REMOVAL OF MERCURY AND LEAD BY BIOADSORBENTS. AN OVERVIEW

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ABSTRACT

Humanity and industrialization have led to ecosystems, in all their matrices, being compromised in terms of pollution generated by different metals. Among them we find mercury and lead, both correspond to metals highly dangerous for all ecosystems and their trophic chains. In this review we will look at the dangers of these metals and the ways in which they can be removed, ranging from more traditional processes to adsorption processes with materials derived from natural sources and how they can be an effective source of heavy metal removal.

Keywords: Heavy metals, contaminants, polymers, removal, bioadsorbent.

1. INTRODUCTION

The great increase in the human population and with it industrialization [1-3] have caused different ecosystems to be severely affected by different types of pollution. Currently, heavy metal pollution in water bodies is a growing and constant concern due to the serious problems generated around the world. These inorganic pollutants affect both surface and groundwater [4] directly affecting aquatic ecosystems and human health. Having the ability to bioaccumulate [5-7] in organisms, generate different types of adverse effects and can lead to death. This type of pollution is mainly associated with mining companies, petroleum refining, textiles, production of pesticides, paints, pigments, among others [8, 9]. Some authors [8] mention that unlike organic compounds, these are no biodegradable to any degree, making them more dangerous. Due to the significant threat to environmental and human health [10], this problem not only occurs in different bodies of water but also includes all matrices: Air pollution substantially affects the quality of both soil and water [11]. In the case of soil pollution, this is generated due to the indiscriminate release of different types of pollutants, among which are hydrocarbons, metals, pesticides, etc. Although these heavy metals are naturally in the Earth's crust, each of the human activities related to these inorganic compounds have led to a strong biochemical and biogeochemical imbalance [3, 12, 13]. Thus, in the case of water pollution, it occurs due to direct factors, such as discharges from industrialists, and indirect factors such as rainfall, or water runoff through the soil [10, 11, 14, 15]. To treat this problem, a number of removal methods have been suggested including chemical precipitation [16], electrodialysis, MOFs [17], flotation [18], membrane filtration [19], photocatalysis [20], nanofiltration [21] and adsorption [22-25]. However, this article will detail the different methods of adsorption, emphasizing removal using environmentally friendly materials.

1.1 Heavy metals

Metals have a wide variety of applications and that is why their importance is great. They are present in different metabolic and biochemical functions, however, serious problems can be caused if there is a deficit or excess of them. However, due to the great industrialization, large amounts of organic and inorganic pollutants have been released. The latter correspond largely to heavy metals that, due to their high molecular weights and densities above 5g cm\(^{-2}\) [26, 27], it becomes more difficult to remove them. As mentioned above, these types of elements generate many non-beneficial impacts for the environment, accumulating in all food webs and seriously threatening the health of all organisms [11, 28-32]. Among the most researched and relevant heavy metals in the environmental sector are As, Cd, Cr, Hg, Pb, Ni, and Zn [33, 34], metals that when in contact with different ligands can influence characteristics such as toxicity and their environmental fate. There are records in which an increase in cell mortality is determined due to EDTA-Cu complexes [35], damage to the lungs and kidneys due to cadmium [23, 36] and other diseases associated with different heavy metals as detailed in Table 1.

Table 1. General aspects of different heavy metals.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Toxicity</th>
<th>Main sources</th>
<th>Permitted levels (domestic water) (mg L(^{-1}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>Dangers to the circulatory system and skin, can cause cancer</td>
<td>Agricultural, electronic waste, metal smelting</td>
<td>0.01</td>
<td>[27]</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Damage to lungs, kidneys and osteoporosis</td>
<td>Batteries, natural sources, mining and/or metal working</td>
<td>0.003 - 0.005</td>
<td>[23, 36]</td>
</tr>
<tr>
<td>Mercury</td>
<td>Damage to the heart, brain, delayed mental development</td>
<td>Mining</td>
<td>0.002</td>
<td>[36]</td>
</tr>
<tr>
<td>Lead</td>
<td>Arthritis, renal dysfunction, fatigue, hallucinations, hypertension.</td>
<td>Mining</td>
<td>0.01</td>
<td>[37]</td>
</tr>
<tr>
<td>Cinc</td>
<td>Severe intoxications</td>
<td>Industrial emissions</td>
<td>5</td>
<td>[38]</td>
</tr>
<tr>
<td>Copper</td>
<td>Damage, in proteins, lipids, DNA, production of free radicals.</td>
<td>Agriculture, mining</td>
<td>1.3</td>
<td>[39]</td>
</tr>
<tr>
<td>Chromium</td>
<td>DNA damage, cancer development</td>
<td>Metal fabrication, energy production</td>
<td>0.05</td>
<td>[40]</td>
</tr>
</tbody>
</table>

This review will look at the general and chemical aspects of the metals mercury (Hg) and lead (Pb), as well as their effective removal.

1.2 Mercury (Hg)

Although different geological processes, such as magmatic intrusion and hydrothermal cycles can be important sources of Hg [41], this is one of the heavy metals that is mostly emitted in different ways into the environment by industries in which the burning of fossil fuels occurs [42] such as coal, production of nuclear fuel corresponding to the purification of uranium and separation of the isotopes U235 and U238 [43] and in addition to the incomplete burning of waste that has mercury [44]. Metal that at room temperature is liquid and where its different forms in which mercury exists, whether elemental, organic and inorganic, causes it to present different types of toxicity to the environment [44-46]. As for inorganic mercury, it can be found in the form of mercury chloride (HgCl\(_2\)), which being a highly volatile compound exists in the form of atmospheric gas, mercury oxide (HgO), mercury hydroxide (Hg(OH)\(_2\)), and mercury sulfide (HgS). It has the organic form of mercury when it combines with carbon and forms methylmercury compounds such as CH\(_3\)HgCl and CH\(_3\)HgOH. This is how mercury species with an oxidation state +2 correspond to a highly toxic form that, as has been exposed, is released into the environment by different anthropogenic and natural sources [19].

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Organic mercury species such as methylmercury (MeHg), ethylmercury (EtHg), diethylmercury (Me2Hg), phenylmercury (PhHg) [47] and their inorganic forms are extremely important because they are used as parameters for the quality of the environment because, as already mentioned, they accumulate at different levels of the trophic chain being absorbed by plants where they then go to higher organisms generating serious problems [48] (see Figure 1).

1.2.1 Methylmercury

It corresponds to one of the organic and highly toxic forms of mercury, contained mainly in fish where it is predominantly found and where records point to a value greater than 80%. Although this species is associated with neuromuscular disorders [49], visual deficit, problems with speech, hearing [50], liver and heart [51], the mechanism by which methyl mercury triggers its toxicity is not fully known [49].

![Figure 1. Methyl mercury and its transport in the different trophic plots.](image)

Recently it was discovered that rice is also an important source of MeHg [52] however, the main sources correspond to mining processes [49], specifically gold mining [52] and where its high persistence and biomagnification, make this species, the neurotoxin that seriously threatens human and wildlife [53].

1.2.2 Ethylmercury.

As well as methylmercury, ethylmercury is one of the common species of mercury [54] and that its greater presence in the environment is due to anthropogenic factors [55]. Exposure to this substance can usually occur at very young ages because ethylmercury is present in some vaccines as a preservative [56, 57] and although it accumulates in different tissues, its half-life is shorter in mammals [49].

1.3 Lead (Pb)

Heavy metal whose main source is given to anthropogenic sources such as lead smelting and extraction [58], lead-based gasoline [59] battery processing and the burning of fossil fuels [58, 60] and that corresponds to one of the metals that at high concentrations turns out to be toxic [61], so like mercury it brings severe consequences for the kidneys [62], liver [63], brain development inducing apoptosis in the tissues of different organs [46]. The damage produced by Pb is such that over time its use in paints [64], gasolines [60, 65], welds [66], etc., where there has been a significant reduction in Pb exposure [59]. However, this element can cause effects that are not only harmful to humans, but also to plants and animals through soil, food, water, dust, etc. (see figure 2) being one of the most toxic due to the destructive influence on different metabolic processes [67]. The toxic nature of lead occurs by coming into contact with the cell and changing the biochemical cycle of life [68].

In addition, there are records where lead, as well as other heavy metals passes through

the blood-brain barrier and leads to a high risk factor for diseases such as senile Alzheimer’s [69] and dementia, decreasing IQ, kidney damage, reduced bone growth, carcinogenic problems, ataxia, central nervous system damage and epilepsy [70, 71].

![Figure 2. Transport of lead through all matrices.](image)

2. REMOVAL OF HEAVY METALS

As already described, heavy metals have a great influence on all ecosystem matrices, affecting at the cellular level the different organisms that are in contact even in small quantities. That is why over the years we have been working on new technologies that are efficient and friendly to the environment so that the removal of metals is as efficient as possible. For this, a wide variety of removal methods have been reported, however, this time we will detail in 2 adsorption methods and in the removal by polymers and some derivatives. As already described, heavy metals have a great influence on all ecosystem matrices, affecting at the cellular level the different organisms that are in contact even in small quantities. That is why over the years we have been working on new technologies that are efficient and friendly to the environment so that the removal of metals is as efficient as possible. For this, a wide variety of removal methods have been reported, however, this time we will detail in 2 adsorption methods and in the removal by polymers and some derivatives.

2.1 Removal by adsorption processes.

A number of adsorption-based remediation techniques have been reported for the effective removal of heavy metals [72]. The efficiency of these techniques is mainly based on the surface of the adsorbent, since the generated system, adsorbate-adsorbent, is the one that will determine the type of interactions: if they are physical they will be Van der Waals forces, or chemical ones such as metallic or covalent forces [73].

2.1.1 Biochar

We well know that mercury and lead are two of the most dangerous heavy metals for

both human and animal health [74], as well as for the ecosystem and all its environmental matrices [75, 76]. In addition, there is a record where both metals mentioned are neurotoxins[77, 78] highly dangerous and that its greatest emissions to the environment are produced by anthropogenic activities and that they are extremely difficult to eliminate due to the high volatility and low solubility in water [79]. Currently, activated carbon is one of the most studied mercury adsorbents but has the disadvantages of being a low yield material and high cost of capital [80], factors that hinder its practical application. Thus, biochar is a good alternative due to its characteristics: porous material, contains various functional groups such as phenol, carboxyl and hydroxyl [81] and are usually made from agricultural, animal and wood residues.

For the elimination of mercury by biochar, a series of methods can be considered, among which electrostatic interactions, ion exchange, precipitation, complexation and physical adsorption stand out [82-84]. There are a number of authors who detail the elimination of mercury, among which is the impregnation of mercury in biochar particles and accumulates on sulfurized biochar surfaces [83]; use of phosphorous-doped biochar as active sites for proper disposal [85]; development of magnetic biochar with tea residues to efficiently and environmentally friendly control the removal of elemental mercury [79]. In addition to mercury, biochar is highly efficient in terms of lead removal, where there is an extensive record in which modified biochar is used for lead removal in aqueous solutions [86-88] and that seems to be a rather promising technique

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[91]; it is also argued that biochar modified with cotton stalks are highly efficient in terms of lead removal [90], where their results yielded six different adsorption mechanisms in which we find precipitation, ion exchange, complexation, among others [91]; other authors mention that the biochar of poplar powder [92] provides a good form of adsorption of metals such as Pb\(^{2+}\) of wastewater, there are also biochar of straw from crops [93], biochar doped with nitrogen and phosphorus in order to increase and improve its adsorption capacity [94], other Biochar modified with MgO derived from croton herbs where the author registers high efficiency and low cost for the elimination of Pb\(^{2+}\) [95], among other methods using biochar.

### 2.1.2 Clays

In general, clays can present a high level of environmental protection due to structural properties, where we find octahedral to tetrahedral structures of 1:1 such as kaolinite and 2:1 such as montmorillonite [96]. Because of their structures, they have been extensively studied for metal removal [97, 98], dyes [99] and other organic compounds [100] and inorganic. While modified clays and clays can remove a number of contaminants, there are some of them that are mostly used for the removal of heavy metals, such as montmorillonite [101], bentonite, kaolinite, vermiculite, and illite [102, 103]. Clays have been recorded to very effectively adsorb heavy metals such as lead and mercury [96]. In general, clay minerals behave as if they were chelating ion exchange absorbers for heavy metals [104], which is why clays can be good elements for the removal of metals and even more so modified clays [103] (see figure 3).

![Figure 3. Classification of the different types of clays. Image adapted [103].](image)

This is why there is a series of works where many types of clays are detailed and their importance in terms of the elimination of heavy metals [96-98, 105-110]. Work is reported in which bentonite grafted with poly(N-acrylylglycinemide) (PNAGA – BNT) is used as a new clay-polymer material for the removal of mercury(II) [111] other works mention the montmorillonite processed with acid where they obtain a reduction of lead toxicity 75% [112]; there is also a mining residue that has developed into a new adsorbent, this is why clays can be good elements for the removal of metals and even more so modified clays [103] (see figure 3).

![Natural biodegradable](image)

![Polymers](image)

![Synthetic biodegradable](image)

**Figure 4. Classification of some natural and synthetic biodegradable polymers.**

### Hydrogels

Hydrogels are considered three-dimensional cross-linked hydrophilic structures [135-138], are usually polymers, and have as their main characteristic to contain large amounts of water [139]. The swelling to which hydrogels are subjected occurs in 3 steps:

a) Diffusion of water in the three-dimensional network of the hydrogel
b) The polymer chains are loosened and
c) Occurs the expansion of the structure of the hydrogel

The networks of these hydrogels are established through covalent bonds [140] or interactions that are usually physical, such as hydrogen bonds [141], hydrophobic interactions [142], coordination [143], electrostatic [144] and supramolecular [145]. Over the years, a number of natural polymers have been studied such as polypeptides [146], polysaccharides [139], chitosan [147], alginites [148] and synthetic polymers such as acrylamide [149] and polyvinyl alcohol [150] to be able to synthesize hydrogels that have attractive properties [151] and efficient for use in different areas. The advance in the study of removal of contaminants with hydrogels arises from the complete non-efficiency of adsorbent materials, which despite being accessible, fast and having relatively good removal percentages, the lack of active sites [152, 153] for the adsorption of highly toxic heavy metals [154] causes their adsorption capacity to be decreased. Hydrogels, among many good characteristics they possess, have a particularity that bulk and porous structures [148] can increase their characteristics as an improvement in water separation and recovery while maintaining a good adsorption performance [155], this capacity increases in metal cations [156] so it makes it an excellent material for the removal of heavy metals. Currently, there is a large number of hydrogels with different functionalities in order to provide improvements in terms of their efficiency.
Recently it has been explored in asymmetric hydrogels, these manage to generate spontaneously incorporated potentials due to the diffusion of counterions [157]. In this way, hydrogels have been developed that contain chemical gradients with forces that drive the transfer of mass and thereby achieve the elimination of heavy metals. This is how active sites are exposed inside hydrogels and polluting ions being permeable within hydrogels facilitate their removal [158].

Figure 5. Common synthetic fibers. Nylon 6, Acrylonitrile, and Polyethylene terephthalate.

Currently, there is a lot of literature associated with the synthesis and application of this type of fibers and the application as chelators of heavy metals [159]: in one of the works the preparation of polymeric absorents functionalized by the amination of acrylonitrile-ethylene glycol-dimethacrylate is presented, this functionalized polymer obtained quite promising results in terms of the adsorption of lead ions in aqueous systems [160]. Other authors [161] have prepared polyacrylonitrile-based fibers with chelated Ag ions (Ag-SH-PANP) by chemical modification in order to obtain materials with highly efficient antibacterial capabilities. Other hydrogels for the removal of heavy metals are those based on cellulose [162-164], which seems to be quite good if we consider that cellulose production is between 75,000 and 100,000 million tons [162] and characteristics such as a high specific surface that allows to have more active sites and that their hydroxy groups allow to have an easier graft of functionalities [165] of amine, ester and sulfate groups [166]. Although there is a series of cellulose-based hydrogels that allows the elimination of organic compounds such as methylene blue [167, 168] and phenol, is also extremely effective in terms of inorganic contaminants and heavy metal ions such as lead (Pb²⁺) where 98% removal percentages have been obtained with cellulose-based hydrogels from multiple active sites where the raw material corresponds to microcrystalline cellulose [169], and lead removal (Pb²⁺) corresponding to 44 mg g⁻¹ from cellulose/diatomic bead hydrogels modified with maleic anhydride [170].

In other cases, lead removal percentages of 70% have been obtained in 6 min, this is based on a porous keratin/polyacrylic acid hydrogel (keratin-PAA). The synthesized hydrogel had a specific surface area of 49.35 m² g⁻¹ with pore distribution of 6.20 nm, which led it to have a maximum lead adsorption of 234.6 mg g⁻¹ [171]. As for lead, hydrogels are highly efficient in mercury removal [172, 173]. To see the ways in which mercury can be removed by hydrogels, it must be taken into account that there must be functional groups related to mercury to obtain effective removals. For example, hydrogels containing amide groups are quite good for the removal of Cu²⁺ and Ni²⁺; amidoxime groups (R-C(NH₂)=N-O) form complexes with heavy metals such as Cu²⁺, Ni²⁺, and Pb²⁺ [174], in addition to showing affinity for uranium [175]. Likewise, compound hydrogels such as poly(2-hydroxymethyl methacrylate-co-acrylamide) cross-linked rubber tragacanth (GT-CI-(HEMA-co-AAm)) and another hydrogel compound poly(2-hydroxymethylmethacrylate-co-acrylamide/zinc oxide) reticulated rubber tragacanth (GT-CI-(HEMA-co-AAm/ZnO)) hydrogel are also recorded; however, the latter is the one who presents a better mercury adsorption capacity [176]. Another of the hydrogels that allow the removal of heavy metals is the ligand of polyacrylamide / carboxymethyl (PAM / CMG) where removal percentages of 78.8% were recorded for zinc, 67.6% for cadmium and 80.4% for mercury [177]. Maximum mercury removal refers to and proves the base principle of hard soft acid [178-180]. In general, hydrogels correspond to highly efficient structures in terms of heavy metal removal [153, 158, 181], however, it is necessary to detail in other elements that are equally or mostly efficient and of natural matrices

2.2.2 Chitosan

Chitosan is a biopolymer generated from the deacetylation (see Figure 5) of chitin that is derived from the exoskeleton of crustaceans [15, 182, 183] corresponds to the most abundant biopolymer after cellulose [184, 185].

Among the properties it has, in addition to being biodegradable [186], non-toxic, biocompatible [187] and economical, it has high adsorption capacities due to the functional groups amine (-NH₂) and hydroxyl (-OH) that it has as active sites for the adsorption of different metal ions [188], so it corresponds to a copolymer consisting of 2-amino-2-deoxy-b-D-glucono linked to β-1,4- (deacetylated D-glucosamine) and N-acetyl-D-glucosamine with less molecular weight (MW) an crystallinity than chitin possessing a molecular weight greater than 100 kDa [189, 190].

2.2.2.1 Physicochemical properties of Chitosan.

Chitosan, increasingly attractive for use, has extremely important characteristics such as chelation, viscosity, solubility, among others. While the unbranched, linear form of chitosan has been reported to possess excellent viscosity, it is also known that this property can be modified by altering the deacetylation conditions. One of the most important characteristics of chitosan is the removal and its high degree of deacetylation, since it enhances it in areas such as pharmacy and biotechnology, so the physicochemical characteristics of chitosan are affected by different factors among which we find crystallinity, MW, degradation methods and its degree of deacetylation (DD). If we detail in parameters such as MW and DD, we can find 2 types of chitosan: a) chitosan of high molecular weight, ranging between 190 and 375 kDa, with a DD > 75% and b) chitosan of low molecular weight, ranging between 20 and 190 kDa, with a DD <75% and (b) low molecular weight chitosan, ranging from 20 to 190 kDa, with a DD <75%.

Authors have reported an inversely proportional relationship between the rate of degradation and DD, which also depends on the distribution of acetyl groups [187]. If you have a higher DD you will see a much lower degradation rate, and on the contrary, if we have a lower DD, we will have a degradation rate, we will have a faster rate of degradation [191, 192]. There is also a relationship between MW and the solubility of chitosan; authors report that there is a biological relationship between these two parameters and that is that the lower the MW, the greater the solubility that the molecule will have [193, 194]. In general, solubility will depend largely on the positioning of the acetyl groups that are throughout the chain, the methods of deacetylation, ionic strength and pH. For this last parameter we can see it through its three reactive positions, an amino group and two hydroxy groups, where the amino group corresponds to the most sensitive to pH changes and is responsible for the cationic nature of chitosan [195-197]. It is recorded that at pH above 6, the amino group deprotonates and chitosan becomes insoluble [187, 198], however modified chitosan products have higher solubility in water over wider pH ranges [193].

2.2.2.2 Chitosan as material to remove heavy metals

Due to the extensive properties of chitosan, a large number of works related to the removal of heavy metals based on modified chitosan and chitosan have been reported. However, due to properties such as solubility in acid medium, low thermal stability, low mechanical strength and low surface area [199] it is that the use of modified chitosan [15] has been preferred to facilitate the removal of metals. Among these modifications are cross-linkers such as glutaraldehyde (GLU) [200, 201], ethylene glycol ether diglicidil (EGDE) [202, 203], epichlorohydrin (ECH) [204, 205], among others. These allow to provide a greater capacity of adsorption (among other characteristics) to the chitosan; for example, there are studies where cross-linked chitosan beads with GLU, EGDE and ECH are used for the removal of Cu(II) obtaining results of 59.67, 62.47, and 45.94 mg g⁻¹ respectively [206]. Other modifications are those of grafted chitosan, which are based on the grafting of active functional groups that allow a better elimination of heavy metals [15], among them we find polyanilines [207], polyethylene glycol [208], acrylonitrile [209], acrylamide [210], among others.
One of the most recent modifications are those related to magnetic chitosan which, although its industrial application is very challenging, including paramagnetic nanoparticles in the design of chitosan-based nanoadsorbents gives it quite promising magnetic properties in terms of metal removal [15]. Based on magnetic chitosan, a series of investigations have been reported detailing the removal of metals such as Cd(II), Cu(II), Zn (II) [211], Cr(VI) [212], Pb(II) [213], among other metals.

### 2.2.2.3 Removal of mercury by chitosan

Different forms of chitosan have been recorded for the removal of many heavy metals. It is not the exception for the case of mercury since there are fluorescent hydrogels based on chitosan for the adsorption of Hg(II) and Hg⁺, for which the authors prepared NH2-BODIPY [214] with reduction of NO2 to NH2 in order to be able to introduce it into chitosan through a Schiff base formation reaction. As seen in Figure 6, mercury is combined with the C=N action site and adsorption capacities of 121 mg·g⁻¹ were obtained, which, according to the authors, corresponds to seven times more than the original chitosan [215].

![Figure 6](image_url)

Figure 6 (a) Chitosan modified with -NH2 BODIPY and (b) chitosan – BODIPY with mercury. Image adapted [215].

In other studies, ionic printing was performed by manufacturing sorbents printed with mercury ions derived from modified chitosan. It has been considered that functionalized chelating materials with electron donor ligands have the high capacity to form extremely stable complexes when they manage to coordinate with metal ions. For that the authors point out the use of the Schiff base ligand that was obtained from the acid-4-amino-3-hydroxybenzoic acid and the 2-pyridinecarboxaldehyde (HPB) to then incorporate it into the chitosan through the amide bonds. Thus, the modified chitosan polymeric ligand that was obtained was combined with the Hg(II) ions to achieve the polymeric complex, achieving the impression in the crosslinking with glutaraldehyde, eliminating the Hg(II) ions and reaching a maximum capacity of 315 mg·g⁻¹ [216].

The use of a compound of Ulva lactuca/chitosan is another of the methods used that allow a good removal of heavy metals such as mercury. The authors used Ulva lactuca (also known by the common name sea lettuce) due to its low economic cost, it is an excellent bioindicator material [217] that allows to evaluate water contaminants, however, despite the fact that mercury removal is quite efficient, the preparation of hybrid materials from natural polymers such as chitosan [218, 219], allows you to have greater and greater adsorption/removal capacities of Hg⁺. In this study, the authors report a sorption capacity of 189, 144 mg·g⁻¹ of Hg⁺, at a rate 93% faster than the utilization of Ulva lactuca alone.

#### 2.2.2.4 Removal of lead by chitosan.

As for mercury and all other heavy metals mentioned in this article, there are a number of methods in which chitosan, mostly modified, is used to remove/restore lead (Pb⁺). A rather attractive technique is based on the use of chitosan with microbial adsorbents [220, 221] in which separate or combined use of chitosan with Bifidobacterium longum and Saccharomyces cerevisiae allowed effective removal of lead (II) in aqueous solutions [222]. However, despite the fact that the elimination was effective, it was recorded that the chitosan/B. longum adsorbent presented a higher percentage of adsorption than the other materials [223]. The study analyzed variables such as initial concentration, contact time, temperature and pH, where the maximum percentage of lead (II) adsorption was 97.6% [221]. Other studies suggest yeast biomass modified with ethylenediamine coated with magnetic microparticles of chitosan, a material that allows the adsorption of lead ions at high capacities. The preparation of these materials was carried out at temperatures of 20, 30, and 40ºC with maximum adsorption capacities of 121.26, 127.37, and 134.90 mg·g⁻¹ respectively [206]. Heavy metal removal studies, specifically lead, are reported with magnetic silica nanoparticles coated with chitosan modified with dietenetriaminapentaaetic acid (DTPA), a chelating molecule with three nitrogen atoms corresponding to tertiary amine and five carboxylic groups that are as a semi-flexible ligand [224], to improve the adsorption of lead from wastewater. In this lead removal system, methyl blue (MB) was used with the aim of improving the removal capacity due to its sulfonic acid groups in the molecules, creating new specific active sites for lead adsorption [213].

**CONCLUSIONS**

As already mentioned, over time a wide variety of techniques have been used for the removal of heavy metals (reverse osmosis, membrane filters, ion exchange, clays, biochar, hydrogels, etc.) from wastewater, however the need to have efficient and low-cost materials has been increasing. In general, the removal of heavy metals such as lead and mercury, with adsorbent materials is considered a fairly economically viable, sustainable, efficient and highly replicable technique that allows the elimination of about 97% for the case of lead and about 93% for mercury, so continuing with research of this type could allow in the future, the removal of 100% of these metal ions that today are a serious problem for the environment and humanity.

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