IJARSCT
ISSN (Online) 2581-9429
International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
Impact Factor: 7.53
Volume 4, Issue 1, June 2024

Phytoremediation: An Eco-Friendly Solution for Environmental Contamination

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Abstract: *Phytoremediation, the process of using plants to clean up environmental pollutants, is becoming increasingly popular due to its eco-friendly nature, sustainability, and cost-effectiveness. This research delves into the potential of phytoremediation in handling different types of pollution, such as heavy metals, radioactive substances, pesticides, and organic chemicals. We explore the inner workings of phytoremediation, shedding light on mechanisms like phytoextraction, rhizofiltration, phytostabilization, phytodegradation, and phytovolatilization. Our research also delves into the genetic and molecular structures that enable these processes in various plant species. Despite its promise, phytoremediation has its hurdles. For instance, there's a risk of bioaccumulation, and the method can only treat a limited selection of contaminants effectively. Our study ends with a look at the future trajectory of phytoremediation, placing special emphasis on the potential role of genetic engineering in amplifying its effectiveness and broadening its scope. Ultimately, our research underscores that, when employed properly, phytoremediation can provide an eco-friendly solution for handling and rehabilitating polluted sites. This contributes to the broader goal of sustainable development and preserving environmental health.*

Keywords: Bioaccumulation, Contamination, Environmental Health, Genetic Engineering, Sustainable Development

I. INTRODUCTION

Phytoremediation emerges as an environmentally friendly method that harnesses plants and their associated microorganisms to combat soil, water, and air pollution. This holistic approach effectively addresses diverse contaminants, including heavy metals, organic pollutants, and radionuclides. The review provides a comprehensive exploration of various phytoremediation types, detailing their advantages, drawbacks, and potential future applications. A notable strength lies in the versatility of phytoremediation, with techniques such as phytoextraction, phytostabilization, phytovolatilization, rhizofiltration, and phytodegradation selectively employed based on contamination nature and extent. Each technique employs specific mechanisms to efficiently target and mitigate pollutants. Furthermore, phytoremediation offers several advantages over traditional methods. It is a cost-effective approach, requiring lower energy consumption and eliminating the need for excavation or disposal of contaminated materials. Its in situ implementation minimizes disruption to the surrounding environment. Additionally, the aesthetic benefits are noteworthy, as green spaces can be established using plants endowed with remediation capabilities. This underscores the practicality and sustainability of phytoremediation as a valuable tool in environmental remediation efforts.

Phytoremediation, despite its numerous advantages, confronts various limitations and challenges. The inherently time-consuming process relies on the gradual growth and development of plants to achieve remediation goals, especially notable in large-scale or heavily contaminated sites, where substantial results may necessitate several years. Moreover, the efficacy of phytoremediation is inherently variable, influenced by factors such as plant species, soil conditions, and climate. Thus, the meticulous selection of appropriate plant species and a comprehensive site assessment become pivotal for the successful implementation of phytoremediation. Regarding heavy metal detoxification, plants have evolved diverse mechanisms to cope with these contaminants. Some plants release root exudates containing chelating agents capable of binding to heavy metals, facilitating their removal from the environment. Additionally, certain plants possess the ability to accumulate heavy metals in their tissues, preventing their entry into the food chain and potential harm. Furthermore, specific plants demonstrate the capability to transform toxic forms of heavy metals, such as lead and cadmium, into less harmful forms, which can be more easily absorbed and detoxified by living organisms . These adaptive strategies underscore the intricate ways in which plants contribute to the detoxification and removal of heavy metals from the environment.

It is no secret that the environment is facing many challenges due to human activities. One of the most serious of these challenges is the contamination of soil and water by pollutants, such as heavy metals, organic compounds, and other toxic substances [1]. Phytoremediation is an emerging technology that uses plants to remediate contaminated soils and water [1]. This review paper will provide an overview of phytoremediation and discuss its advantages and limitations compared to other remediation technologies. Phytoremediation is the process of using plants to remove pollutants from soils and waters. It relies on the natural ability of plants to absorb, metabolize, and accumulate pollutants in their tissues or the surrounding soil through their root systems [2].

Heavy metals are one of the major environmental pollutants that can be taken up and translocated throughout plant tissues [3]. Uptake and translocation of heavy metals can occur through root absorption as well as aerial deposition. In plants, heavy metals are taken up into the root cells and then transported to the xylem vessels, where they can be translocated to other parts of the plant. Translocation occurs when heavy metals are absorbed by the roots and then transported through the xylem to the leaves, stems, and other parts of the plant [4]. Several variables, including the type of heavy metal, soil nutrient availability, soil pH, and plant age, play a role in how plants absorb and transport heavy metals [5]. Plants have the ability to take up heavy metals such as iron, copper, and lead, which are found as ions in the soil [6]. The soil's pH and its nutrient content are crucial factors determining the availability of these ions for plant uptake [7]. Interestingly, the soil pH affects the availability of different heavy metals differently. For instance, iron and copper are more readily absorbed by plants from slightly acidic soil, while lead is easier for plants to absorb from alkaline soils [4]. Despite their availability, heavy metals can be harmful to plants and can build up in soil and water. This accumulation can pose potential health risks to humans and animals [8]. Understanding the process by which plants absorb and transport heavy metals is important for comprehending how they manage to survive in metal-rich environments. Primarily, plants absorb heavy metals through their roots either by ion exchange or diffusion across the root membrane. Once inside the plant, these metals are transported via the stem to various parts of the plant such as leaves, flowers, and fruits, in a process referred to as "metal translocation" [9]. Numerous factors come into play when considering the translocation of heavy metals. Elements such as the concentration of these metals in the soil, the soil type, its pH, and the level of organic matter it holds, all contribute to how these metals are absorbed and distributed within plants [10]. Further, the plant species, its growth stage, and genetic makeup are also vital considerations in determining the metal uptake and translocation process.

It's also essential to understand that not all heavy metals affect plants in the same way. Metals with higher toxicity levels, like lead, mercury, and cadmium, tend to inflict more harm on the plants, while others like zinc, copper, and iron are generally less destructive [11]. Interestingly, some plants can play a crucial role in remediation of soil contaminated with heavy metals. Specific plant species exhibit a higher tolerance to these metals, making them effective tools to decrease metal concentrations in the soil[12]. These plants achieve this by absorbing heavy metals through their root system, storing them within their tissues or distributing them to other parts of the plant, thereby reducing the soil's metal content [13]. In conclusion, understanding how plants handle heavy metal uptake and distribution is crucial for comprehending their response to metal toxicity. Additionally, this knowledge is key in leveraging plants to decrease soil metal concentrations, thereby aiding in environmental conservation efforts [14].

In conclusion, phytoremediation is a promising approach for addressing environmental pollution through the use of plants and associated microorganisms. It offers numerous advantages, such as cost-effectiveness, ecological benefits, and versatility. However, its effectiveness and applicability depend on various factors and require careful consideration. Further research and technological advancements are necessary to optimize phytoremediation techniques and expand their potential applications in the future.

The next session 2 we are discussing the types of phytoremediation which discusses various techniques like phytoextraction, phytostabilization, phytodegradation, rhizofiltration and phytovolatilization. Section 3 shows the factors affecting the effectiveness of phytoremediation like plant species, soil properties, environmental conditions. In section 4, we present the plant species involved in various types of pollutants like heavy metals, organic pollutants, radioactive materials and nutrients. Section 5 is on various heavy metals like zinc, cadmium, iron, arsenic, nickel and their toxic effects on humans leading to dizziness, fatigue, lung damage, brain, kidney, liver damage and so on. Section 6 is on various plant species which can accumulate toxic heavy metals. In section 7 various methods to improve plant performance are being discussed. It can be easily followed as it says about soil, nutrient and water conditions needed for the plants to gain better results. Section 7 is divided into 3 subsections 7.1, 7.2 and 7.3 that can be used to improve the plant efficiency. 7.1 presents the microbes that can be used to improve phytoremediation. 7.2 discusses genetic engineering which enables the enhancement of plant resistance to specific contaminants, making them more effective in environmental cleanup efforts. 7.3 shows the methods to enhance bioavailability of heavy metals to plants like using chelators. In section 8, advantages of phytoremediation are being discussed. Next section 9 is on the disadvantages of phytoremediation. Section 10 presents the future aspects of phytoremediation which is divided into six subsections mentioning about the techniques and methods to improve phytoremediation.

II. TYPES OF PHYTOREMEDIATION

Phytoremediation is primarily categorized into two techniques: phytoextraction and phytostabilization[15]. Phytoextraction employs plants to remove contaminants from soil, water, or air, with its most notable success in eliminating heavy metals from polluted soil [16]. Plant species utilized for this purpose are typically those capable of accumulating significant amounts of metals in their tissues. Once harvested, these plants can be safely disposed of, effectively removing the contaminants [17] Notable examples of phytoextraction plants include Indian mustard (Brassica juncea) and sunflower (Helianthus annuus) [18]. Conversely, phytostabilization focuses on containing pollutants within contaminated soil, hindering their dispersion or leaching into surrounding environments [19]. By using plants to immobilize these contaminants, phytostabilization aims to minimize the spread and potential harm caused by pollutants in the soil.

Table 1: Types of phytoremediation and their description

Types of Phytoremediation	Description
Phytoextraction	The use of plants to remove pollutants from the soil through the roots and transport them to the above-ground parts of the plant for harvesting and disposal [20].
Phytostabilization	The use of plants to immobilize pollutants in the soil and prevent them from spreading by forming a physical or chemical barrier [21].
Phytodegradation	The use of plants to break down or transform pollutants through metabolic processes within the plant [20].
Rhizofiltration	The use of plants to remove pollutants from water by filtering them through the roots [22].
Phytovolatilization	The use of plants to remove pollutants from the soil or water by releasing them into the air through a process called transpiration [22]

2.1 Phytoextraction

This process involves the uptake of contaminants in soil by plant roots and their subsequent accumulation in the above-ground plant parts [23]. Phytoextraction is the process of using plants to absorb, accumulate, and sequester metals and other contaminants from soils into their tissues. This form of phytoremediation involves growing plants in metal-contaminated soils and subsequently harvesting and removing the plant biomass for disposal or further processing [24]. Plants used for phytoextraction typically possess a high capacity for metal uptake and are referred to as hyperaccumulators. Popular hyperaccumulators used for phytoextraction include Thlaspicaerulescens, Brassica juncea, and Sedum alfredii. Metals can be sequestered in the roots, stems, leaves, or fruits of the plant, and the biomass can then be processed to concentrate the metals [25]. This phytoremediation method is effective for the extraction of metals from soils. Still, it is limited by the availability of hyperaccumulators, the slow growth of many species, and the cost of harvesting, processing, and disposing of plant biomass [26].

2.2 Phytostabilization

Phytostabilization is a method where plants are employed to absorb and secure contaminants within their root systems, ensuring they don't permeate the food chain. It's a technique where vegetation is used to limit and hinder the movement of pollutants in soil or sediment [27]. In this technique, plants and their corresponding rhizosphere play a critical role in minimizing the transport of metals and other contaminants within the soil. It's a strategy commonly employed to tackle soil and sediment contamination from heavy metals, radionuclides, and various harmful compounds. To ensure successful phytostabilization, it's crucial to select plant species with a high tolerance and accumulation capacity for the specific contaminants. These plants aid in immobilizing the contaminants in the soil through processes like rhizofiltration or biodegradation, effectively reducing the contaminants' bioavailability [28].

2.3 Phytodegradation

This process involves the use of plants to break down and degrade persistent organic pollutants (POPs) in soil and water. Phytodegradation is a form of bioremediation that uses plants to break down and remove pollutants from the environment [29]. It is a natural process that uses the metabolic activities of microorganisms and plants to degrade, transform or immobilize contaminants. Plants can take up, transform, and store contaminants, making them unavailable for uptake and metabolism by other organisms. Plants can also facilitate the breakdown of contaminants through the release of metabolites and other compounds as well as through their roots and rhizosphere [30]. This process is attractive because it is cost-effective, safe, and ecologically sound.

2.4 Rhizofiltration

Rhizofiltration is a strategy that utilizes plant roots to sieve contaminants, including metals and organic compounds, from water bodies [31]. It's a form of water treatment that capitalizes on the inherent ability of aquatic plant roots to absorb contaminants from their environment.The process is efficient in eliminating a range of pollutants, including heavy metals and pharmaceutical compounds, from various water sources [32]. To implement rhizofiltration, aquatic plants like reeds or rushes are introduced into the contaminated water bodies. As these plants draw water from the source, they concurrently absorb and trap pollutants within their root systems. Once the plants have absorbed the contaminants, they can be harvested and disposed of safely, thus effectively cleaning the water. Rhizofiltration has been successfully employed to purify water sources, including lakes and rivers, from various pollutants [33].

2.5 Phytovolatilization

Phytovolatilization is a process where plants absorb volatile organic compounds (VOCs) from the atmosphere or soil and transform them into less harmful substances. It plays a crucial role in the movement of VOCs from the environment into the atmosphere, aided by plant activity [34]. Plants' uptake of VOCs, either from air or soil, is followed by their release through various mechanisms. These VOCs, once liberated, can travel to other regions, carried by wind or water, potentially affecting air quality and human health [35]. While phytovolatilization can occur naturally, such as the emission of volatile oils from plants, it can also result from human actions, like the release of VOCs from industrial operations [36]. Regardless of the source, this process highlights the role of plants in mitigating environmental pollution.

III. FACTORS AFFECTING THE EFFECTIVENESS OF PHYTOREMEDIATION

Table 2: Factors affecting the effectiveness of phytoremediation

Factor	Description
Type of Pollutant	Different plants are better suited for different types of pollutants, and some pollutants may require multiple plant species for effective remediation [37].
Plant Species	The selection of the appropriate plant species is critical for the success of phytoremediation. Factors such as the plant's ability to tolerate the pollutant, its growth rate, and its root depth are important considerations[38].
Soil Properties	Soil properties such as pH, organic matter content, and nutrient availability can affect the growth and effectiveness of plants in removing pollutants [39].
Environmental Conditions	Environmental factors such as temperature, rainfall, and sunlight can affect plant growth and the rate of pollutant removal [40].
Pollutant Concentration	The concentration of pollutants in the soil or water can affect the effectiveness of phytoremediation, with higher concentrations requiring more time and resources to remediate [41].

Phytoremediation, as an eco-friendly strategy for environmental remediation, is intricately influenced by several key factors. Foremost, the nature of the pollutant is critical, as different plants exhibit distinct capabilities in remediating specific contaminants, sometimes necessitating collaborative efforts of multiple plant species for optimal outcomes. The careful selection of plant species is paramount, with considerations such as the plant's tolerance to the pollutant, growth rate, and root depth playing pivotal roles. Furthermore, soil properties, encompassing pH, organic matter content, and nutrient availability, significantly shape plant growth and effectiveness in pollutant removal. Environmental conditions, including temperature, rainfall, and sunlight, play a crucial role in determining the success of phytoremediation by influencing plant growth and pollutant removal rates. Lastly, pollutant concentration directly impacts the remediation process, with higher concentrations demanding increased time and resources for successful pollutant removal. A comprehensive understanding and consideration of these factors are imperative for the meticulous design and implementation of effective phytoremediation strategies tailored to specific environmental challenges.

IV. PLANT SPECIES ASSOCIATED WITH DIFFERENT TYPES OF POLLUTANTS

Table 3: Different plant species for different types of pollutants

Type of Pollutant	**Plant Species**
Heavy Metals	Indian mustard, sunflower, willow, poplar, ferns [42]
Organic Pollutants	Hybrid poplar, alfalfa, white mulberry, corn [43]
Radioactive Materials	Sunflower, soybean, mustard, hemp [44]
Nutrients	Water hyacinth, duckweed, water lettuce [45]

In the realm of phytoremediation, the careful selection of plant species emerges as a pivotal determinant, intricately tailored to the nature of the targeted pollutant for remediation. In addressing heavy metal contamination, plant species like Indian mustard, sunflower, willow, poplar, and certain ferns have demonstrated exceptional aptitude in accumulating and sequestering metals from the soil, leveraging their hyperaccumulation traits for efficient absorption and storage of heavy metals. Transitioning to the remediation of organic pollutants, the deployment of hybrid poplar, alfalfa, white mulberry, and corn is noteworthy. These species exhibit significant potential in breaking down and metabolizing various organic contaminants, thereby contributing to the effective cleanup of soil or water. In the context of sites tainted with radioactive materials, the selection of sunflower, soybean, mustard, and hemp stands out due to their adeptness in uptakingand accumulating radionuclides. Lastly, for nutrient-rich environments grappling with eutrophication, the inclusion of water hyacinth, duckweed, and water lettuce proves effective in nutrient removal, particularly nitrogen and phosphorus. This strategic curation of plant species underscores the adaptability and versatility of phytoremediation, offering a targeted and natural approach to address a diverse spectrum of environmental pollutants.

V. HEAVY METALS AND THEIR TOXIC EFFECT ON HUMAN

Table 4: Regulatory limits and toxic effects of heavy metals in soil

Heavy Metal	WHO Regulatory Limit (mg/kg)	FAO Regulatory Limit (mg/kg)	Toxic Effects
Zn	99.4	16	Dizziness, Fatigue [46]
Cd	0.26	0.2	Carcinogenic, mutagenic, endocrine disruptor, lung damage and fragile bones, affects calcium regulation in biological systems [47]
Cr	100	3.8	Hair Loss [48]
Fe	50-100	05-50	Damaging the function of the brain, lungs, kidney, liver, blood composition [49]
As	4.5	4.5	Affects essential cellular processes such as oxidative phosphorylation and ATP synthesis [50]
Ni	2.6	2.6	Allergic skin diseases such as itching, cancer of the lungs, nose, sinuses, throat through continuous inhalation, immunotoxic, neurotoxic, genotoxic, affects fertility, hair loss [51]
Pb	55	0.3	Excess exposure in children causes impaired development, reduced intelligence, short-term memory loss, disabilities in learning and coordination problems, risk of cardiovascular disease [52]
Mn	11	11	Continued exposure can damage the lungs, liver, and kidneys. Exposure to manganese dust or fumes can also lead to a neurological condition called manganism[53]
Cu	35	73.3	Brain and kidney damage, elevated levels result in liver cirrhosis and chronic anemia, stomach and intestine irritation [54]
Co	32	24	Asthma attacks with shortness of breath, wheezing, cough, and/or chest tightness[55]

Heavy metals, including zinc (Zn), cadmium (Cd), chromium (Cr), iron (Fe), arsenic (As), nickel (Ni), lead (Pb), manganese (Mn), copper (Cu), and cobalt (Co), present substantial environmental and health hazards. Regulatory limits established by organizations such as the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) play a pivotal role in guiding efforts to mitigate the impact of these metals. Exceeding these established limits can result in severe toxic effects. For example, elevated cadmium levels can lead to carcinogenic and mutagenic effects, along with lung and bone damage. Lead exposure, particularly in children, is associated with impaired development, reduced intelligence, and heightened cardiovascular risks. Chromium concentrations beyond regulatory limits may cause hair loss, while excess iron exposure can harm the brain, lungs, kidneys, liver, and blood composition. Each metal manifests distinct toxic effects, encompassing neurological conditions (as seen in manganese exposure) to skin diseases and immunotoxicity (linked to nickel). A comprehensive understanding of these regulatory limits and associated toxic effects is imperative for the implementation of effective environmental remediation strategies and the protection of human health.

VI. PLANT SPECIES WHICH CAN ACCUMULATE HEAVY METALS

Table 5:Phytoremediation potential of selected plant species in contaminated areas with specific heavy metals

Plants	Category	Contaminated Areas	Heavy Metals	References
Allium schoenoprasum L. (Chive)	Phytoaccumulators	Soil	Ni, Co, Cd	[55]
Brassica juncea L. (Indian mustard)	Hyperaccumulator	Soil and Water	Cd, Cu, Zn, Pb	[56]
Brassica napus L. (canola)	Hyperaccumulator	Soil	Cd, Cu, Zn, Pb	[57]
Cajanus Cajan (L.) Milsp. (pigeon pea)	Phytostabilizers	Soil	As, Cd	[58]
Cicer aeritinum L. (chickpea)	Phytoaccumulators	Soil	Cd, Pb, Cr, Cu	[59]
Cucumis sativus L. (cucumber)		Water	Pb	[60]
Eichhornia crassipes L. (water hyacinth)	Hyperaccumulator	Water	As, Cr, Zn, Cs, Co	[61]
Jatropha curcas L. (purging nut, physic nut)	Phytoaccumulators	Soil	Fe, Al, Cu, Mn, Cr, As, Zn, Hg	[62]
Lantana camara L. (lantana)	Phytostabilizers	Soil	Pb	[63]
Lens culinaris Medic. (lentil)	Phytoaccumulators	Soil	Pb	[64]
Lepidium sativum L.	Phytoaccumulators			

(cress)		Soil	As, Cd, Fe, Pb, Hg	[65]
Lactuca sativa L. (lettuce)	Phytoaccumulators	Soil	Cu, Fe, Mn, Zn, Ni, Cd, Pb, Co, As	[66]
Medicago sativa L. (alfalfa)	Phytoaccumulators	Soil	Cd	[67]
Oryza sativa L. (rice)	Phytoaccumulators	Soil	Cu, Cd	[68]
Pistia stratiotes L. (water lettuce)	Phytoaccumulators	Water	Cr, Cd, As	[69]
Pisum sativum L. (pea)	Phytoaccumulators	Soil	Pb, Cu, Zn, Fe, Cd, Ni, As, Cr	[70]
Rapanus sativus L. (radish)	Phytoaccumulators	Soil	As, Cd, Fe, Pb, Cu	[71]
Spinacia oleracea L. (spinach)	Phytoaccumulators	Soil	Cd, Cu, Fe, Ni, Pb, Zn, Cr	[72]
Solanum nigrum L. (black nightshade)	Phytoaccumulators	Soil	Cd	[73]
Sorghum bicolor L. (sorghum)	Phytoaccumulators	Soil	Cd, Cu, Zn, Fe	[74]
Zea mays L. (corn)	Phytoaccumulators	Soil	Cd, Pb, Zn, Cu	[75]

The table presents a comprehensive compilation of various plant species and their adeptness in remediating specific heavy metals across diverse contaminated areas. Notably, Brassica juncea (Indian mustard) emerges as a versatile candidate, effectively addressing cadmium (Cd), copper (Cu), zinc (Zn), and lead (Pb) in both soil and water environments. Water hyacinth (Eichhornia crassipes) showcases proficiency in remediating a spectrum of heavy metals, including arsenic (As), chromium (Cr), zinc (Zn), cesium (Cs), and cobalt (Co) from water bodies. Cajanus cajan (pigeon pea) is highlighted for its efficacy in mitigating arsenic (As) and cadmium (Cd) in soil. The varied capabilities of these plant species underscore their suitability for targeted heavy metal removal, emphasizing the potential of phytoremediation as a sustainable and plant-specific strategy. This approach holds promise for addressing heavy metal contamination in diverse environmental settings, contributing significantly to environmental sustainability and the overall health of ecosystems.

VII. IMPROVING PLANT PERFORMANCE FOR PHYTOREMEDIATION

The optimization of phytoremediation involves a multifaceted approach, employing various strategies to create an environment conducive to effective contaminant removal by plants. Diversifying the plant species engaged in the process is foundational, as different plants possess unique capabilities to absorb and neutralize a broad spectrum of contaminants, thereby enhancing the overall efficiency of remediation efforts [80]. Ensuring an adequate nutrient supply is vital for the growth and optimal functioning of plants, and this can be achieved through the application of fertilizers or enriching the soil with essential nutrients [81]. Fine-tuning soil conditions, encompassing the enrichment with organic matter, adjustment of pH levels, and refinement of soil texture, creates an optimal environment that supports plant growth and enhances their remediation capacities [82]. Effective water management is essential to provide plants with the required moisture, achieved through modifications in watering routines or the use of moisture-retaining mulches [83]. The provision of shade protects plants from harsh environmental conditions, ensuring their resilience in the face of challenges such as extreme temperatures and water scarcity [84]. Creating a well-aerated environment, crucial for plant growth, can be facilitated by incorporating compost or other organic materials into the soil [85]. Regular oversight of the phytoremediation process is necessary to verify optimal plant functioning and make timely adjustments, ensuring sustained effectiveness [86]. Collectively, these strategies synergize to establish favorable conditions for plant growth and optimize their remediation capabilities, thereby enhancing the success of phytoremediation as an environmentally sustainable solution.

7.1 Microbes for Phytoremediation

Microbes play a crucial role in phytoremediation by providing plants with essential nutrients, aiding in the breakdown of pollutants, and helping to restore the environment [76]. They can enhance plant performance for phytoremediation in various ways [6]. Firstly, the addition of beneficial microbes to contaminated soils can enhance soil quality, facilitating nutrient absorption by plants and the degradation of pollutants [77]. For instance, rhizobia bacteria, which form a symbiotic relationship with legumes, can fix nitrogen in the soil and supply vital nutrients to plants [78]. Moreover, soil-dwelling microbes contribute to the decomposition of organic matter, providing energy for plant growth. Secondly, specific microbes possess the ability to break down and eliminate pollutants from contaminated soils [79]. Bacteria like Pseudomonas and Burkholderia are effective in breaking down petroleum hydrocarbons, while fungi such as Trichoderma can degrade pesticides. These microbes also aid in detoxifying and immobilizing heavy metals, reducing their toxicity and facilitating plant absorption [80]. Lastly, microbes can be utilized to enhance phytoremediation in water environments. Certain bacteria and algae can degrade pollutants, while other microbes improve water quality by oxygenation and nutrient removal.. By harnessing the power of microbes to enhance plant performance, phytoremediation becomes more efficient and effective. With the right combination of microbes, it is possible to reduce pollutant levels in contaminated sites, improve soil and water quality, and restore the environment [81].

Table 6: Microbial species and their functions in phytoremediation processes

Microbe	Type	Function
Pseudomonas putida	Bacteria	Biodegrades hydrocarbons, polychlorinated biphenyls (PCBs), and other organic pollutants [82].
Rhodococcuserythropolis	Bacteria	Biodegrades hydrocarbons, PCBs, and other organic pollutants [83]
Agrobacterium tumefaciens	Bacteria	Facilitates the transfer of genes to plant cells, which can enhance their ability to remove pollutants [84] .
Azospirillumbrasilense	Bacteria	Promotes plant growth and enhances the uptake of nutrients, which can improve the effectiveness of phytoremediation .
Bacillus subtilis	Bacteria	Enhances the growth of plant roots and helps to degrade pollutants in the soil [85].
Burkholderiacepacia	Bacteria	Biodegrades chlorinated solvents, petroleum hydrocarbons, and other organic pollutants [28].
Streptomyces spp.	Bacteria	Biodegrades organic pollutants and produces enzymes that can break down complex molecules[86]
Trichoderma spp.	Fungi	Biodegrades pesticides, herbicides, and other organic pollutants [87]
Aspergillus spp.	Fungi	Biodegrades organic pollutants and produces enzymes that can break

		down complex molecules [88].
Cladosporium spp.	Fungi	Biodegrades pesticides, herbicides, and other organic pollutants [89]
Fusarium spp.	Fungi	Biodegrades organic pollutants and produces enzymes that can break down complex molecules [90]
Penicillium spp.	Fungi	Biodegrades organic pollutants and produces enzymes that can break down complex molecules[91] .
Rhizoctonia spp.	Fungi	Biodegrades organic pollutants and enhances plant growth .[92]
Saccharomyces cerevisiae	Yeast	Biodegrades organic pollutants and produces enzymes that can break down complex molecules [93]
Sinorhizobiummeliloti	Bacteria	Fixes nitrogen in the soil, which can enhance plant growth and improve the effectiveness of phytoremediation [94].
Stenotrophomonas maltophilia	Bacteria	Biodegrades chlorinated solvents, petroleum hydrocarbons, and other organic pollutants [95].
Streptomyces griseus	Bacteria	Biodegrades organic pollutants and produces enzymes that can break down complex molecules [96]
Trichoderma harzianum	Fungi	Biodegrades pesticides, herbicides, and other organic pollutants[97] .
Bacillus firmus	Bacteria	Biodegrades pesticides, herbicides, and other organic pollutants [87].
Brevibacillus brevis	Bacteria	Biodegrades organic pollutants and enhances plant growth [98].
Chlorella vulgaris	Algae	Biodegrades pesticides, herbicides, and other organic pollutants [87]
Chlorella sorokiniana	Algae	Biodegrades pesticides, herbicides, and other organic pollutants [87]
Dunaliella salina	Algae	Biodegrades pesticides, herbicides, and other organic pollutants [87]
Euglena gracilis	Algae	Biodegrades pesticides, herbicides, and other organic pollutants [87]
Scenedesmus obliquus	Algae	Biodegrades pesticides, herbicides, and other organic pollutants[[87]
Spirulina platensis	Algae	Biodegrades pesticides, herbicides, and other organic pollutants [87]
Azolla filiculoides	Fern	Biodegrades nitrogen and phosphorous [99]

Advantages of Microbial-Assisted Phytoremediation

Table 7: Advantages of microbial-assisted phytoremediation

Advantage	Description
Increased Biodegradation	Microbes can help to break down complex pollutants that plants cannot remove on their own [100]
Enhanced Plant Growth	Microbes can promote plant growth by fixing nitrogen and producing growth-promoting hormones [101].
Improved Contaminant Uptake	Microbes can increase the uptake of pollutants by plants through mechanisms such as increased root surface area and production of chelating agents [24].
Increased Pollutant Tolerance	Microbes can help plants to tolerate high levels of pollutants by breaking them down into less toxic forms [102] .

Microbial-assisted phytoremediation is a promising and synergistic approach for remediating contaminated environments. One significant advantage lies in the increased biodegradation facilitated by microbes. These microorganisms excel in breaking down complex pollutants, particularly those with intricate chemical structures, using specialized enzymes. This microbial activity complements the inherent capabilities of plants, expanding the spectrum of pollutants that can be effectively remediated.

Another noteworthy advantage is the enhanced plant growth promoted by microbes. Through mechanisms like nitrogen fixation and the production of growth-promoting hormones such as auxins, microbes contribute to improved plant health and development. This collaboration fosters more robust vegetation, thereby amplifying the overall efficacy of phytoremediation efforts.

Microbes also play a pivotal role in improving contaminant uptake by plants. Certain microbial actions, such as increasing the root surface area and producing chelating agents, enhance the ability of plant roots to come into contact with and absorb contaminants from the soil. The production of chelating agents by microbes aids in making heavy metals more soluble, facilitating their accessibility for plant uptake. This dual action results in a more efficient and thorough contaminant uptake by plants.

Furthermore, microbial-assisted phytoremediation contributes to increased pollutant tolerance in plants. Microbes assist plants in tolerating elevated levels of pollutants by breaking them down into less toxic forms, a process known as phytostabilization. This transformation of toxic compounds ensures that plants can thrive in contaminated environments that would otherwise hinder their growth.

In conclusion, the integrated approach of microbial-assisted phytoremediation harnesses the synergies between plants and microorganisms, offering a comprehensive solution to address a diverse range of environmental contaminants. The strategy's advantages, including increased biodegradation, enhanced plant growth, improved contaminant uptake, and increased tolerance to pollutants, underscore its potential as a sustainable and efficient remediation method.

Disadvantages of Microbial-Assisted Phytoremediation

Table 8: Disadvantages of microbial assisted phytoremediation

Disadvantage	**Description**
Complexity and Variability	The intricate interactions between plants and microbes, influenced by various factors, introduce challenges in predicting and controlling outcomes consistently[111].
Longer Remediation Duration	Microbial-assisted phytoremediation processes often require more time compared to traditional methods, relying on plant growth and microbial activity for contaminant removal[112].
Limited Applicability to Specific Contaminants	The effectiveness of microbial-assisted phytoremediation varies based on the type of contaminants, limiting its applicability and requiring a tailored approach for different pollutant [111].

Potential Impact on Ecosystems	Introducing specific microbial strains may alternative microbial populations and ecosystem dynamics, potentially disrupting the balance within the environment [111].
Risk of Gene Transfer	Some microbial strains may transfer genes to other organisms, raising concerns about unintended ecological impacts and the potential for genetic modifications to spread[113].
High Cost of Implementation	The implementation of microbial-assisted phytoremediation, especially at a large scale, can be financially challenging due to the need for specialized strains and monitoring equipment [113].
Ethical and Regulatory Considerations	The release of genetically modified microorganisms raises ethical concerns and regulatory challenges, necessitating careful consideration of safety and containment measures [113].

7.2 Genetic Engineering

Genetic engineering offers a promising approach to enhance the performance of plants utilized in phytoremediation [103]. Through genetic modifications, scientists can manipulate the genetic composition of plants to improve their ability to absorb and degrade pollutants, thereby increasing their remediation potential [104]. Moreover, genetic engineering enables the enhancement of plant resistance to specific contaminants, making them more effective in environmental cleanup efforts [105]. By optimizing the plants' photosynthetic capabilities through genetic modifications, their growth rate can be increased, allowing for greater pollutant uptake [106]. Furthermore, genetic engineering allows for the development of plants with elevated levels of natural compounds that aid in the breakdown of pollutants, further augmenting their effectiveness in phytoremediation [107]. The utilization of genetic engineering techniques in phytoremediation holds significant promise for advancing the field and optimizing the performance of plants in environmental restoration efforts.

7.3 Bioavailability of Heavy Metals to Plants

There are several strategies to enhance the bioavailability of heavy metals in plants. Firstly, the application of organic amendments like compost and manure can promote the accessibility of heavy metals to plants [108]. These amendments can alter the soil properties and facilitate the release of heavy metals, making them more available for plant uptake. Secondly, chelating agents such as EDTA and EDDA can be utilized to increase the availability of heavy metals in the soil [109]. These agents form complexes with heavy metals, preventing them from being tightly bound to soil particles and thereby enhancing their availability for plants. Thirdly, acidification of the soil can increase the solubility of heavy metals, making them more accessible to plant roots [110]. Lowering the soil pH through acidification can help release bound heavy metals and facilitate their uptake by plants. Finally, the use of biochar can aid in the sequestration of heavy metals in the soil, preventing their entry into the plant root system. Biochar acts as a sorbent, adsorbing heavy metals and reducing their mobility and bioavailability to plants [111]. By employing these strategies, the bioavailability of heavy metals can be increased, enabling more effective phytoextraction and remediation of contaminated soils.

The enhancement of heavy metal bioavailability to plants encompasses several targeted strategies aimed at improving accessibility and uptake in contaminated soils. Primarily, the application of organic amendments, such as compost and manure, proves to be a pivotal approach. These amendments induce modifications in soil properties, leading to the release of heavy metals and rendering them more available for plant uptake. The introduction of organic matter alters the binding sites of heavy metals in the soil, fostering their mobility and facilitating uptake by plant roots. A second effective strategy involves the use of chelating agents, exemplified by EDTA (ethylenediaminetetraacetic acid) and EDDA (ethylenediamine-N,N'-diacetic acid). Chelating agents form complexes with heavy metals, preventing their tight binding to soil particles. This process enhances the solubility and availability of heavy metals in the soil, thereby facilitating their uptake by plant roots.

A third strategy entails soil acidification to increase heavy metal bioavailability. Lowering the soil pH through acidification enhances the solubility of heavy metals, making them more accessible to plant roots. This pH alteration contributes to the release of bound heavy metals, augmenting their availability for plant uptake. Lastly, the incorporation of biochar stands out as a valuable method for sequestering heavy metals in the soil. Biochar, a carbon-rich material produced through the pyrolysis of organic matter, acts as a sorbent. It adsorbs heavy metals, reducing their mobility and bioavailability to plants. The integration of biochar into contaminated soils minimizes the entry of heavy metals into the plant root system, thereby contributing to effective phytostabilization and remediation. In summary, the outlined strategies, including the application of organic amendments, use of chelating agents, soil acidification, and incorporation of biochar, offer diverse avenues to enhance heavy metal bioavailability in soils. These approaches aim to optimize conditions for phytoextraction and other phytoremediation techniques, ultimately facilitating the remediation of contaminated soils.

VIII. ADVANTAGES OF PHYTOREMEDIATION

8.1 Economically Viable: Phytoremediation emerges as a fiscally sensible choice for remediation compared to its counterparts. The expenses associated with nurturing plants for pollutant extraction typically undercut those needed for chemical or mechanical cleanup methods[112].

8.2 Harnessing Nature: Phytoremediation capitalizes on the inherent abilities of plants to metabolize and eradicate pollutants, making it a naturally occurring process. It thus presents a more environmentally sustainable approach to remediation than its chemical or mechanical counterparts [113].

8.3 Gentle Approach: Phytoremediation eliminates the need for intrusive techniques usually employed in decontamination processes. This characteristic contributes to its lower environmental impact and helps protect natural habitats from unnecessary disturbances [114].

8.4 Broad-Spectrum Application: Phytoremediation's utility extends to various types of pollutants, including heavy metals, petroleum derivatives, and diverse organic contaminants [115].

8.5 Scalable Solution: Phytoremediation's ability to function effectively on vast areas establishes it as a practical solution for remediating extensive sites of contamination [116] .

IX. DISADVANTAGES OF PHYTOREMEDIATION

9.1 Time-Consuming Procedure: The pace of phytoremediation is unhurried, potentially spanning several years to adequately purify a polluted site. The duration of the process hinges on factors like contaminant type, soil composition, and plant growth rate [117].

9.2 Contaminant-Specific Efficiency: Phytoremediation's effectiveness is confined to specific contaminants, such as metals, petroleum hydrocarbons, and select organic compounds [118]. It falls short when dealing with pollutants like volatile organic compounds (VOCs), pesticides, and radionuclides [119] .

9.3 Risk of Secondary Pollution: There exists a risk of secondary pollution due to the accumulation of contaminants in the plants and soil. This can transpire during the disposal of contaminated plants or disturbance of polluted soil [85]

9.4 Significant Upkeep Costs: The maintenance costs associated with phytoremediation, such as regular monitoring, fertilizing, and replanting, can be considerable, particularly for large-scale endeavors [120].

9.5 Potential Environmental Repercussions: Phytoremediation can negatively affect the environment, as plants may gather contaminants that could be harmful to other local organisms [120]. Moreover, the application of fertilizers and similar chemicals can contribute to environmental distress [121].

X. FUTURE ASPECTS OF PHYTOREMEDIATION

Phytoremediation serves as a viable, budget-friendly strategy that employs plants to eliminate, break down, and confine pollutants in the environment [121]. This technique has garnered significant interest over recent years, marking it as an eco-friendly substitute to conventional remediation methods [122]The capacity of phytoremediation is immense, with ongoing studies delving into its future prospects. In the following discourse, we will delve into the recent advancements in phytoremediation and its potential to address environmental challenges in upcoming years [123].

10.1 Enhancing the efficiency of phytoremediation: It is dependent on several factors, including plant selection, soil conditions, contaminant type and concentration, and environmental factors [124]. Researchers are continually exploring ways to enhance the efficiency of phytoremediation by improving the factors that affect its effectiveness. For example, studies are being conducted to identify plant species with higher tolerance to contaminants and higher uptake rates.

Additionally, research is ongoing to optimize soil conditions and identify soil amendments that can enhance plant growth and contaminant removal [125].

10.2 Developing new phytoremediation techniques: Phytoremediation methodologies have experienced considerable advancements over time, with novel approaches consistently emerging [126]. One of the recent innovations involves utilizing genetically modified plants to augment their contaminant removal capabilities [127]. For instance, researchers have engineered plants with specific genes that elevate their capacity for metal absorption or disintegration of harmful chemicals [128]. Moreover, the exploration of plant-microbe symbiosis as a means to bolster phytoremediation is gaining traction. This strategy employs microbes that can foster plant growth and boost the efficiency of pollutant elimination [129].

10.3 Scaling up phytoremediation: While phytoremediation has demonstrated its efficacy in smaller-scale projects, its suitability for larger-scale applications remains under investigation [130]. Scholars are devising tactics to broaden the scope of phytoremediation to address environmental issues on a more extensive scale. One such strategy involves combining phytoremediation with other remediation techniques like bioremediation and chemical oxidation [131]. This amalgamation could enhance the removal of contaminants and expedite the remediation process. Furthermore, there's ongoing research into integrating phytoremediation with other land uses, such as agriculture and forestry [132]

10.4 Use of phytoremediation in urban environments: Urban environments frequently bear the brunt of diverse contaminants, encompassing heavy metals, pesticides, and hydrocarbons [133]. The application of phytoremediation in these settings presents a promising solution to manage such pollutants. For instance, studies are underway to use plants in the purification of stormwater runoff, which contributes significantly to urban contamination [134]. Moreover, phytoremediation can be employed to rehabilitate brownfields and other polluted sites within city confines, offering an eco-friendly alternative to conventional cleanup methods [135]

10.5 Phytoremediation in the context of climate change: The anticipated implications of climate change on our environment are substantial, incorporating shifts in temperature, precipitation patterns, and sea levels [135]. Phytoremediation can contribute to mitigating these impacts by curbing the emission of greenhouse gases and facilitating carbon sequestration [112]. For instance, implementing phytoremediation in wetland areas can aid in diminishing the release of methane, a greenhouse gas with significant warming potential. Furthermore, applying phytoremediation within forestry practices can assist in capturing carbon, thereby lowering the concentration of carbon dioxide in the atmosphere [136].

10.6 Use of phytoremediation in developing countries: Developing countries often lacks the resources and technology to address environmental problems effectively [137]. Phytoremediation can provide a low-cost and sustainable solution for these countries. Researchers are exploring ways to use local plant species to remove contaminants from the environment and to develop low-cost soil amendments to enhance plant growth [138].The implementation of phytoremediation in developing countries presents a compelling and sustainable strategy to combat environmental pollution and address remediation challenges. This approach offers several key advantages tailored to the specific needs and conditions of these regions:

10.6.1. Cost-Effectiveness: Phytoremediation proves to be a cost-effective alternative to traditional methods. Given the financial constraints often faced by developing countries, the lower associated costs make phytoremediation an appealing choice, eliminating the necessity for expensive infrastructure and extensive energy consumption [145].

10.6.2 Adaptability to Local Conditions: Phytoremediation's adaptability to diverse environmental conditions allows for tailored solutions to contamination issues specific to developing countries. Leveraging local plant species, well-adapted to prevalent climates and soil conditions, enhances the effectiveness of remediation efforts [147].

10.6.3Community Involvement and Capacity Building: Phytoremediation projects provide opportunities for local community involvement, fostering participation and skill development. This engagement not only instills a sense of ownership but also empowers residents, contributing to the sustainability of remediation initiatives [148].

10.6.4. Versatility for Multiple Contaminants: Phytoremediation's versatility addresses a broad spectrum of contaminants, including heavy metals, organic pollutants, and radioactive materials. This adaptability is crucial for tackling the diverse pollution challenges encountered in developing countries [148].

10.6.5. Improvement of Soil Quality: Beyond pollution remediation, phytoremediation positively influences soil quality. Selected plants enhance soil structure, increase nutrient content, and stimulate microbial activity, promoting overall soil health and fertility [145].

10.6 6. Integration with Greening Initiatives: Phytoremediation aligns seamlessly with greening initiatives and afforestation projects. By strategically choosing plants with remediation capabilities and afforestation potential, developing countries can simultaneously combat environmental contamination and contribute to ecosystem restoration [148].

10.6 7. Potential for Economic Opportunities: Phytoremediation projects open avenues for economic development, such as cultivating plants with remediation capabilities or establishing eco-friendly industries. This economic dimension is particularly significant for developing countries seeking sustainable development pathways [147].

XI. EMERGING TECHNOLOGIES IN PHYTOREMEDIATION

Table 9 Different technologies in Phytoremediation.

Technology	Description
Nanoparticle-Enhanced Phytoremediation	The use of nanoparticles to enhance the uptake and biodegradation of pollutants by plants [139].
Genetic Modification	The use of genetic engineering techniques to enhance the ability of plants to remove pollutants or to produce enzymes that can break down complex molecules[140] .
Endophyte-Assisted Phytoremediation	The use of endophytic bacteria or fungi to enhance the growth and pollutant-removing capabilities of plants [141].
Mycorrhizal-Assisted Phytoremediation	The use of mycorrhizal fungi to improve the uptake of pollutants by plant roots [141], [142]
Biochar-Assisted Phytoremediation	The use of biochar, a type of charcoal made from plant material, to improve soil quality and enhance the effectiveness of phytoremediation [143]

11.1 Nanoparticle-Enhanced Phytoremediation: The application of nanoparticles to augment the absorption and breakdown of pollutants by plants represents a cutting-edge advancement in phytoremediation [150]. Capitalizing on the small size and increased surface area of nanoparticles, this technology enhances contaminant uptake by plant roots. Additionally, nanoparticles may facilitate the biodegradation of pollutants within plant tissues, thereby elevating the overall efficacy of phytoremediation.

11.2 Genetic Modification: The utilization of genetic engineering techniques to boost a plant's innate capacity to eliminate pollutants or induce the production of enzymes for breaking down complex molecules signifies a promising avenue in phytoremediation [151]. Through the manipulation of a plant's genetic makeup, scientists can customize its traits to better align with the remediation of specific contaminants, holding potential for the development of plants with heightened pollutant-removal capabilities.

11.3. Endophyte-Assisted Phytoremediation: Leveraging endophytic bacteria or fungi to enhance both plant growth and pollutant-removing capabilities is a method at the forefront of phytoremediation [152]. Endophytes, residing within plant tissues, play a role in promoting plant health and, in some instances, aid in the breakdown or immobilization of pollutants. This symbiotic relationship contributes to an overall enhancement in the efficiency of phytoremediation.

11.4 Mycorrhizal-Assisted Phytoremediation: The deployment of mycorrhizal fungi to amplify the uptake of pollutants by plant roots signifies another innovative approach in phytoremediation [152], [153]. These fungi form a mutually beneficial association with plant roots, extending their reach and enhancing nutrient and water absorption. In the context of phytoremediation, mycorrhizae can boost the uptake of pollutants, rendering them more accessible for removal or transformation by the plants.

11.5. Biochar-Assisted Phytoremediation: The use of biochar, a form of charcoal derived from plant material, to enhance soil quality and improve the effectiveness of phytoremediation represents a sustainable practice [154]. Acting as a soil amendment, biochar enhances nutrient retention, microbial activity, and water-holding capacity, creating a conducive environment for plant growth and pollutant removal.

These advanced technologies underscore the dynamic evolution of phytoremediation, demonstrating how inventive approaches contribute to the improved efficiency and adaptability of this eco-friendly remediation method.

XII. CONCLUSION

To summarize, phytoremediation stands as an encouraging technology for environmental clean-up, bringing several benefits over conventional methods. It's environmentally benign, cost-efficient, visually agreeable, sustainable, and versatile. Yet, it does come with its share of drawbacks, including a time-consuming process, limited scope, uncertainties, potential for plant pollution, and restrained public approval.

Regardless of its limitations, phytoremediation is increasingly favored as a go-to method for environmental remediation. It proves particularly beneficial for tackling low to moderate levels of pollution, often found in urban and suburban settings. Additionally, coupling phytoremediation with other remediation strategies can enhance the overall efficiency of the decontamination process.

Being a relatively recent technology, ongoing research seeks to amplify its effectiveness and cultivate new plant species that are better equipped to handle diverse pollutants and varied environmental conditions .Public education and outreach endeavors are equally crucial in raising awareness and fostering acceptance of this innovative technology. In essence, phytoremediation emerges as a hopeful strategy for environmental cleanup, poised to tackle the escalating pollution crisis in an eco-friendly and financially sensible way. It epitomizes how we can leverage nature's capabilities to address present-day environmental challenges. As we make strides in research and technological advancement, phytoremediation is likely to take on a progressively significant role in our endeavors to safeguard and conserve our environment.

XIII. SUMMARY

The paper emphasizes the importance of a more refined selection of plant species, highlighting the need to optimize their efficacy in remediating a wide range of contaminants across diverse environmental conditions. They stress the significance of molecular investigations, particularly in understanding the intricate mechanisms that govern phytoremediation processes, with a specific focus on plant-microbe interactions. A notable suggestion is the integration of phytoremediation with other remediation technologies, presenting a promising strategy for developing comprehensive approaches to address complex contaminant mixtures. The paper underscores the critical need for long-term field studies to evaluate the sustainability and ecological impacts of phytoremediation. Additionally, the authors emphasize the necessity of scaling up phytoremediation for large-scale applications, integrating it into environmental policies, fostering community engagement, and addressing emerging contaminants. In summary, the paper provides a roadmap for future research, aiming to enhance and broaden the application of phytoremediation as a robust and environmentally friendly solution for mitigating environmental contamination.

ACKNOWLEDGMENTS

The authors thank the Department of Life Sciences, CHRIST (Deemed to be University), Bangalore for providing the necessary facilities for the successful execution of this review work. I am grateful for the fundingfrom the CSIR-UGC Junior Research Fellowship (Council of Scientific and Industrial Research- University Grants Commission

Declarations

Conflict of interest

The authors have no competing interests to declare that are relevant to the content of this article.

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