



Microbial Assisted Phytoremediation of Arsenic Contaminated Soils: A Review

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Abstract

Soil contamination by heavy metals and metalloids has been a major concern for human health and environmental quality. While many remediation technologies have been tested at the bench scale, there have been only limited reports at the field scale. This paper aims to provide a comprehensive overview of the field applications of various soil remediation technologies performed over the last decade or so. Under the general categories of physical, chemical, and biological approaches, ten remediation techniques were critically reviewed. The technical feasibility and economic effectiveness were evaluated, and the pros and cons were appraised. In addition, attention was placed on the environmental impacts of the remediation practices and the long-term stability of the contaminants, which should be taken into account in the establishment of remediation goals and environmental criteria. Moreover, key knowledge gaps and practical challenges are identified.

1. Introduction

Rapid industrialization and urbanization have resulted in widespread contamination of soil with a host of heavy metals and metalloids, such as chromium (A. Alshahrani et al.), arsenic, cadmium (Lapworth et al.), copper (Cui et al.), mercury (Hg), lead (Pb), selenium (Mouratiadou et al.), zinc (Zn), and nickel. Over 10 million major contaminated sites worldwide, of which more than 50% were contaminated with heavy metals and/or metalloids (Khalid et al., 2017). In the U.S., around 600,000 ha of land (especially at the brownfield sites) have been found contaminated with heavy metals, and the U.S. Environmental Protection Agency (EPA) has designated more than 50,000 heavy metals-polluted sites as national priority sites, which require urgent remediation actions (Clark & McCormick, 2021). In China, the average contents of Cd, Hg, As, Cu, Pb, Cr, Zn, and Ni in soil have been found to have exceeded the regulation levels by 7.0%,

1.6%, 2.7%, 2.1%, 1.5%, 1.1%, 0.9%, and 4.8%, respectively, according to the Ministry of Environmental Protection and Ministry of Land and Resources of China (Contamination, 2014). Heavy metals and metalloids have been a major threat to human and environmental health due to their non-biodegradability, toxicity, persistence, and bioaccumulation in the food chain. They have been found responsible for causing various disorders in humans, including cardiovascular diseases, cancer, cognitive impairment, chronic anemia, and damage to the kidneys, nervous system, brain, skin, and bones (Bhavani et al., 2024). For instance, exposure to lead has been associated with improper hemoglobin synthesis and tumor infection, elevated blood pressure, and dysfunction of the reproductive system (Wang et al., 2021). Consequently, it is imperative to develop and deploy innovative and site-specific remediation technologies for efficient clean-up of heavy metals or metalloids contaminated sites. To remediate soil contaminated with heavy metals or metalloids, many studies

have been carried out at the bench scale and under well-controlled conditions (Raffa et al., 2021). However, due to the complexity of the actual soil biogeochemical conditions, the technical effectiveness and feasibility can greatly deviate from laboratory results. In addition, many practical issues, such as material deliverability, soil phase mass transfer and reaction rates, impacts of delivered chemicals on the local biogeochemical conditions, and the long-term stabilities of immobilized contaminants, remain to be addressed through systematic field-scale studies and long-term monitoring under real-world environmental conditions. Over the last decade or so, various physical, chemical, and biological processes have been aimed at reducing the total concentrations and/or bioavailable fractions of heavy metals or metalloids to mitigate the subsequent accumulation along the food chain (Jayakumar et al., 2021). To reduce the total contaminant mass in soil, a number of remediation methods have been practised, including soil replacement, electrokinetic removal (Sun et al., 2023), thermal treatment (Heidari et al., 2025), soil washing (Zheng et al., 2022), and phytoextraction (Awa & Hadibarata, 2020). On the other hand, to mitigate bioavailability or bioaccumulation, various chemical immobilization techniques are often employed using a range of chemical compounds, such as lime (Cui et al., 2024), phosphate compounds (Li et al., 2025), and organic compounds (Wang et al., 2024); in addition, vitrification (Trifunović, 2021), solidification/stabilization (Li et al., 2022), and phytostabilization (Shackira & Puthur, 2019) have also been investigated at the field. However, most of the field cleanup actions are often practised by remediation industries. As a result, information is often less systematic and long-term monitoring of completed sites is lacking. In addition, the environmental impacts of the remediation practices are often ignored. To our knowledge, most documents and reviews on the heavy metal remediation technologies have been focused on lab-scale results (Viotti et al., 2024).

2. World Scenario

Arsenic is a ubiquitous metalloid introduced into the environment through geological sources and anthropogenic activities such as mining, usage of arsenic-based pesticides or herbicides (Genchi et al., 2022). Arsenic contamination of soil, especially in farmlands, is the primary source of arsenic in crops.

Arsenic is an ancient poison and one of the first elements known to man. It was mined by early Greek, Chinese and Egyptian civilizations and its poisonous qualities were recognized early (Nriagu, 2002). Arsenic originally takes its name from the ancient Persian word *zarnikh*, which was adopted into Greek as *arsenikon* and later anglicized as *arsenic*. In the 18th Century, arsenic was understood enough to be classified as a semi-metal. But today it is more famous worldwide as a toxic killer, as many Southeast Asian countries have arsenic-contaminated water supplies. Even till this day, arsenic crowns the list of hazardous substances by

the Agency for Toxic Substances and Disease Registry and the United States Environmental Protection Agency (Charitos et al., 2022).

Arsenic is a highly toxic metal element that annually threatens the health of millions of people in the world (Genchi et al., 2022). Arsenic is a toxic metalloid, widely distributed due to natural and anthropogenic activities in the environment. It occurs in four oxidation states (+5, +3, 0, and 3), although the arsenate (Khalid et al.) and arsenite (AsIII) are the most common forms, and AsIII is more toxic than AsV (Ghosh et al., 2015; Lenoble et al., 2015).

Arsenic has been recognized as one of the most hazardous contaminants on Earth for over a decade (Murcott, 2012). In Bangladesh and West Bengal, elevated arsenic concentrations are often associated with high iron and manganese levels. Human exposure to arsenic may come from a variety of sources, where drinking water poses the greatest threat (Adeloju et al., 2021). The scale of the problem is grave and unprecedented in the Bengal delta basin, covering a geographic area of 0.173 million km² and putting 31 million people at risk. Since groundwater is also used extensively for crop irrigation in the belt of West Bengal, arsenic uptake by crop plants has been reported by several workers. The deposition of arsenic in soil from the contaminated water may also add to the plant uptake and increase the toxicity beyond the limiting values.

Contamination of soils with heavy metals and metalloids, such as lead, cadmium, arsenic, etc., represents a serious threat to the ecosystem and human health and requires the implementation of appropriate remedial measures. Multi-contaminated soils usually require more than one single treatment option so that all contaminants which may be present in the soil are efficiently removed (Sharma et al., 2018).

High arsenic levels can also come from several arsenic-based pesticides, fertilizers and animal feeding operations. Methyl arsonic acid and dimethyl arsinic acid are used as selective herbicides, insecticides, fungicides, etc. To this day, lead arsenate, copperacetoarsenite, sodium arsenite, calcium arsenate and organic arsenic compounds are still used in agriculture as pesticide components. Commercial arsenic-containing pesticides used in orchards, vineyards, and cotton desiccants give arsenic a free passport into foods and beverages (like wine), tobacco, etc. Accumulation of arsenic in surrounding soils contaminates the soil and increases the risk of arsenic uptake by plants and subsequently the herbivores. In the wood industry, chromated copper arsenite (CCA), sodium arsenate and zinc arsenate are used as wood preservatives (Atiang' et al., 2025).

Arsenic is an omnipresent toxic element in the Earth's crust, in which it is generally present at a low level (0.0001%) (Kar, 2022). Bacteria can play an important role in mediating redox transformations in extreme environments, and arsenic-resistance (Shakoor et al.) operons are commonly found in terrestrial microorganisms. Arsenic exists in a variety of forms such as As (-III), As (2014), As(III), As(V),

monomethylarsonic acid (MMA; V), dimethylarsinic acid (DMA; V), and trimethylarsine oxide, and bacteria are involved in biochemical degradation, detoxification mechanisms, and redox transformation in the natural environment (Hamza et al., 2022).

A systematic screening of groundwater for arsenic contamination started in Pakistan relatively late, in early 2000. The First screening was undertaken in the Attock and Rawalpindi districts of Punjab jointly by UNICEF and PCRWR. Covered approximately 60 % of the districts, and the remaining area was still untouched. Detailed testing was carried out only in eight out of 34 districts. Twelve districts were still untouched. A detailed study was carried out in 2004-5 by UNICEF and PCRWR covering all the remaining

burning also release arsenic in the environment. A major source of anthropogenic arsenic mobilization is weathering of mine waste rock and tailings (Wang et al., 2019).

3.1 Natural Sources

Arsenic is odorless and tasteless, and is naturally occurring in rocks, water, air, and even plants and animals. Its presence is very common in most geological environments, e.g. geothermal springs, igneous, metamorphic and sedimentary rocks, etc. Levels of arsenic in the soil range from 0.1 to 40 ppm. Its crustal abundance is 1.8 ppm, ranging from 0.1 to several hundred ppm. Arsenic is abundant throughout the earth's crust and is leached into the groundwater by erosion, dissolution, and weathering of minerals and ores (Ardini et al., 2020).

Table 1. Natural sources of arsenic and their concentrations.

Location	Concentration
Crust	1.5ppm
Sea water	1.5 ppb
Fresh water	
Normal	1-10 ppb
Polluted	10-1000 ppb
Soil	
Normal	1-10 ppm
Contaminated	Up to 200 ppm
Atmosphere	Trace
Human body	
Average	0.25 ppm
Hair	1 ppm

districts (Javed et al., 2021).

Samples collected from all districts of Punjab up to date are 36,304. The samples having arsenic less than 10µg/L or nil were 60.0% of the total samples. The samples in the range of 10-50 µg/L were 31.0% of the total samples. The samples greater than 50µg/L were 9.0% of the total samples. The maximum arsenic 250-500µg/L was found in Bahawalpur, Layyah, Multan, Muzaffar Garh, Okara and Sahiwal districts.

3. Sources of Arsenic Contamination

Due to global industrialization, war, and nuclear processes, a large amount of toxic compounds have been released into the biosphere. The heavy metals released through the various industries as effluent, nuclear radiation and releases of heavy metals by other processes in the environment may contaminate the soil. The soil contaminants were divided into two major classes, i.e. inorganic and organic. Inorganic pollutants comprise heavy metals such as arsenic, cadmium, mercury, and lead, while organic contaminants include petroleum, hydrocarbons, phenolic compounds, fertilizers, herbicides, and pesticides (Borah et al., 2020). Arsenic can also be released into the environment by brines that are used to produce natural oil and gas, as a by-product of gold and lead mining and the combustion of coal. Industry practices such as copper smelting, mining and coal

3.2 Anthropogenic sources of arsenic

Increased level of arsenic (Mouratiadou et al.) is a threat to mankind, affecting millions of people every year worldwide (Genchi et al., 2022). The middle Gangetic plain, including several districts of Bihar and West Bengal, seems to be the worst-affected area, affecting around 40 million people. In this region, total arsenic concentration is much greater than the prescribed limit (0.01 mg/l) by the WHO. Geochemical weathering of rocks, anthropogenic activities and volcanic emissions are the primary causes of groundwater arsenic (Mouratiadou et al.) contamination. Geo-microbial ecotoxicology is gaining prime importance in the field of environmental science and research (Joshi et al., 2025).

Rapid industrialization and urbanization have resulted in widespread contamination of soil with a host of heavy metals and metalloids, such as chromium (Genchi et al.), arsenic (Mouratiadou et al.), cadmium (Lapworth et al.), copper (Cui et al.), mercury (Hg), lead (Pb), selenium (Mouratiadou et al.), zinc (Zn), and nickel (Khalid et al.). There have been over 10 million major contaminated sites worldwide, of which more than 50% were contaminated with heavy metals and/or metalloids (Medunić et al., 2019).

In the U.S., around 600,000 ha of land (especially at the brownfield sites) have been found contaminated with heavy metals, and the U.S. Environmental Protection Agency (EPA) has designated more than 50,000 heavy metal-polluted sites as the national priority sites, which require urgent remediation actions (Ma et al., 2022).

In China, the average contents of Cd, Hg, As, Cu, Pb, Cr, Zn, and Ni in soil have been found to have exceeded the regulation levels by 7.0%, 1.6%, 2.7%, 2.1%, 1.5%, 1.1%, 0.9%, and 4.8%, respectively, according to the Ministry of Environmental Protection and Ministry of Land and Resources of China (Huang et al., 2019).

Arsenic still silently plays havoc in our daily lives by its presence as component of pigments in many domestic supplies including fancy and colored papers in magazines and children's books, sheets for cardboard boxes, labels of all kinds, advertising cards, wrappers for candies, confectionary and sweetmeats, playing cards, lamp shades, artificial leaves and flowers, artificial wreaths, wax ornaments for Christmas trees and other purposes, children's toys, printed or woven fabric intended for use as garment, curtains, furniture coverings, painted India rubber dolls etc (GREENING).

4. Impacts of Arsenic on Humans and Animals, and Plants

In India, about 40 lakhs of people in West Bengal alone suffer from arsenic poisoning due to drinking water contamination (Ghosh et al., 2015). The diagnosis of chronic arsenicosis in West Bengal was first detected by K C Saha (1999) from patients of Gangapur village of North 24 Paraganas. Most of the arsenicosis occurred from the intake of groundwater. More than 2,00,000 people in 1206 rural areas of 76 blocks of 9 districts of West Bengal have been found to be affected with arsenicosis. Arsenicosis manifests itself first through gastrointestinal symptoms, and the table below shows the annual estimate of child deaths due to gastrointestinal diseases and compares it to known cases of arsenicosis.

Arsenic exposure is a consequence of natural or anthropogenic sources. Ingestion, inhalation and skin absorption are some of the crucial routes for arsenic entering the human body. Both pentavalent and trivalent arsenic compounds are rapidly and extensively absorbed from the gastrointestinal tract. Moreover, sodium arsenate absorption is higher and inorganic tetravalent arsenic is poorly absorbed. However, arsenic disulfide and lead arsenate are some of the arsenic compounds with the lowest rate of oral absorption (Yi et al., 2020).

Distribution of arsenic in the body is fairly constant but widely distributed in organs such as skin, lungs, liver and kidneys (Balali-Mood et al., 2021). In the liver, the metabolism of arsenic involves enzymatic and non-enzymatic methylation. Inorganic arsenic is reduced from pentoxide to trioxide via enzymatic or non-enzymatic (glutathione) processes. About 70% Arsenic (both organic

and inorganic types) is excreted through the renal system via urine (Balali-Mood et al., 2021).

Exposure to arsenic has been linked to several diseases, including arsenical dermatitis, arsenical neuropathy, and cancer in different organs, liver diseases, cardiovascular, pulmonary, gastrointestinal disorders and diabetes mellitus. This has stimulated experimental and clinical research in arsenic metabolism. Rapid progress in analytical chemistry, genetics and proteomics is providing new research tools for advancing and understanding of arsenic exposure, metabolism and biological effects (Ghosh et al., 2015). Inorganic arsenic is a well-documented potent human carcinogen, causing cancer in skin, lungs, urinary bladder, kidney and, possibly, liver (Liu, 2025).

The skin system, along with its appendages such as hair and nails, forms the Integumentary system. It is commonly described as the largest storage of the body. Skin is considered to be more susceptible and highlights initial manifestations of arsenicosis (Liu, 2025). Skin abnormalities hold the hallmark of chronic arsenic exposure in adults. Moreover, men are likely to develop arsenic-induced skin disorders compared to women (Martínez-Castillo et al., 2021).

High arsenic exposure and cardiovascular diseases (CVD), along with their concord risk factors (i.e. atherosclerosis, hypertension, arrhythmia and diabetes), have shown a strong association with each other, affecting in a dose-dependent manner (Chain et al., 2024). Arsenic exposure from either drinking water or occupational sources may lead to respiratory complications over time. Arsenic exposure from drinking water exhibited an association with a high mortality rate in the Bangladeshi population (Tan et al., 2010). On the other hand, correlation of arsenic exposure related lung dysfunction and increased mortality rate due to respiratory diseases has been overwhelming (Invally et al., 2017).

Arsenic dust or fume inhalation during mining or milling of ores often produces respiratory complications such as chronic cough, laryngitis, bronchitis and rhinitis. Some of the common clinical respiratory symptoms observed in a cohort study include chronic cough, chest sounds, shortness of breath, blood in sputum and other breathing problems (Fadeev et al., 2024).

Arsenic exposure affects the hematopoietic system, including bone marrow, spleen and erythrocytes. Highest rates of arsenic accumulation were observed in the spleen, with 2–3 fold higher accumulation compared to other organs such as heart, liver and kidney. Due to arsenic accumulation, epigenetic modifications were observed in the spleen via 5-hydroxymethylcytosine, and it is considered to be a possible explanation for the organ-specific arsenic-induced toxicity (Pereira & Law, 2018).

Immediately after exposure, arsenic enters into systemic circulation. The majority of the arsenic primarily binds to hemoglobin and accumulates in the erythrocytes, inducing hemolysis. Likewise, curtailing the longevity of erythrocytes

leads to a reduced number of healthy erythrocytes and causes the development of anemia. Anemia is one of the most common symptoms in the arsenic-exposed population. However, a significantly negative association was observed between arsenic exposure during pregnancy and the occurrence of anemia (Shi et al., 2022).

Arsenic is a well-known disruptor of the endocrine system (Chatterjee et al., 2021), including thyroid, thyroid hormone (Sun et al., 2016), pancreas (Lu et al., 2011), gonads

pesticide components. Commercial arsenic-containing pesticides used in orchards, vineyards, and cotton dessicants give arsenic a free passport into foods and beverages (like wine), tobacco, etc. Accumulation of arsenic in surrounding soils contaminates the soil and increases the risk of arsenic uptake by plants and subsequently the herbivores. In the wood industry, chromated copper arsenite (CCA), sodium arsenate and zinc arsenate are used as wood preservatives (Ali et al., 2019).

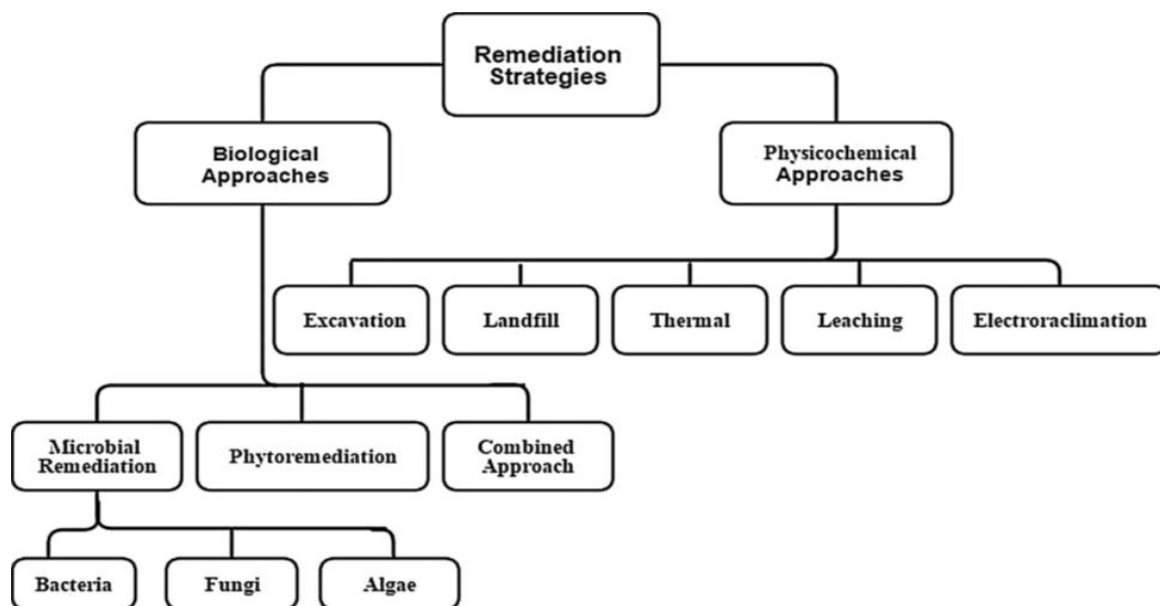


Figure 1. Remediation strategies for heavy metals

(Kim & Kim, 2015) and disrupts the hypothalamic-pituitary-adrenal axis (Sun et al., 2016). Impaired thymic functions were evident with prenatal exposure, possibly via arsenic-induced oxidative stress and apoptosis (Ahmed et al., 2012). However, information about the specific effects of arsenic on the adrenal gland and pituitary gland is rather limited. The thyroid plays a critical role in regulating metabolism in the human body and is responsible for the production of triiodothyronine (T3) and thyroxine (T4) hormones. Interactions between arsenic and the thyroid are not well established; however, a recent study reported a positive relationship between occupational exposure to arsenic in outdoor workers and its effects on thyroid hormones and the thyroid gland. Exposure to low levels of arsenic through groundwater (2–22 g/L) was associated with hypothyroidism among the population living in rural West Texas counties (Egalini et al., 2022; Mihai, 2011).

High arsenic levels can also come from several arsenic-based pesticides, fertilizers and animal feeding operations. Methyl arsonic acid and dimethyl arsinic acid are used as selective herbicides, insecticides, fungicides, etc (Tchounwou et al., 2023). To this day, lead arsenate, copperacetoato arsenite, sodium arsenite, calcium arsenate and organic arsenic compounds are still used in agriculture as

Bioaccumulation of arsenic (Mouratiadou et al.) in staple crops such as rice (*Oryza sativa*) grains is one of the serious concerns in many Southeast Asian Countries, India, China, and Bangladesh (Biswas et al., 2020; Hoang et al., 2021). Due to the widespread use of As-contaminated groundwater for irrigation of crop fields, As-accumulation increases in surface soils and eventually into the plants and grains (Khalid et al., 2022).

5. Different strategies are involved to remediate Arsenic Contamination.

Remediation of heavy metals is necessary to protect the environment from their toxic effects and conserve the environment for future generations (Bhat et al., 2024). Numerous physicochemical and biological techniques have been adopted for the elimination of heavy metals, which is regarded as a challenging job with respect to cost and technical complexity (Rafique et al., 2022).

Physicochemical approaches

Physicochemical approaches include excavation, landfill, thermal treatment, leaching and electro-reclamation. These techniques are rapid but inadequate, costly, cause

Table 2. Studies documenting the toxic effects of chronic arsenic exposure (adapted after Kapaj,2006).

System	Effect	References
Skin	Skin lesions, diffuse hyperpigmentation, localized hyperpigmentation, prickly freckled 'rain-drop 'pattern-pigmentation, allergic contact dermatitis and conjunctivitis.	(He et al., 2025) (Sun et al., 2019)
Hepatic	Hepatomegaly, cirrhosis, altered heme metabolism, Non-cirrhotic portal fibrosis and portal hypertension.	(Bibha et al., 2024)
Respiratory	Chronic bronchitis, bronchiectasis and interstitial lung disease	(Garcia-Vargas & Cebrian, 2023) (Ren et al., 2021)
Hematological	Bone marrow depression	(Galvez-Fernandez et al., 2021)
Endocrine	Diabetes, thyroid disease	(Gangopadhyay et al., 2019) (Esform et al., 2022)
Nervous	Polyneuropathy, encephalopathy, peripheral neuropathy, sensory motor neuropathy, cerebrovascular disease	(Mochizuki, 2019)

Table 3. Arsenic content in rice, vegetables and fruits in arsenic affected area of West Bengal.

Crop	Arsenic(mg/kg)	Crop	Arsenic (mg/kg)
Paddy (Grain)	0.10-0.89	Pointed Ground (Fruit)	1.20-3.65
Potato (Tuber)	0.05-1.05	Kachu (Tuber)	11.6-33.2
Wheat (Grain)	0.45-1.08	Cabbage (Head)	2.50-5.60
Mustard (seed)	1.37-1.60	Chili(Fruit)	1.05-3.80
Sesame(seed)	0.31-1.02	Banana (Fruit)	1.20-4.80
Brinjal (Fruit)	1.50-2.55	Papaya (Fruit)	1.80-5.60

Table 4. Comparative costs for different types of heavy metal soil remediation.

Type of remediation	Cost/cubic meter	Time required
Excavation and removal	\$100-\$400	6-9 months
In situ fixation	\$90-\$200	6-9 months
Phyto-extraction	\$15-\$40	18-60 months

adverse effects on soil physical, chemical and biological properties, and cause secondary pollution (Rahidul Hassan, 2023). Physicochemical approaches only change the problem from one form to another and do not completely remediate the pollutants.

5.1 EX-Situ techniques

5.1.1 Excavation treatment

Excavation and physical removal of the soil is perhaps the oldest remediation method for contaminated soil (Rahman et al., 2023). It is still in use at many locations, including residential areas contaminated with lead in southwestern Missouri. Advantages of excavation include the complete removal of the contaminants and the relatively rapid cleanup of a contaminated site. Disadvantages include

the fact that the contaminants are simply moved to a different place, where they must be monitored; the risk of spreading contaminated soil and dust particles during the removal and transport of contaminated soil; and the relatively high cost. Excavation can be the most expensive option when large amounts of soil must be removed or disposal as hazardous or toxic waste is required (Kanel et al., 2023; Rahidul Hassan, 2023).

5.1.2 Landfill treatment

Landfilling, or “dig and haul,” is the simplest soil remediation technique through which the contaminated soil is removed from its original site and transported to a secure landfill for disposal. A secure landfill is an engineered structure with impermeable liners, leachate drains, and dike

enclosures (Aziz et al., 2023). The double liners (a plastic layer and a clay layer) and the leachate collection and monitoring system are integral components of the facility to prevent potential leakage and groundwater contamination. The top cap/liner system is to minimize rainfall infiltration and keep surface runoff away from the fill. Design, construction, and use of a secure landfill are subject to governmental laws and regulations. Landfilling is a well-established technique for cleaning up hazardous waste sites. It was the most common waste disposal method used in the U.S. before 1984. Depending on the distance between the contaminated site and the secure landfill, the overall U.S. cost of soil landfilling ranges from \$300 ton⁻¹ to \$500 ton⁻¹ (FRTR, 2012). To reduce the disposal cost, landfilling should be considered only for soils excavated from the high-contamination areas (“hotspots”).

5.1.3 Thermal treatment

Thermal treatment is a physical process based on the volatility of contaminants. While the process is more suitable for volatile organic compounds, it has been used for the removal of volatile metals such as Hg (Devesa et al., 2008). It is performed by heating contaminated soil via steam, microwave, or infrared radiation without combustion or melting of the media or contaminants. The volatilized metals are then collected under negative pressure or with a carrier gas (Yu et al., 2024). Compared to verification or incineration, thermal treatment is much less energy-intensive and has the advantage that it can simultaneously remove volatile compounds that are often co-present with metals/metalloids. Inorganic mercury is usually present in soil in the elemental state or as mercurial compounds such as HgS, HgO, and HgCO₃. Thermal treatment can convert the mercurial compounds into the gaseous elemental mercury. The main components of a thermal desorption system include a pre-treatment and material handling unit, a desorption unit, and a post-treatment unit for treatment of off-gas and processed soil (Yu et al., 2024). The pre-treatment involves physical screening to remove extraneous matter such as plastic or rubber and dewatering to achieve a suitable moisture content. A thermal desorption unit was employed to remove Hg from the pre-treated media, which was operated at temperatures from 320 to 700 °C. The high temperature converts mercury into its gaseous form, which is then collected and further treated. It is one of the few methods that have been applied to the field for removing very high concentrations of Hg (>260 mg/kg) in soil (Celebi et al., 2021).

Temperature and treatment time are the main factors determining the decontamination levels as well as the process cost. Temperature and treatment time are the main factors determining the decontamination levels as well as the process cost (Rahidul Hassan, 2023). Greater efficiency is achieved at relatively higher temperatures, e.g. from 460 to 700°C (Neisan et al., 2023) reported that heating soil to 550°C for 1 h was able to remove 99% of Hg. Moreover, thermal

treatment at high temperatures may alter the soil properties and cause the coexisting contaminants, especially trace metals, to transform and repartition (Su et al., 2021) found that thermal treatment at >550 °C reduced the mercury content from 1320 to 6 mg/kg, and altered the binding forms of Cr, Cu, and Ni from those associated with Fe/Mn oxides into acid-extractable, organic-matter bound, and residual forms, which are less mobile. High energy consumption has been a major concern with this technology. To reduce energy consumption, thermal treatment may be operated at a lower temperature for a longer time. Operated thermal treatment at 100 °C for 10 days for remediation of a mercury-contaminated soil, and was able to achieve 32% mercury removal without negative effects on the growth properties of the soil (Zhou et al., 2024).

The advantages of this method include easy and safe implementation, mobility of treatment devices, effective extraction and recovery of mercury, and in particular, simultaneous removal or immobilization of co-contaminants. The major shortcoming is the high energy consumption and capital costs due to the high temperature requirement and the specialized facilities required. Consequently, this technology has been solely used for soil containing very high mercury, as far as heavy metals are concerned. Thermal treatment alters soil properties, which can affect certain functions of soil. It can cause degradation of SOM and changes of soil texture and mineralogy. Combustion of SOM leads to the loss of C and N, altering the available nutrients and elements for plants. Moreover, soil heating is detrimental to microorganisms such as pathogens, bacteria, and fungi (Babaniyi et al., 2024).

5.2 Biological approaches

Plants and microorganisms are used to remove toxic contaminants from the environment; this is known as biological remediation (Abdullahi et al., 2021). Biological remediation is considered the most effective method of toxic metal removal because it is a natural process, environmentally friendly, has a low cost, and high public acceptance. Biological remediation techniques include bioremediation, phytoremediation, bioventing, bioleaching, land farming, bioreactors, composting, bioaugmentation and biostimulation. Among these approaches, bioremediation and phytoremediation are the most useful techniques. These methods have advantages over physicochemical methods because they preserve natural soil properties and depend on solar energy. Bioremediation is a biological technique used for the remediation of heavy metals (Gayathiri et al., 2022).

5.2.1 Phytoremediation

Phytoremediation is an emerging green technology that is used for the uptake of vast quantities of heavy metals from soil and storage of these in a harvestable (removable) component (Sharma et al., 2023). Plants typically cope with contaminants by changing the properties of soil, which conserves soil efficacy and fertility (Mudgal et al., 2023).

After growing the hyper-accumulating plants on a contaminated site, the biomass can be treated to recover the contaminant. Phytoremediation could be a feasible option to decontaminate heavy-metal polluted soils, particularly when the biomass produced during the phytoremediation process can be economically valorized in the form of bio-energy, e.g., biodiesel production. The use of metal accumulating bio-energy crops (such as *Brassica* spp.) might be suitable for this purpose. Certain plants are capable of accumulating contaminants in their tissues (PP & Puthur, 2021), for example, *Eleocharis acicularis* can accumulate As, Cu, Zn and Pb (Wijekoon et al., 2025).

Phytoremediation the use of plants to remove or degrade contamination from soils and surface waters, has been proposed as a cheap, sustainable, effective, and environmentally friendly approach alternative to conventional remediation technologies (Puthur & Dhankher, 2022). Plants use solar energy (through photosynthesis) to extract chemicals from the soil and to deposit them in the above-ground part of their bodies, or to convert them to a less toxic form. These plants can then be harvested and treated, removing the pollutants (Puthur & Dhankher, 2022).

5.3 Microbial Remediation

Microorganisms are found almost everywhere in the environment. They grow in and tolerate soil, air, water, and desert conditions, as well as extreme temperatures. The soil near plant roots (i.e., the rhizosphere) is an important habitat and ecosystem for microorganisms, including bacteria, fungi, algae, and protozoa. These microorganisms are naturally associated with plants in various ways (William & Magpantay, 2023). Microbial cells can generate and sense signal molecules, which allows the entire population to

can also reduce the noxious effects of metals on plants. Some of these rhizosphere microorganisms can work directly on organic and inorganic pollutants using their own degradation capabilities, for instance, volatilization, transformation and rhizo degradation (Mbachu et al., 2020). The resistance mechanisms of bacteria involve efflux, impermeability to metals, volatilization, EPS sequestration, metal complexation and enzymatic detoxification, which are released from cells, e.g., Hg(II) reduction to Hg⁰ (Patil et al., 2024). Moreover, bacterial plasmids have resistance genes to many toxic/heavy metals and metalloids, e.g., Ag⁺, Cd²⁺, Hg²⁺, Ni²⁺, Co²⁺, Zn²⁺, Cu²⁺, and Sb³⁺ (Nnaji et al., 2024).

Microorganisms, especially PGP bacteria, can lessen a number of limiting factors with respect to phytoremediation technology, such as metal solubility, level of contamination, and soil chemistry (Wang et al., 2022). The bacteria that promote plant growth are known as PGP bacteria. These may be free-living bacteria, in symbiotic associations, or endophytic bacteria. Some important genera of PGP bacteria include *Serratia*, *Bacillus*, *Pseudomonas*, *Burkholderia*, *Enterobacter*, *Erwinia*, *Klebsiella*, *Beijerinckia*, *Flavo*, *bacterium* and *Gluconacetobacter* (Gupta et al., 2024).

The PGP bacteria improve plant growth by atmospheric nitrogen fixation (diazotrophs), phytohormone production, specific enzymatic activity, and plant protection from diseases by the production of antibiotics or other pathogen-depressing substances such as siderophores and chelating agents (Timofeeva et al., 2023). In addition, some PGP bacteria have the ability to decrease the level of ethylene in plants, which increases plant growth. This is attributed to ACC deaminase, which hydrolyzes ACC, the biosynthetic precursor for ethylene in plants, into ammonia and a ketobutyrate (Mandal et al., 2021). Consequently, vigorous

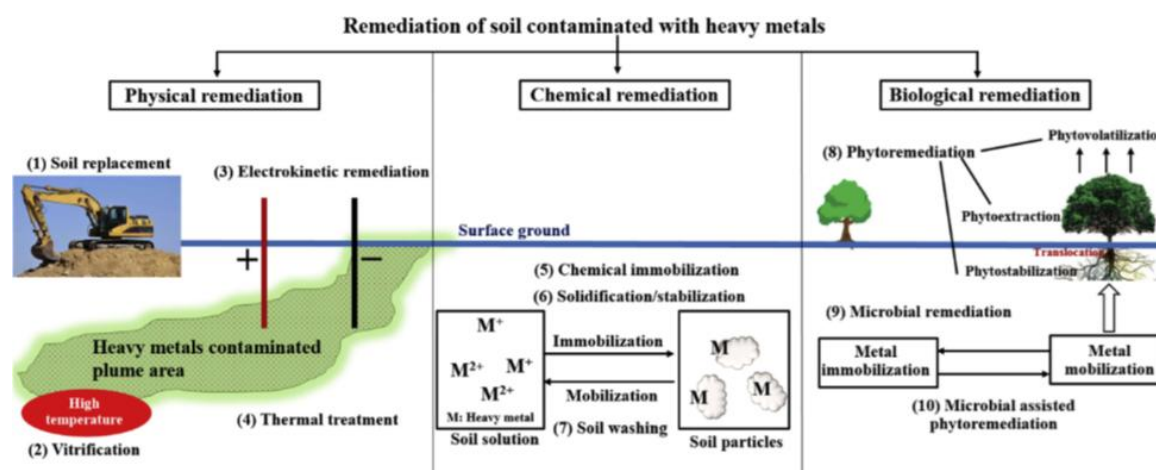


Figure 2. Remediation of soil contaminated with heavy metals

expand as a biofilm over the root surface and commence a concerted action after a particular population density is attained. This phenomenon is recognized as quorum sensing (Mohsin et al., 2023). Microorganisms, which are highly beneficial and play an important role in providing nutrients,

and healthier plants are better able to phytoremediate heavy metals in metal-contaminated soils (Qin et al., 2024).

In addition to plant growth, PGP bacteria have the ability to affect heavy metals' mobility and availability to the plant through the release of chelating agents, acidification,

phosphate solubilization, and redox changes (Ahemad, 2019). Moreover, these bacteria also discovered various metal tolerance mechanisms, including exclusion, biosorption, active removal, precipitation or bioaccumulation both in external and intracellular spaces (Wang et al., 2022). Bacterial resistance mechanisms also involve enzymatic detoxification, e.g., Hg(II) reduction to Hg⁰. As a consequence of all these processes, insoluble metal compounds and minerals transform into bioavailable and soluble forms. For example, in a case, *Solanum nigrum* was inoculated with the PGP bacteria, *Pseudomonas* sp. LK9, which increased Cd uptake from 230 mg kg⁻¹ to 292 mg kg⁻¹ in shoots and roots as compared with inoculated plants (Singh & Kumar, 2020). They concluded that metal accumulation increased due to the production of bio-surfactants, siderophores and organic acids (Rastogi & Kumar, 2020).

Electrokinetic Remediation

The electrokinetic process has been widely applied for decontaminating soil in laboratory and field studies. To achieve the desired process efficiency and system performance, studies have reported enhancement schemes via electrolyte conditioning with acid catholyte for heavy metals (Sun et al., 2023) or alkaline anolyte for anionic contaminants such as As (Yuan & Chiang, 2008). Several studies have examined the electrokinetics enhanced by chelating agents, such as ethylene diaminetetraacetic acid (EDTA) which has most often been tested (Wanitsawatwichai & Sampanpanish, 2021). As the major transport mechanism for the charged compounds in the electric field is electro migration, the anionic EDTA is mainly added in the cathode compartment. Based on the results of previous investigations, EDTA has good selective chelation with Pb, Cu, and Zn and has occasionally achieved competent removal efficiency (Jiang et al., 2023).

6. Conclusions

This comprehensive review of field-scale applications over the past decade underscores that while a diverse toolkit of physical, chemical, and biological technologies exists for the remediation of heavy metal and metalloid-contaminated soils, a significant disparity remains between laboratory promise and field-scale efficacy. The technical feasibility and economic effectiveness of each method are highly context-dependent, varying with the specific contaminant spectrum, soil characteristics, and site hydrology. Crucially, this analysis reveals that field practices often prioritize rapid contaminant concentration reduction or immobilization, while overlooking the long-term environmental impacts of the remediation process itself and the stability of the treatment. The lack of systematic long-term monitoring data at many completed sites poses a substantial risk of treatment failure or unforeseen ecological consequences over time. Therefore, establishing realistic remediation goals and robust environmental criteria must extend beyond initial cleanup

targets to encompass the long-term leachability, bioavailability, and ecosystem recovery, ensuring that the remedy does not become a future liability.

7. Future Studies Focus

To bridge the current knowledge gaps and advance the field of soil remediation, future research and development should be strategically directed toward the following critical areas:

1. **Bridging the Lab-to-Field Gap:** There is an urgent need for more systematic, well-documented field pilots that explicitly test the scalability of bench-scale results. Research should focus on overcoming field-specific challenges such as material deliverability in heterogeneous soils, achieving uniform reactions at the field scale, and managing the influence of fluctuating environmental conditions (e.g., rainfall, temperature) on treatment efficiency.
2. **Long-Term Monitoring and Stability Assessment:** A paradigm shift is required to mandate and fund long-term post-remediation monitoring programs. Future work must systematically evaluate the longevity of immobilization agents, the potential for remobilization of metals due to biogeochemical changes (e.g., pH shifts, organic matter decomposition), and the ecological recovery of treated sites over decadal timescales.
3. **Integrated and Hybrid Remediation Strategies:** Given the complexity of mixed contamination at most real-world sites, future efforts should prioritize developing and optimizing sequential or combined remediation approaches. For instance, coupling gentle chemical immobilization to reduce immediate toxicity with subsequent phytostabilization or enhanced phytoextraction could offer a more sustainable and resilient solution than any single technology.
4. **Environmental Impact and Life-Cycle Assessment (LCA):** A comprehensive evaluation of the secondary environmental impacts of remediation technologies is essential. Future studies must incorporate full Life-Cycle Assessments to compare the energy consumption, carbon footprint, and potential for groundwater pollution or soil ecosystem disruption associated with different remediation strategies, moving beyond a sole focus on cleanup efficiency.
5. **Development of Smart and Sustainable Amendments:** Research should focus on designing next-generation, cost-effective amendments derived from waste streams (e.g., biochar, modified industrial by-products) that are highly efficient at sequestering multiple metals simultaneously. Furthermore, exploring "smart" amendments that respond to environmental triggers to release stabilizing agents could provide long-term, self-regulating containment.

By addressing these priorities, the scientific and remediation communities can develop more reliable, sustainable, and economically viable solutions to mitigate the

global challenge of heavy metal and metalloid contamination in soil.

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10. Authors contribution

Kiran Sahar: Conceptualization. Sumaira Kanwal: Conceptualization. Maria Anwar: Read and edited/improved the paper. Mubeen Shafaqat: read and edited/improved the paper.

11. Conflict of Interest:

Authors declare no conflict of interest.

12. Sustainable Development Goals

This review supports SDG 15 (Life on Land), SDG 3 (Good Health and Well-being), and SDG 12 (Responsible Consumption and Production).

13. Reference

- A. Alshahrani, M., Ahmad, M., Laiq, M., & Nabi, M. (2025). Geostatistical analysis and multivariate assessment of groundwater quality. *Scientific Reports*, 15(1), 7435. <https://doi.org/10.1038/s41598-025-91055-3>
- Abdullahi, U. A., Khandaker, M. M., Shaari, N. E. M., & Alias, N. (2021). Biological processes of heavy metals-contaminated environmental remediation: a review. *Journal of Environmental Treatment Techniques*, 9(3), 601-608.
- Adelolu, S. B., Khan, S., & Patti, A. F. (2021). Arsenic contamination of groundwater and its implications for drinking water quality and human health in under-developed countries and remote communities—a review. *Applied Sciences*, 11(4), 1926.
- Ahemad, M. (2019). Remediation of metalliferous soils through the heavy metal resistant plant growth promoting bacteria: paradigms and prospects. *Arabian Journal of Chemistry*, 12(7), 1365-1377.
- Ahmed, S., Ahsan, K. B., Kippler, M., Mily, A., Wagatsuma, Y., Hoque, A. W., Ngom, P. T., El Arifeen, S., Raqib, R., & Vahter, M. (2012). In utero arsenic exposure is associated with impaired thymic function in newborns possibly via oxidative stress and apoptosis. *Toxicological Sciences*, 129(2), 305-314.
- Ali, W., Rasool, A., Junaid, M., & Zhang, H. (2019). A comprehensive review on current status, mechanism, and possible sources of arsenic contamination in groundwater: a global perspective with prominence of Pakistan scenario. *Environmental Geochemistry and Health*, 41(2), 737-760.
- Ardini, F., Dan, G., & Grotti, M. (2020). Arsenic speciation analysis of environmental samples. *Journal of Analytical Atomic Spectrometry*, 35(2), 215-237.
- Atiang', S., Ndunda, E. N., & Okello, V. A. (2025). Advances in removal of chromated copper arsenate elements in wood waste, contaminated water and soils. *Frontiers in Environmental Chemistry*, 6, 1452837.
- Awa, S. H., & Hadibarata, T. (2020). Removal of heavy metals in contaminated soil by phytoremediation mechanism: a review. *Water, Air, & Soil Pollution*, 231(2), 47.
- Aziz, H. A., Ramli, S. F., & Hung, Y.-T. (2023). Physicochemical technique in municipal solid waste (MSW) landfill leachate remediation: a review. *Water*, 15(6), 1249.
- Babaniyi, B. R., Olaide, T. H., Aparo, I. B., Ajibola, O. K., Olaoluwa, D. O., & Bisi-Omosho, A. (2024). Soil microbes and climate change mitigation. In *Soil Microbiome in Green Technology Sustainability* (pp. 229-254). Springer.
- Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M. R., & Sadeghi, M. (2021). Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. *Frontiers in pharmacology*, 12, 643972.
- Bhat, A., Ravi, K., Tian, F., & Singh, B. (2024). Arsenic contamination needs serious attention: an opinion and global scenario. *Pollutants*, 4(2), 196-211.
- Bhavani, R., Sharma, S., & Singh, K. (2024). Health Impacts Associated with Heavy Metals Exposure. In *Heavy Metal Contamination in the Environment* (pp. 34-45). CRC Press.
- Bibha, K., Akhigbe, T., Hamed, M., & Akhigbe, R. (2024). Metabolic derangement by arsenic: a review of the mechanisms. *Biological Trace Element Research*, 202(5), 1972-1982.
- Biswas, J. K., Warke, M., Datta, R., & Sarkar, D. (2020). Is arsenic in rice a major human health concern? *Current pollution reports*, 6(2), 37-42.
- Borah, P., Kumar, M., & Devi, P. (2020). Types of inorganic pollutants: metals/metalloids, acids, and organic forms. In *Inorganic pollutants in water* (pp. 17-31). Elsevier.
- Celebi, H., Bilican, I., & Bahadir, T. (2021). Applicability of innovative adsorbents in geogenic arsenic removal. *Journal of Cleaner Production*, 327, 129475.
- Chain, E. P. o. C. i. t. F., Schrenk, D., Bignami, M., Bodin, L., Chipman, J. K., del Mazo, J., Grasl-Kraupp, B., Hogstrand, C., Hoogenboom, L., & Leblanc, J. C. (2024). Update of the risk assessment of inorganic arsenic in food. *EFSA Journal*, 22(1), e8488.

- Charitos, I. A., Gagliano-Candela, R., Santacroce, L., & Bottalico, L. (2022). Venoms and Poisonings during the centuries: a narrative review. *Endocrine, Metabolic & Immune Disorders-Drug Targets (Formerly Current Drug Targets-Immune, Endocrine & Metabolic Disorders)*, 22(6), 558-570.
- Chatterjee, A., Jamal, Z., Das, J., Banerjee, A., & Chatterji, U. (2021). The Imperceptible Contagion: Arsenic as a Neuro-Immune-Endocrine Disruptor. *Proceedings of the Zoological Society*.
- Clark, B. T., & McCormick, P. (2021). METAL Contamination, B. o. N. S. o. S. (2014). Bulletin on Natural Survey of Soil Contamination [Bulletin]. *Bulletin*.
- Cui, H., Zhao, Y., Hu, K., Xia, R., Zhou, J., & Zhou, J. (2024). Impacts of atmospheric deposition on the heavy metal mobilization and bioavailability in soils amended by lime. *Science of the total environment*, 914, 170082.
- Devesa, V., Vélez, D., & Montoro, R. (2008). Effect of thermal treatments on arsenic species contents in food. *Food and Chemical Toxicology*, 46(1), 1-8.
- Egalini, F., Marinelli, L., Rossi, M., Motta, G., Prencipe, N., Rossetto Giaccherino, R., Pagano, L., Grottoli, S., & Giordano, R. (2022). Endocrine disrupting chemicals: effects on pituitary, thyroid and adrenal glands. *Endocrine*, 78(3), 395-405.
- Esform, A., Farkhondeh, T., Samarghandian, S., Rezaei, M., & Naghizadeh, A. (2022). Environmental arsenic exposure and its toxicological effect on thyroid function: a systematic review. *Reviews on Environmental Health*, 37(2), 281-289.
- Fadeev, A., Goryaev, D., Shur, P., Zaitseva, N., Fokin, V., & Red'ko, S. (2024). HARMFUL CHEMICALS IN OCCUPATIONAL AIR IN THE ORE MINING SECTOR OF THE METAL INDUSTRY AS OCCUPATIONAL HEALTH RISK FACTORS (ANALYTICAL REVIEW). *PREVENTIVE HEALTHCARE: TOPICAL ISSUES OF HEALTH RISK ANALYSIS*(2), 153.
- Galvez-Fernandez, M., Grau-Perez, M., Garcia-Barrera, T., Ramirez-Acosta, S., Gomez-Ariza, J. L., Perez-Gomez, B., Galan-Labaca, I., Navas-Acien, A., Redon, J., & Briongos-Figuero, L. S. (2021). Arsenic, cadmium, and selenium exposures and bone mineral density-related endpoints: The HORTEGA study. *Free Radical Biology and Medicine*, 162, 392-400.
- Gangopadhyay, S., Sharma, V., Chauhan, A., & Srivastava, V. (2019). Potential facet for prenatal arsenic exposure paradigm: linking endocrine disruption and epigenetics. *The Nucleus*, 62(2), 127-142.
- Garcia-Vargas, G. G., & Cebrian, M. E. (2023). Health effects of arsenic. In *Toxicology of Metals, Volume I* (pp. 423-438). CRC Press.
- Gayathiri, E., Prakash, P., Selvam, K., Awasthi, M. K., Gobinath, R., Karri, R. R., Ragunathan, M. G., Jayanthi, J., Mani, V., & Poudineh, M. A. (2022). Plant microbe based remediation approaches in dye removal: a review. *Bioengineered*, 13(3), 7798-7828.
- Genchi, G., Lauria, G., Catalano, A., Carocci, A., & Sinicropi, M. S. (2022). Arsenic: a review on a great health issue worldwide. *Applied Sciences*, 12(12), 6184.
- Ghosh, P., Rathinasabapathi, B., Teplitski, M., & Ma, L. Q. (2015). Bacterial ability in AsIII oxidation and AsV reduction: relation to arsenic tolerance, P uptake, and siderophore production. *Chemosphere*, 138, 995-1000.
- GREENING, T. Arsenic and old quilts: Towards a better understanding of hazardous materials in the National Collection of Parks Canada through non-destructive XRF evaluation.
- Gupta, R., Khan, F., Alqahtani, F. M., Hashem, M., & Ahmad, F. (2024). Plant growth-promoting Rhizobacteria (PGPR) assisted bioremediation of Heavy Metal Toxicity. *Applied Biochemistry and Biotechnology*, 196(5), 2928-2956.
- Hamza, M., Alam, S., Rizwan, M., & Naz, A. (2022). Health risks associated with arsenic contamination and its biotransformation mechanisms in environment: a review. *Hazardous Environmental Micro-pollutants, Health Impacts and Allied Treatment Technologies*, 241-288.
- He, L., Wei, M., Yang, Q., Huang, Y., & Wei, Z. (2025). Arsenic exposure and risk of skin cancer (melanoma and non-melanoma): A systematic review and meta-analysis. *Anais Brasileiros de Dermatologia*, 100(5), 501161.
- Heidari, S. A., Amiri, M., Harifi, A., & Wu, W. (2025). Effect of thermal treatment on stabilization and solidification of heavy metal contaminated clayey soil. *Scientific Reports*, 15(1), 17197.
- Hoang, A. T., Prinprecha, N., & Kim, K.-W. (2021). Influence of mining activities on arsenic concentration in rice in asia: A review. *Minerals*, 11(5), 472.
- Huang, Y., Wang, L., Wang, W., Li, T., He, Z., & Yang, X. (2019). Current status of agricultural soil pollution by heavy metals in China: A meta-analysis. *Science of the Total Environment*, 651, 3034-3042.
- Invally, M., Kaur, G., Kaur, G., Bhullar, S. K., & Buttar, H. S. (2017). Health care burden of cardiorespiratory diseases caused by particulate matter and chemical air pollutants. *World Heart Journal*, 9(4), 303-317.
- Javed, A., Baig, Z. U., & Farooqi, A. (2021). Arsenic contamination of irrigation wells and associated human health hazards in the Punjab plains of Pakistan. *Environmental Technology & Innovation*, 23, 101678.
- Jayakumar, M., Surendran, U., Raja, P., Kumar, A., & Senapathi, V. (2021). A review of heavy metals

- accumulation pathways, sources and management in soils. *Arabian Journal of Geosciences*, 14(20), 2156.
- Jiang, F., Zhang, C., Zhang, K., Luo, H., Luo, J., & Liu, F. (2023). Effect of ascorbic acid and combination with fulvic acid on the electrokinetic remediation of paddy soil contaminated by arsenic-containing acid mine drainage. *Applied Geochemistry*, 152, 105632.
- Joshi, S. R., Verma, P., & Banerjee, S. (2025). *Mineral Transformation and Bioremediation by Geo-Microbes*. Springer.
- Kanel, S. R., Das, T. K., Varma, R. S., Kurwadkar, S., Chakraborty, S., Joshi, T. P., Bezbaruah, A. N., & Nadagouda, M. N. (2023). Arsenic contamination in groundwater: Geochemical basis of treatment technologies. *ACS Environmental Au*, 3(3), 135-152.
- Kar, S. (2022). Geochemical characteristics of mineral elements: arsenic, fluorine, lead, nitrogen, and carbon. In *Structure and functions of pedosphere* (pp. 209-254). Springer.
- Khalid, S., Shahid, M., Bibi, I., Natasha, Murtaza, B., Tariq, T. Z., Naz, R., Shahzad, M., Hussain, M. M., & Niazi, N. K. (2022). Global arsenic contamination of groundwater, soil and food crops and health impacts. In *Global arsenic hazard: Ecotoxicology and remediation* (pp. 13-33). Springer.
- Khalid, S., Shahid, M., Niazi, N. K., Murtaza, B., Bibi, I., & Dumat, C. (2017). A comparison of technologies for remediation of heavy metal contaminated soils. *Journal of geochemical exploration*, 182, 247-268.
- Kim, Y.-J., & Kim, J.-M. (2015). Arsenic toxicity in male reproduction and development. *Development & reproduction*, 19(4), 167.
- Lapworth, D., Gopal, K., Rao, M., & MacDonald, A. (2014). Intensive groundwater exploitation in the Punjab: An evaluation of resource and quality trends. <https://nora.nerc.ac.uk/id/eprint/509752>
- Lenoble, V., Dang, D., Cazalet, M. L., Mounier, S., Pfeifer, H.-R., & Garnier, C. (2015). Evaluation and modelling of dissolved organic matter reactivity toward AsIII and AsV—Implication in environmental arsenic speciation. *Talanta*, 134, 530-537.
- Li, X., Feng, J., Zhu, F., Ke, W., Huang, Y., Wu, C., Liang, H., & Xue, S. (2025). Remediation of Pb, Cd, and As contaminated soils by phosphate-solubilizing bacteria and iron-doped hydroxyapatite: Multi-pathway immobilization mechanisms. *Chemical Engineering Journal*, 167445.
- Li, Y., Jia, S., & Liu, J. (2022). Solidification, remediation and long-term stability of heavy metal contaminated soil under the background of sustainable development. *Scientific Reports*, 12(1), 10330.
- Liu, Q. (2025). Toxicology of Airborne Inorganic Arsenic: Oxidative Stress, Molecular Mechanisms, and Organ-Specific Pathologies. *Toxics*, 13(9), 753.
- Lu, T.-H., Su, C.-C., Chen, Y.-W., Yang, C.-Y., Wu, C.-C., Hung, D.-Z., Chen, C.-H., Cheng, P.-W., Liu, S.-H., & Huang, C.-F. (2011). Arsenic induces pancreatic β -cell apoptosis via the oxidative stress-regulated mitochondria-dependent and endoplasmic reticulum stress-triggered signaling pathways. *Toxicology letters*, 201(1), 15-26.
- Ma, Y., Wang, L., Cao, Y., Liang, T., Wang, P., Luo, H., Yu, J., Zhang, D., Xing, B., & Yang, B. (2022). Stabilization and remediation of heavy metal-contaminated soils in China: insights from a decade-long national survey. *Environmental Science and Pollution Research*, 29(26), 39077-39087.
- Mandal, S., Saha, K. K., & Mandal, N. C. (2021). Molecular insight into key eco-physiological process in bioremediating and plant-growth-promoting bacteria. *Frontiers in Agronomy*, 3, 664126.
- Martínez-Castillo, M., García-Montalvo, E. A., Arellano-Mendoza, M. G., Sánchez-Peña, L. d. C., Soria Jasso, L. E., Izquierdo-Vega, J. A., Valenzuela, O. L., & Hernández-Zavala, A. (2021). Arsenic exposure and non-carcinogenic health effects. *Human & Experimental Toxicology*, 40(12_suppl), S826-S850.
- Mbachu, A., Chukwura, E., & Mbachu, N. (2020). Role of microorganisms in the degradation of organic pollutants: a review. *Energy Environ Eng*, 7(1), 1-11.
- Medunić, G., Fiket, Ž., & Ivanić, M. (2019). Arsenic contamination status in Europe, Australia, and other parts of the world. In *Arsenic in drinking water and food* (pp. 183-233). Springer.
- Mihai, R. (2011). Physiology of the pituitary, thyroid and adrenal glands. *Surgery (Oxford)*, 29(9), 419-427.
- Mochizuki, H. (2019). Arsenic neurotoxicity in humans. *International journal of molecular sciences*, 20(14), 3418.
- Mohsin, H., Shafique, M., Zaid, M., & Rehman, Y. (2023). Microbial biochemical pathways of arsenic biotransformation and their application for bioremediation. *Folia Microbiologica*, 68(4), 507-535.
- Mouratiadou, I., Stella, T., Gaiser, T., Wicke, B., Nendel, C., Ewert, F., & van der Hilst, F. (2020). Sustainable intensification of crop residue exploitation for bioenergy: Opportunities and challenges. *GCB Bioenergy*, 12(1), 71-89.
- Mudgal, V., Raninga, M., Patel, D., Ankoliya, D., & Mudgal, A. (2023). A review on Phytoremediation: Sustainable method for removal of heavy metals. *Materials Today: Proceedings*, 77, 201-208.
- Murcott, S. (2012). *Arsenic contamination in the world*. IWA publishing.

- Neisan, R. S., Saady, N. M. C., Bazan, C., Zendejboudi, S., Al-nayili, A., Abbassi, B., & Chatterjee, P. (2023). Arsenic removal by adsorbents from water for small communities' decentralized systems: performance, characterization, and effective parameters. *Clean Technologies*, 5(1), 352-402.
- Nnaji, N. D., Anyanwu, C. U., Miri, T., & Onyeaka, H. (2024). Mechanisms of heavy metal tolerance in bacteria: A review. *Sustainability*, 16(24), 11124.
- Nriagu, J. O. (2002). Arsenic poisoning through the ages. *Environmental chemistry of arsenic*, 1, 1-26.
- Patil, A., Chakraborty, S., Yadav, Y., Sharma, B., Singh, S., & Arya, M. (2024). Bioremediation strategies and mechanisms of bacteria for resistance against heavy metals: a review. *Bioremediation Journal*, 1-33.
- Pereira, J. A., & Law, S. (2018). Microenvironmental scenario of the bone marrow of inorganic arsenic-exposed experimental mice. *Biological Trace Element Research*, 181(2), 304-313.
- PP, S., & Puthur, J. T. (2021). Heavy metal phytoremediation by bioenergy plants and associated tolerance mechanisms. *Soil and Sediment Contamination: An International Journal*, 30(3), 253-274.
- Puthur, J. T., & Dhankher, O. P. (2022). *Bioenergy Crops*. CRC Press.
- Qin, H., Wang, Z., Sha, W., Song, S., Qin, F., & Zhang, W. (2024). Role of plant-growth-promoting rhizobacteria in plant machinery for soil heavy metal detoxification. *Microorganisms*, 12(4), 700.
- Raffa, C. M., Chiampo, F., & Shanthakumar, S. (2021). Remediation of metal/metalloid-polluted soils: A short review. *Applied sciences*, 11(9), 4134.
- Rafique, M., Hajra, S., Tahir, M. B., Gillani, S. S. A., & Irshad, M. (2022). A review on sources of heavy metals, their toxicity and removal technique using physico-chemical processes from wastewater. *Environmental Science and Pollution Research*, 29(11), 16772-16781.
- Rahidul Hassan, H. (2023). A review on different arsenic removal techniques used for decontamination of drinking water. *Environmental Pollutants and Bioavailability*, 35(1), 2165964.
- Rahman, S., Saito, M., Yoshioka, S., Ni, S., Wong, K. H., Mashio, A. S., Begum, Z. A., Rahman, I. M., Ohta, A., & Hasegawa, H. (2023). Evaluation of newly designed flushing techniques for on-site remediation of arsenic-contaminated excavated debris. *Environmental Science and Pollution Research*, 30(52), 112052-112070.
- Rastogi, S., & Kumar, R. (2020). Remediation of heavy metals using non-conventional adsorbents and biosurfactant-producing bacteria. *Environmental degradation: causes and remediation strategies*, 1(1), 23-45.
- Ren, C., Zhou, Y., Liu, W., & Wang, Q. (2021). Paradoxical effects of arsenic in the lungs. *Environmental Health and Preventive Medicine*, 26(1), 80.
- Shackira, A., & Puthur, J. T. (2019). Phytostabilization of heavy metals: understanding of principles and practices. In *Plant-metal interactions* (pp. 263-282). Springer.
- Shakoor, M. B., Niazi, N. K., Bibi, I., Rahman, M. M., Naidu, R., Dong, Z., Shahid, M., & Arshad, M. (2015). Unraveling Health Risk and Speciation of Arsenic from Groundwater in Rural Areas of Punjab, Pakistan. *International Journal of Environmental Research and Public Health*, 12(10), 12371-12390.
- Sharma, J. K., Kumar, N., Singh, N. P., & Santal, A. R. (2023). Phytoremediation technologies and their mechanism for removal of heavy metal from contaminated soil: An approach for a sustainable environment. *Frontiers in Plant Science*, 14, 1076876.
- Sharma, S., Tiwari, S., Hasan, A., Saxena, V., & Pandey, L. M. (2018). Recent advances in conventional and contemporary methods for remediation of heavy metal-contaminated soils. *3 Biotech*, 8(4), 216.
- Shi, H., Chen, L., Wang, Y., Sun, M., Guo, Y., Ma, S., Wang, X., Jiang, H., Wang, X., & Lu, J. (2022). Severity of anemia during pregnancy and adverse maternal and fetal outcomes. *JAMA network open*, 5(2), e2147046-e2147046.
- Singh, S., & Kumar, V. (2020). Mercury detoxification by absorption, mercuric ion reductase, and exopolysaccharides: a comprehensive study. *Environmental Science and Pollution Research*, 27(22), 27181-27201.
- Su, W., Li, X., Zhang, H., Xing, Y., Liu, P., & Cai, C. (2021). Migration and transformation of heavy metals in hyperaccumulators during the thermal treatment: a review. *Environmental Science and Pollution Research*, 28(35), 47838-47855.
- Sun, G., Yu, G., Zhao, L., Li, X., Xu, Y., Li, B., & Sun, D. (2019). Endemic arsenic poisoning. In *Endemic Disease in China* (pp. 97-123). Springer.
- Sun, H. J., Xiang, P., Luo, J., Hong, H., Lin, H., Li, H.-B., & Ma, L. Q. (2016). Mechanisms of arsenic disruption on gonadal, adrenal and thyroid endocrine systems in humans: A review. *Environment international*, 95, 61-68.
- Sun, Z., Zhao, M., Chen, L., Gong, Z., Hu, J., & Ma, D. (2023). Electrokinetic remediation for the removal of heavy metals in soil: Limitations, solutions and prospection. *Science of the total environment*, 903, 165970.
- Tan, S. N., Yong, J. W., & Ng, Y. F. (2010). Arsenic exposure from drinking water and mortality in Bangladesh. *The Lancet*, 376(9753), 1641-1642.
- Tchounwou, P. B., Udensi, U. K., Isokpehi, R. D., Yedjou, C. G., & Kumar, S. (2023). Arsenic and cancer. In

- Handbook of arsenic toxicology* (pp. 607-630). Elsevier.
- Timofeeva, A. M., Galyamova, M. R., & Sedykh, S. E. (2023). Plant growth-promoting soil bacteria: nitrogen fixation, phosphate solubilization, siderophore production, and other biological activities. *Plants*, 12(24), 4074.
- Trifunović, V. (2021). Vitrification as a method of soil remediation. *Zastita materijala*, 62(3), 166-179.
- Viotti, P., Marzeddu, S., Antonucci, A., Décima, M. A., Lovascio, P., Tatti, F., & Boni, M. R. (2024). Biochar as alternative material for heavy metal adsorption from groundwaters: lab-scale (column) experiment review. *Materials*, 17(4), 809.
- Wang, H., Huang, P., Zhang, R., Feng, X., Tang, Q., Liu, S., Wen, F., Zeng, L., Liu, Y., & Wang, T. (2021). Effect of lead exposure from electronic waste on haemoglobin synthesis in children. *International Archives of Occupational and Environmental Health*, 94(5), 911-918.
- Wang, X., Chen, J., An, J., Wang, X., & Shao, Y. (2024). Comparison of the effects of different organic amendments on the immobilization and phytoavailability of lead. *Sustainability*, 16(7), 2981.
- Wang, Y.-Y., Chai, L.-Y., & Yang, W.-C. (2019). Arsenic distribution and pollution characteristics. In *Arsenic pollution control in nonferrous metallurgy* (pp. 1-15). Springer.
- Wang, Y., Narayanan, M., Shi, X., Chen, X., Li, Z., Natarajan, D., & Ma, Y. (2022). Plant growth-promoting bacteria in metal-contaminated soil: Current perspectives on remediation mechanisms. *Frontiers in Microbiology*, 13, 966226.
- Wanitsawatwichai, K., & Sampanpanish, P. (2021). The combination of phytoremediation and electrokinetics remediation technology on arsenic contaminated remediation in tailing storage facilities from gold mine. *Heliyon*, 7(8).
- Wijekoon, W., Priyashantha, H., Gajanayake, P., Manage, P., Liyanage, C., Jayarathna, S., & Kumarasinghe, U. (2025). Review and prospects of phytoremediation: Harnessing biofuel-producing plants for environmental remediation. *Sustainability*, 17(3), 822.
- William, V. U., & Magpantay, H. D. (2023). Arsenic and microorganisms: genes, molecular mechanisms, and recent advances in microbial arsenic bioremediation. *Microorganisms*, 12(1), 74.
- Yi, Y., Gao, S., Xia, J., Li, C., Zhao, Y., Zhang, Y., Liang, A., & Ji, S. (2020). Study of the accumulation and distribution of arsenic species and association with arsenic toxicity in rats after 30 days of oral realgar administration. *Journal of ethnopharmacology*, 247, 111576.
- Yu, B., Dong, Q., Zhang, M., Wang, D., Li, J., & Cheng, Y. (2024). Study on the effect of thermal activation on arsenic removal from industrial wastewater. *JOM*, 76(3), 1539-1547.
- Yuan, C., & Chiang, T.-S. (2008). Enhancement of electrokinetic remediation of arsenic spiked soil by chemical reagents. *Journal of hazardous materials*, 152(1), 309-315.
- Zheng, X.-J., Li, Q., Peng, H., Zhang, J.-X., Chen, W.-J., Zhou, B.-C., & Chen, M. (2022). Remediation of heavy metal-contaminated soils with soil washing: a review. *Sustainability*, 14(20), 13058.
- Zhou, F., Yu, Q., Guo, M., Zhang, M., Zhao, N., Xu, Q., Zhang, W., & Qiu, R. (2024). The effect of the synergistic thermal treatment and stabilization on the transformation and transportation of arsenic, chromium, and cadmium in soil. *Science of the Total Environment*, 907, 167948.

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