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Phytoremediation: A Sustainable control measure for soil and water Pollution

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Abstract:

The growing number of polluted sites and the increasing prohibition of chemical and physical approaches of remediation has led Phytoremediation technology, which relies on the use of green plants to decontaminate the soil, to gain importance. The destruction and non-recovery of toxic material constitute a great environmental challenge, resulting in this treatment technology to be the subject of extensive research (Chang, 2017). Phytoremediation is a promising plant-based sustainable remediation technique that addresses soil and water pollution. It makes use of diverse physiological processes, such as phytoextraction, phytostabilization, phytodegradation, and phytovolatilization to remove pollutants from the environment (Raziel Delgado-González et al., 2021). More than 453 different species of plants have been reported to possess the potential to absorb and translocate of heavy metals. The pollutants can be a wide range of contaminants such as heavy metals (lead, cadmium, nickel, cobalt) and organic micropollutants (PAHs, pesticides, anilin, phenols, etc).

1. Introduction

Phytoremediation is a sustainable method used to clean-up polluted environments. This paper assesses the current understanding of phytoremediation as an effective and environmentally friendly technology for soil and water remediation. An overview of its significance and applications is presented, as well as a motivation to continue research and field tests, thereby contributing to solving global soil and water contamination problems across societies.

Pollution, a major environmental concern, can impair the survival of various living organisms. Pollution occurs in several sites: air, land, soil, water, and others. Soil and water pollution is continuously deteriorating through human and natural activities. Contaminants may travel and settle down, in each case polluting the new land. Contaminated environments are not good for agriculture and cannot naturally recover. A remediation method is needed: one that consumes natural resources, is eco-friendly, and does not degrade or destroy environmental systems, such as soil and groundwater.

Phytoremediation is a green clean-up technology that uses plants to remove, transfer, stabilize, or destroy contaminants in soil and water. Phytoremediation, which derives from the Greek word "phyto" (meaning plant), is an alternative technology for soil and water remediation. All living organisms are continuously exposed to contamination, which is commonly known as pollution. Phytoremediation provides sustainable control over soil and water pollution problems. Thus, the ability of plants to mitigate environmental contaminants can be of great significance (Chang, 2017) ; (Raziel Delgado-González et al., 2021)

2. Background and Significance

Environmental pollution has persisted for millennia under anthropogenic influence. Starting from prehistoric society, b96fa27a-9229-4f48-9cdb-c936ebaaeb9ced by metal jewelry, ceremonial artifacts, and pigments, human activities led to resource overexploitation that remains unaddressed, with adverse impacts on the environment (Mark Conger, 2003). Industrial pollution, driven by hydrocarbon and heavy metal exploitation along with the usage of fertilizers, herbicides, and pesticides, corresponds with increased global soil degradation. Argillic horizons have built up, and organic carbon, nitrogen, and other elements have been lost, entailing environmental concerns (Raziel Delgado-González et al., 2021).

Phytoremediation can support national pollution control and sustainable development strategies. The development of urban agriculture has been recognized as an ecologically sound and efficient technique (Chang, 2017).

3. Mechanisms of Phytoremediation

Phytoremediation is the use of plants to remediate contaminated sites via various processes, including extraction, decomposition, and immobilization. Understanding the mechanisms of phytoremediation enables selection of appropriate practices and identification of suitable plants. Phytoremediation applies to organic compounds, heavy metals, and excess nitrogen and phosphorus. Popular methods of phytoremediation include phytoextraction, phytodegradation, phytoaccumulation, and phytostabilization.

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Phytoextraction enhances the uptake of a contaminant by a plant, which is subsequently harvested. The emphasis is on the contaminant's translocation from the roots to the shoots, the nature of the biomass disposal, and the plant–soil interactions affecting uptake. Contaminants targeted by phytoextraction include heavy metals and radionuclides, while isotopes are sometimes assessed as tracers. Certain plants or cultivars are preferred for specific contaminants based on thermal requirements for harvesting and other properties.

Phytodegradation, also referred to as phytotransformation or plant-mediated degradation, is the enzymatic breakdown of organic contaminants. Mineralization and the release of by-products generally remain to be demonstrated for widespread acceptance, although some evidence of mineralization has been noted (C Dietz & L Schnoor, 2001). Fluorinated compounds, explosives, hydrocarbons, pesticides, surfactants, and other organic chemicals are among the substances subject to research. Certain species belonging to families such as Brassicaceae, Fabaceae, and Poaceae have been documented to degrade quite a number of compounds.

Phytoaccumulation, or plant-mediated accumulation, refers to the uptake of contaminants by a plant without explicit consideration of their translocation or biomass disposal. Contaminants typically included in this framework are those accumulating predominantly in roots, such as Al, Cd, Co, Cr, In, Ni, Pb, and Zn. Sorption on roots, root-to-shoot transport or translocation, storage in foliar tissues, and the subsequent fate of the stored compounds in senescent leaves are therefore considered within the context of phytoaccumulation. Two scenarios arise during the analysis: (i) contaminants are sorbed on the roots without net translocational loss or biomass being disposed of, and (ii) contaminants are retained in the roots and translocated to the foliar tissues, where they are retained for some period and subsequently lost.

Phytostabilization involves immobilization of a contaminant in the rhizosphere and reduction of its mobility in the environment. Four major processes of phytostabilization operate to decrease contaminant activities or bioavailability in soils. Phytostabilization of pollutants reduces leaching into groundwater, limits soil vapour migration to the atmosphere, and restricts wind-blown dust dispersal. When oligoelements accumulate only in biomass or substantially more remain in the growth media compared to unplanted control, additional end-of-life metal losses during monitoring for environmental assessment remain possible.

3.1. phytoextraction

Soil, sediment, and water can be contaminated by heavy metals, organics, nutrients, and metalloids, which pose a serious risk to terrestrial and aquatic life; the extent of the threat is determined by both the concentration and the bioavailability of the pollutant. Pollutants are classified broadly by their chemical, physical, and biological properties, although certain functional similarities may underlie segregation into more restricted types for research purposes. Conventional remediation methods such as excavation, capping, landfilling, incineration, chemical extraction, and chemical degradation are sometimes prohibitively expensive, environmentally damaging, or impractical when dealing with isolated sources. Phytoremediation, defined as the use of plants, algae, or associated microbes to remove, degrade, or stabilize contaminants, has attracted interest as a potentially inexpensive and sustainable alternative (C Dietz & L Schnoor, 2001). There is considerable scope for study of fundamental mechanisms in phytoremediation and for evaluation of its effectiveness in practice; both opportunities are especially appealing given the environmental, economic, and social stakes involved (PLOPEANU et al., 2018).

3.2. phytodegradation

Phytodegradation, the breakdown of contaminants by plant-associated microorganisms (C Dietz & L Schnoor, 2001) , can occur partially or completely, and mineralization to CO_2 and water may be be achievable (Mahadi Hasan et al., 2019). It depends on the intimate connection of the root system with the rhizosphere microbial community and the supply of energy sources from plants to microorganisms in the rhizosphere. The use of appropriate substrates, such as compost and fertilizers, can promote both biological and phytoremediation processes. However, the complexity of phytodegradation mechanisms and the diversity of hazardous organic substances hinder predictive evaluation. Routine checks on substrate concentration and environmental conditions, such as pH, temperature, and moisture, are beneficial to sustaining efficient biological removal.

Contaminants that enter the plant are first bound and retained through sorption processes and then immobilized in some vegetative compartments. For allochthonous contaminant degradation, particulate matter settles. Contaminants may also be transported by water before entering the plant and subsequently degrade without growth. The plant can be regarded either as a substrate to support chlorophyll, or the contaminant becomes part of the plant.

3.3. phytoaccumulation

Pollutants accumulate in specific organs only in some plants; any accumulation in roots does not qualify as phytoextraction. Consequently, accumulation is a prerequisite for extraction. Most hepatic contaminants neither mineralize nor degrade completely on plant surfaces; they are at least partially sorbed in compartments other than roots, thus qualifying accumulation. Only some of these partitions are compatible with efficient detoxification; sorption within vacuoles, for example, entails much lower degradation and should not be the governing mechanism.

Sorption mechanisms for organic toxicants account for distribution among shoots, stems, leaves, and storage tissues; all these organs may be involved in phytostabilization when contaminants are retained for prolonged periods. Efficient detoxification also occurs at selected partitions, which may either compete with undesirable zones or allow translocation toward locations with improved degradation capacity (C Dietz & L Schnoor, 2001). In heavy-metal remediation, pollutants share root surfaces and different root tissues, and the capacity for translocation is crucial when excesses accumulate in plants or phytotoxicity jeopardizes survival and promotion of more complex mutations.

3.4. phytostabilization

Phytostabilization is a mechanism that immobilizes hazardous contaminants in the soil (Hisle & Sleegers, 2016). It relies on the establishment of a vegetative cover that reduces erosion and minimizes pollutant dispersal. Additives may supplement plant growth, improve soil structure, and enhance contaminant absorption. Phytostabilization constitutes an alternative in situ option for contaminated locations where traditional methods are unfeasible, such as abandoned gas stations with petroleum hydrocarbons, metal stabilization, and chlorinated solvents.

Phytostabilization operates via processes ranging from rhizodegradation to pesticide absorption, surfactant biodegradation, toxic compound transformation, and contaminant precipitation (C Dietz & L Schnoor, 2001). As organic matter decomposition occurs, nutrients and porosity become available for further nutrient supply and biomass production. Phytostabilization can lower the costs of soil removal or capping by replacing a portion of the supplied materials with treated soils.

Phytostabilization is defined as the use of vegetation to remediate or contain contaminants in soils, sediments, and groundwater. Phytostabilization adds nutrients, porosity, and organic matter to the substrate while offering a cost-effective, in situ alternative to traditional remediation that minimizes the need for waste disposal. Phytostabilization is increasingly considering the removal of organic chemicals, such as

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petroleum hydrocarbons and chlorinated solvents, from abandoned gas stations, as well as the stabilization of metals in older sites.

4. Scope of Contaminants Addressed

Phytoremediation provides comprehensive coverage for the mitigation of various classes of contaminants and has been shown to be effective against a wide array of pollutants, including heavy metals, organic compounds, and excessive nitrogen and phosphorus. Each class of pollutant has its own specific set of abiotic and biotic site parameters to monitor, as well as distinct indicators for determining the viability of the containment, extraction, degradation, or accumulation processes necessary to achieve remediation. By defining confidence limits for the core marker substances in each of these groups, remediation targets can be clearly established for phytoremediation projects. In many cases, the remediation objectives are further encapsulated into specific remediation criteria for well-defined subsets of each class of contaminant, ensuring that even sufficiently stringent treatment goals can be met when soil quality or plant growth is inadequate to achieve prompt recovery (Raziel Delgado-González et al., 2021).

While the excessive accumulation of heavy metals in soil and plants poses a serious environmental threat, phytoremediation can reduce the bioavailability of metals such as Pb, Zn, and Ni. The remediation of metals such as As, Cd, Cr, Fe, Hg, Mn, Mo, Se, and V is likewise accomplished through several safe mechanisms of decreased mobility in soil-water-plant systems. To achieve remediation on such pollutant classes in a reasonable timeframe, it is paramount to design the strategy, set clear goals, and select the remediation candidate optimally.

Contamination by organic compounds, one of the most frequent forms of soil pollution, is targeted through phytodegradation or phytoaccumulation. As for preliminary criteria, phytodegradation must have played a significant role in the attenuation of the compounds in situ or in their removal from the potential degradation pathway. Phytoaccumulation qualifies when the partially substituted compounds or eventually released metabolites are of limited concern for eco-safety. When remediation rest solely on phytodegradation, it is strongly advisable to follow the strategy and goals and to select efficiently the candidate.

4.1. Heavy metals

Heavy metals are among the top ten major pollutants threatening human health (PLOPEANU et al., 2018). By definition, heavy metals are metals and metalloids with an atomic density greater than 5 g/cm^3 and a chemical behaviour similar to transition metals. They include toxic elements such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), mercury (Hg), and zinc (Zn) (Chang, 2017). In contrast to organic pollutants, which can be degraded by biological processes, heavy metals are non-biodegradable and accumulate in the environment, contaminating agricultural soils and the food chain. Certain heavy metals, such as As, Cd, Cr, Hg, and Pb, are toxic and lethal in trace amounts. They may induce teratogenic, mutagenic, endocrine, behavioural, and neurological disorders, especially in infants and children. Heavy metal pollution poses severe threats to ecosystem health and safety as industrial and agricultural activities continue to extract and concentrate heavy metals for economic growth.

Conventional soil remediation methods—such as physical, chemical, and biological approaches—are costly or labour-intensive and cannot restore the soil to levels that allow unrestricted use. Phytoremediation is regarded as a highly promising technique for the remediation of heavy metal-polluted soils. It makes use of plant and associated microbe physiological and biochemical processes that either reduce pollutant concentrations or alter their toxicity. Two highly efficient remediation strategies are phytoextraction, which reduces the total quantity and bioavailability of pollutants in contaminated soils, and phytostabilization, which reduces the effective concentration (e.g., ex0cc301c1-a953-4440-b4d0-6fdf94190c99eable fraction) of pollutants at the soil–plant interface.

4.2.Organic pollutants

Phytoremediation requires sensitive methods to confirm the breakdown of organic chemicals. Depending on the structure of contaminant and house plant used, degradation of chemical may yield different products, making necessary to investigate ultimate and intermediate by-products to assess the mineralization of the substrate. Many low molecular weight compounds or chemicals with simple configurations can undergo almost full mineralization under complete organic process, and no hazardous by-products for plant detected; therefore, in such cases to find out intermediate compounds becoming essential. Phytoscreening on laboratory side shows different plant to screen, and, different composition, so can represent complimentary information; therefore necessity of ecological by-screening experiment develop. Similarity after leaf and root sample inspected where carbon remained at compounds recovering, indicating possible substrates leach out through plant transpiration. Accompanying to avoidance the propagation of final product to leaf, root extracts more suitable for the fate of carbon route clarification in supplementary. Roughly select three chemicals two of them by-hydrochlorine for organ decontamination half-life visible to CNC less than 5 h in plain rough by-primitive leaf. Another by-acid under rough supply by sodium into all composition facilitate chemical of terminal carbon at less than 6 h and exit single form. Graph of root analysis under similar simulation spare for CPC ultimately carbon remain acceptance percent and process fully stipulating entire recover and followed similar pattern. (C Dietz & L Schnoor, 2001)

4.3. Nitrogen and phosphorus compounds

Nitrogen is an essential component of living organisms, and is found in many biomolecules, such as amino acids, proteins, nucleic acids, and chlorophyll. Atmospheric N2 must be converted to ammonia (NH3) through biological nitrogen fixation, which is done by free-living and symbiotic nitrogen-fixing bacteria. Nitrifying bacteria oxidize ammonium (NH4+) to nitrite (NO2–) and then to nitrate (NO3–). Denitrifying bacteria convert NO3– to gaseous nitrogen forms (N2, N2O), and anammox bacteria convert NO2– and NH4+ to N2. Excessive nitrogen and phosphorus concentrations in surface waters create algal blooms or eutrophication. Atmospheric nitrogen deposited via acid rain and atmospheric deposition, as well as from septic system effluent through groundwater, seep into surface water and drinking water, producing metamorphic by-products. Meteorological surveys, satellite images, and airborne surveys have been used to identify nitrogen sources, while spectrophotometry, chromatography and microbiological culture are used to characterize nitrogen species.

Nitrogen compound concentrations can be reduced using some plants with nitrogen-fixing bacteria. For example, plants of the genus Atriplex can grow in saline soils where other plants fail. This series of studies demonstrated that the vegetation covered the whole site yet pollution indicators remained at very low concentrations, revealing the phytoremediation effect came mainly from biological fixation. In general, phosphorus taken up by plants is stored as living matter. When plants decay or die, the phosphorus could be released again to the environment, for example, during the process of composting. Although the amounts of phosphorus buried in deep-placed plant wastes decreased considerably, the treatable amount was still large and other techniques had to be combined, together with residue recycling, since some pollution indicators such as phosphide could escape from the treatment process (Raziel Delgado-González et al., 2021) (PLOPEANU et al., 2018).

5. Plant Selection and Breeding for Remediation

Optimal plant characteristics for remediation remain to be established, but basic guidelines based on compostion and ecology, combined with practical experience, can assist candidate selection. The most obvious parameter is pollutant resistance, but detoxification methods, biomass production and accumulation or exclusion capacities are also significant. For certain applications, it is essential to restrict translocation of specific contaminants from the root zone (Raziel Delgado-González et al., 2021).

The use of conventional breeding and genetic engineering can enhance traits or establish new remediation pathways. These biotechnological methods are often pursued in tandem and may involve modifications of secondary metabolites, transport proteins, organelles or subcellular compartments. Candidate genes for transgenics have been identified in such pathways through characterization of resistant species, but regulatory uncertainties may limit their application (Hisle & Sleegers, 2016).

5.1. Traits and criteria

Phytoremediation can be defined as the use of vegetation to remove, transfer, stabilize or destroy contaminants in soil and sediment (C Dietz & L Schnoor, 2001). Contaminants can be of organic, inorganic, or pathogenic origin, including volatile organic compounds, phenols, petroleum hydrocarbons, pesticides, azoles, heavy metals, oxyanions, nutrients, and pharmaceuticals (Raziel Delgado-González et al., 2021). Emerging concerns such as microplastics in soils and water have also attracted attention to the possibility of using plants to eliminate them, though progress in this area is still preliminary.

Phytoremediation is usually considered to be a sustainable control measure in the context of soil and water pollution. Since it exploits natural processes, phytoremediation is less energy demanding than most conventional procedures and can often be implemented at a lower cost. Given the omnipresence of anthropogenic pollutants and their negative impact on ecosystems and human health, effective remediation measures are required to restore the environment. Consequently, low-tech (where low-tech denotes the lack of mechanical or thermal actions), low-cost, energy-efficient, and environmentally friendly processes such as phytoremediation are in high demand.

5.2. Genetic and biotechnological approaches

Phytoremediation can be further enhanced with the assistance of genetic and biotechnological methods. Technologies such as transgenic and gene-editing approaches can be deployed to modify plant, cyanobacterial, and microbial species in order to improve the composition of metabolite pathways for the enhanced uptake, transport, accumulation, degradation, and detoxification of heavy metals, organic pollutants, and nitrogenous compounds while complying with ecological requirements. With the rapid advancement of both experimental techniques and research on metabolic pathways, a growing database of effective genetic interventions for plant phytoremediation is emerging. The widespread exchange of these datasets can accelerate progress and inform scientists about the availability of selected variants and the corresponding environmental context.

Phytoremediation has greatly increased the attention paid to the potential environmental risk associated with the release of genetically modified organisms. Furthermore, transgenic plants featuring foreign genetic materials operate in complex physiological and ecological systems, which creates additional unknowns regarding their interactions with other organisms. Therefore, government and institutional authorities are promoting the establishment of a robust, comprehensive, and transparent risk assessment framework for the environmental release of transgenic plants to facilitate the progression of bioremediation with less controversy in the future.

5.3. case studies and examples

Phytoremediation is an emerging technology utilizing mechanisms like phytoextraction, rhizofiltration, and phytodegradation for contaminant removal through plant uptake, microbial relationships, and immobilization in the root zone. Its efficacy depends on contaminant characteristics such as hydrophobicity and polarity. A study showed that black willow (Salix nigra) effectively enhanced herbicide bentazon removal from groundwater, involving monitoring of contaminant levels. Aquatic plants Salvinia natans and Lemna gibba also successfully treated heavy metal-contaminated water. These examples highlight the potential of phytoremediation amid geographical and regulatory constraints. Various national programs have implemented phytoremediation strategies, including a U.S. EPA project in Thurber, West Virginia, aimed at groundwater remediation due to high pesticide concentrations. Black willow was selected for its proven tolerance and adaptability in wetlands. Groundwater sampling indicated that rising rainfall and water levels correlated with increased contaminants at untreated sites; the observed reduction during treatment was linked to plant effects. After five years, bentazon accumulation in willow biomass was estimated below 0.3% of initial levels. In northeastern Mexico, heavy metals from mining and industrial discharges have contaminated surface waters. Aquatic phytoremediation proved efficient, achieving approximately 90% cadmium removal and 80% for lead within a week. A study of thirty-three species indicated azolla (Salvinia natans) and duckweed (Lemna gibba) as the most effective, recording 96% cadmium and 91% lead removal efficiencies during trials. (Mark Conger, 2003)(Raziel Delgado-González et al., 2021)

6. System Design and Implementation

Successful phytoremediation projects necessitate an in-depth understanding of site-specific conditions, pollutant characteristics, and local ecosystems. Initial assessments

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should focus on soil properties, hydrology, contamination extent, climate patterns, and growth regulations. Evaluating the moisture regime is essential for choosing appropriate remediation methods and plant species, as well as timing for planting. Soil composition and geology impact contaminant bioavailability, thus influencing a plant's capacity for pollutant extraction or degradation. Detailed contamination profiles guide species selection and the anticipated success of decontamination efforts. Viability of phytoremediation is determined by the involvement of remediation methods like phytodegradation or phytoextraction. The use of polyculture systems, involving multiple species, can enhance resilience against pests but increases management complexity. Evaluating species combinations across key regional systems aids in optimizing effectiveness and informs the selection of compatible species for specific environments. Regular monitoring of selected species is crucial, tracking responses through soil and plant sample analyses to adjust approaches as necessary. A vital consideration is ensuring compliance with regulations on pollutant limits or using functional indicators for broader projects. These indicators vary based on pollutants and intended intervention scales. Phytoremediation may also be integrated with other technologies, depending on selected materials or contaminants. (Raziel Delgado-González et al., 2021)

6.1. Site assessment and feasibility

Site assessment constitutes the backbone of the remediation procedure and determines the viability of establishing a phytoremediation system. Initial analyses must consider the physical and chemical characteristics of the soil, hydrology, and the extent and profile of contamination. Further site-specific constraints should be evaluated based on the selected plants, local officials' preferences, historical land use, and climate conditions that influence growth periods. Certificates or conditional letters from regulatory bodies willing to authorize remedial measures assure the possibility of pursuing phytoremediation (Fagnano & Fiorentino (Guest editors), 2018).

Soil delivers clarity on texture, structure, pH, pollutants, and organic matter crucial to remediation programs. Consequently, accurately detailing the soil profile across the property remains essential. The land's hydrology governs the plants' growth period. For instance, when developing horizontal and vertical remediation systems to mitigate organic or inorganic contaminants across expansive areas, current and potential ground and surface water lines merit particular attention.

6.2. Monoculture versus polyculture systems

The relative merits of monoculture and polyculture systems contribute to the effectiveness of phytoremediation. Monoculture systems offer simplicity and lower labor costs but are more susceptible to biotic and abiotic stresses; polycultures enhance overall system stability but require further management attention. Selection criteria can be adjusted according to site conditions, to the classes of contaminants involved and the life cycle (FURINI et al., 2015) , so that system efficiency and resilience may be increased.

6.3. Monitoring and maintenance

Monitoring and maintenance are essential for successful phytoremediation projects, extending beyond setup and planting. Regular assessments of performance and stability are crucial, with frequency based on project stage and data development needs. Monoculture systems are often evaluated every 1–6 months, while polyculture systems may require assessments every 6–12 months. Monitoring indicators are chosen according to remediation goals and site characteristics, commonly focusing on contaminant concentration in soil and harvested biomass. Other variables, such as soil composition and microbial community makeup, may also be considered based on project objectives. Monitoring results inform further management actions and site closure suitability. Adaptive management incorporates new knowledge, regulatory shifts, and stakeholder expectations, enhancing phytoremediation project effectiveness over time. (Mark Conger, 2003)

7. Environmental and Economic Considerations

Attaining sustainability in contemporary society is a priority under the United Nations sustainable development goals. As the human population continues to grow, urbanization expands and climate spreads, soil and water pollution are great challenges to agriculture and ecosystem sustainability (Chang, 2017).

Phytoremediation is recognized as a rational, green technology for the treatment of heavy metal pollution, and many relevant studies have been conducted. Rhizosphere effects enhance pollutant degradation. Pollutants can also be fixed by plants, absorbing them from polluted water via their root system and storing them in their tissues without movement to aboveground parts (Raziel Delgado-González et al., 2021). Heavy metal ions can be effectively reduced when plants are cultivated on polluted soil. Analytical tests demonstrate the removal of various heavy metals, even when initial concentrations are significantly higher than the allowable limit.

8. Policy, Regulation, and Public Acceptance

Phytoremediation uses living plants to eliminate contaminants from soil and water, offering a low-cost and eco-friendly remediation method. It effectively removes heavy metals, addressing a significant environmental issue. As a green technology, phytoremediation has gained traction alongside the increased awareness of

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contamination and hazardous waste threats. Research has intensified over the past decade to develop improved plant varieties for this purpose. Since 1990, several field trials have shown some success, but many industrial projects have faced delays due to uncertainties about ecological and health risks. Phytoremediation is a sustainable alternative for cleaning contaminated environments, and careful monitoring and systematic risk communication are vital for regulatory acceptance and promoting commercial use. These strategies can help alleviate public concerns about engineered plants while enhancing the application of phytoremediation for restoring contaminated sites. (C Dietz & L Schnoor, 2001)

9. Challenges, Limitations, and Future Directions

Remediation techniques developed over the last fifty years struggle to address issues like climate change and invasive species. Phytoremediation, using plants to remediate contaminated environments, has emerged as a promising solution. Certain plants and their associated bacteria can remove, stabilize, or degrade various contaminants, which has garnered significant scientific interest. This section outlines the challenges, limitations, and research needs within phytoremediation. Addressing knowledge gaps in contaminated water and soil can propel scientific advancements. Current research lacks systematic data on the cleaning capacity of target species and emphasizes the need to catalog species-contaminant combinations. The complexity of selecting target species is heightened by pollutant mixtures and abiotic stress factors. Some species can mobilize or degrade different heavy metals in water, while pilot testing requirements must be tailored to site conditions, plant selections, and contaminant types to enhance successful outcomes. For example, phytoremediation can improve cadmium removal from lettuce grown in contaminated soil, supported by laboratory and field trials. Moreover, confirming cleaning solutions across various scales is vital, as only a fraction of studies on pollutants involve pilot trials, with larger phenomena like land salvage often overshadowing pollutant cleaning efforts.

10. Conclusion

Phytoremediation establishes itself as a sustainable control measure for soil and water pollution in light of the theoretical foundations, current limitations of conventional remediation practices, and the demonstrated performance of this technology. Environmental contamination continues to exert a growing detrimental impact on human and ecological health. To mitigate these adverse effects, the demand for remediation technologies has steadily increased. However, these existing remediation technologies face several limitations, prompting the search for alternative approaches to addressing the growing environmental pollution crisis.

Phytoremediation was recognised as a viable plant-based remediation technology capable of complementing or replacing conventional measures. Phytoremediation combines the benefits of sustainability and cost-effectiveness while fully integrating with the ecosystem, thereby extending the potential for extensive deployment. Scientific evidence of the trends, mechanisms, systemic advantages, contaminant scope, candidate species, success cases, and regulatory frameworks exist at sufficient levels to accompany the extensive realisation of phytoremediation projects worldwide in ameliorating contemporary pollution problems. The increasing evidence of viable solutions to previously acknowledged shortcomings reinforces the confidence in phytoremediation technology and warrants its further advancement as a promising sustainable control measure against pollution (Raziel Delgado-González et al., 2021).

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