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# Bacteria-Based Bioremediation Strategies for Environmental Sustainability

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**Abstract:**

Heavy metal contamination of soils and aquatic ecosystems caused by industrial, agricultural, mining, and urban activities is a persistent global environmental issue. Toxic metals like lead, mercury, cadmium, arsenic, chromium, and nickel are non-biodegradable and accumulate in environmental matrices, endangering ecosystem function and human health. Traditional repair methods are frequently limited by high costs, ecological disruption, and secondary contamination. Bioremediation has evolved as a viable option, employing microbes, plants, fungi, and algae to immobilize, sequester, or change heavy metals into less harmful and bioavailable forms. This paper includes key bioremediation mechanisms such as biosorption, bioaccumulation, biotransformation, biomineralization, and phytoremediation, as well as recent developments in microbial and plant-microbe-assisted remediation.Despite the difficulties associated with large-scale use, bioremediation remains an environmentally friendly method of reducing heavy metal pollution.

**Keywords:** Heavy metal contamination ,Bioremediation, Microbial remediation, Phytoremediation, Biosorption and bioaccumulation, Human health risk, Environmental sustainability

**1. Introduction:-** Heavy metal contamination has become a serious global environmental and public health issue due to the persistent, non-biodegradable, and poisonous character of metallic pollutants introduced into terrestrial and aquatic ecosystems (Ali et al., 2019). Heavy metals like lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), chromium (Cr), and nickel (Ni) are naturally found in the Earth's lithosphere; however, accelerated industrialization and urban expansion have drastically altered their natural biogeochemical cycles, resulting in elevated concentrations in environmental matrices (Sharma et al., 2021).

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Anthropogenic activities such as mining and smelting operations, electroplating industries, fossil fuel combustion, intensive agrochemical use, sewage irrigation, and improper industrial and municipal waste disposal have been identified as the primary causes of heavy metal enrichment above permissible background levels (Khan et al., 2017).Heavy metals, unlike organic pollutants, are elemental in nature and cannot be metabolized or reduced into innocuous end products, leading to their long-term persistence in soils, sediments, and bodies of water (Jaishankar et al., 2014). Their great affinity for soil particles and organic matter allows for long-term retention in the environment, whereas changes in pH, redox potential, and microbial activity can remobilize previously immobilized metals, worsening contamination hazards (Li et al., 2019). Heavy metals enter ecological food webs via plant uptake, aquatic bioassimilation, and trophic transfer, resulting in bioaccumulation within species and biomagnification across successive trophic levels (Singh et al., 2018).

The effects of heavy metal exposure on the environment and human health are significant and complex. Chronic exposure to metals including Pb, Cd, As, and Hg has been shown in numerous epidemiological and toxicological investigations to cause oxidative stress, disturb cellular redox equilibrium, interfere with enzyme activity, and harm nucleic acids and cellular membranes (Bjørklund et al., 2019).

According to the World Health Organization, heavy metal exposure adds significantly to the worldwide illness burden, particularly in low- and middle-income countries with insufficient environmental monitoring, waste treatment facilities, and regulatory compliance.Long-term exposure has been associated to neurodevelopmental problems, endocrine and reproductive toxicity, renal and cardiovascular dysfunction, immunosuppression, and increased carcinogenic risk, even at dosages previously assumed to be environmentally safe (Genchi et al., 2020).Many traditional remediation techniques, including as excavation and off-site disposal, soil washing, chemical immobilization, solidification–stabilization, vitrification, and electrokinetic remediation, have been developed and put into practice to reduce these dangers (Chen et al., 2021).

Although these physicochemical methods can quickly lower metal concentrations, they are often linked to high costs, substantial energy consumption, and the production of secondary hazardous wastes that need to be treated or disposed of (Hashim et al., 2017). Additionally, prolonged remediation methods can disturb soil structure, reduce fertility, and inflict lasting

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damage to native microbial populations, reducing long-term ecosystem resilience and functionality (Tang et al., 2019).

Given these challenges, bioremediation has drawn more attention as a realistic, sustainable, and cost-effective method of controlling heavy metal pollution (Gadd, 2018).Bioremediation utilizes the metabolic, physiological, and biochemical potential of living organisms, such as bacteria, fungi, algae, and higher plants, to immobilize, sequester, detoxify, or transform heavy metals into less harmful and bioavailable forms (Wang et al., 2020). Bioremediation has the advantage of being suitable for in situ applications, which minimizes environmental disruption while allowing for gradual ecosystem restoration (Kumar et al., 2021).Heavy metal detoxification occurs at the microbial level via a variety of mechanisms, including biosorption onto cell walls, intracellular bioaccumulation, enzymatic redox transformations, precipitation as insoluble metal complexes, and biomineralization processes (Priyadarshanee et al., 2022; Gadd & Pan, 2016).

Metal resistance and transformation are frequently regulated by specific genes, operons, and plasmid-encoded systems that regulate metal transport, efflux, sequestration, and enzymatic modification (Wang et al., 2021). These microbial mechanisms are critical in regulating metal speciation, mobility, and toxicity in contaminated settings (Rai et al. 2019).Plant-based remediation techniques, also known as phytoremediation, have shown significant potential for stabilizing, extracting, and containing heavy metals from polluted soils and water bodies (Kumar et al., 2023). Phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration are techniques that use plant physiological processes to limit metal bioavailability and environmental dispersion (Mahar et al. 2016). Importantly, synergistic interactions between plant roots and rhizosphere bacteria improve remediation efficiency by altering soil chemistry, creating metal-chelating chemicals, and activating microbial metal transformation pathways.(Tang et al. 2019).

**2.Review of Literature:-**

| Bacterial Species | Name of Pollutant or heavy metal | Refrence |
|---|---|---|
| **Pleuro-tuscornucopiae** | **Naphthalene,Fluorene,** | **Shao-Heng Liu et al** |

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| | | |
|---|---|---|
| | **Acenaphthene,Anthracene, pd,Cu,Zn,Cd** | **(2016)** |
| **Bacillus firmus** | **Textile effluents** | **Endeshaw Abatenh et al (2017)** |
| **Acinetobacter** | **Fats and hydrophobic dairy residues** | **Alzahrani et al., (2024)** |
| **Bacillus Subtilis, Bacillus Cereus** | **Co,Zn,Cd** | **Hirak R. Dash et al (2012)** |
| **Lysinibacillus sp.** | **Mixed dairy organics** | **Patil et al. (2022)** |
| **Bacillus firmus** | **Textile effluents** | **Abatenh et al. (2017)** |
| **Achromobacte** | **Napthalene,Pb,Cr,Cd** | **Shao-Heng Liu et al (2016)** |
| **Coprinellus radians** | **PAHs,Methylnaphthalenes,Dibenzofurans** | **Endeshaw Abatenh et al (2017)** |
| **Pseudomonas Sp. And Bordetella Sp.** | **Ni,Co,Cd** | **Hirak R. Dash et al (2012)** |
| **Bacillus thuringiensis** | **Phenanthrene,Cd** | **Shao-Heng Liu et al (2016)** |
| **Phanerochaete Chrysosporium** | **Bi & Tri Phenyl methane** | **Endeshaw Abatenh et al (2017)** |
| **Pseudomonas putida** | **Fats and oils** | **Tzirita et al., (2019)** |

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| | | |
|---|---|---|
| **Bacillus** | **Casein, lactose, fats** | **Cardoso et al., (2022)** |
| **Aerococcus sp., Rhodopseudomonas palustris** | **Pb, Cr, Cd** | **Abatenh et al. (2017)** |
| **Flavobacterium, Acinetobacter** | **Aromatic Hydrocarbons** | **Endeshaw Abatenh et al (2017)** |
| **Enterobacter Alcaligenesfaecalis** | **Phenanthrene,Cd** | **Shao-Heng Liu et al (2016)** |
| **Pseudomonas Putida** | **Monocyclic Aromatic Hydrocarbons** | **Endeshaw Abatenh et al (2017)** |
| **Achromobacte** | **Pb,Cr,Cd** | **Shao-Heng Liu et al (2016)** |
| **Aerococcus Sp.,Rhodopseudomonas,Palustris** | **Pb,Cr,Cd** | **Endeshaw Abatenh et al (2017)** |
| **Saccharomyces Cerevisiae** | **Heavy Metals (Hg,Ni,Pb)** | **Endeshaw Abatenh et al (2017)** |
| **Lysinibacillus** | **Mixed dairy organics** | **Patil et al (2022)** |
| **Pseudomonas sp.** | **Phenol** | **Hirak R. Dash et al (2012)** |
| **Geobacter Sp.** | **Fe(III), U(VI)** | **Endeshaw Abatenh et al (2017)** |

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| | | |
|---|---|---|
| **Candida Viswanathii** | **Phenanthrene, Benzopyrene** | **Endeshaw Abatenh et al (2017)** |

**3.Sources of Heavy Metals:-** Human-driven sources are the main causes of dangerous metal concentrations in contemporary ecosystems, according to growing research. Heavy metals enter environmental systems through a complex interaction of natural (geogenic) processes and anthropogenic activities (Sharma et al., 2021). Global metal biogeochemical cycles have been severely disrupted by rapid industrialization, population increase, urbanization, and unsustainable resource extraction, even though geogenic inputs set natural background levels of metals in soils, sediments, and waterways (Wu et al., 2020). Because of this, it is already common knowledge that both developed and developing countries have high levels of hazardous metals in their terrestrial, aquatic, and atmospheric compartments (Ali et al., 2019).

**Natural (Geogenic) Sources**

Natural sources of heavy metals include the weathering of metal-bearing rocks and minerals, volcanic activity, geothermal emissions, and pedogenic processes, all of which work together to manage baseline metal concentrations in the environment (Alloway, 2018). Metals such as chromium (Cr), nickel (Ni), arsenic (As), iron (Fe), and manganese (Mn) are released into soils and surrounding aquatic systems as parent geological materials disintegrate over time, contributing to regional geochemical backdrops (Li et al., 2019).Mercury, arsenic, cadmium, and other trace metals are released into the atmosphere by volcanic eruptions and geothermal vents. From there, they are dispersed over wide geographical areas by wet and dry deposition (Wei et al., 2019). Geogenic inputs are ubiquitous and constant, but unless they are coupled with anthropogenic enrichment or alterations in environmental parameters like pH and redox potential, they hardly ever lead to hazardous accumulation (Rehman et al., 2018).

**Mining and Metallurgical Activities**

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Mining and metallurgical operations are considered as among of the most major anthropogenic sources of heavy metal contamination worldwide due to the large-scale disturbance of metal-rich geological formations (Sharma et al., 2021). Ore extraction, crushing, milling, beneficiation, and smelting all produce large amounts of tailings, waste rock, and slag containing high levels of lead (Pb), cadmium (Cd), arsenic (As), copper (Cu), zinc (Zn), and mercury (Hg) (Chen et al., 2021).Long-term contamination of surface waters, groundwater aquifers, and downstream ecosystems is made easier by the creation of acid mine drainage, which is caused by the oxidation of sulfide minerals and greatly increases metal solubility and mobility (Mishra et al., 2020). Furthermore, long-distance heavy metal transport and deposition are facilitated by atmospheric emissions from smelting operations, which spread contamination well beyond mine borders (Csavina et al., 2012).

**Industrial and Energy-Related Sources**

Industrial activities are a primary source of heavy metal discharge into environmental systems, notably through untreated or insufficiently treated effluents and solid waste (Kumar et al., 2023). Electroplating, battery production, metal finishing, tanning, textile processing, pigment manufacturing, and chemical synthesis industries all release significant amounts of chromium (Cr), cadmium (Cd), nickel (Ni), lead (Pb), and mercury (Hg) into soils and receiving water bodies (Hashim et al., 2017).Energy generation from fossil fuels, particularly coal-fired power plants, is another important source of metal pollution, including mercury, arsenic, and lead in fly ash and flue gases (Wei et al., 2019). These emissions contribute not only to local pollution, but also to regional and global atmospheric metal cycling (Pacyna et al., 2016).

**Agricultural Sources**

Particularly in areas that are heavily farmed and irrigated, agricultural practices contribute to the buildup of heavy metals in a diffuse but permanent manner (Sharma et al., 2021). Cadmium, lead, and arsenic are known to be present in phosphate fertilizers as contaminants from phosphate rock that gradually build up in agricultural soils after extended application (Atafar et al., 2010).Soil metal loads are further increased and soil microbial dynamics are changed by the extensive use of pesticides, fungicides, and herbicides, particularly formulations based on copper and arsenic (Li et al., 2019). Furthermore, the land application

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of sewage sludge and irrigation with contaminated wastewater introduce significant metal loads into soil-plant systems, raising the possibility of crop uptake and eventual entry into the human food chain (Kumar et al., 2023).

**Municipal Waste and Urban Runoff**

Heavy metal inputs from municipal sources have increased due to rapid urbanization, especially in densely populated cities with poor waste management facilities (Ali et al., 2019). Zinc (Zn), copper (Cu), lead (Pb), cadmium (Cd), and mercury (Hg) from domestic goods, commercial operations, and small-scale businesses are frequently found in municipal wastewater, sewage sludge, and landfill leachates (Zhang et al., 2020). Metals deposited on parking lots, roadways, rooftops, and building materials are mobilized by urban stormwater runoff and carried into rivers, lakes, and coastal waterways (Wei et al., 2019). The environmental dispersion and bioavailability of these pollutants are made worse in poor regions by inadequate treatment and disposal methods (Fashola et al., 2016).

**Electronic and Electrical Waste (E-waste)**

Electronic garbage, or "e-waste," is one of the most dangerous and rapidly expanding forms of heavy metal pollution in the world due to the exponential rise in electronic use (Forti et al., 2020). Significant amounts of lead, mercury, cadmium, chromium, and rare metals are embedded in circuit boards, batteries, cathode ray tubes, and display components of discarded electronic gadgets (Needhidasan et al., 2014). These metals are released directly into soils, air, and water bodies through informal recycling methods such open burning, manual disassembling, and acid leaching, which pose serious threats to human health and nearby ecosystems (Robinson, 2019). As a result, e-waste pollution has become a serious environmental and public health issue, especially in low- and middle-income nations (Forti et al., 2020).

**Transportation and Urban Infrastructure**

According to Wei et al. (2019), transportation-related activities have a major role in the deposition of heavy metals in urban environments through various emission pathways. Roadside soils, urban dust, and stormwater sediments contain metals like copper (Cu), zinc

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(Zn), lead (Pb), antimony (Sb), and nickel (Ni) that are released by vehicle exhaust, brake and tire wear, fuel burning, and road surface abrasion (Wei et al., 2019). Furthermore, corrosion of urban infrastructure—such as buildings, pipelines, coatings, roofing materials, and water distribution systems—introduces metals into both indoor and outdoor settings, raising the risk of long-term human exposure (Li et al., 2019). When taken as a whole, these sources highlight the widespread impact of urbanization on the dynamics of heavy metal pollution.

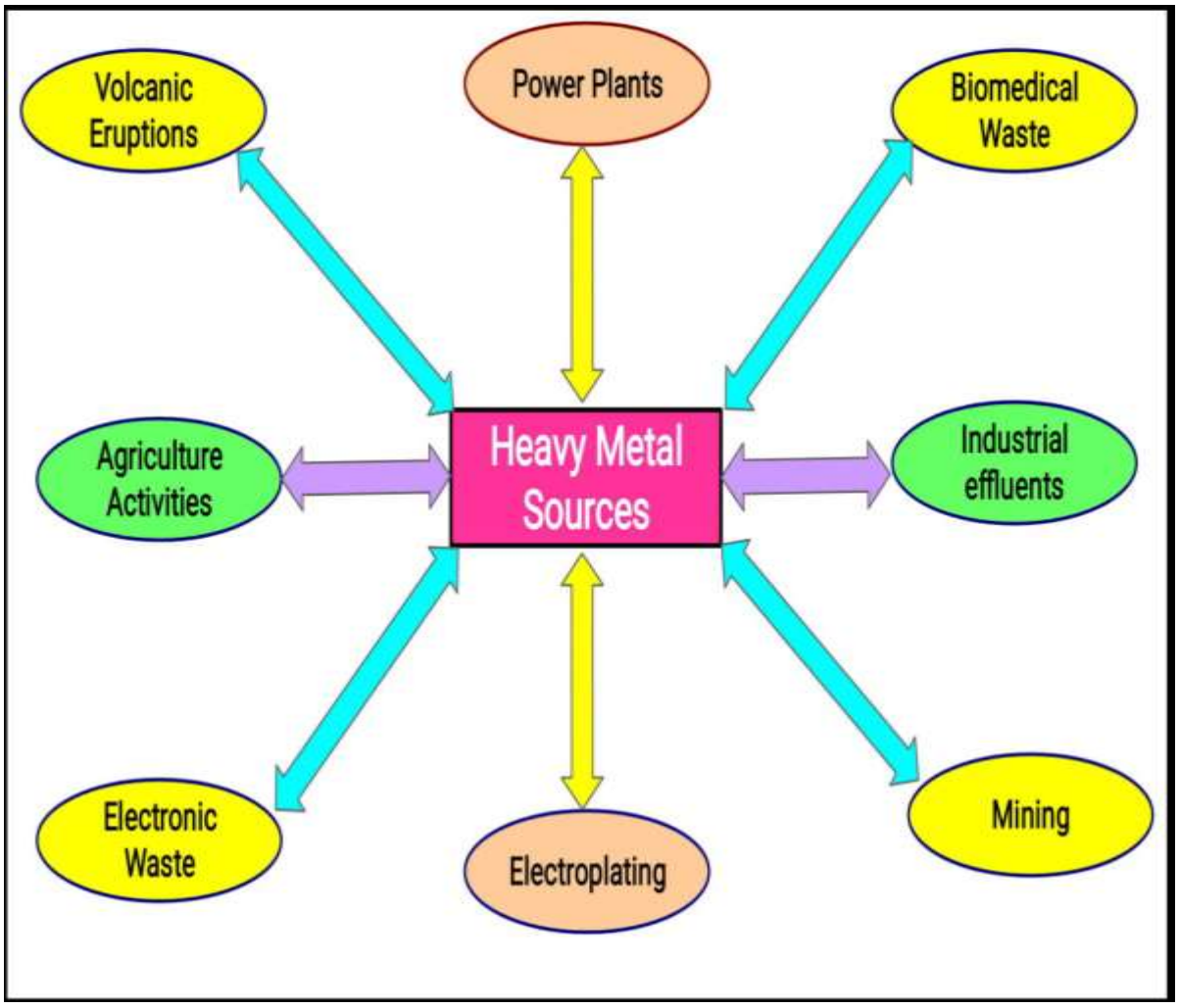


**FIG.:-1 (VARIOUS TYPES OF HEAVY METAL SOURCES)**

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**4.Effects of Heavy Metals on Human Health:-** Due to their environmental persistence, non-biodegradability, potential for bioaccumulation, and ability to disrupt basic biochemical and physiological processes in living things, heavy metals pose a serious hazard to human health (Bjørklund et al., 2019). Long-term systemic toxicity rather than acute consequences are the consequence of chronic exposure to heavy metals, which are mostly caused by contaminated drinking water, food chains, air pollution, and occupational contact. Neurological impairment, endocrine disruption, and behavioral changes are among the many health outcomes linked to metal poisoning that are especially well-documented and represent crucial mechanistic pathways via which heavy metals negatively impact human health (WHO, 2023).

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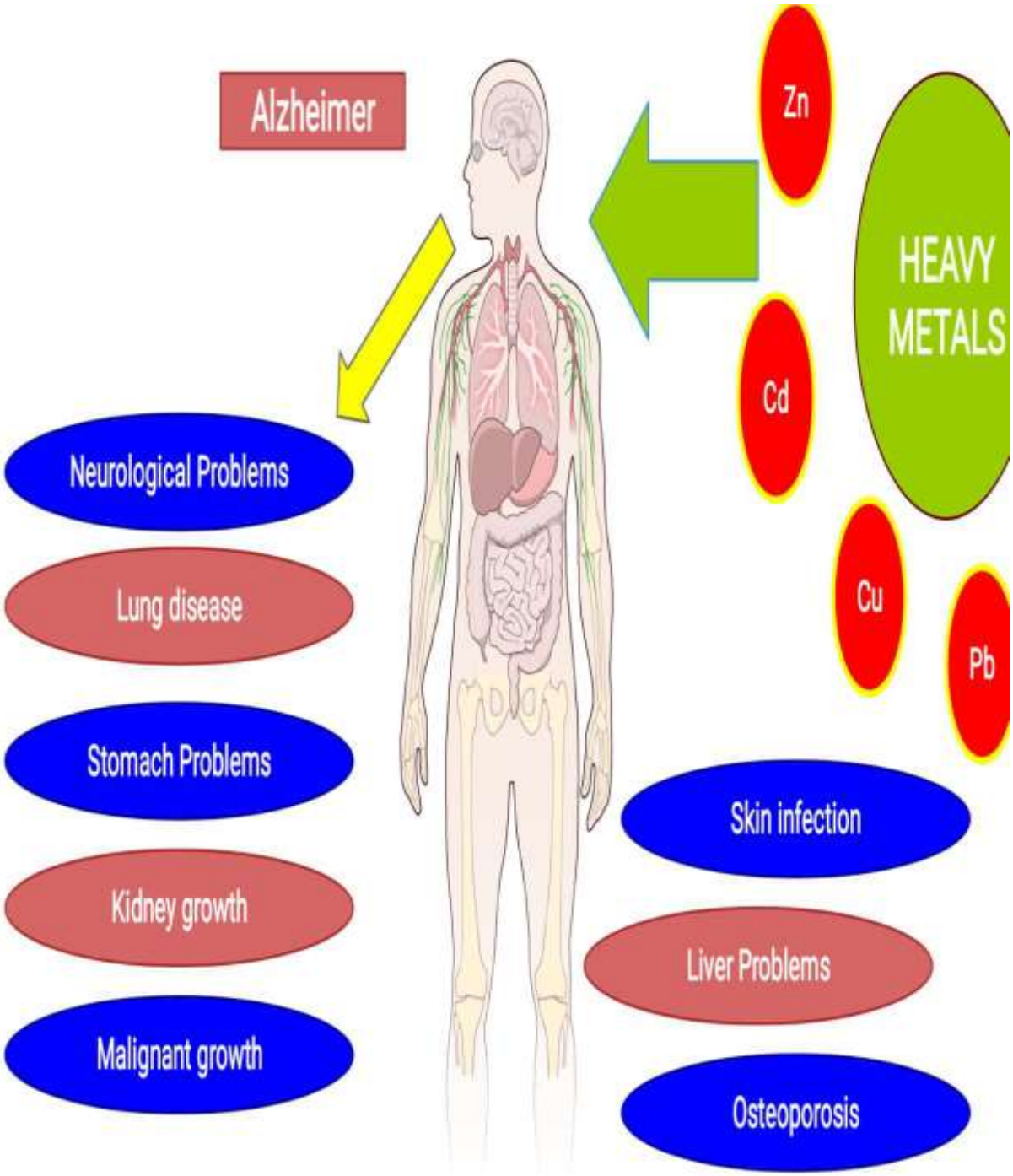


**FIG.-2 (EFFECTS OF HEAVY METALS ON HUMAN HEALTH)**

**Neurological Effects**

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The nervous system is particularly vulnerable to heavy metal toxicity due to its high metabolic demand, lipid-rich composition, and limited regeneration ability, especially during prenatal and early childhood development (Bjørklund et al., 2019). Toxic metals like lead (Pb), mercury (Hg), arsenic (As), and cadmium (Cd) can cross the blood-brain barrier via metal transporters or passive diffusion and accumulate in neural tissues, disrupting neuronal differentiation, synaptogenesis, and neurotransmission (Sharma et al., 2021).

Even at blood lead levels that were once thought to be acceptable, lead exposure is still one of the most well researched neurotoxic insults and is substantially linked to decreased IQ, poor learning capacity, attention problems, and executive dysfunction in children (WHO, 2023). Chronic lead exposure in adults has been associated with decreased motor coordination, peripheral neuropathy, memory loss, and an increased risk of neurodegenerative diseases like Parkinson's and Alzheimer's (Genchi et al., 2020). Developmental delays, motor dysfunction, sensory impairment, and cognitive deficiencies are caused by mercury, especially in its organic form as methylmercury, which interferes with neuronal migration, axonal growth, and neurotransmitter control (Karagas et al., 2018).

Chronic arsenic exposure has been linked to altered neurotransmitter levels, impaired motor coordination, cognitive decline, and decreased memory performance, which are largely mediated by oxidative stress, mitochondrial dysfunction, and disruption of cellular energy metabolism in neural tissues (Sharma et al., 2021). Cadmium, while less capable of crossing the blood-brain barrier, causes indirect neurotoxicity via inflammation, oxidative damage, and alteration of calcium signaling pathways (Genchi et al., 2020). Heavy metals cause neurotoxicity by producing excessive reactive oxygen species, interfering with calcium homeostasis, inhibiting neurotransmitter release, synaptic dysfunction, and activating neuroinflammatory cascades (Rehman et al., 2018).

**Hormonal (Endocrine) Effects**

It is becoming widely know that heavy metals are powerful substances that can disturb endocrine homeostasis by changing hormone synthesis, secretion, transport, metabolism, and receptor binding (WHO, 2020). Important endocrine axes, including as the hypothalamic-pituitary-thyroid (HPT), hypothalamic-pituitary-gonadal (HPG), and hypothalamic-pituitary-

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adrenal (HPA) systems, have been demonstrated to be disrupted by metals like cadmium, lead, mercury, and arsenic (Sharma et al., 2021).

By directly binding to estrogen receptors, cadmium demonstrates estrogen-mimicking activity, changing gene expression and increasing the risk of hormone-dependent cancers like breast and prostate cancer as well as reproductive toxicity, irregular menstruation, and decreased fertility (Genchi et al., 2020). Lead exposure has been linked to changes in the secretion of thyroid hormones, cortisol, luteinizing hormone, and testosterone, which can cause menstruation problems, delayed puberty, poor sperm quality, growth impairment, and metabolic dysregulation (WHO, 2023). Mercury interferes with the production and metabolism of thyroid hormones, which are essential for energy homeostasis, brain development, and thermoregulation, especially during pregnancy and early infancy (WHO, 2020).

Insulin resistance and a higher risk of metabolic diseases like type 2 diabetes mellitus are caused by arsenic's disruption of insulin signaling pathways and glucose metabolism (Sharma et al., 2021). Because hormonal disruptions can happen at low exposure levels and result in delayed, irreversible, and transgenerational impacts, especially when exposure occurs during important developmental windows, endocrine disruption by heavy metals is especially concerning (WHO, 2020).

**Behavioral and Psychological Effects**

Behavioral and psychological disorders are strongly associated with underlying neurotoxic and neuroendocrine mechanisms and constitute a significant but frequently underappreciated symptom of heavy metal toxicity (Bjørklund et al., 2019). Early-life metal exposure has been repeatedly linked to long-term changes in behavior, emotional control, cognitive function, and social interactions, according to epidemiological and longitudinal research (Sharma et al., 2021).

Lead exposure has been linked to increased impulsivity, attention-deficit/hyperactivity disorder (ADHD) symptoms, poor emotional control, aggression, and antisocial behavior, particularly in children exposed during the prenatal and early childhood phases (WHO, 2023). Mercury exposure has been linked to anxiety, irritability, depression, emotional instability, sleep difficulties, and lower stress tolerance due to its impact on neurotransmitter

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pathways and endocrine signaling (Bjørklund et al., 2019). Chronic arsenic exposure has been connected to depressive symptoms, cognitive tiredness, reduced attention span, and poor executive functioning, whereas cadmium exposure has been linked to anxiety-like behavior, mood disorders, and altered stress responses (Sharma et al., 2021).

**5.Bioremediation of Heavy Metals:-** Bioremediation has emerged as a sustainable, eco-friendly, and environmentally compatible strategy for reducing heavy metal contamination in soils, sediments, and aquatic environments, especially when traditional physicochemical methods are economically or ecologically unsustainable (Dixit et al., 2015). Heavy metals, unlike organic pollutants, are elemental in nature and cannot be degraded into harmless end products; thus, bioremediation strategies primarily aim at immobilization, sequestration, transformation, or controlled mobilization of metals to reduce their toxicity, bioavailability, and ecological risk (Priyadarshanee et al., 2022). Recent breakthroughs in environmental biotechnology, microbial ecology, and systems biology have considerably increased the applicability, efficiency, and predictability of biological systems for heavy metal remediation under a variety of environmental situations (Kumar et al., 2023).

**Microbial Bioremediation**

Microorganisms play an important role in heavy metal bioremediation because of their extraordinary metabolic variety, high growth rates, genetic adaptability, and ability to live and function under extreme metal stress (Dixit et al., 2015). Diverse microbial groups, including bacteria, fungi, algae, and archaea, interact with metal ions via a variety of physicochemical and biochemical mechanisms, including biosorption, bioaccumulation, enzymatic redox transformation, precipitation, and biomineralization, regulating metal mobility and toxicity in contaminated environments (Chen et al., 2021).

Biosorption is a passive, metabolism-independent process in which metal ions bind to negatively charged functional groups found on microbial cell walls and extracellular polymeric substances (EPS) (Wang et al., 2020). This process is especially successful for metals like lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), and chromium (Cr), and it can occur even with inactive or dead microbial biomass, making it an appealing option for low-cost wastewater treatment (Chen et al., 2021). The high surface-to-volume ratio of microbial

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cells improves biosorption effectiveness, allowing for fast metal removal from aqueous systems (Priyadarshanee et al., 2022).

In contrast, bioaccumulation is an active, energy-dependent process that involves metal ion transport across the cell membrane, followed by intracellular sequestration via metallothioneins, phytochelatins, and metal-binding proteins, or compartmentalization within vacuoles and granules (Priyadarshanee et al., 2022). This method allows live microorganisms to regulate internal metal concentrations and reduce cytotoxicity, although its effectiveness is heavily regulated by microbial metabolic activity, ambient circumstances, and metal speciation (Kumar et al., 2023).

Microorganisms can also undergo biotransformation, in which enzymatic processes change metal oxidation states, solubility, and toxicity, altering their environmental fate (Chen et al., 2021). A well-documented example is the microbial reduction of hexavalent chromium [Cr(VI)], a highly poisonous and mobile species, to trivalent chromium [Cr(III)], which is substantially less toxic and easier to immobilize in soils and sediments (Priyadarshanee et al., 2022). Similar microbial changes have been seen for mercury, arsenic, and selenium, emphasizing the significance of microbial redox mechanisms in metal detoxification (Dixit et al., 2015).

**Phytoremediation**

Phytoremediation is the employment of plants and rhizospheric bacteria to remove, immobilize, or stabilize heavy metals from contaminated soils, sediments, and water bodies (Kumar et al., 2023). Depending on the main mechanism, phytoremediation includes phytoextraction, phytostabilization, rhizofiltration, and phytovolatilization, each addressing a distinct element of metal mobility and bioavailability (Kumar et al., 2023).Certain plant species, known as hyperaccumulators, have exceptional physiological adaptations that allow them to tolerate and accumulate extremely high levels of metals such as zinc (Zn), nickel (Ni), cadmium (Cd), and arsenic (As) without exhibiting phytotoxic symptoms (Kumar et al., 2023). Metals are absorbed by plant roots and transported to aerial tissues, which are then harvested to physically remove metals from the contaminated area (Sharma et al., 2021).

Phytostabilization, on the other hand, seeks to minimize metal mobility and bioavailability by immobilizing pollutants in the rhizosphere via root adsorption, precipitation, and

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complexation, hence reducing leaching and ecological exposure (Ali et al., 2013).Plant-microbe interactions in the rhizosphere are important for increasing phytoremediation efficiency because they change soil pH, produce metal-chelating chemicals, stimulate microbial metal transformation pathways, and improve plant tolerance to metal stress (Tang et al., 2019). These synergistic interactions highlight the necessity of integrating plant-microbe systems for successful and long-term metal cleanup (Kumar et al., 2023).

**Mycoremediation and Algal-Based Remediation**

Due to their filamentous growth, vast hyphal networks, and large surface area for metal binding, fungi have garnered growing interest as efficient agents for heavy metal bioremediation (Dixit et al., 2015). Chitin, glucans, melanin, and glycoproteins are prevalent in fungal cell walls and offer a variety of functional groups that can bind and immobilize metal ions (Wang et al., 2020). Lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As) have all been successfully removed from contaminated soils, sediments, and industrial effluents by mycoremediation (Chen et al., 2021).

Similarly, microalgae and cyanobacteria have high metal uptake capacities, rapid growth rates, and remarkable adaptation to changing environmental circumstances, making them ideal for treating metal-contaminated wastewater (Priyadarshanee et al., 2022). Their ability to function directly in aquatic systems, along with the possibility for biomass harvesting and resource recovery, increases their practical utility in large-scale cleanup initiatives (Kumar et al., 2023).

**Advantages and Limitations**

Bioremediation has various advantages over traditional remediation methods, including lower operational costs, fewer energy requirements, minimum secondary contamination, and compatibility with in situ applications that maintain soil structure and ecosystem integrity (Dixit et al., 2015). However, bioremediation efficacy is very site-specific and impacted by a variety of environmental parameters including as pH, temperature, redox potential, metal speciation, nutrient availability, and the presence of co-contaminants (Priyadarshanee et al., 2022). Furthermore, problems related to the long-term stability of immobilized metals, potential remobilization under changing environmental conditions, and scalability under field

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circumstances remain major research gaps that require further examination (Wang et al., 2020).

**6.Mechanisms of Bioremediation of Heavy Metals:-** Heavy metal bioremediation is governed by a set of interrelated biological systems that collectively diminish metal toxicity, mobility, and bioavailability rather than removing metals from the environment due to their elemental and non-degradable nature (Priyadarshanee et al., 2022). These mechanisms work at several organizational levels—molecular, cellular, community, and ecosystem—and are mediated by a variety of biological agents such as bacteria, plants, fungi, and algae (Kumar et al., 2023). A thorough understanding of these processes is required to maximize remediation effectiveness, anticipate long-term stability of immobilized metals, and reduce the danger of secondary contamination under changing environmental circumstances (Priyadarshanee et al., 2022).

**Biosorption**

Biosorption is a passive, metabolism-independent technique in which metal ions rapidly bind to functional groups on biological surfaces without requiring cellular energy expenditure (Wang et al., 2020). Bacteria, fungi, algae, and plant-derived biomass all have negatively charged functional groups in their cell walls, such as carboxyl, hydroxyl, phosphate, sulfate, and amino groups, which interact with positively charged metal ions via ion exchange, surface complexation, chelation, coordination bonding, and electrostatic attraction. This physicochemical interaction controls the initial partitioning of metals between the aqueous phase and biological matrix, lowering metal mobility and bioavailability (Wang et al., 2020).
Biosorption is distinguished by its quick kinetics, reversibility, and effectiveness in a variety of environmental circumstances, and it remains functional even when non-living or immobilized biomass is used (Chen et al., 2021). As a result, this method has been widely studied for the removal of metals including lead (Pb), cadmium (Cd), copper (Cu), nickel (Ni), and chromium (Cr) from industrial effluents and contaminated streams (Kumar et al., 2023). Environmental parameters such as pH, metal speciation, ionic strength, temperature,

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and the presence of competing ions all have a significant impact on biosorption efficiency, determining metal-binding affinity and surface saturation dynamics (Chen et al., 2021).

**Bioaccumulation and Intracellular Sequestration**

Bioaccumulation is an active, energy-dependent process in which live cells move metal ions across the plasma membrane using particular or nonspecific transporters, followed by intracellular detoxification and sequestration (Priyadarshanee et al., 2022). Metals are internalized and bound by intracellular ligands such as metallothioneins, phytochelatins, glutathione, and polyphosphate granules, or compartmentalized within vacuoles, lysosome-like structures, and other subcellular organelles to avoid interference with essential metabolic pathways (Kumar et al., 2023). This controlled sequestration enables organisms to maintain intracellular metal homeostasis and endure high metal stress (Chen et al., 2021).

Although bioaccumulation has high removal efficiency, it is limited by cellular tolerance thresholds, metabolic activity, and environmental stresses including severe pH, nutritional constraint, or co-contaminant toxicity (Kumar et al., 2023). Furthermore, because bioaccumulation requires viable biomass, its implementation at the field scale necessitates rigorous environmental management to maintain microbial or plant metabolic function over long remediation periods (Wang et al., 2020).

**Biotransformation and Redox Reactions**

Biotransformation is the biological modification of heavy metals, primarily by enzymatic redox processes that change metal oxidation state, solubility, toxicity, and environmental mobility (Chen et al., 2021). Many microbes have metal-specific reductases, oxidases, and methyltransferases, which catalyze changes that influence metal destiny in soils and aquatic systems (Priyadarshanee et al., 2022). These redox-driven processes are critical in detoxification, especially for metals whose toxicity is highly reliant on oxidation state (Sharma et al., 2021).

One well-documented example is the microbial reduction of hexavalent chromium [Cr(VI)], a highly poisonous, mobile, and carcinogenic species, to trivalent chromium [Cr(III)], which has significantly decreased solubility, bioavailability, and health risk (Chen et al., 2021). Similar biotransformation pathways have been reported for arsenic, where microbial

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reduction and oxidation regulate the interconversion of arsenite to arsenate, and for mercury, where microbial methylation and demethylation processes determine toxicity and bioaccumulation potential (Sharma et al., 2021). These modifications have a significant impact on metal persistence and risk under site-specific environmental circumstances.

**Biomineralization and Precipitation**

Biomineralization is the biological synthesis of insoluble metal-bearing minerals, which results in the long-term immobilization of heavy metals in soils and sediments (Priyadarshanee et al., 2022). Microorganisms establish geochemical conditions that encourage the precipitation of metals as sulfides, phosphates, carbonates, or oxides via metabolic processes such as sulfate reduction, phosphate release, carbonate formation, and pH modulation (Chen et al., 2021). This technique greatly reduces metal mobility and bioavailability, minimizing environmental and human health concerns (Gadd, 2018).Under anaerobic conditions, sulfate-reducing bacteria produce sulfide ions, which react with metals such as lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu) to form very insoluble metal sulfides (Priyadarshanee et al., 2022).

Biomineralization is especially significant in anoxic environments like wetlands, sediments, and subsurface soils because it helps to stabilize pollutants over time and improves the durability of remediation results (Gadd, 2018).

**Phytoremediation-Based Mechanisms**

Plants contribute to heavy metal bioremediation via a variety of root-mediated methods, including phytoextraction, phytostabilization, rhizofiltration, and phytovolatilization, each addressing a distinct aspect of metal mobility and bioavailability (Kumar et al., 2023). Metals are absorbed by plant roots and transported to above-ground tissues, which can then be harvested to physically remove metals from contaminated locations (Kumar et al., 2023). Phytostabilization, on the other hand, aims to reduce metal mobility by immobilizing pollutants in the rhizosphere via root adsorption, precipitation, and soil physicochemical characteristics (Kumar et al., 2023).

Plant-microbe interactions in the rhizosphere are critical for improving phytoremediation efficiency by increasing metal solubility via root exudates, activating microbial metal

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transformation pathways, and improving plant tolerance to metal-induced oxidative stress (Tang et al., 2019). These synergistic interactions underscore the value of integrated plant-microbial systems in attaining successful and long-term cleanup solutions (Chen et al., 2021).

**Biofilm Formation and Microbial Consortia**

Microorganisms commonly exist in communities as biofilms embedded in extracellular polymeric substances (EPS), which provide numerous metal-binding sites and produce microenvironments that modify metal availability (Chen et al., 2021). Biofilm development improves metal resistance by limiting metal penetration, buffering harmful shocks, and dispersing stress among microbial populations, boosting system stability under changing environmental circumstances (Priyadarshanee et al., 2022). Polysaccharides, proteins, and extracellular DNA are among the EPS components that play a crucial role in biosorption and immobilization processes.

Microbial consortia are more effective at heavy metal remediation than single strains because they combine various complimentary mechanisms—such as biosorption, redox transformation, bioaccumulation, and precipitation—into a single functional system (Kumar et al., 2023). Microbial consortia's functional redundancy and metabolic cooperation increase robustness, adaptability, and long-term remediation efficiency, making them ideal for complex, varied field situations (Priyadarshanee et al., 2022).

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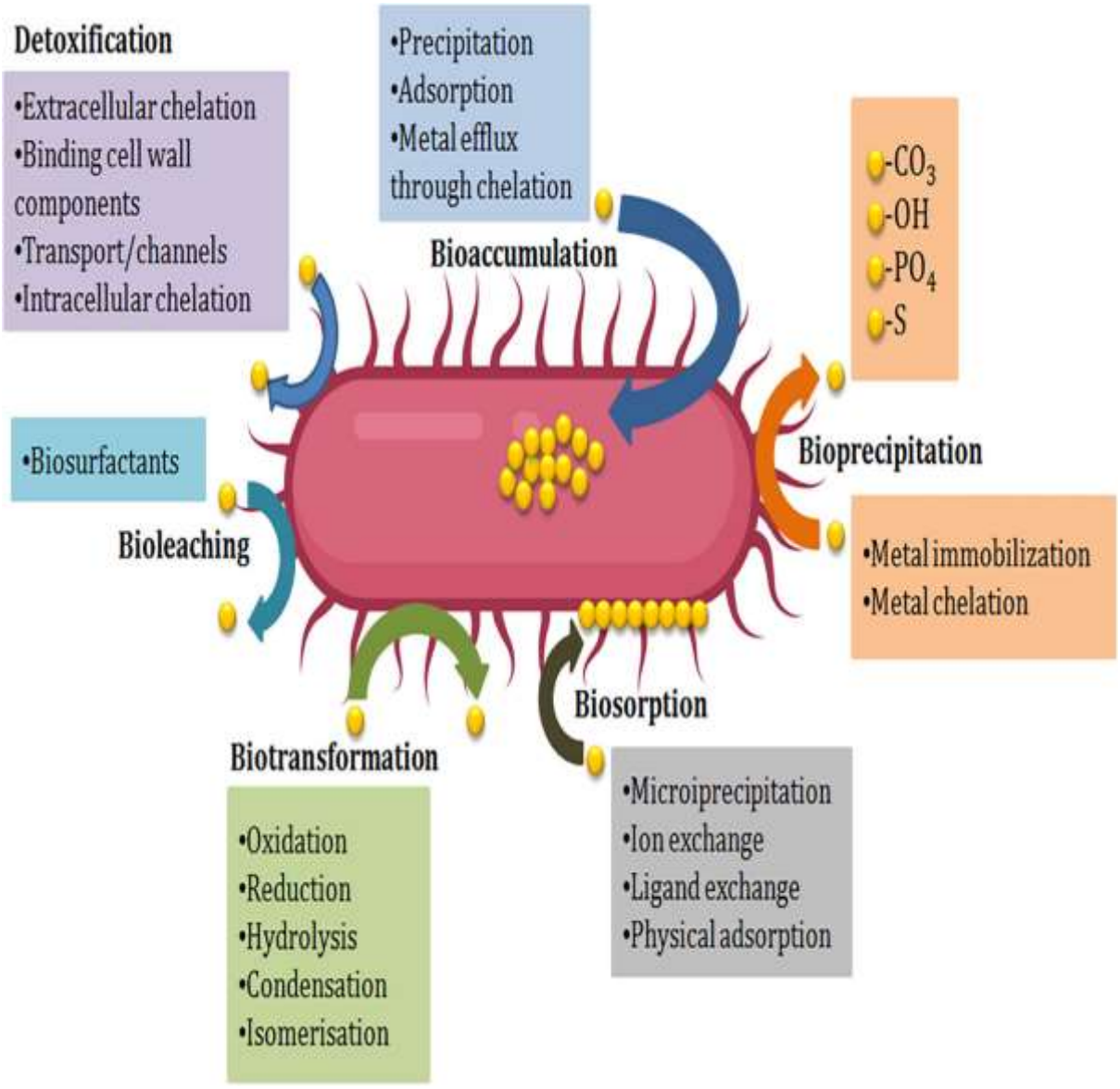


**FIG.:-3 (MECHANISMS OF BIOREMEDIATION)**

**7.Future Prospects in Bioremediation of Heavy Metals:-** Despite significant advances in understanding the biological principles that govern heavy metal bioremediation, successfully translating laboratory-scale and mesocosm-based findings into reliable, predictable, and economically viable field-scale applications remains a significant scientific and technological

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challenge (Priyadarshanee et al., 2022). Field environments are intrinsically complex and heterogeneous, with spatial and temporal variability in physicochemical conditions, mixed pollutant profiles, and ecological interactions that are challenging to mimic in controlled laboratory settings (Kumar et al., 2023). As a result, future research must use integrative, interdisciplinary approaches that combine new molecular tools, engineering advances, and ecological principles to improve the efficiency, resilience, and long-term sustainability of bioremediation systems (Priyadarshanee et al., 2022).

**Integration of Omics and Systems Biology Approaches**

High-throughput omics technologies such as genomics, metagenomics, transcriptomics, proteomics, and metabolomics are expected to play a transformative role in heavy metal bioremediation research by allowing for comprehensive, multi-scale characterization of biological systems in situ (Priyadarshanee et al., 2022). These methods make it easier to identify metal-resistance genes, regulatory networks, stress-response pathways, and metabolic fluxes that control microbial adaptation and detoxification in the presence of metal stress (Chen et al., 2021). Integrating omics datasets with systems biology, network analysis, and bioinformatics modeling will allow for predictive assessment of microbial behavior, community dynamics, and metal fate across environmental gradients, facilitating the rational design of site-specific and mechanism-driven remediation strategies (Kumar et al., 2023).

**Genetic Engineering and Synthetic Biology**

Through focused manipulation of microbial metabolic pathways, recent developments in genetic engineering and synthetic biology present previously unheard-of prospects to improve the metal-removal efficiency of biological systems (Chen et al., 2021; Wang et al., 2020). Under laboratory conditions, engineered microbes that express optimal metal-binding proteins, transporters, redox enzymes, and efflux systems have shown markedly better biosorption, bioaccumulation, and biotransformation capabilities (Gadd, 2018; Priyadarshanee et al., 2022). To ensure the responsible deployment of genetically modified organisms in open environmental systems, however, future research must give priority to biosafety, ecological risk assessment, genetic stability, and regulatory compliance (Chen et al., 2021; Kumar et al., 2023). To reduce unforeseen ecological effects, biological

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confinement techniques like kill switches and dependency circuits must be developed (Wang et al., 2020).

**Plant–Microbe Synergistic Remediation Systems**

Future bioremediation frameworks are projected to rely more on synergistic plant-microbe systems, notably for the treatment of metal-contaminated soils and sediments (Kumar et al., 2023; Ma et al., 2016). Beneficial rhizobacteria, endophytic microbes, and mycorrhizal fungi can improve plant tolerance to metal-induced oxidative stress, increase metal solubilization or immobilization in the rhizosphere, and stimulate microbial detoxification pathways through metabolic cooperation (Tang et al., 2019; Priyadarshanee et al., 2022). The formation of stable, site-adapted plant-microbe consortia is a promising technique for overcoming restrictions associated with slow plant growth, limited root depth, and low biomass output in traditional phytoremediation systems (Kumar et al., 2023; Chen et al., 2021).

**Nanobioremediation and Hybrid Technologies**

Nanobioremediation, or the combination of nanotechnology and biological remediation techniques, is a fast developing field of study that has the potential to significantly increase the effectiveness of heavy metal removal (Kumar et al., 2023; Wang et al., 2020). According to Chen et al. (2021) and Priyadarshanee et al. (2022), engineered nanomaterials can enhance the performance of biological remediation systems by increasing metal adsorption capacity, improving contaminant bioavailability, and acting as delivery platforms for microbial cells, enzymes, or genetic material. To guarantee that hybrid remediation technologies continue to be socially and environmentally acceptable, future research must thoroughly assess the environmental fate, ecotoxicological effects, persistence, and possible bioaccumulation of nanomaterials (Kumar et al., 2023; Gadd, 2018).

**Field-Scale Validation and Long-Term Monitoring**

A critical priority for future bioremediation research is the systematic validation of remediation strategies under realistic field conditions, where environmental heterogeneity, climatic variability, and mixed contamination often constrain remediation performance (Chen et al., 2021; Priyadarshanee et al., 2022). To determine the stability of immobilized or

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transformed metals, evaluate ecosystem recovery, and identify possible remobilization under shifting environmental conditions, such as variations in pH, redox potential, moisture regimes, and land use patterns, long-term field monitoring is crucial (Wang et al., 2020; Kumar et al., 2023). Field-scale bioremediation applications will be more dependable and resilient if real-time sensing technologies and adaptive management frameworks are included (Priyadarshanee et al., 2022).

**Policy Integration and Sustainable Environmental Management**

Scientific and technological developments must be combined with environmental policy frameworks, economic feasibility studies, and social acceptance for bioremediation to become widely used (Kumar et al., 2023; Chen et al., 2021). Future remediation plans should be in line with life-cycle analysis, risk-based site assessment, and circular economy concepts such waste reduction, resource reuse, and metal recovery (Priyadarshanee et al., 2022; Wang et al., 2020). To convert laboratory innovations into scalable, field-ready bioremediation solutions that promote long-term environmental sustainability, researchers, legislators, regulatory bodies, and industry stakeholders must strengthen their interdisciplinary collaboration (Gadd, 2018; Kumar et al., 2023).

**8.Conclusion:-** Heavy metal contamination remains a persistent and global environmental challenge due to metals' elemental, non-biodegradable nature and their continuous introduction into ecosystems via industrial production, mining and smelting activities, intensive agriculture, urbanization, and poor waste management practices (Sharma et al., 2021). Toxic metal accumulation over time alters biogeochemical cycles and jeopardizes ecosystem structure, function, and resilience (Ali et al., 2019). The gradual entry of metals into food chains is of special concern, as it increases exposure hazards for animals and human populations while also posing a significant danger to global environmental sustainability.

Heavy metal exposure is a significant risk factor for the development of chronic diseases, with emerging evidence associating low-level, long-term exposure to negative neurological, endocrine, immunological, and behavioral effects (Genchi et al., 2020). Metals like lead, mercury, cadmium, and arsenic have been proven to cause oxidative stress, disrupt hormonal signaling, damage neurodevelopment, and alter cognitive and behavioral functioning, even at

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previously considered ecologically safe levels (Sharma et al., 2021). According to the World Health Organization, chronic toxic metal exposure continues to contribute significantly to the global illness burden, particularly in low- and middle-income countries with insufficient regulatory enforcement and remediation infrastructure (WHO, 2023).

In this context, bioremediation has emerged as a promising, environmentally sustainable, and cost-effective technique for controlling heavy metal pollution in a variety of contaminated sites (Dixit et al., 2015). Unlike traditional physicochemical remediation techniques, which are frequently associated with high energy demands, secondary pollution, and environmental disruption, biological approaches use natural processes to immobilize, sequester, or transform metals into less toxic and bioavailable forms (Priyadarshanee et al., 2022). Core mechanisms like biosorption, bioaccumulation, biotransformation, biomineralization, and phytoremediation work together at the molecular, cellular, community, and ecosystem levels to provide flexible and site-adaptable remediation solutions (Kumar et al., 2023).

Despite these benefits, the widespread use of bioremediation is hampered by environmental heterogeneity, spatial and temporal variability in metal speciation, mixed contamination scenarios, and uncertainties about the long-term stability of immobilized or transformed metals (Chen et al., 2021). Numerous studies have found that remediation procedures developed in controlled laboratory circumstances are typically less effective in complicated natural environments because to fluctuations in pH, redox potential, nutritional availability, and climatic factors (Priyadarshanee et al., 2022). As a result, mechanism-driven optimization, integration of omics-based techniques, predictive modeling, and rigorous long-term field monitoring are required to improve the reliability, predictability, and sustainability of bioremediation results (Priyadarshanee et al., 2022).

To summarize, bioremediation is a realistic and forward-thinking technique for mitigating heavy metal contamination and lowering associated hazards to environmental and human health when performed within a scientifically sound and context-specific framework (Chen et al., 2021). To bridge the gap between experimental success and large-scale implementation, future advancement will require interdisciplinary research that integrates molecular biology, environmental engineering, ecological risk assessment, and socioeconomic factors (Kumar et al., 2023). By combining technological innovation with long-term environmental management goals, regulatory support, and circular-economy principles, bioremediation has

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the potential to play a critical role in restoring contaminated ecosystems and protecting public health in an increasingly industrialized world (WHO, 2023).

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