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Bioremediation of Contaminated Environments: A Review of Heavy Metal Removal and Ecosystem Restoration

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ABSTRACT

Environmental degradation due to the buildup of heavy metals, which results from industrialization, mining activities, and agriculture, is one of the critical challenges faced worldwide. Heavy metals, such as Lead, Cadmium, Mercury, Chromium, and Arsenic, which are non-degradable, are responsible for these problems through bioaccumulation and toxicity. The classical approaches of bioremediation, which include excavation, soil washing, and chemical precipitation, pose several problems, such as difficulties of implementation and environmental disruption through the generation of secondary contaminants, which are expensive and may be esthetically unpleasing from the environmental point of view. With bioremediation, this is no longer the case, and this alternative has proven to be effective, environmentally friendly, and aesthetically pleasing too. Even though bioremediation is attractive, it cannot be divorced from the overall context and mechanisms by which these processes operate, such as biosorption, bioaccumulation, biotransformation, and biomineralization, as well as the dynamic synergy and impact of phyto-microbe interactions, specified environmental effectors, and other important factors, such as the integrated and innovative approaches and methods of bioremediation, which form the basis of this article, as well as the indispensable roles which bioremediation plays towards integrated ecosystem restoration, which will be discussed further in this article.

INTRODUCTION

The accelerated rate of industrial and agronomical development has triggered an environmental crisis on a global scale; heavy metal pollution ranks among the most persistent features of this crisis. Being elemental, unlike organic pollutants, heavy metals cannot be degraded and thus remain indefinitely in the environment, cycling between geochemical and biological compartments (1). The main anthropogenic sources involve mining and smelting processes, electroplating industries, combustion of fossil fuels, agricultural runoff with pesticides and phosphate fertilizers, and the incorrect disposal of electronic waste (2). The toxicological effects are far-reaching, impacting all levels of biological organization. Chronic exposures in humans have been associated with neurotoxicity (Pb, Hg), nephrotoxicity (Cd), carcinogenicity (As, Cr(VI)), and a host of other disorders (3). Ecologically, metals disrupt soil microbial communities, inhibit plant growth, and bioaccumulate through food webs, posing a threat to biodiversity and ecosystem services.

Unlike the usual methods of remediation known as "Dig and Dump" or "Pump and Treat," the methods include the processes of incineration of soil, solidification/ stabilization of soil, and chemical leaching. Although good results have been obtained from the methods of remediation of soil, the methods are characterized as expensive processes that demand enormous energy consumption, cause destruction of the landscape, and simply shift the problem from one location to another or produce noxious sludge. These disadvantages of the methods have initiated the quest for friendlier technology in the line of green technology (4).

Bioremediation, the technique in which microorganisms and plants are used to reduce the toxic effects of pollutants, has emerged as an alternative solution. It is the technique that uses natural microorganisms and plants to reduce the toxic effects of pollutants upon the environment. Metabolism is used in the process of storing heavy metals. Specifically, the following are the main objectives of the review: First and foremost, the study aims to summarize the present knowledge about the mechanisms used in the process of bioremediation of heavy metals; after that, the contributions made by various biological agents that are used in the process of bioremediation will be discussed (5).

HEAVY METAL CONTAMINATION IN THE ENVIRONMENT

Some of the major heavy metals, which are of particular concern to the environment, are Lead (Pb), Cadmium (Cd), Mercury (Hg), Chromium (Cr), Arsenic (As), Nickel (Ni), Copper (Cu), and Zinc (Zn). While Cu and Zn are considered to be essential micronutrient metals at lower concentrations, at higher concentrations they are considered to be toxic. The effectiveness of these metals depends on their speciation in the soil/water column.

Distribution and Persistence: Both point and non-point sources, such as factory discharge and atmospheric deposition, release metals into the environment. They bind to clays, organic matter, and oxide minerals in soil, but soil texture, pH, and redox potential all affect how mobile they are. Low pH, or acidic conditions, generally increase metal solubility and bioavailability, increasing toxicity and remediation uptake potential (6). Metals can be found in aquatic systems as colloids, dissolved forms, or attached to suspended particles. Eventually, they settle into sediments, which serve as both possible secondary sources and long-term sinks.

Bioaccumulation and Biomagnification: There is a serious ecological risk here. The net increase in metal concentration within an organism over time relative to its surroundings is known as bioaccumulation. When metal concentrations rise at successive trophic levels in a food web, this phenomenon is known as biomagnification. For instance, predators effectively absorb and retain methylmercury produced by aquatic microorganisms, resulting in dangerously elevated levels in piscivorous fish and birds a process notoriously illustrated in Minamata Bay, Japan (7).

Table 1

Major Heavy Metals: Sources, Toxicity, and Permissible Limits

Heavy Metal	Major Anthropogenic Sources	Key Toxic Effects	Permissible Limit (Soil, mg/kg)	Permissible Limit (Water, μg/L)
Lead (Pb)	Batteries, paints, smelting, leaded gasoline	Neurotoxicity, anemia, nephropathy, developmental defects	85-400 (varies) (8)	10-15 (Drinking water) (9)
Cadmium (Cd)	Ni-Cd batteries, phosphate fertilizers, metal plating	Carcinogenic, nephrotoxicity, bone demineralization (Itai-Itai)	0.8-3.0 (8)	3-5 (9)
Mercury (Hg)	Coal combustion, mining, chlor-alkali industry	Neurotoxicity, Minamata disease, renal damage	0.3-10 (8)	1-2 (9)
Chromium (Cr)	Tanneries, electroplating, textile dyes	Cr(VI): Carcinogenic, mutagenic; Cr(III): Less toxic, essential	100-250 (Total Cr) (8)	50 (Total Cr) (9)
Arsenic (As)	Mining, pesticides, wood preservatives	Carcinogenic (skin, lung), cardiovascular disease, neuropathy	20-40 (8)	10 (9)
Nickel (Ni)	Stainless steel, alloys, electroplating	Dermatitis (nickel allergy), carcinogenic in inhalation	35-100 (8)	70 (9)
Copper (Cu)	Mining, electronics, fungicides	Essential but toxic at high doses; liver damage, Wilson's disease	60-200 (8)	1000-2000 (9)
Zinc (Zn)	Galvanization, alloys, rubber industry	Essential but toxic at high doses; gastrointestinal distress	200-300 (8)	3000-5000 (9)

Principles and Mechanisms of Bioremediation

Bioremediation in general may be described as the use of biological systems to catalyze the removal or transformation of environmental contaminants. Based on the site of treatment, it can be categorized as: In-situ-treating contamination at site, e.g., bioventing, phytoremediation, whereas ex-situ involves removal of contaminated material to be treated elsewhere, e.g., biopiles, bioreactors (10). The underlying biological mechanisms that are considered vital for the efficacy of bioremediation concerning metals are:

- **Biosorption:** Passive, metabolism-independent process where metals get bound to the functional groups [carboxyl, amine, phosphate, hydroxyl] of microbial cell surfaces (bacteria, fungi, algae) or plant roots. It is generally fast and reversible, involving ion exchange, complexation, and microprecipitation (11).
- **Bioaccumulation:** the active metabolism dependent intracellular uptake of metals into living cells via transport systems. Once intracellular, metals might be sequestered by metal-binding proteins such as metallothioneins, phytochelatins, or compartmentalized within organelles (12).
- **Biotransformation:** Changes in metal speciation mediated by microbes that affect toxicity and mobility. Examples include redox reactions, such as the reduction of toxic Cr(VI) to less toxic and less mobile Cr(III) by bacteria including Shewanella oneidensis and Pseudomonas aeruginosa; and alkylation/dealkylation, such as microbial methylation of mercury, which may increase its toxicity and mobility (13).
- **Biomineralization:** The formation of insoluble stable metal precipitates, which is brought about mainly by the microbial population's metabolic activities. An

example of this is the production of hydrogen sulfide (H2S) by sulfate reducing bacteria (SRB) that in turn reacts with metals to give insoluble sulfide precipitates such as CdS and ZnS (14).

MICROBIAL BIOREMEDIATION OF HEAVY METALS

Bacterial Bioremediation

Bacteria are ubiquitous and metabolically versatile agents. Metal-resistant bacteria have innate tolerance mechanisms mediated by genes found on chromosomes or plasmids. These include:

- **Efflux System:** Transmembrane ATPases or chemiosmotic pumps that transport metals out of the cytoplasms
- **Enzymatic Detoxification:** Reductases that reduce toxic metals into less toxic forms, e.g., Cr(VI) reductase
- **Extracellular Polymeric Substances (EPS):** EPS present in biofilms act as a shield for the bacteria. Large amounts of EPS are present in the biofilm matrix with maximum binding sites for the efficient removal of metal ions (15).

Table 2

Examples of Microorganisms Used in Heavy Metal Bioremediation (2015-2024)

Microorganism		Target Metal(s)	Primary Mechanism	Key Finding/Application	Reference
Bacteria	*Bacillus cereus* (spore-forming)	Pb(II), Cd(II)	Biosorption via functional groups on spore surface	Spores showed high stability and reusability for wastewater treatment.	(16)
	Pseudomonas taiwanensis	Cr(VI)	Bio-reduction, EPS-mediated sequestration	Demonstrated effective Cr(VI) reduction (98%) in tannery effluent under optimized conditions.	(17)
	Serratia marcescens	Cu(II), Cd(II)	Bioaccumulation, siderophore production	Engineered strain overproducing siderophores showed enhanced metal uptake and plant growth promotion.	(18)
Fungi	*Trichoderma asperellum*	Pb, Cu, Zn	Biosorption, mycoremediation of soil	Combined with biochar, significantly reduced metal bioavailability in contaminated soil.	(19)
	Aspergillus tubingensis	As(III), As(V)	Oxidation, biosorption, methylation	Showed multi-mechanism arsenic detoxification, including volatilization as less toxic trimethylarsine.	(20)
	Penicillium chrysogenum (MR1)	Cd, Pb	Intracellular sequestration, glutathione metabolism	Proteomic analysis revealed upregulation of antioxidant and metal-binding pathways under stress.	(21)
Algae	*Scenedesmus obliquus*	Cd, Pb, Ni	Biosorption, phycoremediation of wastewater	Used in algal turf scrubber system, removing >85% of metals while producing biomass for biodiesel.	(22)
	Chlorella vulgaris (immobilized)	Cr(VI)	Bio-reduction, biosorption	Alginate-immobilized beads showed superior performance and reusability in continuous flow systems.	(23)
	Sargassum muticum (seaweed)	Rare Earth Elements (REEs)	Ion exchange on alginate	Emerging application for recovery of critical metals from electronic waste leachates.	(24)

Fungal Bioremediation (Mycoremediation)

Fungi, particularly filamentous fungi and yeasts, display a large capacity for metal binding. This capacity is attributed to their large biomass and cell wall composition that includes chitin and/or glucans and melanin. Additionally, fungi secrete organic acids, e.g., citric and oxalic acid, and siderophores that chelate iron and other metal ions. The white-rot fungi Phanerochaete chrysosporium are capable of decomposing organic metal complexes, which could result in metal release and subsequent immobilization (25). Moreover, recent research shows the benefits of the synergy between fungi and plants as well as the application of fungal biochar for metal immobilization (19).

Algal Bioremediation

Microalgae and macroalgae-seaweeds-are very effective biosorbents in aquatic systems. The cell wall polysaccharides of marine algae are mainly anionic in nature, providing excellent cation-exchange properties, for example, alginate in brown algae. Algal systems could be applied to constructed wetlands or bioreactors for the treatment of industrial effluents, thereby offering a dual benefit of metal removal and biomass production for further use for biofuels or fertilizers (26). A very significant contemporary research focus involves the concept of the "circular biorefinery," whereby metal-laden algal biomass is processed for both resource recovery and energy (22).

PHYTOREMEDIATION OF HEAVY METALS

Phytoremediation employs plants and their associated rhizosphere microbes to extract, stabilize, or degrade contaminants. It is a solar-driven, aesthetically pleasing technique appropriate for large areas with low-to-moderate levels of contamination.

Phytoextraction

In phytoextraction, hyperaccumulator plants absorb high amounts of metals and translocate them to the parts of the plants that grow above the ground. These parts are then removed and discarded. These hyperaccumulator plants have the ability to accumulate metals 50-100 folds more than normal vegetation (27).

Phytostabilization

The use of plant growth to absorb, precipitate, or complex metals in the rhizosphere, which reduces the bioavailability of metals. Phytostabilization has to be done on sites that have been heavily contaminated. The metals cannot be easily removed.

Phytovolatilization

Plants absorb volatile metals/metalloids (like Se, Hg, As), convert them to more volatile forms, and release them at low concentrations, perhaps less toxic, into the atmosphere. This mechanism is also controversial because of atmospheric dispersal.

Rhizofiltration

The use of plant roots, often grown in hydroponic culture, to adsorb, precipitate, or absorb metals.

Table 3

Promising Plants for Phytoremediation (Recent Advances, 2015-2024)

Plant Species	Common Name	Target Metal(s)	Primary Mechanism	Recent Advancement / Note	Reference
Noccaea caerulescens (formerly *Thlaspi*)	Alpine Pennycress	Cd, Zn, Ni, Tl	Phytoextraction	Model hyperaccumulator; genome sequenced, revealing key transporter genes (e.g., HMA4, ZIP) for bioengineering.	(28)
Pteris vittata	Chinese Brake Fern	As, Pb	Phytoextraction	Arsenic hyperaccumulator; microbiome studies show key rhizobacteria (e.g., *Pseudomonas*) enhance As uptake.	(29)
Helianthus annuus	Sunflower	Pb, U, Cs, ^{90}Sr	Rhizofiltration, Phytoextraction	Used in recent nuclear accident contingency plans; genetic studies aim to improve metal tolerance.	(30)
Salix spp. (e.g., *S. viminalis*)	Willow (Energy)	Cd, Zn	Phytoextraction, Phytostabilization	High biomass; used in Short Rotation Coppice (SRC) systems for combined remediation and bioenergy.	(31)
Brassica napus (Canola)	Canola/Rapeseed	Cd, Se	Phytoextraction, Phytovolatilization (Se)	Fast-growing crop plant; studied for phytomanagement of Se-laden agricultural soils.	(32)
Vetiveria zizanioides	Vetiver Grass	Pb, As, Cr, TPHs	Phytostabilization	Used globally for erosion control and contaminant stabilization on mine tailings and slopes.	(33)
Populus spp. (transgenic)	Poplar	Hg, Se	Phytovolatilization	Engineered with bacterial *merA* and *merB* genes for mercury detoxification and volatilization.	(34)

ROLE OF PLANTS MICROBE INTERACTIONS IN BIOREMEDIATION

The rhizosphere-soil zone affected by plant roots-represents a hotspot of microbial activities and thus plays a key role in the success of phytoremediation. Plants may release up to 20% of their photosynthates as root exudates-sugars, organic acids, amino acids-which significantly stimulate the growth and activity of microorganisms (35).

Plant Growth-Promoting Microorganisms

This includes bacteria, such as Pseudomonas and Bacillus, and fungi, such as mycorrhizae, which improve the tolerance of plants to metals and their accumulation. This they do through various means: 1) Production of phytohormones that enhance root growth (IAA); 2) Producing siderophores, which increase the availability of Fe and chelate other metals; 3) Solubilization of phosphate, which enhances the uptake of P and associated metals; 4) ACC deaminase activity that lowers ethylene stress in plants during metal toxicity [35]. Meta-analysis indeed confirms the plant inoculation with PGPMs may elevate plant biomass and metal accumulation by approximately 20-50% (36).

Myorrhizal Fungi

Arbuscular Mycorrhizal Fungi (AMF) have been known to establish symbiotic relationships with terrestrial plants, with their extensive filaments providing a means to augment the plant root system's ability to absorb metals (phytoextraction) or sequester metals in the biomass of the fungi (phytostabilization) (37). Recent studies investigate the selection of AMF for enhanced metal stabilization by woody plant species for land reclamation.

FACTORS AFFECTING BIOREMEDIATION EFFICIENCY

The effectiveness of any bioremediation scenario depends on a complex interplay of biological, chemical, and physical factors:

pH and Redox Potential

They regulate metal solubility, speciation, and microbial community structure.

Metal Concentration and Speciation

High concentration levels can prove harmful to the remediation species. The chemical form of the metals also influences the toxicity and the biological mechanisms.

Nutrient Availability

Appropriate levels of N, P, K, and micronutrient availability support good plant and microbial development.

An important factor is Temperature and Moisture.

Contaminant Mixtures: A site can have several contaminants, including metals and organics, which can show antagonistic, additive, and synergistic effects.

INTEGRATED AND EMERGING BIOREMEDIATION APPROACHES

To overcome the problems associated with single-method approaches, integrated and advanced methods have been developed:

Genetically Engineered Microorganisms (GEMs) & Plants

They can be genetically designed to increase the expression of any of the metal chelating peptides, transporters, and/or detoxification enzymes. Transgenic poplars carrying bacterial merA and merB gene cassettes display improved tolerance and volatilization of mercury (34). CRISPER-Cas systems are now being used for precise gene editing of hyperaccumulator expression (38).

Nanobioremediation

"Convergence of nanotechnology with bioremediation." As an example, nanoparticles of iron can be employed to decrease Cr(VI) to Cr(III), which can be sequestered via plants or microbes. Nano-sorbents can likewise preconcentrate metals before biotic processing. An essential development is the utilization of biogenic nanoparticles that can be created by plants or microbes; such particles are more stable and non-toxic (39).

Bioelectrochemical Systems (BES)

The use of electroactive bacteria in MFCs or MECs for recovering metals from wastewater through its reduction and deposition at the cathode-e.g., Cu^{2+} to Cu^0 (40). Most recently, pilot-scale studies have been gaining traction and show favorable results for recovering valuable metals such as copper and gold from industrial leachates.

Combined Strategies

Coupling phytoremediation with soil amendments such as chelators, for example, EDTA enhanced phytoextraction or biochar for stabilization, or selected microbial inoculant to create a synergistic treatment train. Application of specifically designed "designed biochars" elaborated from remediation biomass itself is thus one of the recent research growth points (41).

Table 4

Comparison of Bioremediation and Conventional Remediation Methods

Aspect	Conventional Methods (e.g., Excavation, Soil Washing)	Bioremediation Methods (e.g., Phytoremediation, Microbial)
Cost	Very high (capital & operational)	Low to moderate
Environmental Impact	High (site destruction, secondary waste)	Low (in-situ, eco-friendly)
Time Frame	Short to medium (months)	Long (years)
Public Acceptance	Low (disruptive)	High (aesthetically pleasing)
Scope	Localized, point source	Large, diffuse areas
Contaminant Removal	Physical displacement or immobilization	Detoxification, removal, or stabilization
Ecosystem Restoration	Often requires separate restoration phase	Integrates remediation with restoration
Secondary Waste	Generates large volumes (sludge, debris)	Minimal; biomass may require management
Technology Maturity	High, well-established	Moderate to high, rapidly evolving

BIOREMEDIATION AND ECOSYSTEM RESTORATION

A cardinal advantage with bioremediation is its ecological restoration tendency. In addition to the removal of contaminants, it seeks a return of the ecosystem function:

Soil Health Improvement

Microbial and plant activity rebuilds organic matter, improves the structure, water holding capacity, and nutrient cycling in the soil. Adding organic amendments-like composts and biochar-which is often included in phytostabilization methods-accelerates this process even further (42).

Biodiversity Recovery

Reduced toxicity through bioremediation favors the return of native flora and fauna to the site, hence, initiating succession processes. Research on mine sites that are phytostabilized demonstrates soil invertebrate and microbial diversities increase gradually over 5-10 years (43).

Restoration of Ecosystem Services

Implying the return of basic services such as purification of water and air, sequestration of carbon, and habitat creation for a self-sustaining landscape (44). Bioremediation increasingly finds a place within the great blanket concept "Nature-based Solutions" (NbS) to pollution management.

Table 5

Selected Case Studies of Field-Scale Bioremediation (2015-2024)

Site/Location	Primary Contaminants	Bioremediation Strategy	Key Outcomes & Scale	Reference
Doe Run Mine Site, USA	Pb, Cd, Zn in soil	Aided Phytostabilization: Use of compost, lime, and metal-tolerant grasses (*Festuca arundinacea*) and legumes.	Successful reduction of bioavailable Pb by >70%, established vegetative cover, controlled erosion. Multi-hectare scale.	(45)
Industrial Zone, Shanghai, China	Cd, As in agricultural soil	Microbial-Phyto Combined: Inoculation with Cd/As-resistant PGPR (*Bacillus megaterium*) coupled with planting of *Sedum alfredii* (hyperaccumulator).	Synergistic effect increased Cd extraction by 45% and As stabilization compared to plants alone. Field plot demonstration.	(46)
Tannery Wastewater, Bangladesh	Cr(VI) in effluent	Continuous Flow Bioreactor: Use of immobilized *Pseudomonas* sp. on biochar in a pilot-scale packed-bed reactor.	Achieved >95% Cr(VI) reduction to Cr(III) at flow rates of 100 L/day, meeting discharge standards.	(47)
E-Waste Recycling Site, Ghana	Pb, Cu, Cd in soil	Phytomanagement with Biochar: Application of rice husk biochar combined with planting of *Jatropha curcas* and *Panicum maximum*.	Significant reduction in metal leaching and plant uptake; site secured for non-food biomass production.	(48)
Coastal Wetland, Taiwan	Multiple heavy metals (Cu, Zn, Ni) in sediments	Biostimulation & Phyto: Addition of nutrients and planting of native mangrove (*Kandelia obovata*) and reed (*Phragmites australis*).	Enhanced natural attenuation, increased sedimentation and metal sequestration, improved benthic community.	(49)

Environmental, Health, and Risk Assessment

The use of biological agents requires risk assessment. Concerns include:

Pathogenicity of Introduced Microbes: Guaranteeing that non-pathogenic, non-invasive strains are used. The regulations for microbial inoculants are still evolving, though they lag behind their applications (50).

Trophic Transfer: This is the risk of metals being accumulated in the food chain via plants or microorganisms that are utilized as remediation material. This calls for selecting inedible plants and monitoring wildlife.

Secondary Contamination: When harvested biomass is found to have high levels of metal concentration and therefore is subject to secondary issues of safety in handling and disposal. The thermal conversion of the biomass at low temperature for energy production can provide secondary benefits of metal recovery from the ash (51).

Long-term Stability: The stability of immobilized metal should also be guaranteed, especially when there are fluctuations in environment conditions, such as decreases in pH and flooding. It is recommended for phytostabilization monitoring activities to cover long.

Chemical analysis, ecotoxicological tests (earthworm tests, seed germination tests), and ecological indicators are indispensable for validation of efficacy, as well as safety, of the remediation technologies (52).

CHALLENGES, RESEARCH GAPS, AND FUTURE PERSPECTIVES

Though its potential is enormous, bioremediation has challenges that have to be overcome in order for it to be fully accepted:

Scale-up and Timeframe: Lab results are often not easily extrapolatable to the field environment. Remediation can be a slow process, involving one or more crop growth cycles.

Site-Specificity: Success is highly dependent on the local climate, soil properties, and contaminant matrix.

Biomass Management: The safe and cost-effective disposal or utilization of phytoextracted biomass is, however, considered to be a logistical problem.

Regulatory Frameworks: There is no clear guideline for GEM usage, inoculants from commercial sources, and monitoring protocols to measure bioremediation activity (53).

Future Research Should Focus On:

1. Multi-omics and Machine Learning: Integration of genomics, metabolomics, and geochemical data with machine learning models for efficient prediction of bioremediation outcomes, optimization of consortia design, and identification of key functional genes to be engineered.

2. Engineered Plant-Microbiome Systems: Besides working with single-strain inoculants, the design and deployment of synComm-synthetic microbial communities that are specifically tailored to a plant host for a contamination scenario-are becoming increasingly relevant (54).

3. Circular Economy Integration: Creation of integrated biorefineries for polluted biomass by connecting phytomining of value metals with the production of bioenergy and generation of biochar for soil remediation (55).

4. Long-Term Ecological Studies and Socio-Economic Analysis: decadal-scale field site monitoring to determine ecological recovery trajectories; full life-cycle and cost-benefit analyses for comparative evaluation of bioremediation methods versus traditional approaches under realistic conditions (56).

CONCLUSION

Bioremediation reflects a new paradigm in environmental clean-up, departing from the more disruptive approach of engineering-based solutions, while embracing the more subtle, ecological approach of stewardship. This review has highlighted the various tools available in the form of metal-resistant bacteria and fungi, and the complex array of processes contributed by hyperaccumulator plants in the quest against environmental degradation, and the complex processes they adhere to in addressing the problem of heavy metal pollution. The merger of both perspectives, while aided by knowledge of rhizosphere biology and new, genetically and nanotechnologically enhanced techniques, is a powerful approach. Notwithstanding, much more research into these areas, as reflected in new fields of knowledge, such as synthetic biology, data science, and circular economy, portends immense promise. Bioremediation is not merely a clean-up mechanism; it is a process aimed at healing the environmental damage inflicted by pollution, and its further development and application is of critical significance in the quest towards sustainable environmental management in the new age of Anthropocene.

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