one ecological unit, is another area under investigation. This strategy is uncovering novel insights into plant and microbe evolution and adaptation in contaminated environments (Vandenkoornhuyse et al., 2015; Sánchez-Cañizares et al., 2017; Lyu et al., 2021). Moreover, there is a growing interest in understanding plant-induced changes in volatile organic compounds (VOCs) that mediate plant-microbe interactions and their potential applications in stimulating microbial recruitment to enhance contaminant degradation (Fester et al., 2014; Xiong et al., 2023). In addition, it is also an emerging topic to explore microbial consortia and their synergistic effects on the phytoremediation goal oriented to designing more resilient and efficient remediation systems (Lee et al., 2025).

B. Technological advancements that could take off

In addition, the rapid evolution of technology in the next years should boost the performance of these methods and broaden their applicability in phytoremediation. Advances in this field may include the creation of new smart biosensors (Sharma et al., 2022) that allow researchers to monitor contaminant levels, plant health, or microbial activity in real time within phytoremediation systems (Pal et al., 2025). These new sensors could generate valuable data that could inform remediation optimization and serve as an early warning system. Another mode of technological progress is nanotechnology application in phytoremediation, where engineered nanoparticles offers opportunities to increase contaminant bioavailability and plant uptake (Gulzar & Mazumder, 2022; Gomes, 2025). Another fast-growing frontier is the use of artificial intelligence and machine learning algorithms to predict and optimize plant-microbe interactions for phytoremediation (Mohan et al., 2024; Gul et al., 2025). Furthermore, plant breeding and genetic engineering methods like CRISPR-Cas9 are creating new opportunities for creating phytoremediation-capable plants (Naz et al., 2022; Verdezoto-Prado et al., 2025). The other major area of advancement in technology that can improve both the efficiency and cost-effectiveness of remediation projects, is the adaptation of drone technology and remote sensing for large scale monitoring and management of phytoremediation sites (Jia et al., 2021; Alsadik et al., 2024).

C. Interdisciplinary methods to achieve higher efficiency of phytoremediation

Interdisciplinary approaches integrating different fields of science are becoming essential to enhance the efficacy of phytoremediation. Plant biology, microbiology, soil science, and environmental engineering collectively contribute to designing integrated phytoremediation strategies (Thijs et al. 2016; Simmer & Schnoor, 2022). We propose that combining ecological concepts (such as community assembly theory and ecosystem functioning) and phytoremediation research can yield fresh perspective to enhance plant-microbe interactions for achieving optimal contaminant removal. Systems biology approaches, including integration of multi-omics data and mathematical modeling, are proving to be powerful in the understanding and the prediction of the behaviour of complex systems involving plants, microorganisms, and contaminants (Pinu et al., 2019; Gutierrez Reyes et al., 2024). Phytoremediation researchers are developing new programmatic collaborations with bioinformaticians and data scientists in an effort to provide expertise in high throughput datasets interpretation (Mohanty, 2021). Moreover, to overcome the barriers of deployment and social acceptance of phytoremediation technologies at larger scales, it is still difficult to integrate social sciences and policy research within the discipline (Wolfe & Bjornstad, 2002; Montpetit, & Lachapelle, 2017). Another interdisciplinary approach that may increase the sustainability and economic attractiveness of remediation projects is the coupling of phytoremediation with other green technologies (constructed wetlands or bioenergy production) (Grifoni et al., 2021; Breil et al., 2022).

CONCLUSION

Recent advancement in the phytoremediation field has shown that, through plant-microbe interaction, it is a sustainable and cost effective technology. Despite the competition in technologies in the field of phytoremediation, the integration of genome editing, synthetic biology for microbial consortia into phytoremediation tactics recent great strides in enhancing the phytoremediation approaches in complex contaminated contexts. The pragmatic applications including use of bioenergy crops for land treatment and remedial planting of hybrid poplars for ground water cleaning further substantiate these concepts and their massive commercial potential.

Nonetheless, the possibilities of phytoremediation make the challenge very promising in achieving sustainable solution to hazardous waste pollution and more research and academic and interdisciplinary cooperation will be desirable to address the problems related to long remediation time, bioavailability of contaminants and biomass disposal. Therefore, the future of phytoremediation depends on the amount of research and efforts put by the government and other serious minded bodies in conducting field trials and framing policies for further action to help in the revival of damaged ecosystems and combating climate change and verso. The aspirations of future developments of phytoremediation can be established in the unity of high technology and excellence and the worldwide march towards creating cleaner and healthier environments.

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