Chapter

Biological Treatment of Heavy Metals with Algae

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Abstract

The development of industrial activities has caused an increase in the production of various water pollutants, of which heavy metals are among the most important due to their toxicity and harmful environmental effects. Bioabsorption is a promising and environmentally friendly technology, which has been widely used in various wastewater treatment applications in recent years. Among the bioabsorbents, algae are particularly important due to their high absorption efficiency, availability, and cost-effectiveness. In this chapter, the advantages of using algae and their use as biosorbents for removing heavy metals such as copper, aluminum, cadmium, zinc, mercury, chromium, nickel, and lead from aqueous solutions have been investigated. The effect of various factors, including factors related to biomass and process conditions (solution pH, adsorbent dosage, contact time, temperature, and initial concentration of heavy metal ions) has been evaluated. Also, the mechanisms of biological absorption of heavy metal ions in algae have been analyzed. Numerous studies show that algae are effective and economic bioabsorbents for the removal of heavy metals from industrial wastewater, and due to their predictability with simple equilibrium and kinetic mathematical equations, they are suitable for large-scale applications in continuous processes.

Keywords: wastewater treatment, removal of heavy metals, biological treatment, microalgae, absorbing heavy metals

1. Introduction

Nowadays, the development of various industries (such as mining stone refining, battery making, and the creation of pesticides) and the increase of industrial wastewater from factories are considered serious problems for the environment and humans. The lack of usable water resources on the planet and water pollution with various contaminants such as metals, semi-metals, pesticides, drugs, and other persistent organic elements has become a major concern worldwide. Among the various types of water pollutants, heavy metals are among the most important due to their toxicity, stability, resistance to environmental degradation, and long-term accumulation in the food chain. The most dangerous ions for human health and other living organisms are Cr, Fe, Se, V, Cu, Co, Ni, Cd, Hg, As, Pb, and Zn [1–3].

Despite the negative environmental effects, heavy metals are still used as main and important materials in various industries such as mining, coating, smelting, plastic, fabric, painting, etc. Therefore, it is necessary to remove heavy metals from industrial wastewater to reduce their impact on the environment. Also, the separation of heavy metals from wastewater can be economically important due to the high price of these metals. All kinds of physical and chemical methods have been investigated and used to treat industrial wastewater. Methods such as oxidation/reduction, sedimentation, ion exchange, reverse osmosis, membrane filtration, coagulation and flotation and chemical precipitation, electrochemical techniques, and adsorption on activated carbon and plant residues [2–7]. Choosing a specific purification method depends on various factors such as the type and concentration of heavy metals, whether the wastewater is homogeneous or heterogeneous, the required removal percentage, and the cost of the treatment process. But limitations such as cost, time, and efficiency have limited the use of these methods. Activated carbon and Nano adsorbents have a very high efficiency in this regard, but the cost of activation and synthesis of nanoparticles is high [8].

In recent years, biological adsorption has become a promising alternative method for wastewater treatment. Especially in research, it has been determined that surface adsorption is the most effective method for separating heavy ions and dyes from wastewater, and biological adsorbents are very promising to achieve this goal. The most important advantages of this method include high absorption capacity, low cost and economic productivity (especially when the bio absorbent can be recycled and heavy metals can be reused), high efficiency and productivity, minimal consumption of chemicals and creating sludge, the possibility of recovering metals, the renewable nature of biological adsorbents, the ability to be used in a wide range of changes in operating conditions and environmental compatibility pointed out [9].

In this chapter, researches carried out in the field of biological absorption and the use of algae to remove heavy metals from wastewater since 1977 have been studied. The main characteristics of algae that cause the high capacity to absorb metal ions heavy in them are investigated and the mechanisms of biological absorption of metals in algae have been reviewed. Also, the effect of operating parameters on the absorption efficiency of heavy metals by algae and the process conditions reported for optimal absorption of heavy metal ions have been discussed and investigated.

2. Biological removal of heavy metals (mechanism of biosorption)

The process of biological absorption includes two phases: the solid phase and the liquid phase (including particles that will be absorbed). Due to the high affinity of the adsorbent with metal ions, complex processes with mechanisms such as; there are chemical absorption, surface absorption, ion exchange, absorption by physical forces, entrapment inside the fibrillar capillaries and the space between the polysaccharide network in passing through the cell wall and membrane. The amount of absorption is obtained from the following formula, where C0 is the initial concentration and C is the final concentration after contact with the adsorbent, and in the following, the absorption power of all types of adsorbents will be expressed with the help of this formula [9–11]:

$$\%adsorbed = \left(\frac{C_0 - C}{C_0}\right) \times 100 \quad (1)$$

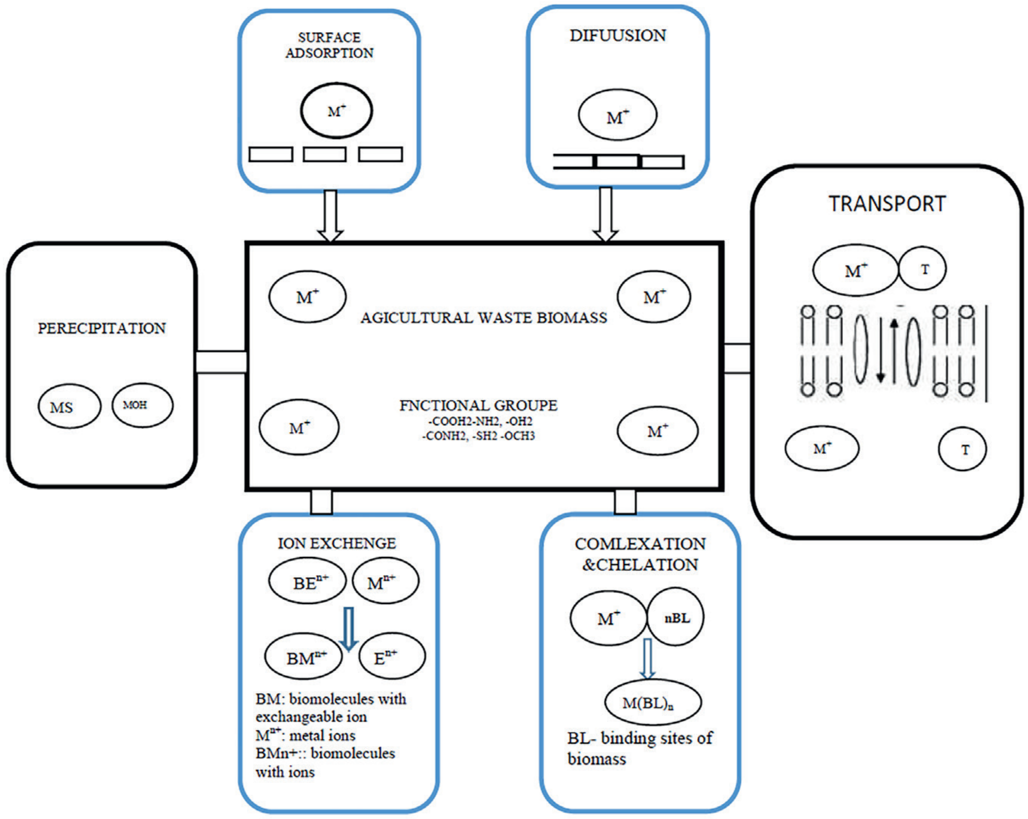

Figure 1.
A plausible mechanism of biosorption.

Accumulation of heavy metals in microorganisms mainly takes place in two phases; the first phase occurs at the cell surface. Absorption is fast and passive and is completely dependent on cell metabolism, the second phase of active absorption of ions into the algal cell cytoplasm, which is dependent on cell metabolism, and its other name is called intracellular absorption (**Figure 1**) [12].

3. The role of algae in the biological removal of heavy metals

The use of algae to remove heavy metals from wastewater has been noticed for more than 40 years, and many studies have been carried out to use algae as bio-absorbents, especially for the removal of heavy metals from aquatic environments.

In recent years, the cell structure of algae, modification and genetic change, and effective factors in their biological absorption, such as biomass concentration, primary ion concentration in the environment, size of present ions, temperature, and pH have been studied and investigated and it has been confirmed that the use of algae in The process of biological absorption of toxic and radioactive ions is a cheap, safe and efficient method; Also, valuable elements such as gold and silver can be extracted by them [12, 13].

In terms of mechanism, heavy metals are absorbed by groups such as hydroxyl, phosphoryl, carboxyl, sulfuryl, amino, sulfate, phosphate, and carbohydrate on the surface of algae. The availability of active sites of algae is determined through the FTIR test. Also, the amount of absorption depends on the number of effective groups in algae cells, their availability, the orientation of metal ions, and the chemical state of

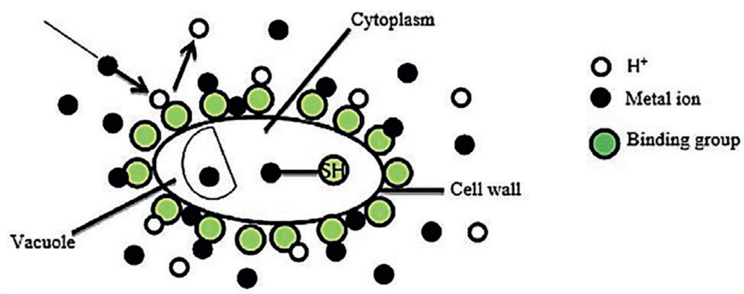

Figure 2.
Adsorption of metal ions on the algal cell surface.

Ligands class	ligands	Metal classes
1. Ligands preferred to class A	F-, O2-, OH, H2O, CO32-, SO4-, ROSO3-, NO3-, HPO42-, PO43-, ROH, RCOO-,C=O, ROR	A: Li, Be, Na, Mg, K, Ca, Sc, Rb, Sr., Y, Cs, Ba, La, Fr, Ra, Ac, Al, lanthanides, actinides
2. Other important ligands	Cl-, Br-, N3-, NO2-, SO32-, NH3, N2, RNH, R3N, =N-, -CO-N-, R, O2, O2-,O22-	Borderline ions: Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Cd, In, SN, Sb, As
3. Ligands preferred to class B	H-, i-, R-, CN-, CO, S2-, RS-, R2S, R3AS	Class B: Rh, Pd, Ag, Lr, Pt, Au, Hg, Ti, Pb, Bi

Table 1.
Specific ligands for the absorption of each ion.

the active sites. Usually, functional groups (OH-, PO4 2-, RS-, RO, SH-, COO-, NO3-, and RNH2-) create a negative charge on the surface. These bonds are located in the cytoplasm of the cell, especially the vacuole, and improve absorption. This is shown in **Figure 2** [14].

Cytosolic proteins transport ions into the cell. Therefore, the vacuole is an organelle for accumulating metal ions. According to **Table 1**, specific ligands for the adsorption of each ion are listed.

Algal cell walls are the first barrier against absorption, and according to the abundance of cell wall compounds in different algal strains, the capacity to absorb metals will be different. According to research, brown algae is a very good absorbent in this area [12, 15].

4. The potential of macro algae in absorbing heavy metals

Macromolecular seaweeds are among the living and renewable resources of the seas and oceans, which are classified into three groups: brown, red, and green algae. Green and brown algae and their derivatives have a high absorption capacity for most metals. The adsorption capacity of brown algae is directly related to the algae content, its availability, and its specific macromolecular structure. It has been determined in the studies that the absorption power of *Sargassum* algae biomass for Cd+2, Pb2+, Zn2+, and Cu2+ ions is 79, 78, 227, and 51 mg/g, respectively. Two filamentous algae, Spirogyra and Cladophora, were also investigated for lead and copper absorption, and the results showed that Spirogyra's absorption power was higher. Also, the capacity of some species of macroalgae to absorb copper has been reported according to the following order [8, 16].

Fucus spiralis > *Ascophyllum nodosum* > *Chondrus crispus* > *Asparagopsis armata* > *Spirogyra insignis* > *Codium vermilara.*

5. The potential of microalgae in absorbing heavy metals

Microalgae are considered microscopic photosynthetic organisms that are found in all aquatic environments (freshwater and saltwater) and their cultivation is possible in closed and open environments. The size of microalgae can be from several micrometers to several hundred micrometers. Criteria and various methods are used to classify microalgae, including their pigment, life cycle, or their primary cell structure. Considering their abundance, the most important types of microalgae are diatoms (Bacillariophyceae), green microalgae (Chlorophyceae), and golden microalgae (Chrysophyceae). The difference between these types of seaweed is mainly in the structure of the cell walls, where the absorption of heavy metal ions occurs. The cell wall of microalgae generally contains significant amounts of starch and glycogen, as well as cellulose, hemicellulose, and polysaccharides. These compounds contain numerous reactive active groups (e.g., amino, hydroxyl, carboxyl, sulfate, etc.) that can It is involved in chemical bonding with metal ions and are known as the main factor of very good biological absorption potential of microalgae [17–19].

Investigations have shown that microalgae are at the forefront of wastewater treatment because, in addition to the biological absorption of heavy elements, they also do nitrogen removal, phosphorus removal, and COD reduction well [20–22].

Dirbaz and Rosta conducted a study on the kinetics and thermodynamics of cadmium biosorption by Parachlorella microalgae. They observed that the absorption capacity of this microalgae at a temperature of 30 degrees Celsius and a pH of 7 is 90.72 mg/g, which is between 3 and 5.5 times that of other studied absorbents [23].

PhongVo et al. presented a review of different designs and applications of microalgae-based photobioreactors for pollutant treatment. In their review article, in addition to summarizing the progress made in the field of removing pollutants with the help of microalgae, they provided a vision of the future of using photobioreactors in this field [24].

Moreira et al. investigated the biological removal of copper metal using the microalgae *Chlorella pyrenoidosa* with experiments designed by the factorial Box–Behnken method. They reported the removal of 83.14% under optimal conditions of pH 3.6, metal ion concentration of 5 mg/L, and adsorbent dose of 1.28 g/L [25].

Saavedra et al. conducted a comparative study on the removal of toxic elements arsenic, boron, copper, manganese, and zinc from solutions containing single metal ions and mixed metal ions by four different species of green microalgae [26].

Their results, in addition to confirming microalgae as efficient and economic adsorbents for removing heavy metals, showed that the presence of other metal ions strongly affects the removal rate of metal ions by microalgae.

Areco et al. studied the effect of zinc metal ions on the growth and photosynthetic metabolism of microalgae *Botryococcus braunii* and the ability of this microalgae to remove metal ions from aqueous solutions. They studied concentrations of 0 to 80 mg/L of metal ions and observed that increasing the concentration of zinc metal ions in the solution significantly reduces the growth of microalgae. Also, the metal absorption capacity in the period of 200 days was 3.4 grams per gram of absorbent [27].

In another study, Pradhan et al. studied the removal of hexavalent chromium using the Scenedesmus microalgae. They investigated the factors affecting this process, including initial pH, contact time, initial metal ion concentration, adsorbent dose, particle size, and temperature, and reported the effective removal of hexavalent chromium with a maximum of 92.89%. They also found the presence of aldehyde, amide, carboxylic acid, phosphate, and halide functional groups to be effective in this process by examining the FTIR spectra taken from the microalgae used. Regarding the adsorption mechanism, they concluded that the removal is done by anionic surface adsorption [28].

5.1 The mechanism of removing heavy metals by microalgae

Adsorption processes are usually very complex, and the mechanism of metal adsorption includes a combination of various elementary mechanisms such as electrostatic collisions, ion exchange, complex formation, adsorption with chelate formation, micro-deposition, etc., which occur simultaneously or sequentially. The basic mechanism of the biological absorption process can be divided into two categories: chemical biological absorption and physical biological absorption. As their names suggest, the first category includes chemical reactions and the second category involves the absorption of metal ions by van der Waals forces or electrostatic attraction forces. Ion exchange, complex formation, and microscopic sedimentation are the main mechanisms of heavy metal absorption by microalgae [29].

The primary interactions in the ion exchange mechanism can be from electrostatic or van der Waals forces to chemical bonds (ionic or covalent). In general, microalgae have mobile metal ions in their structure such as K+, Na+, Ca2+, Mg2+, etc. attached to the functional groups of microalgae. In the biosorption process, these mobile metal ions are exchanged with heavy metal ions according to the following reaction:

$$R^{-} - X^{+} + M^{+} \leftrightarrow R^{-} - M^{+} + X^{+} \quad (2)$$

where R- is the functional group of the microalgae surface, X+ is the mobile metal ion and M+ is the heavy metal ion in the aqueous solution. The mechanism of complex formation includes the formation of a complex on the cell surface, between heavy metal ions in the solution and a functional group of microalgae. For example, it has been shown in research that the absorption of Cu(II) ions on *Chlorella vulgaris* is done by a complex formation mechanism in which dative bonds are formed between metal ions and the amino and carboxyl groups of the microalgae cell wall polysaccharide. Microscopic sedimentation occurs when the pH of the biosorption solution increases sharply and/or the concentration of metal ions in the aqueous solution increases to the saturation level. In this case, heavy metals in an aqueous solution can be precipitated and the resulting microscopic sediments settle on the surface of the bioabsorbent [30].

5.2 Effective factors on the biological absorption of heavy metals by microalgae

In the case of microalgae, the most important factors affecting their biological performance in the process of removing heavy metals can be divided into two categories:

1. Biomass factors such as the growth environment, specific surface characteristics of microalgae, and pretreatment of cells.

2. Process factors such as the initial pH of the aqueous solution, bioabsorbent concentration, contact time, temperature, test method, bed height, solution flow intensity, and heavy metal concentration.

Growing conditions can affect the biological performance of microalgae. Although the data reported in the articles show that microalgae grown in saline environments contain higher amounts of polysaccharides than freshwater microalgae, their efficiency in the biological absorption process varies widely.

It was also shown that microalgae that have a large number of functional groups available on their surface show better biosorption characteristics. Of course, this depends on the nature of the microalgae and the pretreatment of the biomass cells before being used as a biosorbent. Normally, to obtain raw bioabsorbent, microalgae biomass is separated by centrifugation at different speeds and at different time intervals. This biomass is then pretreated. In most cases, pretreatment involves drying the biomass so that it can be stored more easily and for a longer period of time. The main process factors that affect the biological performance of microalgae and should be optimized for the discontinuous system are solution pH, adsorbent dose, contact time, and temperature. These factors for the continuous process are the pH of the solution, height of the bioabsorbent bed, flow rate of wastewater containing heavy metals, and initial concentration of heavy metal ions. A summary of the optimal process conditions for the removal of heavy metals from wastewater with microalgae is presented in **Table 2**.

The pH of the solution is one of the most important experimental parameters that not only affects the characteristics and solubility of heavy metal ions but also the degree of separation and dissociation of functional groups that are considered adsorption sites (such as hydroxyl, carboxyl, carbonyl, amino, etc.) from the bio absorbent surfaces [31].

According to research and review articles, the highest absorption rate of algae occurs at pH between 3 and 5 (because the acidity of the environment affects the surface bands of ions and biomass and the chemical structure of ions), and the dried biomass of algae has a much higher capacity and in the first 120 minutes, most of the absorption process will take place.

Biosorbent dosage is another parameter that should be optimized in order to ensure the economic and environmental efficiency of the bioremediation process. Using large amounts of bioabsorbent not only increases the cost of the bioabsorption process but also leaves a large amount of waste contaminated with heavy metals, which has a negative impact on the environment. On the other hand, the use of very small amounts of microalgae will significantly affect the efficiency of biological absorption, and the biological treatment process with low efficiency will not be used for industrial applications.

Contact time also plays an important role in ensuring the efficiency of the biological absorption process. The inappropriate value of this parameter can significantly limit the practical and industrial use of a biological adsorption process, even if its efficiency in removing heavy metal ions is high. The absorption rate of heavy metal ions on microalgae increases with increasing contact time, and the absorption process usually reaches equilibrium in about 180 min [32].

The investigated microalgae	heavy metal investigated	pH	Contact time (minutes)	Absorbent dose (gr/L)	Temperature	Reference
Chlamydomonas reinhardtii	Au(III)	2–3	70	0.1	26°C	[25]
Chlorella vulgaris	Cr(VI)	2	240	1	25°C	[26]
Cyanophyta & Chlorophyta	Ra226 U238	6–7 4–5	60	0.2	Environment temperature	[27]
Spirulina platensis	Cd2+	8	90	2	26°C	[28]
Scenedesmus obliquus	Cu(II)	5–7	60	0.03	Environment temperature	[29]
Scenedesmus quadricauda	Cd(II) & Pb(II)	5	60	0.2	Environment temperature	[30]

Table 2.
Optimal conditions for removing heavy metals using microalgae.

The important of the effect of temperature in the case of microalgae bioabsorbents is more important for the thermodynamic description of the absorption process than increasing the efficiency of heavy metal absorption. Many studies have shown that increasing or decreasing the temperature (even up to 40°C) has a small effect on the absorption of microalgae.

Discontinuous systems are usually only suitable for the biological treatment of small volumes of wastewater, and for larger scales, it is necessary to use continuous systems in which biological absorbents are used in several cycles of absorption and desorption (recovery). However, it should be noted that the use of microalgae in continuous systems has an important drawback, which is column clogging due to the small size of the bioabsorbent particles. Therefore, in order to ensure the sufficient intensity of wastewater flow through the column, in many types of research, the immobilization of microalgae in different matrices has been proposed, which increases the mechanical strength, particle size, and resistance to chemicals in wastewater [30].

According to the results reported in the articles in continuous systems, the metal absorption capacity and breakthrough time increase with the increase in bed height, which means an increase in the total surface area of the surface absorber. The metal adsorption capacity during adsorption decreases with an increasing initial metal concentration in the solution because the biosorbent becomes saturated faster at high concentrations. For this reason, optimal values for each of these parameters should be determined for practical applications.

Generally, the process of biological absorption in non-living microalgae follows a chemical mechanism, and the main factors that determine the nature of the primary processes are the type of functional groups on the microalgae surface, the nature of heavy metals in the aqueous solution, and the characteristics of the aqueous solution (pH, ionic strength, presence of competing ions, etc.). The absorption of various heavy metals such as Pb(II), Cd(II), Cu(II), Zn(II), etc. using different types of microalgae is mainly done by ion exchange. In confirmation of this point, laboratory studies showed that the concentration of light metal ions increases at the end of the biological absorption process [33].

In the complex formation mechanism, both electrostatic interactions and covalent and/or dative bonds are involved and compared to the ion exchange mechanism, the formed surface complexes are more stable. For this reason, the recovery of such biological attractants requires the use of strong agents. Nevertheless, the complex formation mechanism has been proven as the primary interaction in many adsorption processes on different types of microalgae, especially in high initial concentrations of heavy metal ions [34].

Microscopic sedimentation can occur depending on the nature of the microalgae or independent of it and can distort the results of biological absorption and prevent the determination of the absorption rate of metal ions. Although processes such as liming and turning into activated carbon are also used to increase the absorption capacity of microalgae. If the pretreatment of microalgae is done only by drying at 50–60°C (usually for 12–24 h), biomass is not decomposed and the functional groups of its surface are not changed [35–37].

Many studies have shown that pH values in the range of 2–8 lead to an increase in the absorption capacity of most heavy metals by microalgae. In this pH range, heavy metals have high solubility and are in solution as simple ions with the most toxic effect and the highest biological absorption. At lower pH values, the adsorption capacity of microalgae is lower due to the competition between protons and heavy metal ions to bind to biosorbent sites. At higher pH, heavy metal ions are precipitated as hydroxides and only a small amount of heavy metals remain in solutions to be absorbed by interacting with surface groups of microalgae. Due to the insignificant effect of temperature on the absorption capacity of heavy metals by microalgae, it is recommended that, for large-scale applications, the absorption of heavy metals from aqueous solutions in microalgae is carried out at an ambient temperature, because operating costs will be lower in this case. The use of microalgae to absorb heavy metals in continuous systems facilitates the treatment of a large volume of aqueous wastewater, however, research in the fields related to biological absorption in continuous systems is still ongoing [38, 39].

5.3 The difference between the performance of the living and non-living microalgae in the absorption of heavy metals

Although living microalgae have shown promising capabilities in the process of removing heavy metals from various types of wastewater, the ability to treat wastewater depends on their growth rate, biomass concentration, absorption capacity, and their use by various factors that affect their growth. The pH of wastewater, the concentration of heavy metals in wastewater, etc., is limited and can severely affect the efficiency of the treatment process. Therefore, non-living microalgae are more economical for industrial applications for the following reasons:

- Dead biomass can be stored at room temperature for a long time.
- The toxicity of heavy metals in wastewater does not affect them.
- Non-living microalgae have an absorption capacity comparable to or even higher than living microalgae, and their absorption capacity can be significantly improved by different chemical methods.

In general, there are few reports of the use of live algae because the life of algae is very much affected by environmental conditions. Absorption of heavy ions in living species is more complicated because absorption occurs in the growth phase and is intracellular. On the other hand, non-living algae absorb ions on their surface and it is considered an extracellular process that is easier to control and optimize.

A great advantage of non-living algae is the possibility of reusing biomass, which can be used in deionized water while living algae have little resistance to regeneration. Another advantage of non-living algae is the ease of use in physical and chemical modification and no need to add nutrients to the environment. Due to the growth of live algae, substances resulting from its metabolism may interfere with the absorption process. The only advantage of living algae is higher absorption power and absorption of a wide range of elements [12, 16].

5.4 The functional potential of stabilized microalgae in the absorption of heavy metals

The methods of flocculation, surface absorption, creating covalent bonds with carriers, transverse bands of algae, and trapping algae in a polymer network are among the methods of immobilization or stabilization of algae. Natural biopolymers such as agar and alginate or synthesized materials such as silica gel and polyacrylamide can be used as base materials. Natural polymers such as calcium alginate are widely used to create a stationary substrate for algae due to their non-toxicity. Among the synthetic polymers, polyacrylamide is the most used because it has good resistance and does not create a toxic environment, and is relatively cheaper [40].

Ashfaq Ahmad et al. studied the biosorption of Fe2+, Mg2+, and Zn2+ ions from aqueous solutions by free and stabilized *C. vulgaris* microalgae biomass on calcium alginate and the factors affecting this process in a laboratory manner. The results of their investigations showed that the biological absorption of all tested metal ions by cells fixed on calcium alginate is economical and with higher efficiency [41].

5.5 Use of modified algae (metal ion sorption by pretreated algae biomass)

With a variety of physical and chemical methods, the strength and number of active sites of algae can be increased. Physical improvement methods such as heating, boiling, crushing, freezing, and drying usually increase biological absorption because they provide more surface area for connecting bonds, and removing cell contents increases the possibility of forming metal bonds. The most famous chemical

Chemical modification	Its effect on the biological absorption process
$CaCl_2$	By binding calcium to algae, ion exchange becomes stronger
Formaldehyde	It strengthens the crosslink between effective groups (especially hydroxyl and amino)
NaOH	It increases electrostatic interactions and creates better conditions for ion exchange.
HCl	It replaces light metal ions with a proton and dissolves cell wall polysaccharides

Table 3.
The effect of different types of chemical modifications on algae absorption.

modifications are with formaldehyde, $CaCl_2$, HCl, NaOH, and glutaraldehyde, whose effects can be seen in **Table 3** [12].

6. Conclusions

The presence of heavy elements from the effluents of factories and industries has a severely destructive effect on the structure of living organisms and their performance. Because these elements cause various severe kidney, nervous, genetic, and cancer diseases in humans, therefore their absorption from polluted wastewater is very important. Absorption of heavy elements with the help of algae is a suitable, productive, and useful method in this field due to its availability, very low cost, and significant effect on the removal of pollutants.

Biological treatment of wastewater containing various heavy metals with biological absorption by microalgae is a simple method that has received much attention in recent years due to its high efficiency, leaving minimal secondary waste and using cheap materials. The research shows that these bioabsorbents have a very good performance in removing heavy metals from large amounts of wastewater with low concentrations of heavy metals. Microalgae can be grown in large quantities in different climates and in fresh and salty waters. The performance of microalgae in absorbing heavy metals is mainly due to the presence of various functional groups on the surface of microalgae and the tendency to replace the alkaline earth metal ions present in them with heavy metal ions. The efficiency of biological absorption of metals by microalgae depends on the characteristics of microalgae (particle size, growth conditions, biomass pretreatment, etc.) and process operating conditions (solution pH, adsorbent dose, contact time, temperature, work method, adsorbent bed height, the wastewater flow rate through the absorption column, heavy metal concentration, etc.) that should be optimized.

The biochemical sorption process can be easily modeled using several well-known equilibrium and kinetic models, which provide useful information about the mechanism of heavy metal sorption onto microalgae. Preliminary absorption experiments should be performed in batch systems to obtain preliminary information. Then the design and sizing of industrial-scale absorption system equipment and the necessary economic estimates are examined by conducting tests in continuous and dynamic systems. In general, the studies conducted in this research show that microalgae have a very high potential to be used as a cost-effective and efficient bio-absorbent in the removal of all types of heavy metals from industrial wastewater.

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