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Review of Phytoremediation for Arsenic-Contaminated Soils: Mechanisms and Challenges

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ABSTRACT

Environmental pollution has become and increasing concern due to growing risk to human health. Soil pollution is an aspect of environmental pollution that has received comparatively less attention than water pollution. However, considering direct effects of contaminants transmission through ingestion to the human body, it can lead to greater risks for human health. Arsenic is a highly prevalent environmental pollutant, and considerable number of people worldwide suffer from constant exposure to it. While there are several ways to manage and remediate contaminated soils, phytoremediation has been paid special attention due to its higher social acceptability and lower cost. Nevertheless, this approach faces challenges, including effectively handling significant quantities of contaminated biomass, managing it appropriately, and selecting suitable plant species for the remediation process. In this regard, numerous endeavors have been undertaken to tackle these obstacles like strategies encompass the utilization of amendments, adept management of biomass, and the implementation of hybrid remediation approaches. This study aims to review prior research on mechanisms, challenges, and enhanced phytoremediation of arsenic-contaminated soils, encompassing reduction of contaminated biomass after phytoremediation.

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INTRODUCTION

One of the most important environmental concerns on a worldwide scale is that the planet's air, surface water, groundwater, and soil are increasingly contaminated with potentially toxic elements (PTE) or substances (Shahid et al., 2015; Khalid et al., 2017). In most cases, these are toxic to various forms of life, including, flora, fauna, and humans, and could even be deadly (Mombo et al., 2016). Of the potentially hazardous elements, arsenic is widely identified as being among the most hazardous and cancer-causing elements (Abid et al., 2016; Mehmood et al., 2023). Arsenic is categorized as a Group-1 cancer causing substances by the US Environmental Protection Agency (EPA), the International Agency for Research on Cancer, and the Agency for Toxic Substances and Diseases. It is also ranked in the top 20 dangerous materials (Niazi et al., 2018; Rosas et al., 2014). As well as its high toxicity, this element is present in more than 240 minerals in the earth's crust, which indicates the abundance of this substance (Mandal & Suzuki, 2002; Souri et al., 2022). More than half of the minerals that contain arsenic are in the form of arsenate, one-fifth in the form of sulfide and sulfosalts, and the rest in the form of arsenides, silicates, and oxides (Thornton & Farago, 1997).

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There are four different oxidation states of arsenic oxide in aqueous and terrestrial environments: As(-III), As(0), As(III), As(V) (Panda et al., 2010). Arsenate (As(V)), which is often present in oxidation conditions, and arsenite (As(III)), commonly found in reduction conditions, are two dominant, highly toxic, and mobile species (Khalid et al., 2017). Although inorganic arsenic species are generally more harmful than organic species (Karbassi et al., 2014), different organic species do have varying toxicities; for example, monomethyl arsonic acid (MMA(V)) and dimethyl arsinic acid (DMA(V)) are less harmful than inorganic arsenic, while monomethylarsonous acid (MMA(III)) and dimethylarsinous acid (DMA(III)) varieties have higher toxicity than inorganic arsenic (Petrick et al., 2000; Singh et al., 2022). Consequently, the sequential toxicity of different species of arsenic, respectively, are as follows: As(III) > DMA(V) > MMA(V) > AsV > DMA(III) > MMA(III) (Sun et al., 2014).

Exposure to arsenic for an extended period can cause arsenicosis. The World Health Organization (WHO) defines arsenicosis as a "chronic disease caused by ingestion of arsenic for at least six months and beyond the safe doses." As shown in Table 1, exposure to arsenic leads to three categories of complications that are epidemiological, cytotoxic, and genotoxic (Nasrabadi et al., 2015). These include serious health problems such as skin, lung, kidney, and bladder cancers, coronary heart disease, hyperkeratosis, hypertension, myocardial infarction, liver damage, diabetes, neonatal mortality, and movement disorders in children (Bhat et al., 2022; Chakraborti et al., 2018; Saha & Ray, 2019). Although chronic exposure to arsenic causes neurobehavioral problems and deterioration of mental function in children (Von Ehrenstein et al., 2007), the symptoms of intoxication in children are minimal, except in children who are malnourished or exposed to high concentrations of As (Rahman et al., 2001). Subsequently, there are special concerns about the health of infants due to the ingestion of arsenic through breast milk (Samiee et al., 2019). Arsenic can accumulate in cereals, vegetables, and agricultural products (Cubadda et al., 2015), hence enter the food network. For example, rice, as a basic food which is consumed all around the world, often contains higher levels of pentavalent arsenic (monomethylarsonic acid (MMA) and dimethylarcinic acid (DMA)) than other cereals (Cubadda et al., 2017). These pentavalent methylated substances are probably formed before arsenic uptake by microbial populations associated with plant rhizosphere (Lomax et al., 2012).

In many cases, natural sources of arsenic depend on the geochemistry of the site and the volcanic activity of adjacent areas (Cubadda et al., 2015; Mestrot et al., 2011). Man-made arsenic sources include mining, metallurgy, agriculture, forestry, fossil fuel refineries, municipal waste incineration, and livestock farming. In addition, past human activities which ended may continue to affect the entry of arsenic into the food cycle (Nasrabadi & Bidabadi, 2013). For example, lead arsenate ($Pb_5OH\ (AsO_4)^3$) was one of the most common pesticides in agriculture in the United States until 1988 (Schooley et al., 2009). As a result of the widespread use of this pesticide in agriculture, there is a possibility of a high concentration of Pb and As existing in the soil of former and current agricultural lands (Wolz et al., 2003). It is estimated that more than 29 million people worldwide are exposed to highly arsenic-contaminated water, a quarter of which exhibit signs of poisoning (Caussy, 2003; Landberg & Greger, 2022). Children may experience modest health hazards from unintentional eating and breathing of soil particles polluted with

Table 1. Effects of exposure to Arsenic

Genotoxicity	Cytotoxicity	Epidemiologic
Dermal disease	Cell cycle arrest	Deletion mutation
DNA damage	Cell aberrant differentiation	Cardiovascular disease
DNA strand breaks	Cell Dysfunction	Skin cancer
Sister chromatic exchange	Cell excess proliferation	Bladder cancer
Chromosomal aberrations		Diabetes mellitus

arsenic, primarily as a result of their habitual hand-to-mouth actions (Gosselin & Zagury, 2019; Hsi et al., 2018). Considering all exposure routes for humans, including swallowing, inhalation, and skin contact, the exposure route for swallowing is the main pathway of exposure to arsenic for humans. It can be said that, globally, the principal pathways via which individuals are exposed to arsenic are via soil and water (Li et al., 2022; Smedley & Kinniburgh, 2002). Also, over two hundred million people worldwide are directly or indirectly exposed to arsenic-contaminated soil (Wan et al., 2020). In this regard, the treatment of arsenic polluted lands needs to urgently treated efficiently and effectively on a wide scale.

MATERIALS & METHODS

In this study, the Web of Science, Scopus, and Science Direct databases were screened out. These online databases provide the reader with a wide range of research papers. In this study, we retrieved related papers by using general search keywords such as Arsenic phytoremediation, Phytoremediation of As contaminated soil, enhanced phytoremediation, and As-contaminated soil. To be more specific, this research involved a comprehensive exploration where we accessed relative literature, focusing on arsenic species, exposure pathways, and the sources of As pollution. Furthermore, we provided an overview of types of available remedial approaches for arsenic-contaminated sites, evaluating their respective efficacy and offered comparative analysis with phytoremediation techniques.

Arsenic-contaminated soil remediation technologies for reducing the risk of exposure are divided into two categories: firstly, removing contaminants from the soil; and secondly, curtailing the biotoxicity of the contaminant. These technologies include chemical degradation, electrochemical, bioremediation and solidification/stabilization. Given that each of these techniques is currently situated at a specific stage of development (Wan et al., 2020). As shown in Fig. 1 arsenic remediation methods are divided into three categories.

Physical remediation processes for arsenic-contaminated soils mostly consist of the replacement of soil, covering contaminated soil, natural dilution, and electrokinetic remediation. Replacement and covering procedures are identical, and both requireuncontaminated soil derived using

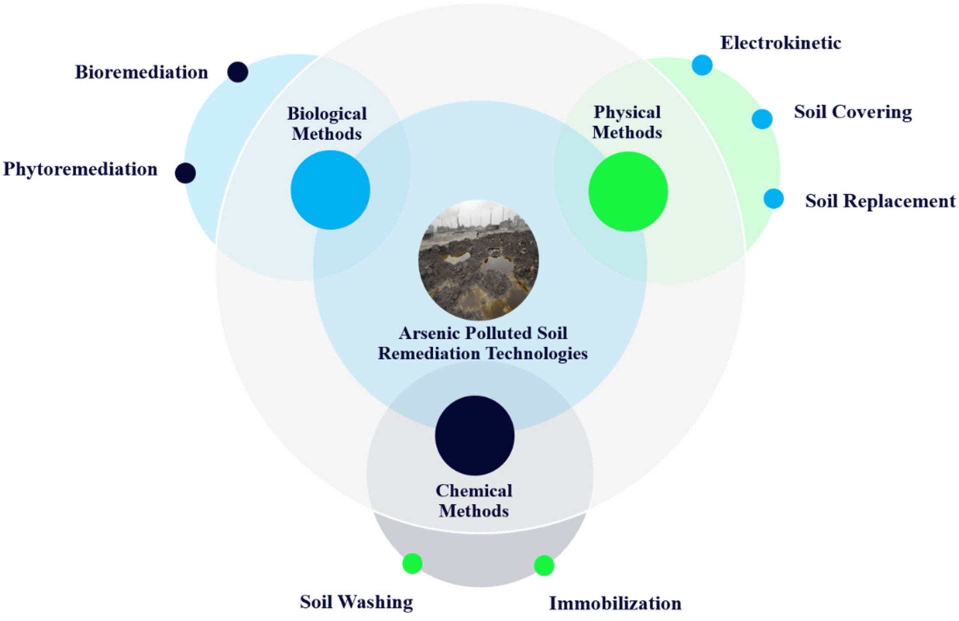

Fig. 1. Arsenic contaminated soil remediation technologies

alternative sources. while the elevation of the primary soil is slightly lesser than the adjucent land, the second method is more compatible. When the initial soil elevation is equal to the surrounding soil, the first approach could serve better. These physical technologies can expeditiously reduce the concentration of arsenic in the soil and greatly help the remediation of other contaminants in the soil (P. Song et al., 2022). Dilution involves mixing the top surface of contaminated media with uncontaminated one in irder to reduce the level of contaminants in the polluted area. This method is popular in Japan and is widely used to treat contaminated soils there (Chen & Chiou, 2008). Electrokinetics is also a quick and efficient method for remediation of arsenic polluted site, and it has the capacity to enhance the efficiency of cleanup (P. Song et al., 2022).

Chemical methods for the remediation of polluted soils mainly comprise soil washing and contaminant immobilization. Soil washing leads to the separation of the contaminant from the soil, while immobilization leads to stabilizing the contaminant and prevents its transfer to the next media (Wan et al., 2020). Soil washing is the technology of injecting chemical reagents that can dissolve contaminants, thereby removing contaminants from the soil, and then collecting liquid with high concentrations of contaminants and removing contaminants from the soil. Washing reagents include inorganic bases and acids, organic ligands, chelates, and biosurfactants(P. Song et al., 2022; Wei et al., 2017). Immobilization is defined as using chemical reagents to stabilize soil contaminants and reduce possible risks of contaminants. Due to this technology's low cost and ease of operation, the immobilization of soil contaminants has received more attention. Metal compounds (especially iron oxides), biochar, and compost are frequently utilized as materials for preventing mobilization of arsenic (Doherty et al., 2017).

Biological remediation approaches for arsenic-contaminated soils mainly incorporate animal bioremediation, microbial bioremediation, and phytoremediation, the last two of which have been investigated in more depth (Wan et al., 2020). The term "phytoremediation" mostly pertains to the process of phytoextraction, wherein specific plant species are utilized to extract substantial quantities, particularly arsenic, from polluted soil. These plants possess the ability to accumulate in their shoots. For example, Pteris vittata can accumulate very high concentrations of arsenic (Gupta et al., 2022a). Microbial bioremediation of arsenic-contaminated soil can require different functions and be classified into two types: immobilization or increasing mobility. For example, oxidation of As(III) to As(V) reduces the mobility of arsenic and in turn reduces its bioavailability in soil. Despite the effectiveness of these methods, given the complexity of soil media, using a single treatment method can fail to meet the desired requirements, so the simultaneous or consecutive use of several methods can lead to better remediation.

RESULTS & DISCUSSIONS

Phytoremediation of arsenic-contaminated soils

Plants can use two different methods for remediation including phytoextraction and phytostabilization. Phytostabilization is defined as the immobilization of pollutants in the rhizosphere, while phytoextraction involves the transfer of pollutants from the environment and their accumulation in plant tissue (**Fig. 2**). Certain plant species can transfer contaminants to plant tissue, so plants with this ability need to be identified (Thakur et al., 2020). For example, P. vittata, which is known as an arsenic accumulator, can store 20 times the concentration of arsenic in the soil and can even extract it from groundwater (Boorboori & Zhang, 2022). Recently, Cyanoboletus pulverulentus has been introduced as an arsenic accumulator and can store it in a concentration as much as 1300 mg/kg dry mass (Braeuer et al., 2018). Meanwhile, other species such as eucalyptus, are suitable for plant stabilization of arsenic (King et al., 2008; Vázquez et al., 2006). Plants used in site remediation to extract pollution from the soil, in addition to being able to accumulate, must have rapid growth, ease of reproduction, short life, high shoot biomass, and preferably non-edible to prevent contaminants from entering the food chain (Imran et al., 2013; Kohda et al., 2022).

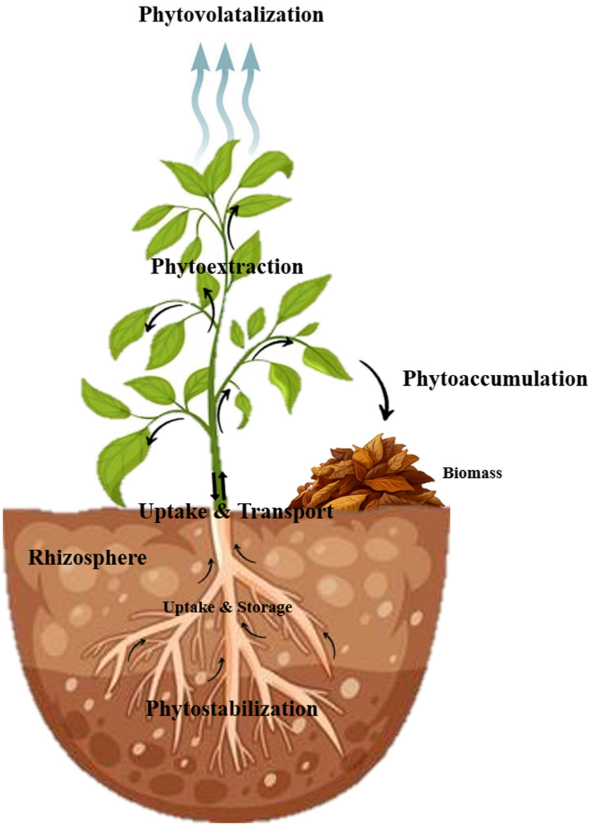

Fig. 2. Arsenic phytoremediation mechanisms

Arseic-plant interaction

It should be noted that different species of arsenic (As(III), As(V), MMA, DMA) are present in the soil at the same time. Arsenic is categorized as an unnecessary element for plants and other organisms (Khalid et al., 2017; Oladoye et al., 2022). The degree to which plant species absorb arsenic is contingent upon the overall concentration of this element, As species in the soil, and the concentration of bioavailable arsenic, the latter two of which are the most important factors(Rafiq et al., 2017). Plants primarily assimilate As in an inorganic state, either As(III) or As(V) (Kristanti & Hadibarata, 2023; Neidhardt et al., 2015). This is accomplished by the action of transporter proteins that are regulated by the arsenic concentration gradient between the growth media and plant cells. It is noted that information on specific As transmitters into plants is scarce, but it appears A(V) uses the same transporters as phosphate (Pi) to cross the membrane of the root cell. In the realm of plant physiology, it is noteworthy to mention that a comparable mechanism exists for the absorption of essential nutrients and various trace elements (Niazi et al., 2017; Thakur et al., 2020).

Effects of the Plant on Arsenic's Mobility in Soil

Plant roots employ a complex system of processes to alter the availability and solubility of soil minerals (H. Marschner, 2012). In fact, plants wield a direct effect on biogeochemical conditions in the root region. As an illustration, it is worth noting that organic molecules with low molecular weight possess the capability to render nutrients accessible, which are typically found in limited quantities within the soil. Consequently, anions such as phosphates and cations like iron and copper can become readily obtainable to a plant. Plants can also alter the pH of the root zone by releasing organic acids and using this mechanism to neutralize toxic elements; for example, the immobilization of aluminum in the soil by changing the pH of the rhizosphere(Majumdar et al., 2022; Mariano & Keltjens, 2003). Most plants interact with microorganisms in the rhizosphere (fungi and bacteria) and affect the biogeochemical cycle of the root zone. When the bacterial activity within the rhizosphere is elevated, there is a corresponding increase in the probability of various bacterial-mediated biochemical processes such as occurrence, methylation, regeneration, and other related activities (Renella et al., 2007). Although there is no accurate information on the mechanisms that affect the bioavailability of toxic elements in the soil, it has been reported that the rhizosphere's performance in such conditions is inherently dependent on plant species (Kidd et al., 2009; Kristanti & Hadibarata, 2023).

Many plant species increase the mobility of Phosphorus using the root mechanism via the emission of organic acids into the root zone. These low-weight organic acid (such as citric and malic acids) release phosphate from their position in the soil. Then they form chelate metal complexes with Phosphorus (Patel et al., 2020). As well, phosphorus (P) motility and uptake by plants are are connected to flavonoid root-secretion (Tomasi et al., 2008). Due to the chemical similarity of arsenate and phosphate, these mechanisms are likely to increase the mobility of arsenic. So in this way, organic acids can transport arsenate in the soil (Awa & Hadibarata, 2020). Plant strategies for acting on iron oxides and hydroxides can potentially increase the mobility of As (Gupta et al., 2022b).

Arsenic uptake

Being able to comprehend the uptake process would help to manage improved phytoremediation as well as the creation of safe crops that may be cultivated in polluted soils. Different forms of arsenic in soil, including (As(V), (As(III), monomethylsaronic acid (MMA), and dimethylsaric acid (DMA), have Several absorption processes in plants. The most prevalent variety of As in oxidation conditions is As(V), while As(III) is predominant in reduction environement, and these 2 forms can be converted into each other. The transportation of As(V) into plant tissues is facilitated by high-affinity phosphate drivers, owing to their structural resemblance (Meharg & Whitaker, 2002). The identification of the transporter PHO84 in Saccharomyces cerevisiae was initially documented (Vandana et al., 2020). Two phosphate transporters PHT1:1 (key determinant of phosphorus acquisition in Arabidopsis natural accessionsand) and PHT1:4 (a member of the Pht1 family of phosphate transporters) are involved in the process of taking up phosphate in Arabidopsis thaliana in conditions of both moderate and elevated phosphate contents.. In P. vittata, which is an arsenic hyperaccumulator, While both PvPht1;3 and PvPht1;5 exhibit comparable behavior towards phosphate, it is worth noting that PvPht1;3 demonstrates a greater affinity for As(V) (Vandana et al., 2020).

Arsenic (III) is a very poisonous compound and is the primary inorganic form of arsenic found in reduction environments, such as wetlands. The compound has the ability to interact with sulfhydryl groups present in proteins, leading to the disruption of their overall functionality (Abedin et al., 2002). Duan et al., (2015) bealived that, the ptake of As(III), is mediated by many different transporters, such as nodulin-like intrinsic proteins (NIPs), tonoplast intrinsic proteins (TIPs), inositol (INT), and Si transporters. ABC-type transporter and arsenic-resistant components (ACR3) transport are known to accumulate As(III) into the vacuolei (Indriolo et al., 2010; W.-Y. Song et al., 2014). The underlying process by which organic forms of arsenic, such as monomethylarsonic acid (MMA) and dimethylarsinic acid (DMA), are absorbed remains little comprehended. Several studies reveal that plants could absorb methyl arsenic via the roots and transport it to the upper parts of the plant (Burló et al., 1999). Morover, the presence of Si transporter (Lsi1), which has been established as a significant determinant in the absorption of As(III), also plays a role in the absorption of methylation arsenic compounds in rice. (Vandana et al., 2020).

Advantage of phytoremediation

There are several benefits to using phytoremediation to remediate contaminated soils. If the plants are picked correctly, and suitable methods are employed to ensure they have high access to pollutants, this method is economically viable because it is a simple and low-cost method to implement and maintain. It is also a method powered by solar energy. As a result, its continuation does not require any special expenses or management. This method is environmentally friendly and its implementation has no impact if the appropriate and native plants of the area are selected. It is fairly simple to implement in a large area. Planting prevents wind and water erosion of the soil because it leads to the provision of surface cover on the soil and roots of plants, thereby stabilizing the soil mass. This system reduces the mobility of contaminated soils and afterward prevents the spread of contamination. Planting leads to increased fertility of the treated soil by increasing organic matter, nutrients, and oxygen due to microbial plant activities. As well as the advantages mentioned earlier, this method can be applied in all geographical conditions (Gavrilescu, 2022; Preetha et al., 2023; Schwitzguébel, 2017; Tripathi et al., 2020; Wiszniewska et al., 2016; Yan et al., 2020).

Challenges of phytoremediation

Apart from the claimed benefits of plant bioremediation, there are several drawbacks to implementing this approach. Each plant has the ability to access the soil within its root area, so there may be restrictions for deep soil contamination because, in most cases, the root depth of plants is limited to 50 cm (Pilon-Smits, 2005; Schwitzguébel, 2017; Lee et al., 2023). Normally, the growth rate and production of plant biomass are slow, and this factor controls the rate of phytoremediation. As a result, in comparison with chemical and physical methods, the phytoremediation method is slower. The presence of contaminants in the soil can create more unfavourable conditions for plant growth and survival, leading to a slower remediation process (F. et al., 2002; Huang et al., 2005; Shen et al., 2022). Furthermore, it may even take several planting and harvesting periods to completely remediate a site (Farraji et al., 2016). Plant growth and survival usually occur under the influence of climate conditions, and in some seasons, plant growth is slower or stops completely. Water stress due to lack of rainfall, the possibility of competition with other plants, and the possibility of plant extinction by insects and animals are other factors that control plant life, thereby affecting the remediation process (Prasad et al., 2022). Non-uniformity of pollutant concentrations at the site, the need to control the access of humans and animals to the consumable parts of plants to prevent contaminants from entering into the food cycle, and the need to manage contaminated biomass are other challenges of phytoremediation (Ghosh and Singh, 2005; van Dillewijn et al., 2007; Lee et al., 2023)

Enhanced phytoremediation of arsenic-contaminated soils

The challenges of using phytoremediation to remediate arsenic polluted soils can be categorized into two kinds. For example, by conducting thorough experimental and sufficient studies, the challenge of finding the right species to remove the target contaminant can be eliminated. However, some challenges require intervention measures to improve the remediation process. Some of these methods are discussed below in more detail.

Rhizobacterial enhancement

In June 2016 in Sendai, Japan, field experiments were conducted, with an initial concentration of 12 mg/kg arsenic in the soil to investigate the effect of inoculation with m.318 on P. vittata and P. multifida seedlings. It demonstrated the ability of bacterial inoculation to improve remediation by these plants. After six months, shoots biomass, root biomass, maximum arsenic concentration in shoots, and maximum arsenic concentration in root increased, respectively, by

50, 10, 10, and 60%. This study reveals that the amount of biomass and arsenic concentration in the shoot and root of plants known as arsenic accumulators can be increased, and the process of arsenic phytoremediation can be improved (Yang et al., 2020a). Bacterial inoculation experiments with soybean using Bradyrhizobium japonica demonstrated an increase in root biomass in the existance arsenic in the contaminated site, while the level of arsenic in the shoot remained constant. These results suggest that the increase in tolerance of soybean plants using bacterial inoculation occurred without affecting the amount of arsenic taken up by the plant. Therefore, good yields can be expected from the phytoremediation of contaminated soil with hogh concentration of arsenic (Boorboori & Zhang, 2022; Seraj et al., 2020). For this purpose, it is necessary to isolate and detect bacterial strains affecting plant extraction of arsenic and inoculant into the rhizosphere. For example, in another study, the isolated r507 strain from P. vittata, called Cupriavidus basilensis strain r507, was choosed due to its notable capacity to withstand high levels of arsenic, ability to quickly oxidize arsenite, and coexist well with P. vittata. The r507 strain was employed in field trials with Pteris vittata for a duration of six months. The findings of the study revealed that the introduction of bacteria resulted in a significant increase in the buildup of arsenic in Pteris vittata, with levels rising by almost 70% (Yang et al., 2020b).

Furthermore, in addition to the aforementioned strains, two strains of bacteria that exhibit resistance to arsenic, namely Pseudomonas gessardii and Brevundimonas intermedia, as well as two fungal strains classed as Fimetariella rabenhortii and Hormonema viticola, have been isolated for the purpose of conducting further experimental study. This concentrated on enhancing the phytoremediation of arsenic polluted sites. The plant growth-promoting qualities of the microorganisms were assessed based on their capacity to create indoleacetic acid, siderophores, and facilitate phosphate dissolution. Additionally, their resistance to arsenic was also examined. While not all of the microorganisms that were examined resulted in advantageous outcomes for plants, the wheat plant exhibited growth when inoculated with P.gessardii and B.intermedia. The microbes isolated from arsenic-contaminated soils exhibited an enhanced enzymatic antioxidant response, suggesting their potential in facilitating soil restoration by supporting the growth of other plant species. It seems that further studies are needed to comprehend the nature of the mechanisms involved in the interaction between microorganisms and plants to find its applications in the expansion of bioremediation methods. Using beneficial bacteria and fungi resistant to heavy metals has emerged recently as an excellent phytoremediation strategy (Preetha et al., 2023; Soto et al., 2019).

Amendment application

Plant growth in contaminated sites can be challenging because of high heavy metal levels and meager fertility. Biochar can be utilized to overcome these impediments. The biochar made from animal waste or plant biomass decomposed under the least amount of oxygen showed advantageous results on soil characteristics and plant growth. A field experiment that lasted 1.5 years was conducted to remediate an arsenic-contaminated mine with the help of biochar and iron sulfate. Its findings indicated that the iron sulfate and biochar combination can result in higher pH and EC, better soil properties, and a smaller metal concentration of pore water. These changes improved plant growth in polluted soil, while plant growth without biochar and ferrous iron sulfate was insufficient (Simiele et al., 2020).

Since the alkaline nature of biochar provides higher arsenic mobility in soil, using biochar in combination with arsenic-accumulating plants increases the efficiency of arsenic-hyperaccumulating plants. However, increasing the mobility of arsenic in the soil can pose environmental dangers, as it increases the possibility of contaminant leakage into groundwater. As a result, researchers recommend that biochar of less than 1% (w% BC to soil) is suitable for groundwater protection, unless laboratory studies in accordance with the geological and climatic conditions of the site allow further use of biochar (Zheng et al., 2019). To enhance the effect of biochar, it can be combined with composts. The combination of biochar with compost was reported to increase efficiency. It was indicated that compared to the use of compost or biochar alone, a combination of them provides favorable conditions for phytoremediation (Lebrun et al., 2019; Sugawara et al., 2022).

Nanomaterials can utilized in the phytoremediation system via direct decontamination, increasing plant growth, and increasing plant access to contaminants. Among nanomaterials, zero-valent iron nanoparticles, due to their high engineering capabilities in soil and groundwater remediation, are particularly popular for assisting phytoremediation (B. Song et al., 2019). By combining these nanoparticles with biochar, the positive effects of biochar on phytoremediation can be exploited without any concern about arsenic mobility and the possibility of leakage into groundwater because iron nanoparticles can have a neutralizing effect on arsenic's high mobility in the soil (Diego Baragaño et al., 2020). However, the use of iron gratings in combination with biochar can undermine the plant, probably due to their high concentration (D Baragaño et al., 2022; Lebrun et al., 2019).

As well as the aforementioned parameters, a chemical additive can be employed to increase the mobility of arsenic and subsequently increase its bioavailability. For example, the use of K_2HPO_4 elevates the bioavailability of arsenic to three plant species, Brassica juncea, Helianthus annuus, and Zea mays. This improvement in bioavailability will lead to an 80% increase in the efficiency of arsenic phytoremediation by these three plant species. However, when these additions are employed in conjunction with bacterial inoculation of the rhizosphere, the total uptake of arsenic, particularly in Brassica juncea, can be boosted as much as 140%. Therefore, using chemical additives alone or in combination with other approaches can be very effective in improving phytoremediation (Franchi et al., 2019).

Managing biomass after remediation

The objective in each of the aforementioned cases is to augment plant biomass, accelerate plant growth pace, and elevate arsenic content in plant shoots, hence improving the overall efficacy of phytoremediation in arsenic polluted soils. However, one of the major challenges of arsenic phytoremediation is how to deal with arsenic-contaminated plants' biomasses. Due to their potential to pollute the environment, plant biomasses should be kept away from the human food chain and properly eradicated. Biomass containing high levels of arsenic can be recovered, but its poor value and high danger of producing arsenic-rich biomass is a major challenge during phytoremediation by P. vittata.

Combustion was used to dispose of large amounts of polluted biomass in low-income rural parts of China. This procedure is able to cut both the volume of waste and the cost of disposal. In order to control the emission of arsenic into flue gas streams, experiments on a larger scale are required to determine the mechanism of arsenic adsorption during burning. Without emission control, the flue gas concentration of arsenic was greater than the national standard. Adding calcium oxide (CaO) dramatically reduced arsenic emissions, and adsorption was effective when CaO was combined with biomass at a concentration of 10% of total weight. Recovery of arsenic from ash increased to 76% when 10% of calcium was added, which is eight times higher than the control (Lei et al., 2019). In their work, (Cai et al., 2021) claim that, due to the high concentration of antioxidants, anti-cancer, and anti-bacterial compounds, as well as bioactive compounds such as flavonoids found in P. vittata extracts with no acute toxicity observed, the extraction process can result in the recovery of 100% of phytoremediation costs associated with arsenic-contaminated soil. Based on this finding it is possible to undertake phytoremediation at virtually no cost.

Da Silva et al. conducted numerous trials to determine the ideal ethanol concentration for maximal extraction of As. Ultimately, it was determined that a concentration of 35% ethanol proved to be the most effective in extracting arsenic (As) from Pteris vittata biomass. Using particle size of less than 1 mm, liquid to solid ration 50:1, pH 6 for 2 hours can lead to more than 90% of arsenic being removed from P. vittata biomass. In other to precipitate As, adding $MgCl_2$ at Mg to As ratio of 400 with pH 9.5 served to precipitate As as $Mg_3(AsO_4)_2$, which resulted in removing 98% of soluble As. These results indicate that practical pre-disposal As removal from P. vittata biomass increases the viability of phytoremediation. Another method for managing arsenic-contaminated P. vittata is to combine ethanol extraction and anaerobic digestion. This method can reduce the concentration of arsenic in the biomass of this plant by 98% and decrease it from 2665 mg/kg to 60 mg/kg. This amount of arsenic concentration based on EPA is in the range of safe substances, and the biomass of this plant can be managed normally (da Silva et al., 2018; da Silva et al., 2019).

The ferns of the species Pteris cretica, one of the plants known for the phytoremediation of arsenic-contaminated sites, can achieve approximately 4800 mg of arsenic per kg dry biomass. It is therefore necessary to manage its biomass properly. Water-ethanol, water-methanol, and water can be used to extract arsenic in the fern fronds, and over 94, 80, and 70% were obtained, respectively. $Mg_3(AsO_4)_2$ was precipitated after stripping at a pH between 8 and 10. The $Mg_3(AsO_4)_2$ precipitation efficiencies were 96 ± 7.2%. Arsenic nanoparticles generated from the recovered $Mg_3(AsO_4)_2$ could be various practical applications, including medical uses, conversion to more useful compounds, or as pesticides. The recovery of these high-value products from phytoremediation biomass should be enough to encourage commercial enterprises to focus on the remediation of contaminated sites.

CONCLUSION

Arsenic is one of the most toxic and abundant pollutants and due to its special physical and chemical properties, engages in a lot of interaction with biological systems and facilitate the entry of this contaminant into the human body. While the remediation of contaminated soil play vital role in restoring the ecosystem and preventing adverse effects on human health, conventional methods are often expensive, inefficient, require a lot of labor, and in some cases can change the soil and ecosystem conditions (Shukla & Srivastava, 2019). Phytoremediation as green remediation approach could remove/immobilize contaminants by stabilizing them in soil or absorbing them into plant tissues (Ali et al., 2013). As discussed in this study, phytoremediation techniques are highly effective in remediation of arsenic-contaminated sites, and also are one of the most accepted methods by the society as environmental friendly approaches. Studies show that in addition to much lower cost (about 5% of the cost of other methods), some plants are able to grow even in highly contaminated soils (Beresford et al., 2016; Singh et al., 2022) and could effectively remediate the highly concentration of arsenic in contaminated sites. However, using this method can face some challenges. To date, many efforts have been made to address these challenges such as using amendments, managing biomass, and applying hybrid remediation methods to not only improve environmental remediation efficiency, but also prevent the retention of pollutants to the medium due to improper disposal of contaminated biomass, and also contribute to rendering the phytoremediation process with more economically viable.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

LIST OF ABBREVIATIONS

MMA(V)	Monomethylarsonic acid
DMA(V)	Dimethylarsinic acid
MMA(III)	Monomethylarsonous acid
DMA(III)	Dimethylarsinous acid
Pi	Phosphate
P	Phosphorus
PHO84	High-affinity phosphate transporter
NIPs	Nodulin-like intrinsic proteins
TIPs	Tonoplast intrinsic proteins
INT	Inositol
ACR3	Arsenic-resistant components
Lsi1	Si transporter

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