



Bioremediation of chromium and arsenic-contaminated soil using the potential of fungi for a healthy ecosystem

Prashad J^{1,2}, Singh R^{1,3}, Yadav A¹ and Singh N^{1*}

¹*Department of Bio and Nano Technology, Guru Jambheshwar University of Science and Technology, Hisar Haryana India -125001, India*

²*Department of Microbiology, College of Basic Sciences, CCS HAU Hisar, Haryana, India-125004*

³*Cleantech Loop, Cleantech One #02-26, Singapore 637141*

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Abstract

Heavy metal contamination has become a major environmental concern and research topic for scientists and scholars. Chromium and arsenic are well-known pollutants with serious health effects. They are discharged into the environment by both natural and artificial sources and are highly toxic even at low concentrations; non-biodegradable and can persist in the environment for long periods. Arsenic exposure can lead to serious health issues such as nausea, vomiting, skin lesions, and heart diseases, whereas health problems like skin irritation, emphysema, and headache arise due to chromium exposure. Therefore, there is a need to mitigate the increasing pollution caused by these heavy metals. Bioremediation is a microbe-assisted technology that deals with elevated levels of heavy metals. Mushrooms are a powerful weapon in the fight against these metals. They are natural decomposers containing various extracellular enzymes. Fungi use a variety of mechanisms for bioremediation and can be used in a wide range of applications. The mechanisms involved in bioremediation are biosorption, bioaccumulation, chelation, and biotransformation. In future perspectives, there is a need to conduct molecular-level studies to identify the genes involved and study the metabolic pathways and enzymes which are employed in bioremediation. This review focuses on the different sources of chromium and arsenic emissions, their toxicity and associated health issues, various mechanisms of bioremediation, and future aspects.

Keywords – Arsenic – Bioremediation – Chromium – Heavy metals – Pollution

Introduction

Pollution is an acute problem that continues to worsen every day as a result of numerous human-caused variables like rapid industrialization, urbanization, the widespread use of chemical pesticides and fertilizers, and the development of advanced technology that further worsens the environment. Due to their toxicity and persistence in nature, heavy metals pose serious risks to a broad spectrum of living species when emitted into the environment. Heavy metals are an ill-defined collection of inorganic chemical dangers, including lead (Pb), cadmium (Cd), nickel (Ni), arsenic (As), copper (Cu), zinc (Zn), mercury (Hg), and chromium (Cr). These metals are commonly found at contaminated sites. The organisms' metabolic functions are impacted by the presence of a high number of heavy metals (Nematian & Kazemeini 2013). The human body may

be vulnerable to these heavy metals via contaminated food and water. Heavy metal contamination in soil, such as that caused by arsenic (As) and chromium (Cr), is extremely destructive for both the environment and human health. These contaminants, generated by a variety of human and industrial activities, can remain in the soil for prolonged periods and cause long-term impacts on the environment. Several well-known cases of heavy metal poisoning are Minamata disease (Japan), triggered by exposure to mercury from contaminated fish; Itai-Itai disease (Japan), caused by high cadmium levels in rice due to pollution from zinc ore waste; and the most current instance of general arsenic toxicity (Bangladesh), which is caused by polluted groundwater. Some of the conventional techniques for eradicating heavy metals include chemical precipitation, ion exchange, ultra-filtration, reverse osmosis, electrowinning, carbon adsorption, and solvent extraction. For heavy metal removal, most of these conventional methods are inadequate (Fu & Wang 2011, Gunatilake 2015). They are less successful because of their costly nature and the environmental issues they generate, including the development of potentially dangerous byproducts.

Bioremediation is an innovative method that uses bacteria to treat contaminated environments by converting poisonous heavy metals into less hazardous forms (Okoduwa et al. 2017). Microorganisms such as fungi, bacteria, algae, and yeasts have generated interest owing to their widespread accessibility, cost-effectiveness, and enhanced efficiency (Ahemad & Kibret 2013). Another emerging trend is the utilization of algae. Algae represent a beneficial option in bioremediation owing to their capacity to absorb metals and extract dangerous elements from the surrounding environment. Due to their ability to adapt to variances in pH, temperature, and nutrient availability, including excessive metal concentrations, fungi are essential to the bioremediation process (Mitra et al. 2012; Anahid et al. 2011). A possible advantage of eliminating lead, nickel, cadmium, copper, mercury, chromium, and tin from wastewater is that the fungi develop extracellular enzymes that aid in the breakdown of damaging organic contaminants. Metal ions are attached by polysaccharides and proteins containing carboxyl, hydroxyl, sulphate, phosphate, and amino groups found in fungal cell walls (Kumar et al. 2020). The best biosorbents for removing heavy metals from wastewater and wastewater from industries that include significant amounts of heavy metals are believed to be a variety of fungal strains, including *Phanerochaete chrysosporium*, *Aspergillus awamori*, *Aspergillus flavus*, and *Trichoderma viride*. Enzymes involved in bioremediation are generated at each phase of the fungal life cycle (Fatoki & Badmus 2022, Deshmukh et al. 2016, Joshi et al. 2011, Kumar & Dwivedi, 2019).

In this review, we discuss the bioremediation technique employed to remove chromium and arsenic contamination in soil. The review further explores the causes, effects, and potential dangers to both the ecosystem and human health associated with soil contamination by chromium and arsenic. There is an extensive discussion of the microbial communities that bio-transform Cr and As ions, with an emphasis on the enzymes and metabolic pathways that carry out their reduction, oxidation, methylation, and volatilization.

Sources of heavy metals

Arsenic

Arsenic can be found in soil, water, and the atmosphere, making it the twenty-first most abundant element on Earth. Arsenic pollution primarily originates from two categories of sources: both natural and human-made. Anthropogenic sources of arsenic include pesticide and phosphate fertilizer application, mining, smelting, electroplating, and rock weathering, while natural sources include volcanic eruptions, forest fires, and more (Fatoki & Badmus, 2022). Sixty percent of the arsenic emissions from anthropogenic sources come from the smelting of copper and the burning of coal. Chemical pesticides are another significant source of contamination. According to Duttagupta et al. (2020), permissible limits for arsenic concentrations are 46 times lower in atrazine and malathion.

Chromium

In worldwide distribution, chromium is the sixth most common element (Mohanty & Kumar Patra 2013). The environment naturally receives its chromium emissions through volcanic eruptions, forest fires, and weathering. Anthropogenically, fertilizers and sewage are two ways that chromium enters the environment. Additionally, chromium is widely employed in many industries, including metallurgy, electroplating, paint manufacture, tanning, and the preservation of wood and paper. These industries have a negative impact on soil, water, and air quality and contribute significantly to chromium contamination (Hossini et al. 2022). Tanneries belong to the main industries that release huge amounts of waste with high chromium content. Rangasamy et al. (2015) reported that the majority of the soil samples from Tamil Nadu's Vellore area showed high levels of chromium (>200 mg/kg). Some of the significant sources of chromium and arsenic are shown in Table 1.

Table 1 Environmental sources of chromium and arsenic pollution.

HEAVY METALS	
Anthropogenic sources	Natural sources
ARSENIC	
- Pesticides	- Weathering of parent rocks
- Wood preservation	- Volcanic eruptions
- Combustion of fossil fuels	- Forest fires
- Smelting	
CHROMIUM	
- Tanneries	
- Steel industry	
- Paint Manufacturing	
- Metallurgy	

Toxicity of heavy metals

Arsenic

Because of its global prevalence, toxicity, and carcinogenicity, arsenic (As) is considered one of the deadliest compounds on the earth (ATSDR, 2017). Arsenic is generally present in the soil, water, and sediments and enters the human body mainly through contaminated water and food consumption. The presence of arsenic in the soil and groundwater of many countries like India, Bangladesh, Thailand, Argentina, Nepal, and Poland is a major health concern (Mukherjee et al. 2010). Once it enters the body, most of it accumulates in the body, and only a small amount of it is excreted. Arsenic is mainly deposited in the nails, hairs, bones, and vital organs, such as the liver and kidneys (WHO, 2001). Arsenic in its inorganic forms [arsenite (As III) and arsenate (As V)] is more hazardous than its organic counterparts. Keratosis is one of the most common side effects of chronic arsenic exposure, and it has been observed in drinking water at low arsenic concentrations of 5–10 g/L (Yoshida et al. 2004). Long-term inorganic arsenic exposure (for 5–10 years) can cause diseases like arsenicosis, skin disorders, skin malignancies, and internal organ cancers such as bladder cancer, kidney cancer, and lung cancer. It can also cause blood vessel disease, diabetes, cardiovascular disease, and problems related to reproduction (Santra et al. 2013) (Figure 1).

According to several studies, long-term exposure to arsenic, even at low concentrations, causes vomiting, nausea, decreased erythrocyte and leukocyte production, abnormal heartbeat and blood vessel damage, stomachache, nausea, diarrhoea, muscle pain, fatigue, skin problems, muscular cramps, delirium, and organ failure (Smith et al., 2000, Rahman et al. 2011). Arsenic also has various bad impacts on children as it causes altered levels of neutrophils, eosinophils, lymphocytes, and haemoglobins. Telomere length was also slightly higher in arsenic-exposed children (Chatterjee et al. 2018).

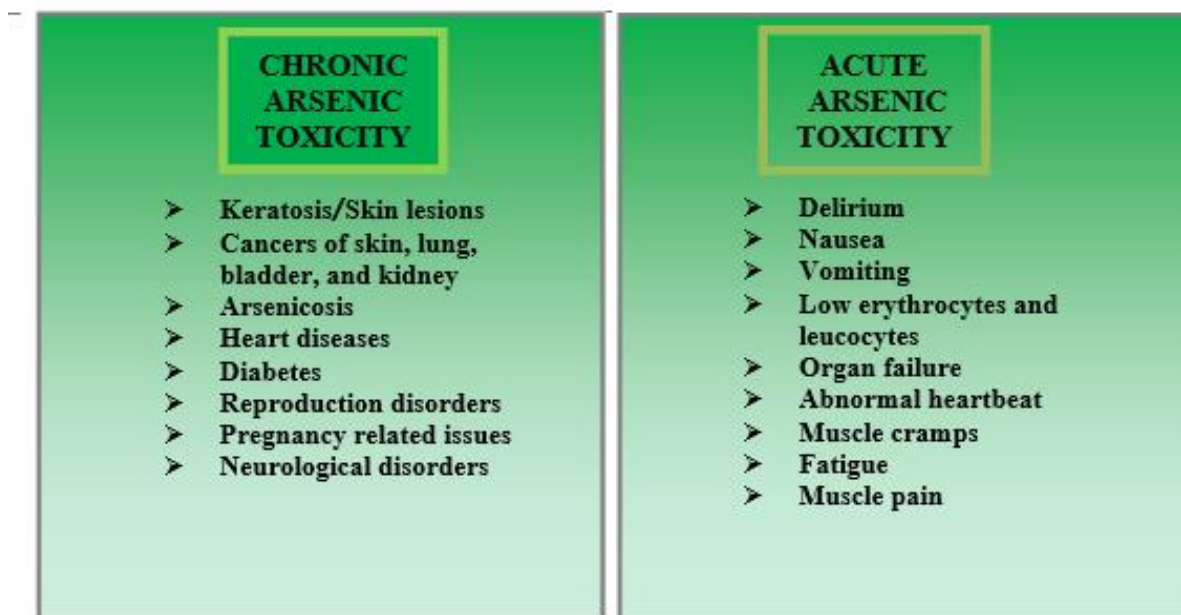


Fig. 1 – various health issues caused by arsenic

Mechanism of arsenic toxicity

Inorganic arsenic is more toxic as compared to organic forms. The inorganic forms, which are mainly present in the environment, are arsenate (V) and arsenite (III). These two forms are inter-convertible, and arsenite (III) is more toxic than arsenate (V) (Wang et al. 2018). Arsenite (III) binds with the sulfhydryl groups of dihydrolipoamide, which inhibits pyruvate dehydrogenase. This results in the reduced conversion of pyruvate to acetyl coenzyme A (CoA), which decreases the cellular production of ATP and the activity of the citric acid cycle (Bergquist et al. 2009). The arsenic (trivalent) binds with the sulfhydryl groups, causing inhibition of numerous other enzymes. The production of antioxidant glutathione is also reduced, making cells more vulnerable to oxidative stress (Miller et al. 2002). The pentavalent form of arsenic [As (V)] imitates inorganic phosphate and substitutes phosphate in mitochondrial pathways and glycolysis. Uncoupling of oxidative phosphorylation occurs due to the formation of ADS-arsenate in place of ATP (Hughes 2002).

Chromium

Chromium [Cr (VI) (hexavalent)] and [Cr (III) (trivalent)] are the most stable forms of chromium. Compared to trivalent chromium, Cr (VI) is extremely soluble, carcinogenic, and 100 times more poisonous (Kaushik et al. 2009). Chromium ions are important nutrients in biological systems because they are involved in electron transport reactions; however, microbes, plants, and humans are very sensitive to both deficiency and excess chromium and its compounds. Chromium also induces bacterial cell elongation and enlargement, as well as cell division, which is primarily responsible for the prevention of cell growth (Mishra & Bharagava 2015). Bronchopneumonia, chronic bronchitis, diarrhoea, emphysema, headache, skin disorders, respiratory tract irritation, hepatic illnesses, lung cancer, nausea, renal failure, reproductive toxicity, and vomiting are among the known side effects of Cr (VI) (Rafi et al. 2017). The high levels of chromium beyond the permissible limit are also damaging to plants, resulting in reduced biological factors of the plant. Major symptoms of chromium toxicity are reduced root growth, leaf chlorosis, seed dormancy and low biomass. Chromium disrupts biological processes in plants such as maize, wheat, barley, cauliflower, citrus, and vegetables, making them poisonous. Chromium poisoning in plants causes chlorosis and necrosis (Ghani 2011). Some of the toxic effects, along with the sources of these heavy metals, are shown in Table 2.

Table 2: Sources and toxic effects of chromium and arsenic

Heavy metal	Source	Toxicity	References
As	Mineralization of arsenic, water logging, coal mining, excessive pesticide use	Higher hazard quotient and cancer risk possibility	Shahab et al. (2019)
As	Groundwater	Liver and cardiovascular diseases	Das et al. (2012)
As	Chemical fertilizers and pesticides	Chronic kidney disease of unknown etiology	Jayasumana et al. (2015)
As	Groundwater	Melanosis and Keratosis	Kazi et al., 2009
As	Geological activities (volcanic activities)	Cancer (lung, skin, and bladder)	Zuzolo & Vivo (2020)
As	Drinking groundwater resources of Southeast Iran	Higher hazard quotient for non-carcinogenic risk in children and adults	Eslami et al. (2022)
Cr	Tannery	Adverse effects on iron metabolism and excessive chromium accumulation in the body	Kornhauser et al. (2002)
Cr	Tannery	Hyperpigmentation of skin	Al Hossain et al. (2019)
Cr	Tannery	Impairment of haematological, renal, and hepatic functions	Khan et al. (2013)
Cr	Municipal solid waste, paint industry and sawmill environment	Renal and hepatic dysfunction	Adienbo et al. (2021)
Cr	Steel and scrap welding, leather tanneries and paint industry	Bronchitis, wheezing, shortness of breath, asthma, sneezing attacks, and tonsillitis	Were et al. (2013)

Mechanism of chromium toxicity

Trivalent chromium is considered less toxic due to its low membrane permeability, while hexavalent chromium is highly toxic due to its high membrane permeability. Chromium (III) needs a simple diffusion process to enter the cell without the requirement of any specific membrane carrier (Chandra & Kulshreshtha 2004). Hexavalent chromium is mainly present in chromate oxyanion (CrO_4^{2-}). The chromate oxyanion is structurally analogous to the sulphate oxyanion (SO_4^{2-}) and thus uses common sulfate transporters on the cell surface to enter the cell. Once it enters the cell, it produces hydrogen peroxide and other free radical species, causing high levels of oxidative stress (Figure 2). As a result, it damages cellular lipids, proteins, and DNA (Salnikow & Zhitkovich 2008).

Bioremediation

Bioremediation is a microbe-assisted process for removing pollutants from the environment. It uses plant and microbial biological systems to deal with hazardous contaminants in the environment. By modifying pH, redox processes, and the adsorption of pollutants from the contaminated environment, bioremediation reduces the solubility of contaminants (Jain & Arnepalli 2016). The fungal community has evolved several defence mechanisms against harmful heavy metals (Figure 3). Fungi have used extracellular and intracellular mechanisms for managing excessive concentrations of heavy metals. Extracellular methods like biosorption and metal chelation are employed to resist the entry of metals into the cells. After the metal invades the cell, intracellular mechanisms such as in vivo accumulation and metal outflow are used.

Bio sorption

Biosorption refers to the adsorption of metals with fungal cellular complexes through physicochemical interactions (Kapoor & Viraraghavan 1998). Biosorption prevents metal ions from

entering the cell through electrostatic interactions, van der Waals forces, and covalent bonding on the microbial cell surface. Various functional groups on the microbial cell surface, such as hydroxyl, carbonyl, amine, and phosphoryl groups, give the cell surface a net negative charge. The negatively charged surface of the fungus attracts the cationic heavy metal ions (Blanco 2000, Choi & Yun 2006). Fungi are one of the most effective bioadsorbents because their cell walls contain approximately 90% polysaccharides.

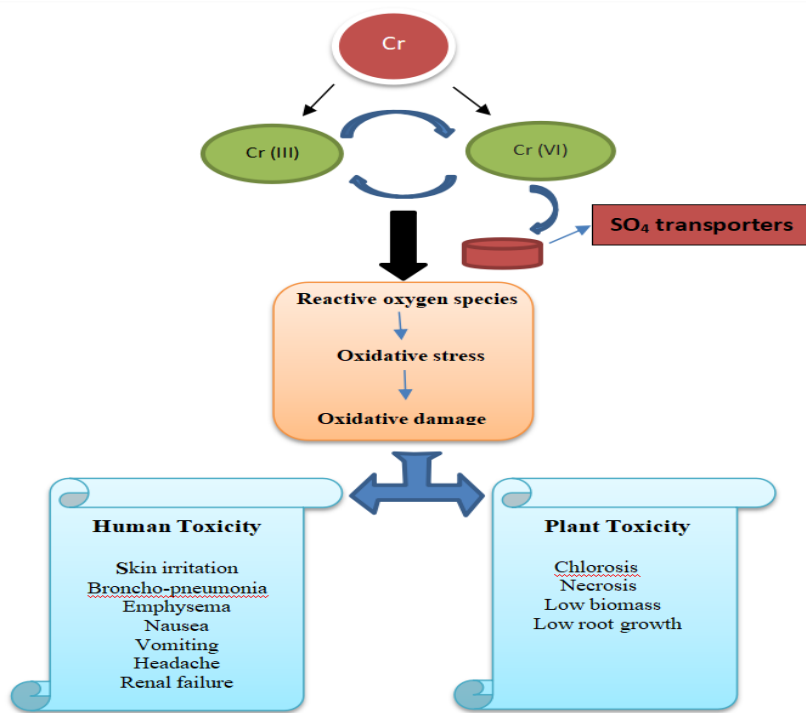


Fig. 2 – Human and plant diseases caused by chromium toxicity

The most typically utilised fungus in biosorption studies are *Aspergillus* sp. and *Penicillium* sp. *Aspergillus niger* showed better adsorption of Cr than *Streptococcus equimilise* and *Saccharomyces cerevisiae*. *Aspergillus flavus* and *Sterigmatomyces halophilus* have significant adsorption capacity for all heavy metals (Goyal et al. 2003, Bano et al. 2018). *Trichoderma* species play an essential role in the bioremediation of chromium (hexavalent) present in tannery effluents. Fourier Transform Infrared Spectroscopy (FTIR) analysis reported that carboxyl and amino groups are the binding sites for chromium on the fungal cell surface. Efficient biosorption of chromium by fungi has been observed in the Cr⁶⁺ oxidation state (Shukla & Vankar 2014). A comparison of Cr adsorption capability between *Aspergillus* sp. and *Rhizopus* sp. found that *Rhizopus* sp. outperforms *Aspergillus* sp. (Ahmad et al. 2005). In biosorption, dead biomass can also be used for the removal of heavy metals. The dead fungal biomass of *Aspergillus flavus* showed significant biosorption for toxic components of textile industrial effluent. Methyl orange biosorption was 53.62%, chromium (Cr) biosorption was 72.18%, and lead biosorption was 76.12% (Takey et al. 2013). Tanvi et al. (2020) investigated five fungal strains resistant to arsenic collected from industrial sewage of Davangere District, Karnataka, India, and examined for biosorption of arsenic. Out of these five, *Aspergillus* sp. Strains APR1 and APR2 reported biosorption efficiencies of 53.94 and 52.54%, respectively. This biosorption efficiency was increased by immobilizing these strains on the *Luffa aegyptiaca* sponge, an agro-waste material. Abigail et al. (2015) isolated *Penicillium griseofulvum* from tannery effluent sites, and it showed a chromium biosorption efficiency of 79.9%. The biosorption of chromium ions by *Saccharomyces cerevisiae* was investigated after it was immobilized in alginate extract, and it was discovered to be 85% at an initial concentration of 200 ppm of heavy metal ions (Mahmoud & Mohamed 2017).

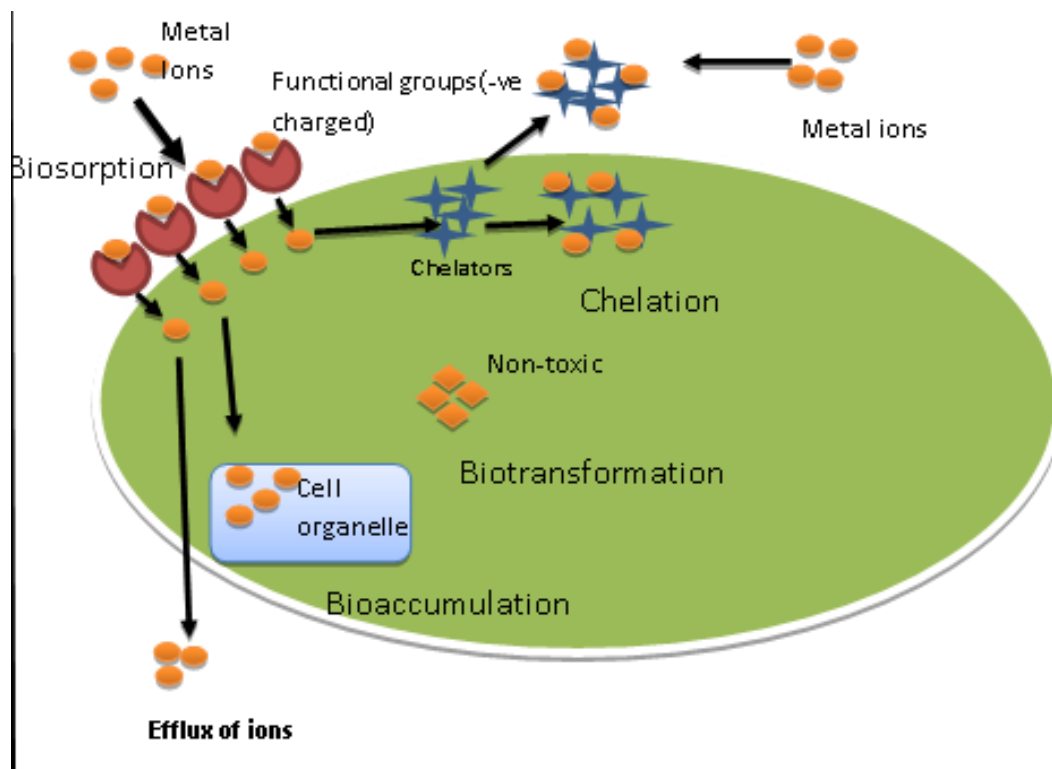


Fig. 3 – Bioremediation of heavy metals (Cr and As) by fungus via several methods.

Metal chelation

Another way to confer heavy metal resistance is through metal chelation. In stressful situations produced by heavy metals, fungi produce chelating molecules that bind to the metal ions, reducing the toxic consequences. Metal detoxifying agents include thiol, metallothioneins, homogeneous and heterogeneous proteins, peroxidases, and organic acids (Leong & Chang 2020). The toxic metal ions combine with the chelating molecules, making a non-toxic metal complex sequestered in different cellular organelles.

The microbial metabolism is highly increased in contaminated soil due to the increased energy requirement of microbial functional groups related to metal ion uptake and chelation (Giller et al. 2009). Some fungi secrete various organic acids that help to solubilize heavy metals. The organic acid, i.e., oxalic acid, produced by *Rhizopus javanicus*, *Ceratocysti spiliifera*, *Alternaria alternata*, *Aspergillus niger*, *Aureobasidium pullulans*, *Gliocladium virens*, *Trichoderma viride*, *Penicillium funiculosum*, *Cladosporium herbarum* and *C. peceae* helps in the removal of chromium and arsenic from chromated copper arsenate (CCA) treated wood (Kartal et al. 2006). Cr(VI) is absorbed on the cell surface of fungi via the formation of chemical interaction with functional groups present on cell surface proteins. Hexavalent chromium binds to the fungal cell mostly via chemical components, such as proteins, lipids and polysaccharides involving chitin, glycan and galactosamine. Additionally, a variety of functional groups, including carboxyl (-COOH), phosphate (PO_4^{3-}), amines (-NH₂), thiol (-SH) and hydroxide (-OH) groups, were involved in chemical interaction (Ayele & Godeto 2021)

To prevent arsenate toxicity, *Aspergillus* sp. P37 strain utilises reduced glutathione (thiol group compounds)-like substances. The molecule forms an As (G.S.)₃ complex with reduced arsenate, which accumulates in the vacuoles. The entrapped As (G.S.)₃ is stabilised by the vacuole's low pH (Canovas et al. 2004). Some of the studies regarding the bioremediation mechanism, removal efficiency, and fungus involved are shown in Table 3.

Table 3 Fungi-mediated bioremediation of chromium and arsenic.

S No.	Heavy Metal	Fungus Employed	Mode of bioremediation	Removal capacity	Initial metal concentration	References
1	As	<i>Aspergillus</i> sp. APR-1 and APR-2	Biosorption	53.94% and 52.54%	250 mM	Tanvi et al. (2020)
2	As	<i>Humicola</i> sp.	Bioaccumulation and bio-volatilization	53.39 mg kg ⁻¹ biomass	10 mg/l	Tripathi et al. (2020)
3	Cr	<i>Aspergillus flavus</i> CR 500	Biotransformation adsorption	79.4%	5 mg/l	Kumar and Dwivedi (2019)
4	Cr	<i>Aspergillus fumigatus</i> , <i>Rhizopus</i> sp. <i>Penicillium radicum</i> <i>Fusarium proliferatum</i>	Biotransformation	95%	1.5 µmol/mL	Hussain et al. (2018)
5	Cr	<i>Beauveria bassiana</i>	Bioaccumulation and biosorption	84.5% in multi-metal solution	6 mg/l	Gola et al. (2016)
6	Cr	<i>Aspergillus flavus</i>	Biosorption	72.18%	200 ppm	Takey et al. (2013)
7	Cr	<i>Aspergillus fumigatus</i>	Biosorption	40%	800 ppm	Shazia et al. (2013)
8	As	<i>Penicillium</i> sp. FA-18	Bioaccumulation/ Biosorption	58.38% As(V)	10 mg/l	Srivastava et al. (2011)
9	As	<i>Rhizopus</i> sp. FA- 19	Bioaccumulation/ Biosorption	60.21% As (V)	10 mg/l	Srivastava et al. (2011)
10	As	<i>Aspergillus flavus</i>	Bioaccumulation	11.1773 mg/g of fungus	50 mg/l	Vala (2010)
11	Cr	<i>Aspergillus niger</i>	Biosorption	98%	50mg/l	Chatterjee et al. (2022)

Bioaccumulation

Bioaccumulation occurs when metal ions precipitate in distinct cellular organelles (compartmentalization), resulting in non-toxic metal ions. Bioaccumulation is a metabolism-dependent process that, unlike biosorption, can only occur in living cells. (Ahalya et al. 2003). Biosorption is followed by bioaccumulation, which is followed by non-metabolic metal ion uptake in various cellular organelles, according to specialised studies. For example, *Penicillium* sp. uses biosorption and bioaccumulation to avoid Pb toxicity. The Pb is taken up both passively and actively after biosorption. Transmission electron micrographs (TEM) generated by Pb precipitation revealed the presence of electron-dense entities, indicating Pb transport inside the cell (Ezzouhri et al. 2009). *Beauveria bassiana* has the heavy metal removal ability in individual and multiple metal mixtures of copper (Cu), chromium (Cr), cadmium (Cd), zinc (Zn), and nickel (Ni). The minimum inhibitory concentration of metal was 100-2500 mgL⁻¹. A maximum metal removal of 84.5% was reported for multi-metal mixtures. Hyphal SEM and AFM studies have demonstrated that bioaccumulation and bioabsorption are involved in heavy metal removal (Gola et al. 2016). Forty-five strains were isolated from three arsenic (As) contaminated sites in West Bengal, India. Out of 45 fungal strains, 21 tolerant fungi up to 5000 mgL⁻¹ Arsenic were investigated for arsenic removal (10 mgL⁻¹) after 21 days of cultivation. Among all the fungal strains, bioaccumulation and volatilization were highest in *Humicola* sp (53.39 mg kg⁻¹biomass) (Tripathi et al. 2020). The bioaccumulation capacity of fungal cells depends upon various factors like temperature, metal concentration, pH, and the presence of other elements. Temperature plays a significant role in the

bioaccumulation of Cr and Ni in *Aspergillus* sp. and *Micrococcus* sp. (Congeevaram et al. 2007). From polluted soil in Pakistan, three metallotolerant fungal strains were identified: *Aspergillus niger* (strains M1DGR and M3Ai), *Aspergillus fumigatus* M3Ai and *Penicillium rubens* M3Aii. *Aspergillus fumigatus* M3Ai exhibited 69% chromium bioleaching efficiency, whereas *Aspergillus niger* M1DGR demonstrated a 43% bioaccumulation of chromium ions (Khan et al. 2019).

Efflux of metals

The efflux system of the cells manages the concentration of metals inside the cells. Different non-specific transport mechanisms are employed in the uptake of both essential and non-essential metals. However, when the concentration of metal ions becomes hazardous to the microorganisms, the exclusion is aided via specific active efflux mechanisms. Active transport or efflux mechanism enables the microorganisms to resist change in significant metal ion concentrations present in the environment. Some fungi are well known to have the ability to exclude or throw out the metal ions that accumulate in the cytoplasm of the cell. *Aspergillus* sp. P37 mitigates arsenate toxicity by utilizing the extracellular efflux mechanism accompanied by intracellular accumulation. The fungus reduces As (V) to As (III) and effluxes the reduced arsenate out of the cell (Canovas et al. 2004). A similar mechanism was observed in a wild-type arsenic-tolerant fungus, *A. niger* (Mukherjee et al. 2010).

Conclusion and future perspectives

Traditional methods used for the removal of chromium and arsenic heavy metal ions from contaminated soil have several pitfalls, such as releasing a lot of secondary pollutants into the environment and only dealing with low concentrations of heavy metal ions. Bioremediation offers a better approach to addressing the availing problems of heavy metal pollution due to its eco-friendly nature. It does not target the essential soil microbial flora. Arsenic and chromium are released into the environment from both natural and anthropogenic sources, and they cause some health problems in humans, animals, and plants. Bioremediation through fungi is an excellent approach to coping with these heavy metals. Fungi employ various pathways in bioremediation, making them potent candidates for remediation efforts. The use of fungi can decrease pollution caused by chromium and arsenic while also reducing the need for chemicals released in conventional treatments of heavy metals in soil and water.

There is a need to combine different microorganisms to work together for future perspectives in bioremediation. While many studies focus on bioremediation by bacteria, a high level of metal removal can be observed by combining both bacteria and fungi. Such combinations can provide far better results. Additionally, fungal consortia containing different fungal species can also be tested for their relationship with each other and their surroundings. There is a need for in-depth knowledge of the various enzymes and metabolites involved in detoxification for the future bioremediation perspective. Further studies up to the molecular level are required to identify the genes conferring the resistance towards the metals. This knowledge will help in designing genetically modified fungal strains to control heavy metal pollution. Most of the present work is conducted in laboratory conditions rather than field trials. There are many studies on bioremediation or bio-removal in laboratory conditions, but their applications on polluted sites like wastewater, sewage, and other wastes are still lacking. Conducting field trials can lead to massive success and provide the best solution to this problem.

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