Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 57 Issue: 10:2024
DOI: 10.5281/zenodo.13901640

AN OVERVIEW OF COMBINING CHEMICAL AND MICROBIAL METHODS FOR THE REMEDIATION OF HEAVY METALS FROM CONTAMINATED SOILS: BENEFITS, LIMITATIONS, AND INFLUENCING FACTORS

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Abstract

Concerns are increasing about heavy metals in soil that harm human health and the integrity of ecosystems. Traditional treatment methods are insufficient to solve the problem. Therefore, new and sustainable methods should be investigated. Removal of heavy metals from the soil matrix through microbial and chemical treatments are a great concern these days. Many chemical methods for the soil improvement involve the use of lime, phosphate, zeolites, and chelating agents. The application of these changes also changed the physical and chemical properties of the soil, led to the formation of stable metal complexes or the precipitation of poorly soluble metals. Although chemical treatment is fast and effective, its long-term impact on the environment is worth considering. Alternatively, bacteria can metabolize the contaminated soil by removing the heavy metals, which is the basic concept of microbial remediation. In addition to iron transfer, bacteria and viruses can reduce iron mobility and facilitate plant growth or mineralization. This method of bioremediation is generally environmentally friendly because it employs the natural processes and minimizes the need for external inputs. However, environmental conditions and other soil diseases can affect its performance. A combination of chemical and microbial remediation strategies can provide an integrated approach to remediating heavy metals in soil. The interaction between chemical treatments and microbial methods may provide further solutions in terms of an effective remediation of heavy metals contamination in soil.

Keywords: Bioremediation; Heavy Metals; Soil Contaminants; Beneficial Microbes; Pollution Control; Sustainable Practices; Soil Remediation.

1. INTRODUCTION

The contamination of soils by heavy metals poses a significant threat to ecosystems, human health, and biodiversity [1]. A variety of human activities, including mining, industrial processes, agricultural practices, and the improper disposal of electronic waste, can also lead to cadmium, mercury, arsenic, chromium, and nickel, which are naturally occurring elements [2,3]. Once the heavy metals released into the soil, their accumulation can adversely affect plants, animals, and humans. As a result of their high density and atomic weight, heavy metals are remarkably persistent.

Abiotic deposition, the weathering of rocks, or the direct action of humans can cause these metals to accumulate in soil [4,5]. Using fertilizers and pesticides, as well as industrial processes, mining, and smelting, have substantially increased the concentrations of heavy metals in soil [6]. Numerous factors influence heavy metals mobility and bioavailability in soils [7]. These factors include soil properties (e.g., pH, organic matter content, clay mineralogy), competing ions, and metal oxidation states. Therefore, local conditions and routes of exposure determine their impact on ecosystems and human health [8].

Worldwide, the soil is contaminated with more than 5 million heavy metals (loids) [9]. There are more than 100 million hectares of heavy metal-contaminated land in China [10]. As a result of degrading natural ecosystem services and contaminating food chains, heavy metals in soil are harmful to human health. Five strategies have been developed to remediate soils contaminated with heavy metals: surface capping, soil flushing, electrokinetic extraction, solidification, vitrification, and phytoremediation [11]. Since they use different working mechanisms, they all have advantages and limitations. There can be considerable differences between regions regarding the cost effectiveness of field practices [12].

The proper implementation of new bioremediation techniques and the unification of new measures are necessary for adequate soil, water, and air ecosystem restoration and protection from heavy metals contamination [13]. It has been conventionally used to remediate heavy metals-contaminated soils by landfilling, leaching, excavating, washing, piling, coagulation, reverse osmosis, evaporation, chemical reduction, cementation, or stabilization (ion exchange, precipitation, adsorption, biosorption, filtering, coagulation, reverse osmosis, evaporation, chemical reduction, cementation, or stabilization) [14,15].

In contrast, some technologies are labor-intensive, environmentally damaging, and extremely expensive [16]. Thus, this review comprehensively examined the primary sources of heavy metal contaminants, as well as their biological (microbial) and chemical remediation techniques to mitigate heavy metals contamination in soil.

In addition, the principles, mechanisms, advantages, and limitations of bioremediation technique have been discussed. Moreover, the synergy of both chemical and microbial remediation strategies to achieve optimal and sustainable results have been described.

2. PRIMARY SOURCES OF HEAVY METALS CONTAMINATION

The pollution of the environment with heavy metals comes from a variety of artificial and natural sources [17]. Due to their release into the soil, water, and air, chemicals pose a serious threat to both humans and the ecosystem. To design mitigation plans and properly manage the environment, it is essential to understand the extent of heavy metals contamination. The chemical industry is a major producer of heavy metals. Numerous metals, including lead, cadmium, mercury and arsenic are released into the environment as a result of mining activities.

Various industries, including paint manufacturing, e-waste production, and metal plating, also release heavy metals into the air, water and soil [18]. The use of pesticides, fertilizers and animal dung in agriculture is a significant source of heavy metals. Fertilizers containing phosphate are particularly full of lead and cadmium. When fertilizers are applied to crops, heavy metals in the soil can build up over time, lowering crop quality and jeopardizing food safety [19]. Domestic and urban waste contain a considerable amount of heavy metals pollution, particularly in urban areas. Household appliances, batteries and abandoned electronics all contain heavy metals. Both landfills and incineration are used to get rid of heavy metals [20].

Heavy metals can damage surrounding areas when these wastes combine with soil and groundwater. Air currents carry heavy metals from anthropogenic and natural sources to the earth’s surface, where they are deposited through atmospheric deposition [21]. After being released into the atmosphere by vehicle emissions, industrial emissions and the burning of fossil fuels, heavy metals can travel great distances before building up in soil and water bodies [22]. Agricultural waste improper disposal and industrial emissions can all lead to heavy metals pollution in rivers, lakes, and coastal waters.

Since the aquatic organisms absorb heavy metals when humans or other animals eat food products containing these metals, they can bioaccumulate and biomagnify [11]. Both geological processes and human activity can cause heavy metal pollution. The environment contains heavy metals because of weather, agriculture industry, air pollution, urban waste-contaminated water, and erosion. Planning for improvement and assessing the significance of pollution are necessary to safeguard human health and the environment.

3. BIOREMEDIATION OF HEAVY METALS CONTAMINATION

Living things can break down or immobilize heavy metal contaminants through metabolism that is why bioremediation is used [23]. The method adheres to basic principles: (a) Biodegradation is the process by which microorganisms metabolize heavy metals to create less mobile or toxic forms. During this process, the metals are frequently reduced or oxidized, which lessens their danger [24]. (b) Plants and microorganisms may accumulate heavy metals as a result of bioaccumulation. Through the accumulation of the metals in their tissues, these organisms lower the concentrations of heavy metals in soils and water [25]. (c) Through a process known as biosorption, certain microbes and plants are able to absorb heavy metals. In this manner, physical adsorption from the aqueous phase immobilizes heavy metals and reduces their mobility [26].

The utilization of bioremediation to reduce the levels of heavy metals is a viable and eco-friendly approach [27]. By employing the process of bioremediation, plants, bacteria, or fungi can restore, detoxify, or sequester heavy metals pollution, bringing it back to its natural state [28]. In addition to being successful and economical, bioremediation also has a minimal negative influence on the environment and can provide a permanent solution. The different types of heavy metals bioremediation are discussed below in detail.

3.1. Microbial bioremediation

Microbial bioremediation is a technique that uses the special metabolic potentials of microorganisms like fungi and bacteria to remove the heavy metals from contaminated sites [29]. By taking up or giving away electrons from heavy metals during their metabolic processes, they convert metal ions into harmless forms. Various mechanisms can facilitate the process of microbial bioremediation, including redox transformation, which occurs when microorganisms change their oxidation states to facilitate redox transformation [30]. Currently, some bacteria are capable of reducing toxic hexavalent chromium (Cr(VI)) to less toxic trivalent chromium (Cr(III)) [31]. The precipitation of heavy metals in microbes occurs through the formation of stable metal precipitates, which reduce the mobility and bioavailability of heavy metals.

Microorganisms produce extracellular substances, such as exopolysaccharides, which can precipitate heavy metals [32]. Some microorganisms produce organic molecules called chelators, which are capable of complexing with heavy metal ions, increasing their solubility and facilitating their removal from soil. Using contaminants as a source of energy and nutrients, microorganisms use microbial bioremediation as their primary mechanism [33]. As a result, complex organic compounds are decomposed into simpler substances, such as carbon dioxide, water, and harmless minerals. Providing indigenous microorganisms with essential nutrients, such as nitrogen, phosphorus, and carbon, promotes their growth and metabolism.

It works on several principles, such as biostimulation [34]. As a result of bioaugmentation, specific strains of bacteria that have specialized capabilities to degrade specific contaminants are introduced into the environment. Microbial communities can be enhanced by using this approach to improve the degradation of contaminants [35]. The complementary effects of phytoremediation and microbial bioremediation: Plants aid in the remediation process by producing an environment that is conducive to microbial growth and supplying nutrients through root exudates. In situ or ex-situ application of microbial bioremediation is possible at contaminated sites, and it is contingent upon the type of contaminants present and the environmental factors [36].

Microbial bioremediation methodology is used to remove contaminants from contaminated sites in an ecologically approachable method as described in **Table 1**. The normal competencies of microbes enable them to frugally and sustainably reinstate impaired environments [37]. Although microbial bioremediation compromises have many benefits, site-specific factors, and possible drawbacks need to be measured for their proper application. Merging microbial bioremediation with phytoremediation, biostimulation, bioaugmentation, or both can greatly help clean up adulterated areas and cultivate more robust and sustainable ecosystems [38].

3.1.1. Mechanism of microbial bioremediation

As an environmentally friendly method of degrading, transforming, or immobilizing contaminants in the environment, microbial bioremediation utilizes microorganisms such as bacteria and fungi [39]. The diverse metabolic capabilities of microorganisms make them ideal for microbial bioremediation. The following mechanisms characterize the process of microbiological bioremediation.

3.1.1.1. Redox transformation

A redox reaction is a fundamental chemical reaction involving electron transfer between two or more species [40]. Redox oxidation results from two opposing chemical processes simultaneously called reduction and oxidation. The redox transformation of microorganisms is crucial for the success of microbial bioremediation [41]. During the metabolic processes of microorganisms, heavy metals can take part in redox reactions as electron donors or acceptors. Some bacteria can convert hexavalent chromium Cr (VI) into trivalent chromium through a redox process.

This process increases the bioavailability and toxicity of metals, reducing their impact on the environment. Natural and artificial systems, industrial applications, and environmental processes all require these materials. Our understanding of redox reactions aids in the advancement of science, technology, and environmental management by expanding our knowledge of how elements, pollutants, and chemical compounds behave in diverse settings.

3.1.1.2. Metal precipitation

Microorganisms produce exopolysaccharides and other extracellular materials during the microbial bioremediation process [42]. By forming stable metal precipitates, these compounds bind with ions of heavy metals. In soils and sediments, metal precipitates effectively immobilize heavy metals because they are less soluble and mobile as compared to the heavy metals. There is less chance of heavy metals contamination of plants and animals because of this precipitation mechanism, which reduces the likelihood of heavy metals migrating and becoming bioavailable. From soluble metal ions in a solution, metal precipitation forms solid metal complexes or compounds [43].

This procedure is comprised of water treatment, environmental remediation, and metal retrieval from industrial waste streams. Metal precipitation efficiently eliminates the metal pollutants by removing heavy metals from the environment and lowering their levels in water and wastewater. Metal precipitation is a more forthright technique for removing metal pollutants from water and wastewater [44]. Use of water purification, metal-retrieval, and ecological remediation, are all valuable. Positive metal precipitation requires an understanding of complicated chemistry as well as a cautious courtesy in particulars like pH control, hastening agent selection, and sludge management [45].

3.1.1.3. Chelation

Chelation is comprised of additional vigorous tools that microbes employ in bioremediation procedures. In order to expedite the enlistment and preoccupation of metal ions from the contiguous environment, microbes in microbial remediation should use a chelating agent [46]. Chelators are organic compounds concealed by certain microbes that have a robust anti-heavy metal ion effect. In soil resolutions, metal ions liquefy more readily when chelators that create stable complexes exist. Because of their higher solubility, leakage can be used to remove heavy metals from polluted sites [47]. Chelation enables the uptake of heavy metals and aids in their confiscation or alteration by microorganisms [48].

Chelation enhances the availability and uptake of metal contaminants, which is a major factor in microbial remediation. Chelating agents can be used to improve the effectiveness of metal remediation procedures in conjunction with other bioremediation strategies. Microbial remediation techniques need to take into account which chelators will be used, how they could affect the environment, and whether or not metals should be released again after the process in order to be an effective and environmentally friendly approach.

3.1.1.4. Bioaccumulation

The bioaccumulation of pollutants and chemicals occurs when they gradually accumulate and concentrate in living organisms. These substances can be introduced into the food chain from various sources, including natural and human activities [49]. Bioaccumulation can negatively impact human and environmental health since it increases exposure and may negatively affect organisms at higher trophic levels. The accumulation of heavy metals in some microorganisms does not cause significant damage to the cells [50]. The bioaccumulation mechanism of these microorganisms results in metal reservoirs that minimize heavy metal exposure.

Harvesting and removing microorganisms that accumulate heavy metals from soil and water is possible. In living organisms, substances accumulate and concentrate through a natural process called bioaccumulation [51]. Although bioaccumulative substances play an important role in ecological processes, they are also potentially toxic and harmful to humans and the environment. Bio-accumulative substances need to be understood and managed to protect ecosystems and humans [51].

3.1.1.5. Biotransformation

Microorganisms and plants participate in biotransformation, also known as biodegradation, a biological process in which pollutants and natural compounds, including contaminants, are chemically transformed and decomposed [52]. By metabolizing complex or harmful substances, organisms can convert them into more straightforward, less hazardous forms, which is vital to natural recycling and detoxification mechanisms. Transformations are crucial to the remediation of the environment, pharmaceutical development, and nutrient cycling within ecosystems [53]. By enzymatically breaking down heavy metal compounds into less toxic or less mobile forms, microbial biotransformation occurs [53]. Heavy metal ions are metabolized by microorganisms using specific enzymes, resulting in a less harmful compound. Biological transformation is one of the most important mechanisms for reducing heavy metal toxicity as well as the environmental impact of these metals [54]. Biotransformation is dynamic for decontamination, ecological remediation and nutrient cycling in living entities. Biotransformation contrivances are vital for refining drug effectiveness and safety and addressing contamination [54].

3.1.1.6. Biovolatilization

It takes the proclamation of gases and other volatile ingredients into the air through living things such as plants, animals, and microbes. For volatile materials to cycle and scatter through the surroundings, breakdown is a necessity. Both are logically happening, and artificially induced biovolatilization procedures can release volatile chemicals [55]. Microbial volatilization is the procedure that turns heavy metals into volatile forms [56]. Heavy metals can be mined as volatiles and released into the atmosphere from polluted places. Mercury is among them.

This mechanism must be carefully considered in order to prevent the spread of heavy metals [32]. Volatile organic compounds (VOCs) are unconfined into the atmosphere when microorganisms and plants volatilize. Also, biogeochemical cycling air quality, climate change, and atmospheric chemistry are all wedged by this process. Regulatory the impact of volatile substances on ecosystems and the environment requires a sympathetic of the instruments and crops of bio-volatilization [57].

3.2. Application and Considerations

Bioremediation has been revealed to be an effective way to eliminate heavy metal contaminants in removal agrarian and manufacturing settings [58]. A wide range of variables, including plant species, microbial action metal speciation, and environmental factors, can wedge its efficiency. The proper selection of organisms, optimization of environmental conditions, and precise site identification are all necessary for the successful application of bioremediation techniques [59].

Cleanup of heavy metal-contaminated sites can be accomplished through the environmentally benign process of bioremediation. Reducing heavy metal pollution, restoring ecosystems, and safeguarding human health are all made possible by bioremediation as shown in **Figure 2**. Studies conducted in this area are showing that bioremediation is probably going to be crucial in dealing with heavy metal pollution [60].

Table 1: Potential microbes involved in the remediation of different heavy metals.

Microorganism	Target metal	Reference
Microbacterium arabinogalactanolyticum Microbacterium oxydans	NI	[61,62]
Bacillus pumilus, Bacillus subtilis Brevibacterium halotolerans , Pseudomonas pseudoalcaligenes	Cr, Cu	[63-66]
Agrobacterium radiobacter, Arthrobacter mysorens, Azospirillum lipoferum, Flavobacterium sp., *Bacillus* sp.	Cd, Pb	[67,68,69]
Mycobacterium sp., *Pseudomonas fluorescens* *Pseudomonas tolaasii, Paecilomyces lilacinus*	Cd	[70,71]
Pseudomonas sp., *Delftia* sp., *Variovorax* sp. *Pseudoxanthomonas sp., Bacillus sp., Comamonas sp.*	As	[72,73]
Burkholderia cepacia	*Cd, Zn*	[74]
Cedecea davisae, Rhodococcus erythropolis	Cd	[75]
Bacillus cereus, Psychrobacter sp. *Psychrobacter* sp. *Achromobacter xylosoxidans* *Pseudomonas* sp.	Ni	[76,77]
Phyllobacterium myrsinacearum *Enterobacter intermedius*	Cd, Zn	[78,79]
Bacillus mycoides, Micrococcus roseus, Klebsiella sp.	Cd	[80,81]
Pseudomonas jessenii	*Ni, Cd, Zn*	[70]
Bacillus megaterium Bacillus subtilis	Ni	[82,83,84]
Pseudomonas putida, *Comamonas aquatic, Bacillus* sp.	Cd	[84]
Microbacterium saperdae, Pseudomonas monteilii, Enterobacter cancerogenus	Zn	[85,86]
Delftia sp., Rhodococcus sp., Streptomyces lividans	As	[87,88]
Fusarium oxysporum	Cd, Cu, Pb, Zn	[99]

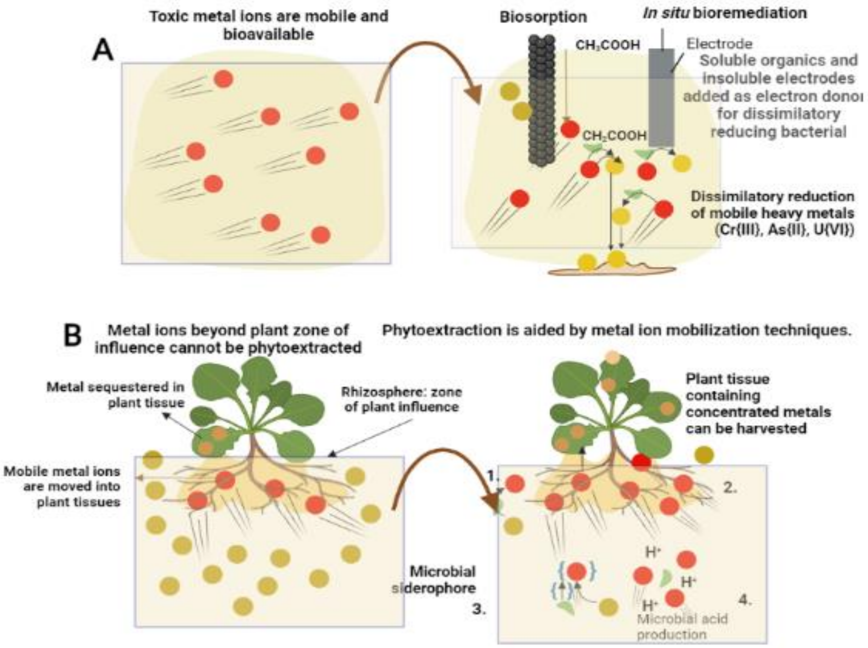

Figure 1: Schematic demonstration of heavy metals remediation in soil

3.3. Advantages and limitations of microbial remediation

A powerful and environmentally friendly method for removing contaminants from soil, water, and other environmental media is microbial remediation. As a sustainable method of degrading, transforming, or immobilizing contaminants, microorganisms offer several benefits: microbial remediation uses microorganisms to break down contaminants [100]. The inherent biological processes of microbes rely upon overcoming contamination problems for an extended period. Microbial remediation is often more cost-efficient than traditional remediation methods, which require the excavation and disposal of contaminated materials.

Performing this technique in situ reduces the need for costly transportation and treatment of large quantities of contaminated soil or water [101]. Microbial remediation can be directly applied to contaminated sites without the need for excavations or engineering structures due to its non-intrusive nature. This non-invasive method minimizes disruption to the environment and ecosystem. Because it can be adjusted to handle different contaminants, including pesticides, hydrocarbons, heavy metals and organic pollutants, it is adaptable. It is possible to select microorganisms based on their qualities or to engineer them to target particular contaminants.

According to Yap et al. [95] bioremediation is a less intrusive and more ecologically friendly method because it emulates actual biological processes. Pollutants frequently completely degrade when they are converted into innocuous byproducts like carbon dioxide, water, and harmless minerals. Microbial remediation generates fewer waste products than other bioremediation techniques. Large volumes of waste do not need to be disposed off or given additional treatment as a result [103].

Given that bioremediation is nondestructive and relies on natural processes to restore contaminated sites, stakeholders and communities generally embrace it [104]. Microbial remediation is a flexible and versatile technique that can be used in both terrestrial and aquatic environments as well as subsurface settings. Microbiological remediation is flexible enough to be applied in difficult-to-reach places where other remediation techniques might not be feasible. Microbial populations can maintain contaminant degradation on their own once ideal conditions are met, requiring no additional assistance [105].

Despite the variety of advantages, there could be several limitations of microbial remediation. For instance., when applied to large-scale or highly contaminated sites, the microbial remediation process can be sluggish and time-consuming [106]. The speed at which contaminants degrade is influenced by microbial activity, the availability of nutrients, and environmental factors.

Climate variables that impact the efficacy of microbial remediation include temperature, pH, oxygen concentrations, and moisture [35]. Remedial work may be more challenging in unfavorable or extremely harsh environmental conditions. Because certain contaminants are complex and resistant, microorganisms may have a harder time breaking them down.

It may be necessary to use specific bacterial strains or consortia with specialized enzymatic properties in order to eradicate specific pollutants [107]. Corrective microorganisms that have been presented to the remediation site may contest with native microbial populaces for resources and obtainable space. This kind of rivalry may disturb newly introduced microbes in the scheme, theoretically disturbing their efficacy and ascendancy [108].

3.4. Factors influencing the process of microbial remediation

Intended for a diversity of details, the kind of impurity affects microbial remediation. The type of contamination controls which microbial strains or consortia are most effective at transforming or debasing the designated pollutants [109]. The amount and variety of native microbial populations present at the site must be considered if efficacious bioremediation is to be measured.

A diverse microbial community might maintain a more malleable and robust system. Temperature pH, dampness content, and oxygen obtainability are climate variables that directly influence microbial activity and the rate at which pollutants degrade [110]. During the bioremediation process, nutrients such as carbon, nitrogen, and phosphorus are essential for microbial growth and breakdown.

Many bioremediation methods, such as bioaugmentation, which involves adding specific microorganisms, or biostimulation, which involves increasing native microbial activity, can be applied based on the type of contamination and the circumstances unique to the site [111]. The distribution and mobility of contaminants and microorganisms are prejudiced by the physical and chemical features of the site, such as the organic matter content penetrability and soil texture [112].

4. REMEDIATION OF SOIL BY USING CHEMICALS

Because heavy metals contamination in soil has a negative impact on ecosystems and human health, concerns have been raised in the environmental community. Chemical remediation has proven to be a successful solution for this issue [113]. Many heavy metals, including lead, cadmium mercury, arsenic, and chromium, are naturally present in the crust of Earth [114].

However, increased soil concentrations of heavy metals from mining, industrial processes, and farming pose a major threat to ecosystems and public health [1]. By decreasing mobility and bioavailability, chemical remediation techniques diminish potential hazards and remove heavy metals more effectively [115].

There is a thorough discussion of the various chemical remediation techniques used to reduce soil heavy metal contamination. One potential solution to the growing environmental concerns is the chemical remediation of heavy metals from soil [116]. Given the benefits and drawbacks of each technique, a thorough and knowledgeable selection process is crucial.

To ensure that the environments of future generations are cleaner, chemical remediation should be used in conjunction with other tactics and implemented as a whole. Technical developments and ongoing research will be needed to create more effective and long-lasting solutions for remediating heavy metal-contaminated soil.

4.1. Chemical stabilization

The mobility and bioavailability of contaminants are decreased when chemicals are used to stabilize soil and other environmental matrices. Chemical agents are added to a contaminated site to stabilize or amend it. These agents react with pollutants to form less toxic and less soluble compounds [117,118].

Chemical stabilization immobilizes pollutants, preventing them from migrating into groundwater or being absorbed by plants, hence lowering the risk to human health and the environment [119]. According to Palansooriya et al. [113] the principles and mechanisms of chemical stabilization vary depending on the kind of contaminants and amendments used. One popular strategy is for the stabilizing agent to combine with the target pollutants to form stable chemical complexes. Common materials include lime (calcium hydroxide), portland cement, and phosphate-based materials [120].

Chemical stabilizers are also included in the materials. Chemical soil stabilization is achieved by adding lime portland cement or other materials containing phosphate. Consequently, heavy metals are changed by these amendments into less hazardous and soluble forms [121]. Adsorbent materials like zeolites activated carbon and clay minerals, which effectively bind heavy metal ions, are used in chemical immobilization [122].

Due to their restricted mobility, plants and organisms are less likely to be exposed to heavy metals [123,124]. Chemical immobilization can increase efficacy and limit efficiency when used in conjunction with other remediation techniques. It is necessary to identify and measure soil contamination prior to applying chemical stabilization. Considering the contaminants and site conditions, this information is crucial for choosing the appropriate chemical amendment.

Characterizing a site is a prerequisite for selecting chemical amendments [125]. Lead, zinc, and cadmium are good metals to stabilize with lime-based materials; copper and lead are better with phosphate-based materials. To treat soils contaminated with hazardous chemicals, the chosen stabilizers can be applied mechanically or by injecting them into the soil. Specialized equipment is frequently required to mix the stabilizer uniformly throughout the contaminated area as shown in **Figure 2**.

Chemical amendments react with soil contaminants as soon as they are applied [22]. Less soluble metal hydroxides or carbonates may form in the soil as a result of an increase in pH brought on by the addition of lime. These materials diminish the opportunity for heavy metals to leak into groundwater or be engrossed by vegetation by immobilizing them. Incessant intensive care is vital after stabilization to make sure the action is employed and to spot any glitches [126].

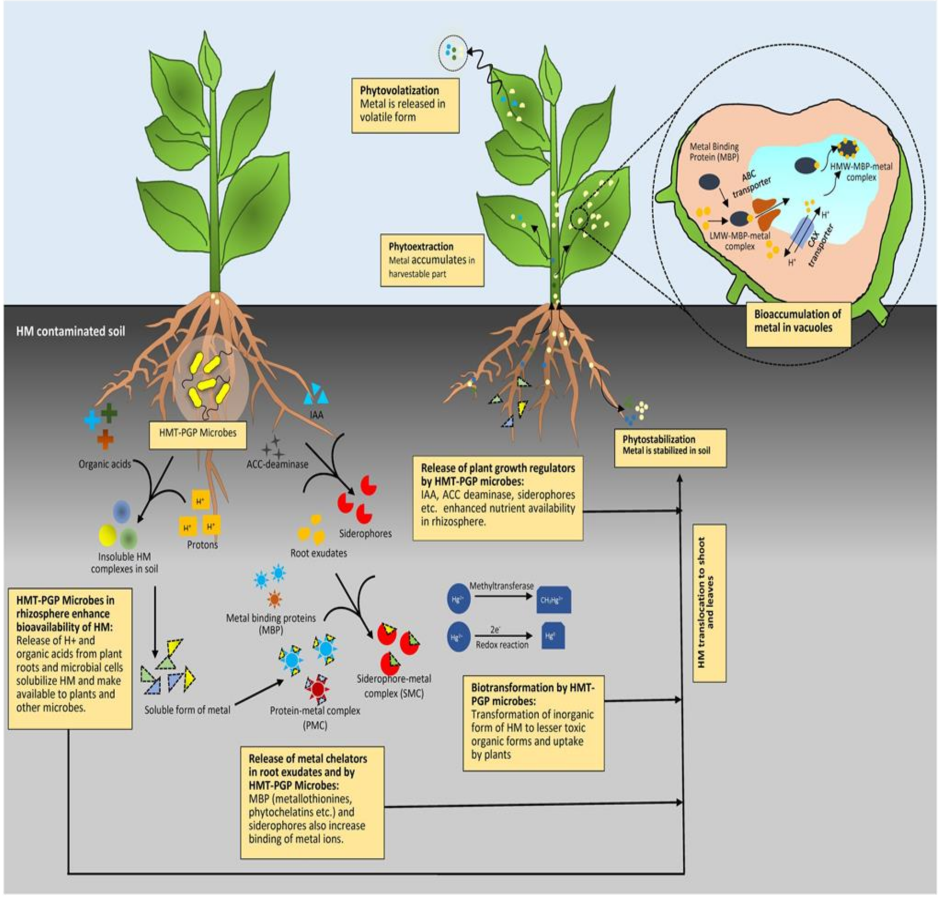

Figure 2: Contrivances tangled in the remediation of heavy metals-contaminated soil [121]

4.2. Chemical reduction

According to specifications from [127], chemicals decrease mainly when heavy metals and exact organic compounds are contemporary, which is an efficient remediation method for dirty environments [127]. By means of reducing agents, toxic or mobile contaminants can be less harmful, or their size can be reduced. By cumulatively reducing the contaminant's stability and decreasing its solubility, the reduction process lessens the likelihood that it will seep into groundwater and be absorbed by plants [128]. Reductants like zero-valent iron (ZVI) are used in chemical reduction to change heavy metal ions into less unsafe forms like metallic mixes or metal sulfides [129]. Achieving successful chemical reduction requires selecting the appropriate reductant based on the specific contaminant and site circumstances. According to a research, the most commonly used reductants are zero-valent iron (ZVI) and hydroxylamine sodium dithionite [130]. The fact that each reductant shows distinct reactivity and selectivity toward different contaminants is a crucial discovery. To treat the contaminated site, either direct injection into the subsurface or mixing with the reductant-contaminated soil is used [130]. Permeable reactive barriers and reductants can be used together to treat contaminants in situ. Applying the reductant to the material causes it to absorb electrons from the contaminant during redox reactions [131].

The contamination gains electrons as a result of the reduction process, which makes it less mobile and toxic. Heavy metals can be reduced from their ions by chemical means to metal sulfides, which are less soluble and, therefore, less likely to seep into groundwater or be taken up by vegetation. Certain organic compounds have the ability to reduce to more basic less toxic forms. Continuous monitoring is necessary for a realistic and long-term reduction process [132].

A less hazardous product must be produced, redox reactions must be carried out, the reducing reagent must be applied, and the process must be monitored and verified. Chemical reduction can be used to lessen the effects of heavy metal contamination and certain organic compounds [133]. The environment and public health are safeguarded by minimizing harmful or movable pollutants. To ensure long-term effectiveness, site-specific factors must be taken into account, and ongoing monitoring must be carried out. To achieve thorough and long-lasting environmental remediation, chemical reduction must be combined with other remediation techniques [134].

4.3. Chemical oxidation

By starting redox reactions at contaminated sites, chemical oxidation—a potent and adaptable remediation technique—minimizes the amount of hazardous or challenging-to-remove contaminants and effectively removes organic compounds and some heavy metals [135]. Certain contaminants lose some of their mobility due to chemical oxidation, which decreases their impact on the environment and public health. In addition to potassium permanganate and hydrogen peroxide, ozone and hydrogen peroxide can also oxidize heavy metals [136]. Hydrogen peroxide (H_2O_2), ozone (O_3), potassium permanganate ($KMnO_4$), and persulfate ($S_2O_8^{2}$-) are examples of chemical oxidant products [137]. These agents promote electron transfers during oxidation, making them electron-withdrawing [138].

Oxidizing agents may be added directly to contaminated media mixed with soil or submitted through reactive barriers. When choosing the best application technique, site-specific factors must be taken into consideration. Oxidizing agents remove electrons from contaminants and transfer oxygen atoms to targets in order to oxidize objects [139]. This procedure transforms complex organic molecules into less dangerous, simpler compounds that can be disposed of physically or naturally [140]. Apart from organic pollutants, some heavy metals can become less mobile due to chemical oxidation. Heavy metals can be rendered immobile by precipitating metal oxides and hydroxides through chemical oxidation, thereby reducing their bioavailability and leaching [141]. By dissolving complex organic contaminants, their mobility and toxicity are decreased. According to a study in which the obtained synergistic outcomes with this technique by permitting quick and comparatively noninvasive remediation in place [142].

Additionally, organic and heavy metal contaminants can be treated with this technology. Chemical oxidation is a remediation technique that greatly reduces heavy metals and organic pollutants. Chemical oxidation can lessen the toxicity and mobility of pollutants by encouraging redox reactions that break down complex compounds. Ojuederie and Babalola [138] stated that the chemical oxidation had shown to be a very successful technique for environmental remediation when used and monitored appropriately [138]. Future technological developments and more research will make environmental cleanups more worthwhile and productive.

4.4. Chemical chelation

Zhu et al. [139] described the use of chelation as a chemical remediation technique for heavy metal-contaminated soils and water [139]. Metal ion complexes made of organic substances that are able to form stable soluble complexes with metal ions are also utilized in addition to chelating agents. As implied by the Greek word chele, which means claw, chelating agents encircle and bond metal ions using a grip akin to a claw [143]. By chelating with heavy metal ions, chelating agents create stable complexes that decrease the ion's toxicity and mobility. Because metal ions have numerous coordination sites, they can form complex bonds with chelating agents [144].

Challenging agents include remediation chemicals like nitrilotriacetic acid (NTA), diethylenetriaminepentaacetic acid (DTPA), and ethylenediaminetetraacetic acid (EDTA) [145,146]. In contaminated environments, stable water-soluble complexes of heavy metal ions are attracted to chelating agents through chemical interactions with the metals. These compounds' low precipitation or insoluble compound formation qualities reduce the likelihood of them leaching into groundwater or becoming bioavailable. Chelation agents display varying degrees of selectivity towards distinct metal ions in addition to changes in ion size charge and coordination chemistry [147]. This selectivity has the benefit of allowing the removal of particular heavy metals from a mixed-contaminant environment [147].

Metals can be extracted from ores and waste streams using the chelation process, which can also be used to recover valuable metals from waste streams. According to research, the soluble metal-chelate complexes are created using chelating agents to aid in the recovery and separation of metals [111]. Chelation captures and immobilizes heavy metals, but it also keeps contaminants out of the environment. Releasing metal into the soil or water is a potential consequence of improperly managed chelate complexes.

Potential negative effects on the environment and unforeseen consequences should be taken into account when employing chelating agents [148]. By selective binding, heavy metal ions can be extracted and trapped in stable complexes. It also reduces the need for large excavations, soil disposal, and metal extraction because it can be used in situ. The persistence of chelate complexes in the environment is linked to certain restrictions and difficulties. The soil conditions and heavy metals can restrict the effectiveness of chelating agents. If insufficient chelation management is not put into place, heavy metals may leach more easily [149].

5. THE SYNERGY BETWEEN CHEMICAL AND MICROBIAL SOIL REMEDIATION

Remedial efforts in soil and water are enhanced when chemical stabilization or chelation is used in tandem with phytoremediation [150]. Plant extracts are used in phytoremediation to either stabilize or degrade environmental contaminants. Chemical remediation and phytoremediation together offer advantages that can improve pollutant removal and environmental cleanup [151]. Chemical remediation techniques like chelation and chemical stabilization can alter the availability and mobility of pollutants in soil. Plants can more readily absorb certain heavy metals through chelation, but chemical stabilization reduces their toxicity and bioavailability [152]. Because of their superior ability to absorb and store pollutants, plants can, therefore, improve the results of remediation [150]. Plants may not be able to absorb or receive some contaminants readily. To facilitate roots' access to pollutants, for example, a chemical amendment can increase their solubility and accessibility in the soil. Because of this focused strategy, plants are able to target pollutants that need more attention. Plant development and growth can be improved in contaminated environments by using chemical remediation techniques to reduce the phytotoxicity of specific contaminants. If the stress level is lowered, plants should thrive and perform become better during the remediation process [152].

Chemical additions can decrease certain contaminants in their mobile or toxic forms, improving phytoremediation efficacy. This cooperation makes it possible to treat pollutants more comprehensively and effectively [147]. Chemical stabilization is how chemical remediation techniques work, keeping pollutants out of the environment over time. After phytoremediation is complete, the latter may be beneficial in order to stop pollutant runoff or leaching. They often combine chemical treatment and phytoremediation, which results in a more cost-effective and long-lasting remediation strategy [122]. One way to lessen the need for extensive excavation and the disposal of contaminated soil is to use plant capabilities and optimize their performance with specific chemical amendments. However, while developing and putting into practice this integrated approach, a number of factors need to be taken into account, such as the type of contamination plant selection and site-specific conditions [152]. The success and sustainability of the combined remediation effort also depend on effective management and oversight.

6. CONCLUDING REMARKS AND PROSPECTS

Chemical and microbiological remediation methods are required to clean up contaminated areas. Depending on the site and contaminants, these remediation techniques have varying degrees of efficacy and present different challenges and benefits. If one is aware of the advantages, constraints, and influences of remediation, the results can be successful and long-lasting. Contaminants can be eliminated from environmental matrixes using a variety of chemical remediation techniques such as oxidation chelation reduction and stabilization. Stabilization decreases the bioavailability and migration of heavy metals in addition to immobilizing them. It is possible to degrade dangerous pollutants by reducing and oxidizing toxic compounds efficiently. By causing metal ions to be released and taken up by microorganisms, chelation improves bioremediation. In microbial remediation, microorganisms break down, change, or immobilize pollutants.

The adaptability and sustainability of microbial remediation make it a valuable method for cleaning contaminated sites. The three most successful microbial remediation techniques are bioaugmentation, biostimulation, and biotransformation. When alternative techniques are impractical or not cost-effective, microbial remediation can be used. Besides surpassing the constraints of chemical and microbiological remediation methods, synergistic approaches present immense potential for enhancing efficacy. Chemical stabilization can aid in the absorption and immobilization of pollutants by plants in addition to phytoremediation.

Furthermore, chelating agents produced by microbial processes can be used to degrade metal contaminants. When developing remediation strategies, the characteristics of the site and contamination should be taken into account. Regulations, pollutants, and environmental factors all play a role in the selection and application of remediation techniques.

To reduce its negative effects on the environment, remediation planning should take sustainability into account. Monitoring and assessment are essential for remediation to be effective and flexible. Remediation project success depends on stakeholder cooperation as well as public awareness and involvement. Chemical and microbiological methods can be used to clean up contaminated areas and the environment. Combining these two methods will result in remediation strategies that are creative and effective. Each approach has its own set of benefits and drawbacks. Environmental effects, community involvement, and site-specific considerations must all be taken into account when improving clean and healthy environments.

To improve the field of chemical and microbial remediation in the future, a number of important recommendations have been made. These recommendations are meant to increase the efficacy, sustainability, and applicability of environmental cleanup efforts and ecosystem restoration.

1) Invest in innovative technologies and methodologies to enhance our understanding of microbial and chemical remediation processes, addressing emerging pollutants effectively.

2) Develop genetically engineered bacterial strains that are resilient to harsh conditions and highly effective at degrading specific pollutants, improving remediation efficiency.

3) Combine multiple remediation techniques—physical, chemical, and microbial—to create comprehensive and durable solutions for contaminant removal tailored to specific site needs.

4) Establish real-time monitoring and adaptive management strategies to evaluate and adjust remediation techniques based on ongoing effectiveness and site-specific conditions.

5) Foster community involvement and education in remediation efforts while advocating for legislative frameworks that promote sustainable practices and transparency in decision-making.

It is feasible to advance the field more quickly by promoting cooperation between the public and private sectors. For this reason, chemical and microbial remediation has enormous potential in the future for dealing with environmental contamination and reestablishing ecosystems. By funding research aided new technologies and encouraging sustainable practices, we can improve the efficacy and efficiency of these remediation techniques in the future. Policymakers, communities, and scientists must work together to implement these recommendations and promote progress in the remediation field.

Author Contributions

Muhammad Zeeshan Basheer: Formal analysis, writing-original draft, editing, and visualization. **Cai Xiaolin:** Supervision, reviewing, investigation, and data curation. **Huang Xuhan and Murad Muhammad:** Reviewing, editing and data analysis. **Yanshan Cui**: Funding acquisition, supervision, formal analysis, writing review and editing, and project administration.

Funding

This research was financially supported by the National Natural Science Foundation of China (No. 41571451).

Data availability

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Declarations

Ethical approval: Not applicable

Consent to participate: All authors are informed and provided consent for this submission.

Consent for publication: All authors have approved the manuscript and declare that this is an original contribution, and none of the material in this paper is under consideration for publication elsewhere.

Conflict of interest

The authors declare they have no conflict of interest with the contents of this article.

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