Water Air Soil Pollut (2024) 235:629
https://doi.org/10.1007/s11270-024-07436-3

Unlocking the Potential of Algae for Heavy Metal Remediation

Avryl Anna Machado · Jithu George Valiaparampil · Lavanya M

Received: 3 March 2023 / Accepted: 11 August 2024

Abstract Algae have emerged as a promising approach for the removal of heavy metals from wastewater due to their low-cost, efficient, and eco-friendly characteristics. The unique structural and biochemical properties of algae enable them to remove heavy metals from wastewater using various mechanisms, including physical adsorption, ion exchange, complexation, precipitation, phycoremediation, and bioaccumulation. Algal modification techniques such as pre-treatment, immobilization, and genetic modification are also discussed as means of enhancing the efficiency and specificity of heavy metal removal. Additionally, the regeneration of algal biomass is presented as a sustainable solution to the issue of algal disposal.

Keywords Heavy metals · Bioremediation · Algae · Modified Algae · Biosorption · Regeneration

A. A. Machado · J. G. Valiaparampil · L. M (✉)
Department of Chemical Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India
e-mail: lavanya.m@manipal.edu

A. A. Machado
Chemical and Bioprocess Engineering, Hamburg University of Technology, 21073 Hamburg, Germany

1 Introduction

Elements that are not biodegradable and may persist permanently in the environment are known as heavy metals (HMs). One of the most important environmental issues facing the globe today is heavy metal contamination. In the last fifty years, 22,000 tons of cadmium (Cd), 939,000 tons of copper (Cu), 783,000 tons of lead (Pb), and 1,350,000 tons of zinc (Zn) have been released globally into the soil, atmosphere, and water bodies (Cao et al., 2024). Once heavy metals are present in aquatic ecosystems, they are hard to eliminate. Smaller quantities have the ability to build up in organisms, disturbing aquatic ecosystems and endangering human health (Lee et al., 2024). Environmental contamination is mostly caused by human activity; vehicles, industrial pollutants, and roads emit harmful heavy metals (HMs) like lead (Pb), cadmium (Cd), and arsenic (As) into the environment. Furthermore, the deposition of heavy metals in plants and soil might result from the discharge of sludge in agricultural fields (Upadhyay et al., 2024). Moreover, aquatic species absorb heavy metals found in sediments and seawater, which then bioaccumulate via the food chain and endanger human health and marine ecosystems. Fish and other marine animals that have high concentrations of heavy metals are signs of environmental pollution. One can determine the effects of ambient heavy metal pollution on marine biodiversity and the possible threats to ecosystems by looking at heavy metals in marine fauna (Yang et al., 2022). It's

Published online: 23 August 2024

speculated that concerns about the welfare of human populations are developing as a result of the growing threat to the natural environment (Jermsittiparsert, 2021). Children are particularly exposed to the health concerns posed by heavy metals in soil, which can permeate agricultural products and cause both carcinogenic and non-carcinogenic effects. The primary heavy metal and metalloid forms found in soil are Cd, Hg, As, Pb, Cr, Cu, Zn, Ni, and so forth (Angon et al., 2024**).** Depending on the kind and duration of exposure, these effects can vary in severity. There is no denying the urgency of dealing with heavy metal toxicity. We need to create cleaner technologies, educate the public about the health concerns connected with industrial activities, enforce stronger restrictions on waste disposal and industrial activities, and enhance research funding for remediation and treatment approaches in order to meet this problem (Salahshoori et al., 2024). In the past, studies have generally used pollution index approaches to analyze possible sources of heavy metals using statistical methods and to determine the risk of sediments contaminated with heavy metals. Xiao et al. (2021) used principal component analysis (PCA) and correlation analysis to monitor 61 sediment samples from the Lijiang River basin in China. They analyzed ten heavy metals (Co, Cr, Cu, Mn, Ni, Pb, Zn, As, Hg, and Cd) to identify urbanization, agricultural practices, and recreational activities as sources of heavy metal pollution (Xiao et al., 2021). The evaluation of health risk is a great way to accurately estimate the potential harm that heavy metals could pose to people through a variety of routes, including ingestion, inhalation, and skin contact (Duan et al., 2020). To this purpose, heavy metals are eliminated on an industrial scale using standard physicochemical techniques as chemical precipitation, electrochemical treatment, evaporation, ion exchange, and membrane technologies. These traditional techniques have a number of disadvantages, including high energy consumption, high operating costs, and the production of hazardous sludge, which burdens industry and causes secondary contamination. Furthermore, while conventional procedures offer certain benefits including simplicity of use and minimal space and time requirements, they are less effective at low concentrations of dissolved metal (1–4 mg/L) (Greeshma et al., 2022). Consequently, it develops a method that is safe for the environment and encourages interest in biological techniques. Various techniques have been devised thus far to eliminate heavy metals. Due to its low cost, biosorption, which uses microbial biomass and their products, is one of the more modern approaches (Rajivgandhi et al., 2021).

2 Structure of Algae

Algae are classified as eukaryotes because they have chlorophyll and perform photosynthesis. The majority of algae have microscopic diameters; however, several are macroscopic in nature and can grow to lengths of more than 100 feet (Rindi et al., 2012). There are more than 100,000 strains of terrestrial, freshwater brackish, and marine algae, with an estimated 55,000 species (Rangabhashiyam & Balasubramanian, 2019).

Macroalgae, also called seaweed, are a type of rapidly growing multicellular aquatic creatures. They are commonly divided into three classes based on the colour of the thallus, which correspond to Phaeophyceae (brown algae), Chlorophyta (green algae), and Rhodophyta (red algae) (Balboa et al., 2013). Microalgae, on the other hand, are microscopic photosynthetic organisms that can be found in freshwater and marine habitats. They have a photosynthetic process that is somewhat comparable to that of terrestrial plants. They make up the largest primary producer group in terms of biomass and are accountable for at least 32% of the world's photosynthesis. These have molecular mechanisms that enable them to distinguish between heavy metals that are necessary for growth and those that are not (Perales-Vela et al., 2006)(Suresh Kumar et al., 2015).

Several functional groups found in the algal cell wall, including hydroxyl (-OH), carboxyl (-COOH), amino (-NH2), phosphoryl (-PO3O2), sulphydryl (-SH), and others, give the cell surface a negative charge (Mehta & Gaur, 2005) (Pavithra et al., 2020). Since metal ions in water are found in their cationic form, they get adsorbed on the surface of the cell. These functional groups have been linked to a variety of cell wall building blocks, including proteins, peptidoglycan, teichouronic acid, and teichoic acids (Spain et al., 2021). Similar to the distribution and abundance of cell wall components, different algal groupings exhibit differences in the number and kinds of functional groups. The majority of the metal binding sites are found in polysaccharides and proteins, which are separate components of cell walls (Kuyucak & Volesky, 1989).

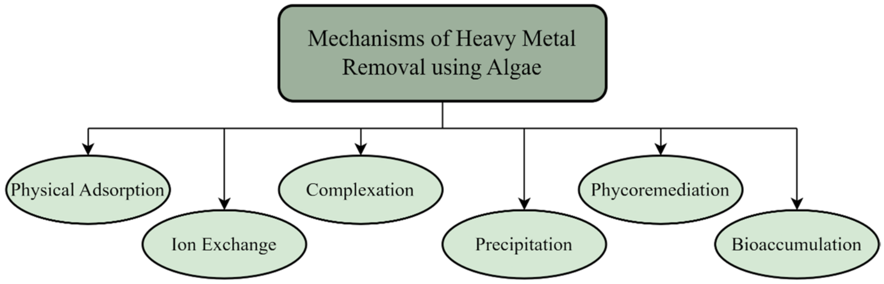

Fig. 1 The mechanism followed for heavy metal extraction with the aid of algae

3 Mechanism of Heavy Metal Removal using Algae

The effectiveness of the marine algae's adsorption is dictated by their fundamental biological makeup. More specifically, the characteristics of cell wall components like alginate and fucoidan are primarily in charge of the sequestration of heavy metals. The algal cell walls of brown algae, red algae, and many forms of green algae are typically composed of a fibrillar skeleton and an amorphous embedding matrix. Cellulose is the most common form of fibrillar skeletal material. The embedding matrix for brown red algae comprises of alginic acid or alginate (alginic salts), sulfated polysaccharide (fucoidan), and sulfated galactans (He & Chen, 2014).

During the biosorption process, toxic metal ions are passively confined to inert biomass in aqueous solutions. Many different mechanisms, such as physisorption, ion exchange, and chelation help to enhance metal binding (Nishikawa et al., 2018). In fact, biosorption can be a mechanistically quite complex process depending on the structure and specific preconditions. Other plausible mechanisms that could develop and conceal sorption and/or desorption include precipitation and crystallisation. It can result in very large input volumes, but this could prevent desorption (Gadd & White, 1992).

A successful method for eliminating heavy metal ions from industrial emissions is biosorption, which is the dominant process in the intake of heavy metals by either active or passive algal biomass. While there is no metabolic pathway involved in the biosorption of passive algal biomass, it is comparable to the binding of metal ions using ion-exchange resins because it relies entirely on the association between the biomass and the metal ion. Biosorption, in contrast to ion-exchange resins, involves a variety of processes, including partial adsorption, chelation, complexation, micro-precipitation, etc. In contrast, metal ion transport through the cell membrane is mediated by energy in the biosorption of active algal biomass (Bilal et al., 2018) Fig. 1.

Following are the different mechanisms in use for the extraction of heavy metals using algae Table 1:

3.1 Physical Adsorption

In order to achieve electroneutrality, a metal ion in solution physically binds to the polyelectrolytes present in microbial cell walls through electrostatic interactions like covalent bonding, Van der Waals forces, redox interaction, and biomineralization. It is reversible and irrelevant to the metabolism of the algae (Perpetuo et al., 2000). The major benefits of using biosorption over traditional treatment methods include: lower cost, greater effectiveness, reduction of chemical and biological sludge, selectivity for specific metals, lack of additional nutrient requirements, renewal of the biosorbent, and the potential for metal recovery (Kratochvil & Volesky, 1998). It has been noticed that the entire process of physical adsorption, in which metal ions are drawn to the cell wall's negative potential, is dependent on physical factors such as pH, temperature, etc. (Suresh Kumar et al., 2015).

3.2 Ion Exchange

Polysaccharides, proteins, and lipids found in the microalgal cell play a critical role in ion exchange. The cell surface has an overall negative charge as a result of the functional groups that these components contribute to, such as hydroxyl, carboxyl, amino, phosphate, sulfhydryl, alkyl, amide, and aromatic chemicals. This makes the algal cell surface a potent metal cation binding site as it participates in metal exchange via the ion-exchange mechanism. (Crlst et al., 1988). Metal ions harmonised in the

Table 1 Different algae used for the removal of heavy metals

Algae	Heavy metal	Reference
Sargassum sp. Padina sp. Ulva sp. Gracillaria sp.	Lead, Copper, Cadmium, Zinc, and Nickel	(Sheng et al., 2004)
Coriallina mediterrane *Galaxaura oblongata* *Jania rubens* *Pterocladia capillacea*	Cobalt, Cadmium, Chromium and Lead	(Ibrahim, 2011)
Chondracanthus chamissoi	Lead and Cadmium	(Yipmantin et al., 2011)
Chlorophyceae sp.	Arsenic, Boron, Copper, Manganese and Zinc	(Saavedra et al., 2018)
Sarcodia suiae	Arsenic	(Libatique et al., 2020)
Ulva lactuca	Mercury, Chromium, Nickel, Arsenic and Cadmium	(Henriques et al., 2019)
Chlorella vulgaris L	Chromium	(Rai et al., 2013)
Laminaria digitata	Chromium	(Dittert et al., 2012)
Chlorella sorokiniana	Galium	(Li et al., 2018)
Hizikia fusiformis	Cadmium, Copper, Nickel and Lead	(Pham et al., 2021)
Gracilaria sp.	Cadmium	(Ardiyansyah et al. 2019)
Chlorella miniata	Chromium	(Han et al., 2006)
Calcium-alginate based ion exchange resin	Lead and copper	(Chen et al., 2002)

organisation of complex groups through interaction between metal ions and proteins on biological surfaces. In contrast, a large portion of active sites in marine systems are bound to protons at low pH or to alkaline earth metals like sodium, calcium and magnisium at higher pH. The previously bound protons and metals are released in the presence of the heavy metal cations, and these cations are adsorbed on cell surfaces. However, when it comes to anions, an algae's adsorption properties substantially alter in favour of the competitive binding of metal ions to the cell surface (Ahmad et al., 2020).

3.3 Complexation

Complexation is described as the association of two or more species that results in the establishment of a complex. Covalent associations between the ligands and the metal ions result in mononuclear (monodentate) complexes, where the metal atom is located in the centre. Several metal ions come together to create a polynuclear (multi-dentate) complex, and depending on how many binding ligands are present, the metal atom in the centre may have a positive, negative, or neutral charge. Monodentate ligand complex formation is preferred to multidentate since the latter contains various ligands and may lead to the binding of multiple species (Kanamarlapudi et al., 2018).

3.4 Precipitation

The act of precipitation can happen either through a process that is reliant on cellular metabolism or one that is not. In the former scenario, the elimination of metal from the solution is often associated with a defensive mechanism that is actively carried out by microorganisms. When toxic metals are present, they react, generating chemicals that aid in the precipitation process. n the latter case, precipitation can occur due to a chemical reaction between heavy metals and the surface of an algal cell. Additionally, multiple biosorption techniques, as previously mentioned, can also take place within algae (Ahalya et al., 2003).

Functional groups and metal ions combine to form deposits on the surface of the microbial cell that is left unaffected, as opposed to permeating the microbial cell. In a vast majority of cases, indissoluble non-organic sediments develop. Extracellular polymeric polymers make up a majority of the materials that bacteria expel, and these materials play a role in the formation of organic detritus. A study can be found by Mohammed et al. regarding the distortion, accumulation and damage to the cell superficial layer and this is caused by the precipitation of Cu^{2+} onto *Mesorhizobium amorphae* (Mohamad et al., 2012).

3.5 Phycoremediation

The word "phycoremediation" was used by John to characterise the use of algae in the removal or mitigation of harmful pollutants. The methods employed in phycoremediation can vary and are dependent on factors such as the specific heavy metal and its speciation, the type of microalgae utilized (living or non-living), and the operating conditions involved (González-Dávila, 1995). Heavy metal removal and detoxification are made possible by the numerous adaptive mechanisms that living microalgae have developed over many generations (Suresh Kumar et al., 2015).

The removal of heavy metals using phytoremediation involves two steps and the use of microalgae. During the initial stage of the process, heavy metals are adsorbed onto the surface of the cell. This stage can occur rapidly and may or may not involve cell metabolism. As a result, it is known as the quick extracellular passive process. Because they have various functional groups on their cell surfaces, algae can operate as biosorbents (Zohoorian et al., 2020). In the second stage, heavy metals move beyond the cell membrane and enter into the cytoplasm or other organelles. This causes the concentration of heavy metals to increase inside the algal cells. With the aid of the detoxification phenomena these contaminants are then eliminated or transform into a non-toxic complex (Chugh et al., 2022).

3.6 Bioaccumulation

Bioaccumulation is a metabolism-dependent process whereby metal ions are taken up by microbial cells inside the cell (Abbas et al., 2014). The removal of heavy metals using this process, as opposed to other methods, can only be done using living algae cells. As a result, it is important to maintain and keep an eye on the algae's living conditions, such as pH and temperature. In contrast to the other methods mentioned above, which merely depend on the physical or chemical structure of the algal cell wall, the removal of the ions is a slow and irreversible process since it depends on the metabolism of the algal cells (Vijayaraghavan & Yun, 2008).

To carry out the bioaccumulation process, the biomass of a microbe is grown in close proximity to the metal to be accumulated. The presence of the growth medium in the solution initiates the metabolic activities of the organism, which activates the intracellular transport systems to accumulate the sorbate. The main drawback of the method is that the nutritive media for the microorganism's development contains organic carbon sources (Chojnacka, 2010).

4 Algal Modification

It has repeatedly been found that organic pollutants percolate in untreated algae during analysis. Several advantageous adsorptive components, such as operational and functional groups, may be simultaneously released by the leachate, reducing the capacity for biosorption. As a result, it is preferable to modify algae using chemicals or physical means before making use of them Table 2.

4.1 Algal Pre-treatment

Modification of raw biomass via appropriate methods result in increased efficacy of heavy metal removal. The formulation procedure can make use of a physical, chemical, or combined activation process. There are a number of traditional techniques that can be used, including temperate drying, abrasions, washing, and retraction of biomass particles Fig. 2. The extent of drying temperature is typically set below 100 °C, taking into account natural regeneration and magnetization (Ezeonuegbu et al., 2021).

A majority of research is initiated by specific physical processes by the development of biosorbents. The steps that follow it are known as thermal or heat processing which requires a large amount of energy to activate the biomass. Activation results in a surface with larger effective area with more accessible active spots increasing the adsorption potential. The pyrolysis process for biomaterials is frequently carried out at temperatures lower than 800 °C. Chemical changes then follow, creating gradually powerful and dynamic areas on the carbonized planes (Kumar & Chauhan, 2019). Chemical processing can be employed to

Table 2 Algal modification techniques for heavy metal removal

Modification	Algae	Heavy metal	Reference
Pre-treatment	*Chlamydomonas reinhardtii*	Arsenic	(Ramírez-Rodríguez et al., 2019)
	Pediastrum boryanum	Lead, Cadmium and Copper	(Joseph et al., 2017)
	Caulerpa serrulata	Copper, Lead and Cadmium	(Mwangi & Ngila, 2012)
	Turbinaria turbinata	Chromium	(Yacou et al., 2018)
	Synechocystis sp.	Chromium, Copper, Lead and Cadmium	(Shen et al., 2020)
Immobilization	*Chlorella vulgaris*	Mercury	(Peng et al., 2017)
	Chlorella sp.	Copper and Zinc	(Zainol et al., 2012)
	Laminaria digitata	Lead and Platinum	(S. Wang et al., 2017)
	Jania Rubens	Thorium	(Gok et al., 2011)
	Chlorella homosphaera	Cadmium, Zinc and Gold	(da Costa & Leite, 1991)
Live vs inactivated	*Chlorella* *Oscillatioria*, *Scenedesmus* *Spirogyra* *Pandorina*	Arsenic	(G 2014)
	Chlorococcum sp.	Chromium	(Sun et al., 2018)
	Sargassum	Copper, Cadmium and Zinc	(Figueira et al., 1999)
Gene modification	*Chlamydomonas reinhardtii*	Cadmium, Copper, Aluminium, Zinc and Manganese	(Ibuot et al., 2017)
		Cadmium	(Hu et al., 2001)
		Zinc and Cadmium	(Ibuot et al., 2020)
	Dunaliella tertiolecta	Zinc	(Hirata et al., 2001)
	Chlorella sp.	Mercury	(Huang et al., 2006)

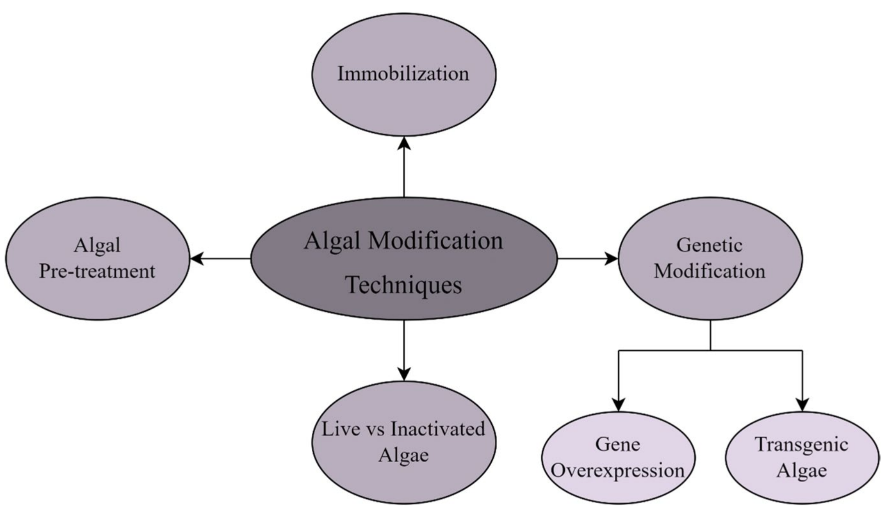

Fig. 2 Various modification methods conducted on algae

enhance the interaction between the adsorbent and metal ions by improving electrostatic communication through either a single or combined activation process. This process involves the modification of the distribution of operational groups and surface plane charge to enhance adsorption (Znad et al., 2022).

Algae that have been subjected to an acid pre-treatment cause the carboxylic acid to carbonyl stretch, revealing potential sites for the needed heavy metal ions to bind. Acid treatment causes functional groups to become protonated, which increases their affinity to heavy metals (Yacou et al., 2018).

4.2 Immobilization

Algal cells are gathered and dehumidified to immobilise them. Compared to algal cells grown in free suspension, immobilised algal cells have several advantages, including: (1) taking up less surface area; (2) having improved biosorption capacity, photosynthetic activity, and bioactivity; and (3) being more resistant to harmful effects and extreme weather conditions. The ability of entrapped algal cells to participate in repeated biosorption processes is improved by immobilisation (Eroglu et al., 2015). For the removal of heavy metal, polysaccharide gels have frequently been utilised to immobilise algae cells. Algal cells have been reported to be sufficiently immobilised and to have increased removal efficiencies from aqueous environments when they are trapped in alginate (Ahmad et al., 2020).

Cell or biomass immobilisation can be accomplished using a few methods, including adsorption on surfaces, flocculation, covalent binding to carriers, encapsulation in polymer gel, cell crosslinking, and encapsulation in polymer gel. The supporting substance used for immobilising biomass can be either natural, like agar, alginate, and carrageenan, or synthetic, such silica gel, polyurethanes, and polyacrylamide. Since synthetic polymers are hazardous to biomass, natural polymers are preferable. The most common method for immobilising algal and other types of biomass is alginate. Alginate is obtained from algae as a sodium salt that is water soluble. Ionic cross-linking between carboxylic acid groups happens when calcium takes the place of sodium, resulting in a gelatinous material (Mehta & Gaur, 2005).

4.3 Live vs Inactivated Algae

Both living and dead cells can undergo the biosorption process. Yet, as it offers several advantages to employing living algal cells, dead biomass is more frequently used. Dead cells can be utilised for a variety of experimental variables since they don't need any nourishment or special environmental conditions of temperature, pH, etc. Additionally, they are simple to store and can retain their potency for extended periods of time (Michalak et al., 2013). Living algal cells have the capacity to bioaccumulate heavy metals, as opposed to non-living material. In most situations, this is exceedingly poisonous to the cells and has a significant impact on their metabolism. Furthermore, as live cells can maintain enzyme activity, enzymes can alter pollutants through biotransformation or biodegradation, which may impact the recovery of pollutants (Torres, 2020).

Additional benefits of employing dead biomass rather than living cells include the capacity for regeneration and reuse of the biomass, the flexibility of immobilising the dead cells, and the convenience of kinetic mathematical modelling (Chu & Phang, 2019). The most significant factor is that inactive microalgal cells have been shown to more effectively absorb heavy metals than living cells (Aksu & Kutsal, 2008) (Spain et al., 2021).

The effectiveness of living algae in heavy metal adsorption can be impacted by environmental conditions. Elevated heavy metal concentrations can surpass their tolerance levels and adversely affect their metabolic processes, reducing their effectiveness in adsorption. To prevent exceeding tolerance thresholds, living algae should only be utilized to treat heavy metal concentrations less than 10 mg/L. Different heavy metals have varying effects on algae depending on the binding mechanism. Due to the toxicity of heavy metals, living algae typically have a lower tolerance than non-living algae. Heavy metal ions are mainly absorbed by non-living algae through functional groups on their surface. Algal powder can be produced by grinding the algae to reduce particle size, which increases the surface area exposed to heavy metal ions. Non-living algae are more commonly used as adsorbents to treat industrial wastewater (Mohamed, 2001).

4.4 Genetic Modification

Algae can also undergo genetic modification to enhance its heavy metal removal efficacy. This is mainly done in cases where physical and chemical treatment of the algae does not cause a significant increase in the heavy metal removal. The genetic modification of algae can typically involve two techniques: gene overexpression and the creation of transgenic algae through the introduction of foreign DNA into the algae.

4.4.1 Gene Overexpression

Algae can be genetically or cellularly modified to increase their selectivity for metals with high affinity for metalloregulatory proteins. The effectiveness and productivity of gene-manipulation activities can be improved by having a greater understanding of algal genomes, especially those that encode metalloregulatory and related proteins (Cheng et al., 2019).

Metal-binding proteins being overexpressed on the surface of algae has a variety of benefits. First off, the processing time will be significantly reduced as the amount of ligand on the cell surface increases. Second, such a change would make a target metal more selective. Hence, this adsorbed metal can be easily retrieved with a modest pickling reagent rather than rupturing the cell wall to collect the metals inside the cell. As a result, such biosorbent is both recyclable and affordable. Last but not least, dead biomass can be used since surface adsorption is not dependent on metabolism (Danouche et al., 2021) (Cai et al., 2006).

Metal-tolerance proteins also help with metal sequestration (MTPs). One of the main synthetic biology-based methods for increasing protein level and function is gene overexpression (Ibuot et al., 2020). Furthermore, it has been noted that heavy metal bioremoval is promoted by the overexpression of genes involved in the manufacture of metal-binding peptides. The two best prospects for metal-binding peptides are PCs (phytochelatins) and MTs (metallothioneins). PCs are produced by enzymes from naturally occurring substrates (Filiz et al., 2019).

Studies have shown that increasing the expression of MTs may not be enough to enhance metal absorption in algae as excessively high levels of these proteins can lead to the formation of misfolded proteins that are unstable or ineffective, ultimately reducing the rate of metal uptake (Diep et al., 2018). On the other hand, the overexpression of MT fusion proteins, which are produced when MTs and soluble proteins are combined, can boost metal uptake rates (Balzano et al., 2020).

4.4.2 Transgenic Algae

The development of genetically altered algae that can overexpress metalloregulatory proteins is the result of the identification of metalloregulatory proteins and pathways for heavy metal detoxification in algae. These alterations enable the production of metalloregulatory proteins both on the surface and in the cytoplasm, as well as helping to reduce the negative consequences of heavy metal-induced stress. Several studies have examined the enhanced selectivity and adsorption capacities of transgenic algae (Ahsan et al., 2009).

Recently, transgenic methods for treating heavy metals with microalgae, particularly in wastewater and sediments, have been established. The primary goal of this method is to improve microalgae's heavy metal specificity and binding capacity. To do this, techniques including overexpressing enzymes, which result in metabolic by-products that mitigate the effects of stress caused by heavy metals, and expressing high-affinity, heavy metal-binding proteins on the surface and cytoplasm of transgenic cells have been used (Rajamani et al., 2007).

In order to avoid any unfavourable effects from transgenic algae with improved metal remediation capabilities, it is crucial to take into account both technological and biological considerations. To prevent the possible dangers of releasing live transgenic microalgae into the environment, one possibility is to employ nonviable transgenic algae with higher binding ability and selectivity. This is due to the possibility that live transgenic microalgae could quicken the biogeochemical cycling of heavy metals, which could result in their buildup in the food chain and potential injury. The dangers connected with their release into the environment must be carefully examined, even though there may be a demand for these more efficient bioremediation agents.

5 Regeneration

Every adsorption process needs to have a way to safely dispose of used sorbent and/or recover and reuse its materials in an environmentally friendly manner. Heavy metals are useful and can be recycled in a number of industrial processes. In order to recover metals, algal biomass is often treated with acid solutions to remove the metals. Two potential methods for recovering heavy metals from adsorbents are desorption and precipitation. Desorption involves releasing the heavy metal from the adsorbent and transferring it into a concentrated media with a low volume, while precipitation involves causing the heavy metal to precipitate out of solution under low-solubility pH conditions. Another strategy would involve destroying algae at high temperatures while recovering the heavy metal (Li et al., 2018).

The treated wastewater can be discharged safely into the environment, which helps to reduce the environmental impact of heavy metal pollution. Moreover, the biomass produced during the heavy metal removal process can be used for a variety of purposes, including the production of biofuel and as a source of nutrients for agriculture. However, if not properly disposed of, remaining heavy metals from the biomass production process could endanger the ecosystem. Hence, it is important to regenerate the algal biomass in a way that minimizes the emission of leftover heavy metals into the environment (Salama et al., 2019).

6 Advantages and Disadvantages of Algae-based Heavy Metal Removal

Algae have several benefits over other bioremediation practices, including a high capacity for absorbing heavy metals, the ability to be regenerated, the ability to use algal biomass all year round, the lack of any harmful metabolites produced, and cost effectiveness (Chugh et al., 2022). Because to its speed, low cost, environmental friendliness, and adaptability to various experimental settings, this method offers several gains over other, more well-known metal removal techniques. As a result of biomass' low cost and ease of production, the cost of the treatment as a whole is quite low (J. Wang & Chen, 2009). As algae can simultaneously eliminate several different types of heavy metals, both the biomass and the metals can be claimed after the treatment (Fomina & Gadd, 2014). However, a major drawback is the rapid saturation of active sites on the surface of the biomass and the reversible sorption of metals to binding sites (Spain et al., 2021).

7 Conclusion

The use of algae for heavy metal removal from wastewater is a promising approach due to its unique structural and biochemical characteristics. Due to the variable interactions between the heavy metal and the algae, many mechanisms, including physical adsorption, ion exchange, complexation, precipitation, phycoremediation, and bioaccumulation, are responsible for the removal of heavy metals using algae. Techniques that improve the interaction between the heavy metal and the algae can further increase the efficacy of these mechanisms. Also, the problem of disposing of algae can be resolved sustainably by the regeneration of algal biomass. All things considered, using algae to remove heavy metals has a lot of potential and should be investigated and improved upon in future studies.

Funding Open access funding provided by Manipal Academy of Higher Education, Manipal

Data Availability Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Conflicts of Interest The authors declare no conflicts of interest. This study received no funding.

References

Abbas, S. H., Ismail, I. M., Mostafa, T. M., & Sulaymon, A. H. (2014). Biosorption of heavy metals: a review. *Journal of Chemical Science and Technology, 3*(4), 74–102.

Ahalya, N., Ramachandra, T. V., & Kanamadi, R. D. (2003). Biosorption of Heavy Metals. *Research Journal of Chemistry and Environment, 7*(4), 71–79.

Ahmad, S., Pandey, A., Pathak, V. V., Tyagi, V. V., & Kothari, R. (2020). Phycoremediation: Algae as Eco-friendly Tools for the Removal of Heavy Metals from Wastewaters. In *Bioremediation of Industrial Waste for Environmental Safety* (pp. 53–76). Springer Singapore. https://doi.org/10.1007/978-981-13-3426-9_3

Ahsan, N., Renaut, J., & Komatsu, S. (2009). Recent developments in the application of proteomics to the analysis of plant responses to heavy metals. *Proteomics, 9*(10), 2602–2621. https://doi.org/10.1002/PMIC.200800935

Aksu, Z., & Kutsal, T. (2008). A comparative study for biosorption characteristics of heavy metal ions with C. vulgaris. *Environmental Technology, 11*(10), 979–987. https://doi.org/10.1080/09593339009384950

Angon, P. B., Islam, M. S., Kc, S., Das, A., Anjum, N., Poudel, A., & Suchi, S. A. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon*.

Ardiyansyah, O., Sudarno, & Rosmanida. (2019). Bioaccumulation of Cadmium (Cd) Heavy Metal on Seaweed (*Gracilaria* sp.) in Traditional Fishpond of Jabon Subdistrict, Sidoarjo District. In *IOP Conference Series: Earth and Environmental Science* (p. 012059). https://doi.org/10.1088/1755-1315/236/1/012059

Balboa, E. M., Conde, E., Moure, A., Falqué, E., & Domínguez, H. (2013). In vitro antioxidant properties of crude extracts and compounds from brown algae. *Food Chemistry, 138*(2–3), 1764–1785. https://doi.org/10.1016/j.foodchem.2012.11.026

Balzano, S., Sardo, A., Blasio, M., Chahine, T. B., Dell'Anno, F., Sansone, C., & Brunet, C. (2020). Microalgal Metallothioneins and Phytochelatins and Their Potential Use in Bioremediation. *Frontiers in Microbiology, 11*, 517. https://doi.org/10.3389/fmicb.2020.00517

Bilal, M., Rasheed, T., Sosa-Hernández, J., Raza, A., Nabeel, F., & Iqbal, H. (2018). Biosorption: An Interplay between Marine Algae and Potentially Toxic Elements—A Review. *Marine Drugs, 16*(2), 65. https://doi.org/10.3390/md16020065

Cai, X. H., Brown, C., Adhiya, J., Traina, S. J., & Sayre, R. T. (2006). Growth and Heavy Metal Binding Properties of Transgenic Chlamydomonas Expressing a Foreign Metallothionein Gene. *International Journal of Phytoremediation, 1*(1), 53–65. https://doi.org/10.1080/15226519908500004

Cao, Y., Li, Y., Jia, L., Wang, Q., Niu, T., Yang, Q., Wang, Q., Zeng, X., Wang, R., & Yue, L. (2024). Long-term and combined heavy-metal contamination forms a unique microbiome and resistome: A case study in a Yellow River tributary sediments. *Environmental Research, 252*, 118861.

Chen, J. P., Hong, L., Wu, S., & Wang, L. (2002). Elucidation of Interactions between Metal Ions and Ca Alginate-Based Ion-Exchange Resin by Spectroscopic Analysis and Modeling Simulation. *Langmuir, 18*(24), 9413–9421. https://doi.org/10.1021/LA026060V

Cheng, S. Y., Show, P. L., Lau, B. F., Chang, J. S., & Ling, T. C. (2019). New Prospects for Modified Algae in Heavy Metal Adsorption. *Trends in Biotechnology, 37*(11), 1255–1268. https://doi.org/10.1016/J.TIBTECH.2019.04.007

Chojnacka, K. (2010). Biosorption and bioaccumulation – the prospects for practical applications. *Environment International, 36*(3), 299–307. https://doi.org/10.1016/J.ENVINT.2009.12.001

Chu, W. L., & Phang, S. M. (2019). Biosorption of heavy metals and dyes from industrial effluents by microalgae. *Microalgae Biotechnology for Development of Biofuel and Wastewater Treatment*, 599–634. https://doi.org/10.1007/978-981-13-2264-8_23/COVER

Chugh, M., Kumar, L., Shah, M. P., & Bharadvaja, N. (2022). Algal Bioremediation of heavy metals: An insight into removal mechanisms, recovery of by-products, challenges, and future opportunities. *Energy Nexus, 7*, 100129. https://doi.org/10.1016/J.NEXUS.2022.100129

Crlst, R. H., Oberholser, K., Schwartz, D., Marzoff, J., Ryder, D., & Crlst, D. R. (1988). Interactions of Metals and Protons with Algae. *Environmental Science & Technology, 22*(7), 755–760. https://doi.org/10.1021/es00172a002

da Costa, A. C. A., & Leite, S. G. F. (1991). Metals biosorption by sodium alginate immobilizedChlorella homosphaera cells. *Biotechnology Letters, 13*(8), 559–562. https://doi.org/10.1007/BF01033409

Danouche, M., el Ghachtouli, N., & el Arroussi, H. (2021). Phycoremediation mechanisms of heavy metals using living green microalgae: Physicochemical and molecular approaches for enhancing selectivity and removal capacity. *Heliyon, 7*(7), e07609. https://doi.org/10.1016/j.heliyon.2021.e07609

Diep, P., Mahadevan, R., & Yakunin, A. F. (2018). Heavy Metal Removal by Bioaccumulation Using Genetically Engineered Microorganisms. *Frontiers in Bioengineering and Biotechnology, 6*, 157. https://doi.org/10.3389/fbioe.2018.00157

Dittert, I. M., Vilar, V. J. P., da Silva, E. A. B., de Souza, S. M. A. G. U., de Souza, A. A. U., Botelho, C. M. S., & Boaventura, R. A. R. (2012). Adding value to marine macro-algae Laminaria digitata through its use in the separation and recovery of trivalent chromium ions from aqueous solution. *Chemical Engineering Journal, 193–194*, 348–357. https://doi.org/10.1016/j.cej.2012.04.048

Duan, Y., Zhang, Y., Li, S., Fang, Q., Miao, F., & Lin, Q. (2020). An integrated method of health risk assessment based on spatial interpolation and source apportionment. *Journal of Cleaner Production, 276*, 123218.

Eroglu, E., Smith, S. M., & Raston, C. L. (2015). Application of Various Immobilization Techniques for Algal Bioprocesses. In N. , Moheimani, M. , McHenry, K. , de Boer, & P. Bahri (Eds.), *Biomass and Biofuels from Microalgae. Biofuel and Biorefinery Technologies* (Vol. 2, pp. 19–44). Springer, Cham. https://doi.org/10.1007/978-3-319-16640-7_2

Ezeonuegbu, B. A., Machido, D. A., Whong, C. M. Z., Japhet, W. S., Alexiou, A., Elazab, S. T., et al. (2021). Agricultural waste of sugarcane bagasse as efficient adsorbent for lead and nickel removal from untreated wastewater: Biosorption, equilibrium isotherms, kinetics and desorption studies. *Biotechnology Reports, 30*, e00614. https://doi.org/10.1016/J.BTRE.2021.E00614

Figueira, M. M., Volesky, B., Azarian, K., & Ciminelli, V. S. T. (1999). Multimetal biosorption in a column using Sargassum biomass (pp. 503–511). https://doi.org/10.1016/S1572-4409(99)80139-4

Filiz, E., Saracoglu, I. A., Ozyigit, I. I., & Yalcin, B. (2019). Comparative analyses of phytochelatin synthase (*PCS*) genes in higher plants. *Biotechnology & Biotechnological Equipment, 33*(1), 178–194. https://doi.org/10.1080/13102818.2018.1559096

Fomina, M., & Gadd, G. M. (2014). Biosorption: Current perspectives on concept, definition and application. *Bioresource Technology, 160*, 3–14. https://doi.org/10.1016/j.biortech.2013.12.102

G, S. (2014). Biosorption of Arsenic by Living and Dried Biomass of Fresh Water Microalgae - Potentials and Equilibrium Studies. *Journal of Bioremediation & Biodegradation*, *05*(06). https://doi.org/10.4172/2155-6199.1000249

Gadd, G. M., & White, C. (1992). Removal of thorium from simulated acid process streams by fungal biomass: potential for thorium desorption and reuse of biomass and desorbent. *Journal of Chemical Technology & Biotechnology, 55*(1), 39–44.

Gok, C., Turkozu, D. A., & Aytas, S. (2011). Removal of Th(IV) ions from aqueous solution using bi-functionalized algae-yeast biosorbent. *Journal of Radioanalytical and Nuclear Chemistry, 287*(2), 533–541. https://doi.org/10.1007/s10967-010-0788-x

González-Dávila, M. (1995). The role of phytoplankton cells on the control of heavy metal concentration in seawater. *Marine Chemistry, 48*(3–4), 215–236. https://doi.org/10.1016/0304-4203(94)00045-F

Greeshma, K., Kim, H. S., & Ramanan, R. (2022). The emerging potential of natural and synthetic algae-based microbiomes for heavy metal removal and recovery from wastewaters. *Environmental Research, 215*, 114238.

Han, X., Wong, Y. S., & Tam, N. F. Y. (2006). Surface complexation mechanism and modeling in Cr(III) biosorption by a microalgal isolate, Chlorella miniata. *Journal of Colloid and Interface Science, 303*(2), 365–371. https://doi.org/10.1016/J.JCIS.2006.08.028

He, J., & Chen, J. P. (2014). A comprehensive review on biosorption of heavy metals by algal biomass: Materials, performances, chemistry, and modeling simulation tools. *Bioresource Technology, 160*, 67–78. https://doi.org/10.1016/j.biortech.2014.01.068

Henriques, B., Teixeira, A., Figueira, P., Reis, A. T., Almeida, J., Vale, C., & Pereira, E. (2019). Simultaneous removal of trace elements from contaminated waters by living Ulva lactuca. *Science of the Total Environment, 652*, 880–888. https://doi.org/10.1016/j.scitotenv.2018.10.282

Hirata, K., Tsujimoto, Y., Namba, T., Ohta, T., Hirayanagi, N., Miyasaka, H., et al. (2001). Strong induction of phytochelatin synthesis by zinc in marine green alga, Dunaliella tertiolecta. *Journal of Bioscience and Bioengineering, 92*(1), 24–29. https://doi.org/10.1016/S1389-1723(01)80193-6

Hu, S., Lau, K. W. K., & Wu, M. (2001). Cadmium sequestration in Chlamydomonas reinhardtii. *Plant Science, 161*(5), 987–996. https://doi.org/10.1016/S0168-9452(01)00501-5

Huang, C.-C., Chen, M.-W., Hsieh, J.-L., Lin, W.-H., Chen, P.-C., & Chien, L.-F. (2006). Expression of mercuric reductase from Bacillus megaterium MB1 in eukaryotic microalga Chlorella sp. DT: an approach for mercury phytoremediation. *Applied Microbiology and Biotechnology, 72*(1), 197–205. https://doi.org/10.1007/s00253-005-0250-0

Ibrahim, W. M. (2011). Biosorption of heavy metal ions from aqueous solution by red macroalgae. *Journal of Hazardous Materials, 192*(3), 1827–1835. https://doi.org/10.1016/j.jhazmat.2011.07.019

Ibuot, A., Dean, A. P., McIntosh, O. A., & Pittman, J. K. (2017). Metal bioremediation by CrMTP4 over-expressing Chlamydomonas reinhardtii in comparison to natural wastewater-tolerant microalgae strains. *Algal Research, 24*, 89–96. https://doi.org/10.1016/j.algal.2017.03.002

Ibuot, A., Webster, R. E., Williams, L. E., & Pittman, J. K. (2020). Increased metal tolerance and bioaccumulation of zinc and cadmium in *Chlamydomonas reinhardtii* expressing a AtHMA4 C-terminal domain protein. *Biotechnology and Bioengineering, 117*(10), 2996–3005. https://doi.org/10.1002/bit.27476

Jermsittiparsert, K. (2021). Linkage between energy consumption, natural environment pollution, and public health dynamics in ASEAN. *International Journal of Economics and Finance Studies, 13*(2), 1–21.

Joseph, J. O., Mwangi, I. W., Swaleh, S. N., Wanjau, R., Ram, M., Ngila, J. C., et al. (2017). A Comparative Study of Modified and Unmodified Algae (Pediastrum boryanum) for Removal of Lead, Cadmium and Copper in Contaminated Water. *Water Quality, 11*, 245–66. https://doi.org/10.5772/65745

Kanamarlapudi, S. L. R. K., Chintalpudi, V. K., & Muddada, S. (2018). Application of Biosorption for Removal of Heavy Metals from Wastewater. In *Biosorption*. InTech. https://doi.org/10.5772/intechopen.77315

Kratochvil, D., & Volesky, B. (1998). Advances in the biosorption of heavy metals. *Trends in Biotechnology, 16*(7), 291–300.

Kumar, P., & Chauhan, M. S. (2019). Adsorption of chromium (VI) from the synthetic aqueous solution using chemically modified dried water hyacinth roots. *Journal of Environmental Chemical Engineering, 7*(4), 103218. https://doi.org/10.1016/J.JECE.2019.103218

Kuyucak, N., & Volesky, B. (1989). The mechanism of cobalt biosorption. *Biotechnology and Bioengineering, 33*(7), 823–831. https://doi.org/10.1002/bit.260330705

Lee, D. H., Lee, S. I. and Kang, J. H., (2024). Machine learning approaches to identify spatial factors and their influential distances for heavy metal contamination in downstream sediment. *Science of The Total Environment,* 174755.

Li, M., Shadman, F., & Ogden, K. L. (2018). Algae-based sorbents for removal of gallium from semiconductor manufacturing wastewater. *Clean Technologies and Environmental Policy, 20*(4), 899–907. https://doi.org/10.1007/S10098-018-1497-3

Libatique, M. J. H., Lee, M. C., Yeh, H. Y., & Jhang, F. J. (2020). Total and inorganic arsenic biosorption by Sarcodia suiae (Rhodophyta), as affected by controlled environmental conditions. *Chemosphere, 248*, 126084. https://doi.org/10.1016/J.CHEMOSPHERE.2020.126084

Mehta, S. K., & Gaur, J. P. (2005). Use of Algae for Removing Heavy Metal Ions From Wastewater: Progress and Prospects. *Critical Reviews in Biotechnology, 25*(3), 113–152. https://doi.org/10.1080/07388550500248571

Michalak, I., Chojnacka, K., & Witek-Krowiak, A. (2013). State of the Art for the Biosorption Process - a Review. *Applied Biochemistry and Biotechnology, 170*, 1389–1416.

Mohamad, O. A., Hao, X., Xie, P., Hatab, S., Lin, Y., & Wei, G. (2012). Biosorption of Copper (II) from Aqueous Solution Using Non-Living Mesorhizobium amorphae Strain

CCNWGS0123. *Microbes and Environments, 27*(3), 234–241. https://doi.org/10.1264/JSME2.ME11331

Mohamed, Z. A. (2001). Removal of cadmium and manganese by a non-toxic strain of the freshwater cyanobacterium Gloeothece magna. *Water Research, 35*(18), 4405–4409. https://doi.org/10.1016/S0043-1354(01)00160-9

Mwangi, I. W., & Ngila, J. C. (2012). Removal of heavy metals from contaminated water using ethylenediamine-modified green seaweed (Caulerpa serrulata). *Physics and Chemistry of the Earth, Parts A/B/C, 50–52*, 111–120. https://doi.org/10.1016/J.PCE.2012.08.015

Nishikawa, E., da Silva, M. G. C., & Vieira, M. G. A. (2018). Cadmium biosorption by alginate extraction waste and process overview in Life Cycle Assessment context. *Journal of Cleaner Production, 178*, 166–175. https://doi.org/10.1016/j.jclepro.2018.01.025

Pavithra, K. G., Kumar, P. S., Jaikumar, V., Vardhan, K. H., & SundarRajan, P. (2020). Microalgae for biofuel production and removal of heavy metals: a review. *Environmental Chemistry Letters, 1*, 3. https://doi.org/10.1007/s10311-020-01046-1

Peng, Y., Deng, A., Gong, X., Li, X., & Zhang, Y. (2017). Coupling process study of lipid production and mercury bioremediation by biomimetic mineralized microalgae. *Bioresource Technology, 243*, 628–633. https://doi.org/10.1016/J.BIORTECH.2017.06.165

Perales-Vela, H. V., Peña-Castro, J. M., & Cañizares-Villanueva, R. O. (2006). Heavy metal detoxification in eukaryotic microalgae. *Chemosphere, 64*(1), 1–10. https://doi.org/10.1016/J.CHEMOSPHERE.2005.11.024

Perpetuo, E. A., Souza, C. B., Augusto, C., & Nascimento, O. (2000). Engineering Bacteria for Bioremediation. *Current Opinion in Biotechnology, 11*(3), 262–270. https://doi.org/10.1016/S0958-1669(00)00094-X

Pham, B. N., Kang, J.-K., Lee, C.-G., & Park, S.-J. (2021). Removal of Heavy Metals (Cd2+, Cu2+, Ni2+, Pb2+) from Aqueous Solution Using Hizikia fusiformis as an Algae-Based Bioadsorbent. *Applied Sciences, 11*(18), 8604. https://doi.org/10.3390/app11188604

Rai, U. N., Singh, N. K., Upadhyay, A. K., & Verma, S. (2013). Chromate tolerance and accumulation in Chlorella vulgaris L.: Role of antioxidant enzymes and biochemical changes in detoxification of metals. *Bioresource Technology, 136*, 604–609. https://doi.org/10.1016/j.biortech.2013.03.043

Rajamani, S., Siripornadulsil, S., Falcao, V., Torres, M., Colepicolo, P., & Sayre, R. (2007). Phycoremediation of heavy metals using transgenic microalgae. *Advances in Experimental Medicine and Biology, 616*, 99–109. https://doi.org/10.1007/978-0-387-75532-8_9/COVER

Rajivgandhi, G., Vimala, R. T. V., Maruthupandy, M., Alharbi, N. S., Kadaikunnan, S., Khaled, J. M., Manoharan, N., & Li, W. J. (2021). Enlightening the characteristics of bioflocculant of endophytic actinomycetes from marine algae and its biosorption of heavy metal removal. *Environmental Research, 200*, 111708.

Ramírez-Rodríguez, A. E., Bañuelos-Hernández, B., García-Soto, M. J., Govea-Alonso, D. G., Rosales-Mendoza, S., Alfaro de la Torre, M. C., et al. (2019). Arsenic removal using Chlamydomonas reinhardtii modified with the gene acr3 and enhancement of its performance by decreasing phosphate in the growing media. *International Journal of Phytoremediation, 21*(7), 617–623. https://doi.org/10.1080/15226514.2018.1546274

Rangabhashiyam, S., & Balasubramanian, P. (2019, February 1). Characteristics, performances, equilibrium and kinetic modeling aspects of heavy metal removal using algae. *Bioresource Technology Reports*. Elsevier Ltd. https://doi.org/10.1016/j.biteb.2018.07.009

Rindi, F., Soler-Vila, A., & Guiry, M. D. (2012). Taxonomy of marine macroalgae used as sources of bioactive compounds. *Marine Bioactive Compounds: Sources, Characterization and Applications, 9781461412472*, 1–53. https://doi.org/10.1007/978-1-4614-1247-2_1/COVER

Saavedra, R., Muñoz, R., Taboada, M. E., Vega, M., & Bolado, S. (2018). Comparative uptake study of arsenic, boron, copper, manganese and zinc from water by different green microalgae. *Bioresource Technology, 263*, 49–57. https://doi.org/10.1016/J.BIORTECH.2018.04.101

Salahshoori, I., Nobre, M. A., Yazdanbakhsh, A., Malekshah, R. E., Asghari, M., Khonakdar, H. A. and Mohammadi, A. H., (2024). Navigating the molecular landscape of environmental science and heavy metal removal: A simulation-based approach. *Journal of Molecular Liquids*, 125592.

Salama, E. S., Roh, H. S., Dev, S., Khan, M. A., Abou-Shanab, R. A. I., Chang, S. W., & Jeon, B. H. (2019). Algae as a green technology for heavy metals removal from various wastewater. *World Journal of Microbiology and Biotechnology, 35*(5), 1–19. https://doi.org/10.1007/S11274-019-2648-3/METRICS

Shen, L., Wang, J., Li, Z., Fan, L., Chen, R., Wu, X., et al. (2020). A high-efficiency Fe2O3@Microalgae composite for heavy metal removal from aqueous solution. *Journal of Water Process Engineering, 33*, 101026. https://doi.org/10.1016/j.jwpe.2019.101026

Sheng, P. X., Ting, Y.-P., Chen, J. P., & Hong, L. (2004). Sorption of lead, copper, cadmium, zinc, and nickel by marine algal biomass: Characterization of biosorptive capacity and investigation of mechanisms. *Journal of Colloid and Interface Science, 275*(1), 131–141. https://doi.org/10.1016/j.jcis.2004.01.036

Spain, O., Plöhn, M., & Funk, C. (2021). The cell wall of green microalgae and its role in heavy metal removal. *Physiologia Plantarum, 173*(2), 526–535. https://doi.org/10.1111/ppl.13405

Sun, Y., Liu, C., Zan, Y., Miao, G., Wang, H., & Kong, L. (2018). Hydrothermal Carbonization of Microalgae (Chlorococcum sp.) for Porous Carbons With High Cr(VI) Adsorption Performance. *Applied Biochemistry and Biotechnology, 186*(2), 414–424. https://doi.org/10.1007/S12010-018-2752-0

Suresh Kumar, K., Dahms, H. U., Won, E. J., Lee, J. S., & Shin, K. H. (2015). Microalgae – A promising tool for heavy metal remediation. *Ecotoxicology and Environmental Safety, 113*, 329–352. https://doi.org/10.1016/J.ECOENV.2014.12.019

Torres, E. (2020). Biosorption: A Review of the Latest Advances. *Processes 2020, Vol. 8, Page 1584*, *8*(12), 1584. https://doi.org/10.3390/PR8121584

Upadhyay, V., Kumari, A., & Kumar, S. (2024). From soil to health hazards: Heavy metals contamination in northern India and health risk assessment. *Chemosphere, 354*, 141697.

Vijayaraghavan, K., & Yun, Y. S. (2008). Bacterial biosorbents and biosorption. *Biotechnology Advances, 26*(3), 266–291. https://doi.org/10.1016/j.biotechadv.2008.02.002

Wang, J., & Chen, C. (2009). Biosorbents for heavy metals removal and their future. *Biotechnology Advances, 27*(2), 195–226. https://doi.org/10.1016/j.biotechadv.2008.11.002

Wang, S., Vincent, T., Roux, J.-C., Faur, C., & Guibal, E. (2017). Pd(II) and Pt(IV) sorption using alginate and algal-based beads. *Chemical Engineering Journal, 313*, 567–579. https://doi.org/10.1016/j.cej.2016.12.039

Xiao, H., Shahab, A., Xi, B., Chang, Q., You, S., Li, J., Sun, X., Huang, H., & Li, X. (2021). Heavy metal pollution, ecological risk, spatial distribution, and source identification in sediments of the Lijiang River. *China. Environmental Pollution, 269*, 116189.

Yacou, C., Altenor, S., Carene, B., & Gaspard, S. (2018). Chemical structure investigation of tropical Turbinaria turbinata seaweeds and its derived carbon sorbents applied for the removal of hexavalent chromium in water. *Algal Research, 34*, 25–36. https://doi.org/10.1016/J.ALGAL.2018.06.014

Yang, C., Yu, G., Liu, Y., Shan, B., Wang, L., Sun, D., & Huang, Y. (2022). Heavy metal distribution in surface sediments of the Coastal Pearl Bay. *South China Sea. Processes, 10*(5), 822.

Yipmantin, A., Maldonado, H. J., Ly, M., Taulemesse, J. M., & Guibal, E. (2011). Pb(II) and Cd(II) biosorption on Chondracanthus chamissoi (a red alga). *Journal of Hazardous Materials, 185*(2–3), 922–929. https://doi.org/10.1016/j.jhazmat.2010.09.108

Zainol, M., Sahid, I., & Muhamad, H. (2012). Fate of Thiram in an Oil Palm Nursery During the Wet Season. *Journal of Oil Palm Research, 24*(2), 1397–1403.

Znad, H., Awual, Md. R., & Martini, S. (2022). The Utilization of Algae and Seaweed Biomass for Bioremediation of Heavy Metal-Contaminated Wastewater. *Molecules, 27*(4), 1275. https://doi.org/10.3390/molecules27041275

Zohoorian, H., Shourian, M., Ahmadzadeh, H., Molazadeh, M., & Lyon, S. (2020). Microalgal bioremediation of heavy metals and dyes. *Handbook of Algal Science, Technology and Medicine*, 659–674. https://doi.org/10.1016/B978-0-12-818305-2.00041-3