Review Article

Sustainable remediation of the toxic impact of heavy metal pollutants in soil and water ecosystem using diverse approaches and microalgal cultivation

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Abstract: Heavy metal pollutants are metallic elements with high atomic weights that can be toxic to living organisms at specific concentrations. These metals have properties that make them persistent and potentially harmful to both the environs and human health. These heavy metals can contaminate water bodies, soil, and air through natural processes as well as industrial and human activities. They can adversely affect ecosystems; disrupt aquatic food chains, and causing long-term environmental damage. In addition to their environmental impact, heavy metals can pretense severe health risks to humans, especially when they enter the food chain. The impacts of heavy metal pollutants are influenced by factors such as the type of heavy metal, its concentration, and the properties of the soil and water. To mitigate the impacts of heavy metal pollutants, non-biological and biological approaches are used. In contrast, microalgal cultivation has shown promise as a sustainable remediation approach for heavy metal contamination in ecosystems. This approach involves using specially selected microalgae to uptake, sequester, and potentially detoxify heavy metals from aquatic environs. This review deliberates the toxic effect of various heavy metal contaminants on the soil and water along with its remediation technique.

Keywords: Microalgae; Heavy metals; Ecological toxicity; Mitigation; Sustainable ecosystem

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1. Introduction

Environmental deterioration, whether caused by human activity or natural causes, has increased dramatically with industrialization, urbanization and development. One of the most frequently contaminated areas of the environs is aquatic habitats. As a result of precipitation, surface runoff, rock and solid waste leaching, and other processes, contaminants in the air, soil, and land eventually find their way into aquatic habitats (Davies et al., 2009). Aquatic ecosystems act as significant reservoirs for a range of contaminants due to the uncontrolled discharge of sewages from industries, mining, and aerial precipitations (Kabata-Pendias 2004). In many emerging nations, rising industrial activity and population growth are hastening environmental exposure to various pollutants, like heavy metals. There has long been an understanding that heavy metals are significant ecological contaminants because of their persistence and hazardous profile in ecosystems as well as their bio-magnifications along the food-chains (Dahunsi et al. 2012). Heavy metal pollutants in the river systems are a severe problem for aquatic life and people interacting with these bodies of water (Boohene and Agbasah, 2018). More specifically, due to the possibility of considerable runoff and industrial discharges, areas close to industrial layouts and agricultural regions offer high risk to aquatic ecosystems. Sediments contain heavy metals primarily from anthropogenic sources, such as farming discharges, industrialized waste, and sewage runoffs, and natural sources (such as weathering and erosion). Pollution from extensive industry, rapid urbanization, and new farming methods adversely impacts coastal areas globally. Heavy metals may have hazardous effects at high concentrations on plant and marine life in coastal habitats along with human health. However, it's important to note that the effectiveness of microalgal-based remediation can depend on factors such as the choice of microalgal species, the concentration, and type of heavy metal pollutants, nutrient availability, and environmental conditions. Research is ongoing to optimize the cultivation and application of microalgae for heavy metal remediation, and this approach might not be suitable for all types of contamination scenarios (Li et al., 2021).

The disproportionate concentrations of heavy metals (including Pb, Hg, and Cu) in aquatic habitats harm ecological systems. In another study by Sinclair et al. (1989), Zheng et al. (2008), and Sheng (2017), suspended particulate matter (SPM) and sediments are known to carry more than 90% of the heavy metal burden in aquatic systems. To effectively manage and avoid heavy metal pollution in aquatic ecosystems, it is necessary to understand the concentration of heavy metals in particulate matter during transport. Rivers are the primary carriers and provide channels to transfer particulate matter to final sediment sinks, such as lakes, estuaries, and the world's oceans.

According to Ali et al. (2016), sediment is a crucial and dynamic component of the river basin, which receives metals from different sources. Physiological adsorption procedures, ligand exchange, and complexation determine how well heavy metals are stabilized. According to Long & Chapman (1985), the deposition rate of heavy metals in sediment is more than 1000 times higher than in water (Liu et al., 2020). Additionally, with any changes in the environmental climate, these metals bonded to the sediment and released back into the submerged waters (Liu et al., 2020). In addition, the accumulation of heavy metals in the soil influences food production, quality, and growth of plants (Muchuweti et al., 2006). Some heavy metals can be toxic to plants at deficient concentrations, while others can build up in plant tissues to mildly abnormal states without causing any noticeable side effects or a reduction in yield. Growing plants in these heavily polluted environments cause changes in their metabolism, physiological processes, and biochemical mechanisms, leading to metal buildup, decreased biomass synthesis, and slower growth. Fishes are among the aquatic species that are most vulnerable to heavy metals found in water and can store significant amounts of toxicants in their body, especially Hg (Dahunsi et al., 2012). The high percentage of protein found in fish and other essential amino acids which are necessary for healthy growth and development of the human body. Many fish products are a significant component of human meals; through meals, heavy metal transfers to the human body (Dahunsi et al., 2012; Hadjiliadis, 2012). In summary, microalgal cultivation has the potential to offer a sustainable and environmentally friendly method for remediating heavy metal pollution. It can be part of a broader strategy for improving water quality and restoring ecosystem health.

2. Heavy metals sources

Heavy metals pollutions are released into mainly two ways i.e. the environment in natural and anthropogenic ways (Figure 1).

2.1 Natural sources

Volcanic eruptions and the corrosion of metal rocks are two examples of their natural sources. Igneous and sedimentary rocks are the greatest frequent natural sources of heavy metals. It has been found that the amounts of various elements fluctuate between different rock kinds and within a single rock type (Bradl, 2005).

2.2 Anthropogenic sources

Mining, industry, and agricultural practices are examples of anthropogenic sources of heavy metals in the environment. Mining and extracting different elements from their respective ores release these metals. Dry and wet deposition causes heavy metals discharged into the atmosphere during mining, smelting, and other industrial processes to fall back to the earth. Utilizing chemical fertilizers and burning fossil fuels are two additional human-caused sources of heavy metal contamination.

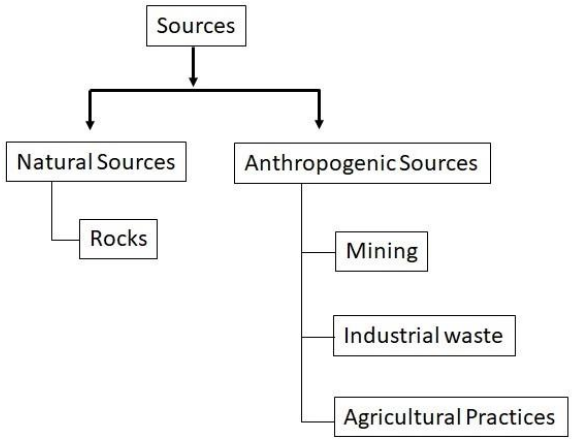

Figure 1 Different source of heavy metal pollutions in environments

2.2.1 Mining

The legacy of widespread dispersion of heavy metals in soil has been left to many nations by mining, milling, and processing metal ores and industries. Large-scale mining and smelting of metal ores cause soil pollution that is hazardous to human and environmental health. As a result of the direct dumping of tailings, or heavier particles that have collected at the bottom of flotation cells, into onsite wetlands and natural depressions during mining, the soil has been contaminated with a considerable amount of heavy metal pollutions (Sankhla et al., 2016; DeVolder et al., 2003).

2.2.2 Industrial sources

Because of this, various industries, including metallurgy, chemical, textile, leather tanning, petrochemical, and metal processing, produce different waste products that contain heavy metals. Using petroleum and pharmaceutical goods and waste from these businesses may also be sources of heavy metals in the soil. Wastes from various sectors have a very diverse chemical makeup. Although some of these wastes are dumped on land, few benefit forestry or agriculture. Furthermore, many are seldom, if ever, applied to land that may be hazardous due to heavy metals (Cr, Pb, Hg, Ni, and Zn), or harmful organic compounds. These wastes also contain little or no plant nutrition (Wuana et al., 2011, Shentu et al., 2015; Sumner 2000).

2.2.3 Agricultural practices

Agricultural pollutants, sometimes called biotic and abiotic consequences of farming practices, frequently harm agro-ecosystems. The agro-ecosystem in the area is often contaminated and degraded by these contaminants. According to Alloway B.J. (2013), the primary sources of heavy metals in agriculture are fertilizers and pesticides. Heavy metal deposition in agricultural soils caused by excessive fertilizer usage over an extended period diminishes soil fertility, inhibiting plant development and production (Alengebawy et al., 2020).

3. Heavy metals toxicity in soil

The accumulation of heavy metals in soil is a major problem due to the adverse impacts on living biota. Heavy metals' non-biodegradable and persistent nature facilitates their accumulation in the environment. Heavy metals are metallic elements with a large atomic weight and a density greater than 5 g/cm3. (Xiaoran Zhang et al., 2019). The ecosystem and human populations have been subjected to a wide range of chemical toxins, particularly pesticides (including fungicides, herbicides, and insecticides), as a result of the rapid advancement of technology (Ozkara et al., 2016). Consideration of environmental toxicity surpassing maximum allowable residue levels (MRL) has increased among global research organizations (Su, Jiang, and Zhang 2014; Toth et al., 2016).

Numerous investigations have concluded that agriculture, agrochemicals, industry, and mining are the primary sources of heavy metal contaminants. The accumulation of heavy metals is an accumulation of elements in the environment. Plant roots are the primary point of interaction for heavy metal ions diffused from the sediment. The uncontrolled application of pesticides leads to an accumulation of these substances in food chains, so presenting a substantial risk to mammals and other creatures that are not the intended targets (Liu et al., 2016). Pesticide's direct or indirect impact on non-target organisms destabilizes the ecosystem (Rosell et al. 2008). The prevalence of toxicants in the food chain and their long-lasting presence in the biota has led to a rise in the adverse health effects of these substances (Verger and Boobis, 2013).

Various fertilizers are distributed globally to provide essential soil nutrients, promoting plant growth and production while enhancing organic matter levels. There are two types of fertilizers: organic (natural) and inorganic (synthetic). Organic or biofertilizers are ammonium fertilizers (sulfate and nitrate) produced by the anaerobic digestion (AD) method. Inorganic fertilizers, often chemically manufactured/synthetic fertilizers, combine inorganic and chemical ingredients (Cai et al., 2019; Alengebawy et al., 2021). Phosphorus is commonly employed in fertilizer production and is essential in heavy metal accumulation through soil application. Phosphorus fertilizers that are not soluble in water might undergo a process of transformation that leads to the production of phosphate rocks, according to earlier studies (Chen et al., 2020; Bolan et al., 2003). It has been discovered that these rocks are essential for the metal phosphate precipitation that immobilizes metals in the soil. It is complicated to restore the soil ecology after heavy metal contamination. Due to the prolonged use of fertilizers, Cd, Cu, and Zn have more potential for accumulation in agricultural soil (Wang et al., 2020).

Everyone is aware that excessive levels of heavy metal concentrations have an impact on both soil and plants. The WHO has established the allowable limits/MRL of their attention in soil and plants (WHO 1996). Metals with high permitted limits are presumed to be safe. Pb has the most excellent acceptable levels in the soil, which is 85mg/Kg, followed by Zn, Cu, and Cd to be 50 mg/Kg, 36 mg/Kg, and 0.8 mg/Kg, respectively, has the lowest tolerable values. The values of these limitations indicate that Cd buildup in soil, even at lesser concentrations, is more harmful than Cu, Zn, and Pb. Cu is the most abundant element in plants, followed by Pb, Zn, and Cd. Cu has the safest limits in soil, trailed by Pb and Zn, whereas Cd buildup in plants is the maximum harmful.

3.1 Cadmium toxicity on soil

The issue of Cd buildup in the soil is widespread due to advancements in agricultural technology, the economic revolution, and rapid industrial development. The deposition of cadmium typically exerts the most significant influence on soil pH and organic matter concentration. Cd bioavailability rose as soil pH decreased, indicating an imbalance in soil characteristics. (Liao et al., 2005) lead a comprehensive study on the harmful influence of Cd on paddy soil parameters. They used various kinetic and sigmoid dose-response models to calculate ecological dosages of Cd. According to their findings, Cd inhibited soil microbial activity, microbial growth, and microbial metabolic methods. Raiesi and Sadeghi (2019) have also investigated the effects of Cd and salinity on soil microorganisms and enzymatic activity. Their findings revealed a deleterious synergistic effect of Cd and salinity on soil characteristics. Furthermore, their combined action reduced soil microbial respiration and microbial biomass.

3.2 Lead toxicity on soil

The primary cause of Pb impurity in soil is geogenic pollution, which lowers soil microbial activity. The presence of Pb in soil has been found to have several implications, such as a decline in soil nutrients, microbial diversity, and soil fertility (Dotaniya et al., 2020). Additionally, Pb toxicity frequently affects earthworms (Eisenia fetida), which can cause earthworm death. Using phytoremediation or phytostabilization strategies to reduce Pb bioavailability in the soil is a crucial topic that should be emphasized (Lan et al., 2020). The effect of soil characteristics have been investigated on Pb absorption and retention. According to the findings, soil pH and cation exchange capacity were the most relevant factors inclined by Pb accretion. In a study conducted by Kumar et al. (2020), it was shown that there exists an adverse correlation between the solubility of Pb and soil pH. This suggests that the occurrence of Pb in the soil disrupts the plant's ability to absorb nutrients from the soil. Pb also influences the soil's sorption capacity and humic acids (Placek et al., 2016). Pb and Cd solitary and combined effects on soil microbial populations and some enzyme activities were investigated. The findings revealed that the contamination significantly impacted the microbial communities. Additionally, the inhibition of enzyme activity has been observed. The number of microbes and actinomycetes decreased substantially due to the combined toxic effects of lead and cadmium. In the context of soil, some fundamental soil factors, including soil texture, organic matter content, ionic exchange capacity, and pH, are influenced by the accumulation of Pb in the soil. These factors play a crucial role in governing the mobility and bioavailability of Pb within the soil.

3.3 Copper toxicity on soil

Cu is a crucial micronutrient that is important and required by organisms. Moreover, it is a necessary component of the soil. Cu toxicity is a form of poisoning that impairs any system in which supra-optimal levels of Cu are present. Several factors, including soil pH typically influence Cu availability in agricultural soil, as its availability generally is more significant in acidic soil than in alkaline and organic soil. The high rate of Cu accumulation in the soil is frequently the result of the use of copper-based fungicides or agro-activities.

3.4 Zinc toxicity on soil

Zn is an essential micronutrient that stimulates plant growth hormones and protein synthesis. However, Zn toxicity threatens soil microorganisms that increase soil fertility and structure (Alloway, 2012). Zn scarcity impacts soil features such as pH, organic matter content, and bicarbonate contented and inhibits the function of Mg and Fe in the soil. In Poland, researchers examined the harmful properties of heavy metal toxicity on soil characteristics, microorganisms, and enzymes (Wyszkowska et al., 2013). The contamination problem caused by heavy metals has turn into imperative and requires radical and practical keys to minimize the dangers as much as prospective.

4. Mitigation of heavy metal contaminations

Due to the adverse effects on the ecosystem, heavy metal contamination is a global concern, and remediation efforts are being pursued. Mining, metal smelting, agriculture, waste management, and atmospheric deposition are some of the activities that result in heavy metal pollution. Various physical, chemical, and biotechnological methods are being explored to address metal pollution (Figure 2). Mitigation of heavy metal contaminations is crucial for protecting human health and the environment. Heavy metals, such as Pb Hg, Cd, As, and Cr, can accumulate in the soil, water, and air through various anthropogenic activities like industrial methods, mining, agriculture, and improper waste disposal. These metals can be toxic even at low concentrations, and long-term exposure can lead to severe health issues.

4.1 Non-biological strategies

Remediation of heavy metal contaminations using non-biological approaches involves using physical and chemical methods to remove, immobilize, or degrade the toxic heavy metals from the environment. These methods are often efficient, scalable, and may not rely on living organisms for remediation. Here are some common non-biological approaches for heavy metal remediation

4.1.1 Soil washing

Soil washing is used by physically removing heavy metals and other pollutants from soil. It involves separating and washing the contaminated soil with a liquid solution to extract impurities, leaving behind clean soil that meets regulatory standards (FRTR, 2001). Acids, bases, and surfactants are commonly employed in aqueous solutions for extraction or flushing to recover various substances such as metals, organic compounds, and oil pollutants, including phenol (ICS, 2005; Jankaite and Vasarevicius, 2005). This method is effective for moderately contaminated soil and can be performed on-site, reducing transportation and disposal costs (Martin et al. 2004). However, it may not be suitable for highly contaminated soils or large-scale rehabilitation projects due to the volume of wash water. A recent study by Hu W et al. (2021) provided theoretical evidence for using citric acid and water-soluble chitosan as effective washing agents to treat soils contaminated with heavy metals.

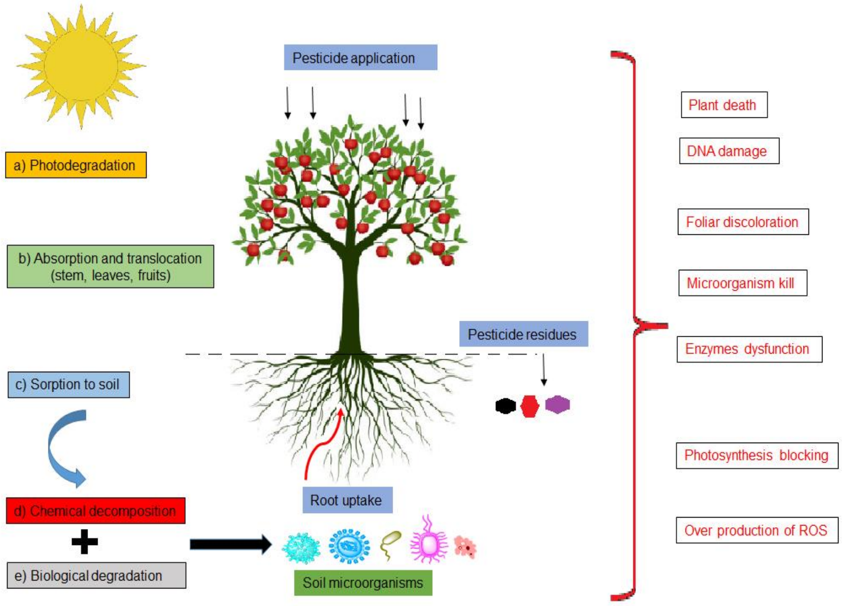

Figure 2 Sources and mitigation of heavy metal pollutant pollution

4.1.2 Chemical precipitation

Chemical precipitation is an extensively and practical approach to remediate HMs contamination from water and soil. It involves adding chemicals that react with the HMs to generate insoluble precipitates. Sedimentation, filtering, or other physical techniques can extract these precipitates from the water or soil. Commonly used chemicals include lime, NaOH, $FeSO_4$, alum, and $FeCl_2$. The choice of chemicals and other factors can affect the efficiency of the process (Wang et al., 2005). The precipitating agent reacts with the HMs ions in solution, forming metal hydroxides, metal sulphides, metal carbonates, or metal phosphates. Chemical precipitation is commonly used in wastewater treatment and environmental remediation, but proper optimization and waste management are necessary for effective and sustainable results.

4.1.3 Adsorption

Adsorption involves attaching heavy metal ions to certain materials called adsorbents due to their high affinity and specialized binding sites. This method can be applied to liquid solutions and solid materials like soil, using various natural and synthetic adsorbents. Commonly used adsorbents include activated carbon, zeolites, clay minerals, metal oxides, and chitosan (Lakherwal et al., 2014). The choice of an adsorbent depends on the specific metal ions and the polluted medium. During adsorption, there are physical and chemical interactions between the adsorbent and the HMs ions. These interactions include ion exchange, electrostatic attraction, complexation, and surface precipitation. Adsorption is a versatile and efficient method for cleaning up HMs contamination due to its convenience, low cost, and broad applicability. To properly utilize this strategy, optimizing and understanding the adsorption process is critical.

4.1.4 Electro-kinetic remediation

Electro-kinetic procedures involve using electric currents to initiate chemical reactions that result in the precipitation or degradation of HMs into less toxic forms, allowing for their removal. Electro-kinetic extraction uses electrical adsorption to remove HMs from contaminated soils. The efficacy of electrochemical remediation depends on specific environmental factors such as the level of contamination, soil type, pH levels, and organic matter (Figueroa et al., 2016). This technique is effective for fixing saturated or partially saturated soils, has low permeability and low electrical conductivity, and is made up of fine particles. It removes the metal contaminants that can dissolve in water or be easily exchanged for soil contaminants (Reddy et al., 2013). A selective strategy and acceptable operation in electrokinetic-coupled remediation should be used to eliminate HMs from contaminated soil effectively. (Wang et al., 2020)

4.1.5 Solidification/stabilization

This process includes combining contaminated soil or sediment with chemicals immobilizing HMs, minimizing their leach ability and environmental exposure. Metal stabilization is a highly regarded method for heavy metal-contaminated soil remediation approaches (Cui et al., 2023). Using chemicals to stabilize metals is an economical option for mine area restoration in southeastern Spain, as shown by a successful program that used pig manure, sewage sludge, and lime to diminish acid mine drainage, metal movement, and toxicity, while also providing nutrients for plants to grow (Zanussi, A., Faz and Acosta, 2013).

4.1.6 Nano-material remediation

Nanomaterials, such as nanoparticles, can be engineered to have high surface areas and unique properties that enhance their ability to adsorb, immobilize, or catalytically degrade heavy metal contaminants. According to Gong X et al., 2017 nanoparticles at low concentrations can boost phytoremediation efficiency. Thus, a promising innovative technique can be developed by combining nanotechnology and phytoremediation in the cleanup of HMs contaminated sites.

4.2 Biological strategies

Mitigating HMs contaminations using biological approaches involves using living organisms or their components to remove, sequester, or transform HMs contaminants from the environment (Figure 3). The bioremediation process is carried out by living organisms such as algae, fungi, bacteria, protozoa, worms, insects, and plants and their enzymes. Bioremediation techniques can be active (metabolic and energy-reliant) or passive, employing dead or living organisms/biomass. These methods are often eco-friendly and can be particularly effective for treating specific types of HMs pollution.

4.2.1 Phytoremediation

Phytoremediation utilizes plants to eradicate heavy metals from polluted soil, water, or sediments. Certain plants can tolerate and hyper-accumulate metals without showing significant toxicity. Once the plants have absorbed the contaminants, they can be collected and safely disposed of, effectively eliminating heavy metal pollution. Phytoremediation would be an excellent method for removing heavy metal pollution (Cheng et al., 2003) as numerous studies have been undertaken to understand better the molecular mechanisms underpinning heavy metal tolerance and develop techniques to improve the efficiency of phytoremediation

4.2.2 Biochar

Biochar is a high-Carbon material generated by pyrolyzing organic materials like agricultural residue or wood waste. Site density, specific surface area and pore structure of biochar are essential in its ability to improve soil contaminated with heavy metals by limiting their bioavailability and mobility in the environment. (Xiong et al., 2021). Biochar is a cost-effective and environmentally friendly material that is often made from agricultural waste or other organic waste streams. Yin et al., (2019) present a green, environment-friendly, and scale-up technique for producing biochar-based functional compounds from biowaste for heavy metal pollution treatment. Biochar can be combined with microorganisms to effectively remediate HMs contamination in soil, sediment, and water bodies.

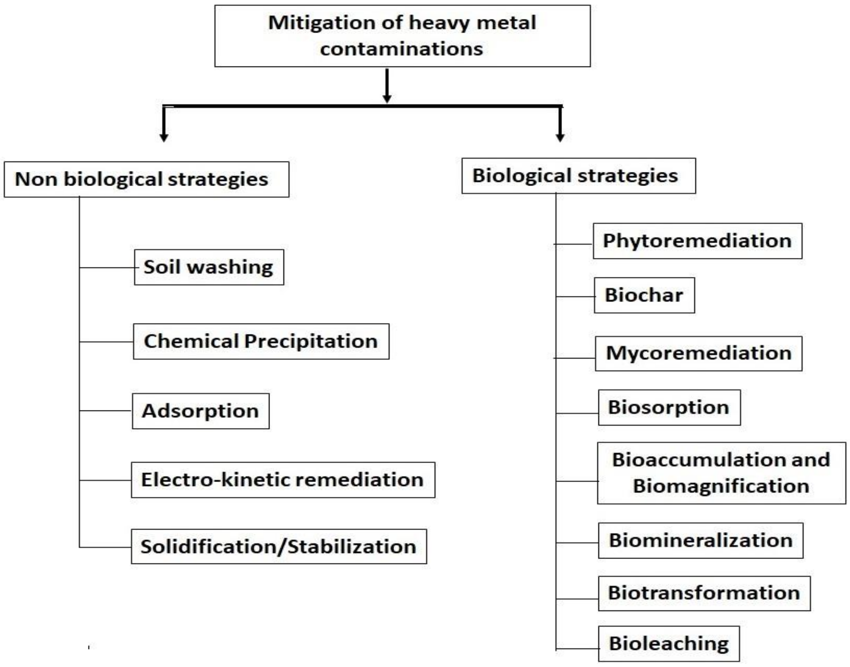

Figure 3 Mitigation of heavy contaminations

4.2.3 Mycoremediation

Mycoremediation involves the use of fungi to remediate HMs contaminated sites. Certain fungi can bind heavy metals to their hyphal structures or accumulate them within their fruiting bodies, leading to the sequestration and immobilization of contaminants.

4.2.4 Biosorption

Biosorption is a potential and environmentally friendly treatment option for heavy metal-contaminated sites, where heavy metal ions bind to the surface without any active metabolic involvement from the organism. The biosorbents used in this process can be living organisms (such as algae, fungi, bacteria, and plants) or non-living biomaterials (such as dead biomass, cell walls, and biopolymers). They possess functional groups, such as carboxyl, hydroxyl, amino, and phosphate groups, that attract and bind heavy metal ions. Biosorption has various advantages, including simplicity, cost-effectiveness, ease of implementation for both point-source and diffuse-source pollution and application to a diverse spectrum of heavy metal contaminants (Gavrilescu et al., 2004). Factors such as pH, temperature, initial metal concentration, and interference with other ions can affect its efficiency. Biosorption is a sustainable option for environmental management, but proper selection of biomaterials, optimization of conditions, and disposal of loaded biomaterials are crucial for successful implementation in bioremediation projects.

4.2.5 Bioaccumulation and bio-magnification

Bioaccumulation is the process by which organisms absorb and store substances, such as HMs, from the environment faster than they can eliminate or excrete them. When organisms are exposed to HMs in their surroundings, they may absorb and accumulate these metals in their tissues. This can occur through ingesting contaminated food, direct contact with contaminated water or sediment, or skin absorption. The level of bioaccumulation depends on factors such as the amounts of HMs in the environment, the biology of the specific organism, and the duration of exposure (Ali Hazrat et al., 2019). As these organisms are consumed by other organisms in the food chain, the HMs can biomagnify, leading to higher concentrations in higher trophic levels.

4.2.6 Biomineralization

Biomineralization is a process in which microorganisms and plants produce minerals that can immobilize heavy metals in a stable form. This process can be used to minimize the mobility and toxicity of heavy metals in the environment. Certain microorganisms and plants can secrete organic molecules that can catalyze the formation of minerals. This biomineralization process is environmentally friendly, reliable, and has the potential to be incorporated into various applications.

4.2.7 Biotransformation

Biotransformation is a process where microorganisms, plants, or enzymes convert toxic HMs into less harmful or less mobile forms. Instead of forming stable mineral compounds, biotransformation focuses on changing the chemical speciation of HMs to minimize their toxicity or mobility. This technique shows promise for the remediation of HMs contamination. Biotransformation involves reducing or oxidizing HMs. Further research and optimization of this method and a better understanding of microbial interactions with HMs may result in effective and sustainable solutions for HMs contamination in various environmental settings.

4.2.8 Bioleaching

Bioleaching is a biotechnological method that uses microorganisms to remediate heavy metals from contaminated environments. Microorganisms like algae, bacteria, and fungi are chosen for their ability to bind to or solubilize metals. These microbes metabolize and interact with the metals, secreting or chelating chemicals that dissolve or mobilize heavy metals. These microbes were chosen for their tolerance to heavy metals and capacity to induce metal solubilization. This process is environmental-friendly and inexpensive. It is beneficial for large contaminated sites and can be conducted on-site.

Selecting the appropriate approach (both biological and non-biological) to handle heavy metal pollution is determined by multiple factors, such as the type and extent of contamination, the environment, and the availability of suitable agents. Combining these methods or integrated approaches may yield the most effective and sustainable results. Furthermore, before implementing any remediation procedure, it is critical to assess the chosen method's potential dangers and environmental implications.

5. Microalgal in heavy metal contaminations remediation and ecological sustainability

The twenty-first century is still seeing a rapid rise in urbanization, commercialization, and the increasing industrializations, all to the loss of energy and resources, with increased rates of carbon releases and contamination of aquatic habitations with toxic heavy metal contaminates. Microalgae have been reported to survive under various ecological stresses, including various heavy metals and pollutants (Jaiswal et al., 2020a; Jaiswal et al., 2020b; Nanda et al., 2021; Jaiswal et al., 2021a; Jaiswal et al., 2021b). These toxic heavy metals affecting water bodies frequently build up and essentially go untreated. Heavy metals are metals with atomic densities more significant than 4000 kg/m3. All life forms are toxic to them because of their diverse sources, toxicity, inability to degrade, and accumulative nature (Satya et al., 2023). Essential and non-essential heavy metals can be life-threatening at high natural concentrations. Heavy metals can be extremely toxic and potentially cause cancer and mutagenesis even at low concentrations (Satya et al., 2023). Heavy metals are hazardous pollutants that can reach aquatic and terrestrial life forms, developing biomagnification processes through the food chain and being extremely harmful. Heavy metals' non-biodegradable nature causes these processes, bioaccumulation capacity, toxic nature, and ability to migrate great distances (Chakravorty et al., 2023).

Many nations use a variety of chemical and physical treatments. Still, their acceptance is typically low because they take a long time, are expensive, and are ineffective in contaminated areas with high levels of metal contents (Dutta et al., 2020). In this context, with the help of potential microorganisms and plant species, bioremediation is a safe and effective way to restore heavy metal-contaminated soils and waters (Carolin et al., 2017). Bioremediation is gaining significant attention for removing heavy metals due to the high efficacy, low cost, and widespread availability of biological organisms, particularly bacteria, algae, yeasts, and fungi. The aptitude of microalgae to tolerate heavy metals could potentially assist in finding solutions to several environmental problems (Kumar et al., 2022a). Microalgae could be used to address global issues like the need for environmentally friendly and cost-effective methods of cleaning up contaminated water and for the generation of bioenergy (Nanda et al., 2021; Jaiswal et al., 2022a; Jaiswal et al., 2022b). Microalgae use a variety of mechanisms to take up the metal and further detoxify it in a medium that contains heavy metals. Two of these critical steps are the biosorption and bioaccumulation processes, both of which depend on various transporters at various stages of heavy metal tolerance.

The capacity of this process to withstand and thrive under various abiotic stresses, including high levels of heavy metals, saline environments, extreme temperature changes, and nutrient-depleted situations. Microalgae have acquired the capacity to express particular peptides that bind heavy metals. These organometallic complexes control the concentration of heavy metals in the cytoplasm to counteract their toxic effects by partitioning them into intracellular compartments. Many heavy metals, including chromium, copper, lead, arsenic, mercury, nickel, and cadmium, have been successfully eliminated from the environment by using this capability. Different microalgal species can contribute to the production of biofuels like biodiesel and biohydrogen as a result of their heavy metal resistance properties (Jaiswal and Pandey, 2014; Fatima et al., 2020a; 2020b; Talukder et al., 2022). Due to its pertinent characteristics, microalgae have also been extensively researched for their potential role in the formation of nanoparticles in nanotechnology.

Numerous studies have also demonstrated the wide range of uses for biochar derived from microalgal biomass or a blend of microalgae and biochar, mainly in the elimination of heavy metal pollutants from the environment along with biofuels generation (Jaiswal et al., 2021c; 2021d; Kumar et al., 2022b; Verma et al., 2023). Lead and cadmium could be removed from contaminated sites using the alga *C. reinhardtii*, nickel, and cadmium. Microalgae bioremediation can be integrated with other remediation technologies to enhance overall efficiency. For instance, coupling algal bioremediation with constructed wetlands or microbial remediation can provide a comprehensive and synergistic approach to heavy metal cleanup.

6. Conclusion

The toxic impact of heavy metal pollutants changes soil's physicochemical and biological properties. These metals that plants absorb from the soil decrease crop productivity by preventing physiological metabolism. Agricultural runoff containing heavy metals enters the water environment, harming aquatic life. As a result, pathogens and heavy metals should not be present in the compost if it is to be used in agriculture. Efforts to mitigate heavy metal contamination include improved industrial practices, proper waste disposal, soil and water management, and the use of remediation technologies such as biological phytoremediation (using plants to clean up contaminated sites), bioremediation (using microorganisms to break down or immobilize contaminants), and engineered solutions or non-biological like sediment capping and electrokinetic remediation. Microalgal cultivation has the potential to offer a sustainable and environmentally friendly method for remediating heavy metal contamination in aquatic ecosystems. It can be part of a broader strategy for improving water quality and restoring ecosystem health. To eventually contribute to ecological sustainability, this study aims to provide researchers and industrial stakeholders with novel perspectives on green alternatives.

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