A critical review of the application of biosorption as alternative methods in wastewater treatment
Una revisión crítica de la aplicación de la biosorción como métodos alternativos en el tratamiento de aguas residuales.
Uma revisão crítica da aplicação da biossorção como métodos alternativos no tratamento de águas residuais

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Abstract
Conventional technologies for wastewater remediation have limitations, including low removal of refractory organic pollutants, high operating costs, and the need for a large installation area. In order to overcome these barriers, other alternative processes, such as adsorption, have been used. These stand out for the possibility of reusing the adsorbent, low cost with the use of biosorbents, and high versatility. In the literature, the most commonly used biomaterials are agro-industrial waste and plant residues. This article developed a qualitative review with an exploratory character, describing biosorption in the removal of contaminants in wastewater. The literature shows that a large group of living and dead biomasses have demonstrated excellent results in the capture of pollutants, being highly viable in the remediation of industrial effluents. The lack of proper management of agro-industrial waste generates accumulation in the environment, and therefore their transformation as biosorbents has demonstrated high removal of metal ions with high adsorption capacity values. The major limitation is that these materials are dependent on several parameters such as pH. However, when using biomass of microbial origin, removal values are lower when compared to those of agro-industrial origin. Biomasses of microbial origin require greater control of variables necessary for the survival of cells and nutrients. Organic compounds are generally more difficult to remediate, since they have specific functional groups of different ionic nature in their chemical structures. This chemical property can hinder the mechanisms of interactions between the organic molecule and the surface of the biosorbent. Therefore, the biosorption process is highly versatile since the use of alternative materials is highly efficient and environmentally friendly.

Keywords: Wastewater Treatment; Contaminants; Biosorbents; Adsorption Process.

Resumen
Las tecnologías convencionales para la remediación de aguas residuales tienen limitaciones, una de las cuales es la baja eliminación de contaminantes orgánicos refractarios, los altos costos operativos y la necesidad de una gran área de instalación. Buscando superar estas barreras se están utilizando otros procesos alternativos como la adsorción. Estos destacan por la posibilidad de reutilizar el adsorbente, bajo costo con el uso de biosorbentes y alta versatilidad. En la literatura los biomateriales más utilizados son los residuos agroindustriales y los residuos vegetales. Este artículo desarrolló una revisión cualitativa de carácter exploratorio, describiendo la biosorción en la remoción de contaminantes en aguas residuales. La literatura muestra que un gran grupo de biomasas vivas y muertas demostraron excelentes resultados en la captura de contaminantes, siendo altamente viables en la remediación de efluentes industriales. La falta de un correcto manejo de los residuos agroindustriales genera acumulación en el ambiente, por lo que su transformación como biosorbentes ha demostrado una alta remoción en comparación con los iones metálicos con altos valores de capacidad de adsorción. La principal limitación es que estos materiales dependen de varios parámetros, como el pH. Al utilizar biomasa de origen microbiano los valores de remoción son menores si se comparan con los de origen agroindustrial. Las biomasas de origen microbiano requieren un mayor control sobre las variables necesarias para la supervivencia de las células y los nutrientes. Los compuestos orgánicos son generalmente más difíciles de remediar, ya que tienen grupos funcionales específicos de diferente naturaleza iónica en sus estructuras químicas. Esta propiedad química puede dificultar los mecanismos de interacción entre la molécula orgánica y la superficie biosorbente. Por tanto, el proceso de biosorción es muy versátil ya que el uso de materiales alternativos es altamente eficiente y ecológico.

Palabras clave: Tratamiento de Aguas Residuales; Contaminantes; Biosorbentes; Proceso de adsorción.

Resumo
As tecnologias convencionais na remediação das águas residuais têm limitações, sendo uma dela a baixa remoção frente a poluentes orgânicos refratários, alto custo operacional e necessidade de grande área de instalação. Buscando superar estas barreiras outros processos alternativos como a adsorção, veem sendo usados. Estes se destacam pela possibilidade de reuso do adsorvente, baixo custo com o uso de biossorventes e alta versatilidade. Na literatura os biomateriais mais usados são os resíduos agroindustriais e resíduos vegetais. Este artigo desenvolveu uma revisão qualitativa com caráter exploratório, descrevendo a biossorção na remoção de contaminantes em águas residuais. A literatura evidencia que um grande grupo de biomassas vivas e mortas demonstraram ótimos resultados na captação de poluentes, sendo altamente viável na remediação de efluentes industriais. A falta de um correto gerenciamento dos resíduos agroindustriais gera a acumulação no meio ambiente, com isso a sua transformação como biossorventes tem demonstrado alta remoção frente a ions metálicos com altos valores de capacidade de adsorção. A grande limitação é que estes materiais são dependentes de vários parâmetros como o pH. Já o uso de biomassa de origem microbial os valores de remoção são menores, quando comparados aos de origem agroindustrial. As biomassas de origem microbial necessitam de maior controle variáveis necessárias à sobrevivência das células e dos nutrientes. Os compostos orgânicos são geralmente mais difíceis de remediar, uma vez que apresentam em suas estruturas química grupos funcionais específico de natureza iônica diferente. Esta propriedade química pode dificultar os mecanismos de interações entre a molécula orgânica e a superfície do biossorvente. Portanto, o processo de biossorção é altamente versátil uma vez que o uso de materiais alternativos é altamente eficiente e ecológico.

Palavras-chave: Tratamento de Águas Residuárias; Contaminantes; Biossorventes; Processo de Adsorção.

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1. Introduction

Industrial effluents are highly complex and contain a large volume of various pollutants. Before being released into the environment, they must be remediated in order to reduce the possible impacts on the ecosystem (Saha and Mazumdar, 2019). Various industrial sectors, such as metallurgy, electrolysis, fertilizers, and leather, use contaminants that are highly toxic to the environment, and even after treatment, they still remain in small concentrations. This inadequate disposal contaminates water compartments indirectly and directly, bioaccumulating throughout the food chain (Ekramul Mahmud, at al., 2016). To deal with this problem, the use of more effective treatments can support the safe reuse of water resources (de Sá et al., 2017). These industrial sectors release pesticides, metals, drugs such as antibiotics, pesticides and dyes into their wastewater. Many of these contaminants are persistent, difficult to remove, highly toxic, bioaccumulating and highly chemically stable (Agoro et al., 2020; Trojanowicz, 2020).

Due to their high surface area and high chemical reactivity, nanomaterials have begun to be used in wastewater remediation. Studies show that water remediated with nanocomposites has better quality; however, the operating cost is higher compared to biosorbents (Yu and Xu, 2017). Generally, the group of nanomaterials most used are those containing carbon structures such as graphene, carbon nanotubes and graphene oxide (Wong et al., 2016). In addition, once present in the environment, they can be toxic, since the literature does not clarify the potential harm of nanomaterials to different microorganisms. Studies describe that the highly morphologically heterogeneous surface can generate a certain degree of toxicity to animals and humans (Jiang et al., 2018).

Regarding tertiary water treatment processes, the most commonly used are heterogeneous photocatalysis, ion exchange, advanced oxidative processes, membrane separation processes, and electroprecipitation (Azimi et al., 2017). Many studies highlight the high removal/degradation efficiency of some of these processes. However, high sludge production, incomplete removal with generation of intermediates, formation of membrane fouling, high energy and reagent consumption, and residual sludge with precipitated metals often make their application unfeasible (Kanamarlapudi et al., 2018). In this sense, biosorbents can become an excellent alternative for the remediation of contaminated water. Their high efficiency regardless of pollutant concentration, the possibility of reuse, the simple design, and the low cost encourage their application (Salman and Abdul-Adel, 2015; Singh et al., 2020). Initially, obtaining a biosorbent is linked to its precursor source, which can be inactive biomass or living matter (Alothman et al., 2020). In inactive biomass, the form of interaction of the contaminant generally involves the ionic charges present in the biomass, whereas in the case of living materials, the interaction mechanisms are more complex (Fomina and Gadd, 2014). Biosorbents of microbiological origin remove the contaminant through an active bioaccumulation mechanism that depends on the metabolism of the organism, where the interior of living cells accommodates the contaminants (Chen et al., 2020). Therefore, biosorption corresponds to the removal of organic molecules using a solid of biological origin, where the organic molecules of the adsorbate adhere to the surface through chemical or physical interactions. Generally, non-specificity and low energy corroborate the occurrence of physical mechanisms (Mrvčić et al., 2012). Physical processes are generally reversible, which supports the reuse of solids. Chemical processes, on the other hand, involve desorption, which is more difficult (Gavrilescu, 2020). Biomass can have a variety of origins, including biopolymer sources, plant-derived waste, industrial waste, or agricultural waste (Ali et al., 2023; Dehmani et al., 2023b, 2023a; Franco, Dison S.P. et al., 2023; Franco, Dison Stracke Pfingsten et al., 2023).

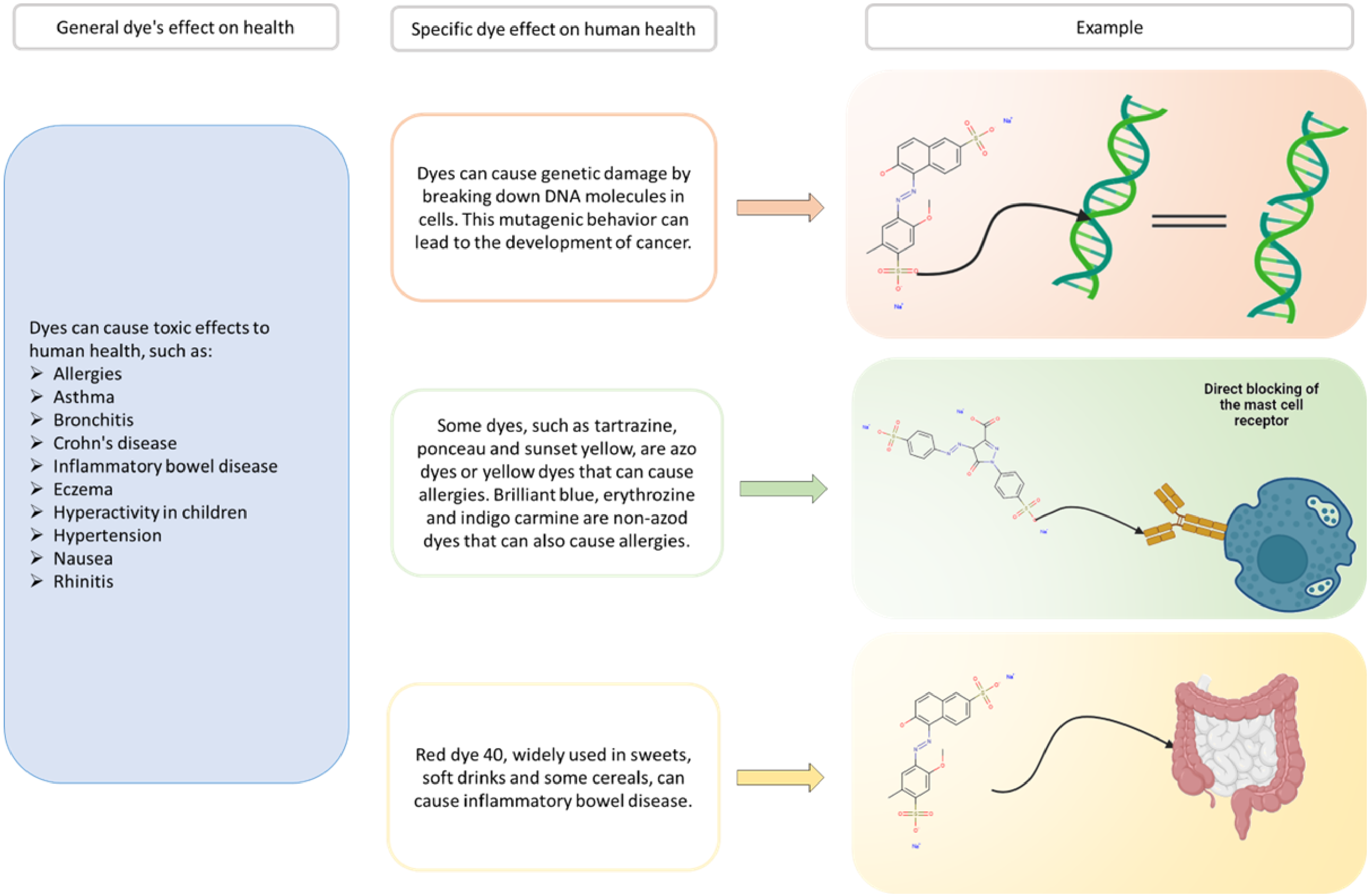
This study provides an integrative systematic literature review on the application of various biosorbent materials used to remediate metal ions, persistent organic pollutants, and emerging organic pollutants. This review is important because it aims to outline an overview of the application of biosorption in the treatment of contaminated waters.

2. Literature review

2.1 Main pollutants of wastewater

Heavy metals are among the main pollutants frequently detected in water bodies. The major concern surrounding these ions is that they are bioaccumulators and carcinogens for both humans and animals (Ayangbenro and Babalola, 2017). In more severe cases of constant ingestion, metals can cause serious poisoning, especially in the most vulnerable segment of the population, such as the elderly and newborns. In the group of persistent organic compounds, insecticides, polychlorinated biphenyls, pesticides, and organochlorines stand out (Wahlang, 2018). Another aspect is that emerging contaminants generally have an anthropogenic origin, and because it is a class that emerged more recently, it does not have clear and specific legislation. Continuous discharges and high concentrations are generally present in livestock and agricultural activities, as well as in industrial, domestic, and hospital effluents. Natural occurrence, however, in lower concentrations, can occur through various plant species (García et al., 2020; Georgin et al., 2022b, 2023b). The group of pharmaceutical compounds is also a problem, with their main discharge occurring through industrial activities and effluents from veterinary clinics, hospitals and domestic water. These sectors are related to incomplete absorption by the organism of animals and humans, where most of it ends up being released via urine and feces. In the case of the group of antibiotics, in addition to being difficult to remove, once present in water compartments they increase the generation of resistant bacteria (Turolla et al., 2018). Dyeing agents are also manufactured on a large scale, so continuous discharges are released into nature, causing the deterioration of the planet (Lellis et al., 2019). Like metals, dyes can also be carcinogenic and toxic. In addition, their pigmentation, even in low concentrations, can change the color of the water, altering the penetration of solar rays, which directly affects the photosynthetic organisms that live there (Figure 1) (Donkadokula et al., 2020). There are different groups of dyes and these are divided according to their chemical structure, the most common groups are characterized by sulfurous, azo, metallized and anthraquinones (Zanoni and Yanamaka, 2016).

Figure 1. General and specific dye effects on the human health



Dyes can cause toxic effects to human health, such as:
- Allergies
- Asthma
- Bronchitis
- Crohn's disease
- Inflammatory bowel disease
- Eczema
- Hyperactivity in children
- Hypertension
- Nausea
- Rhinitis

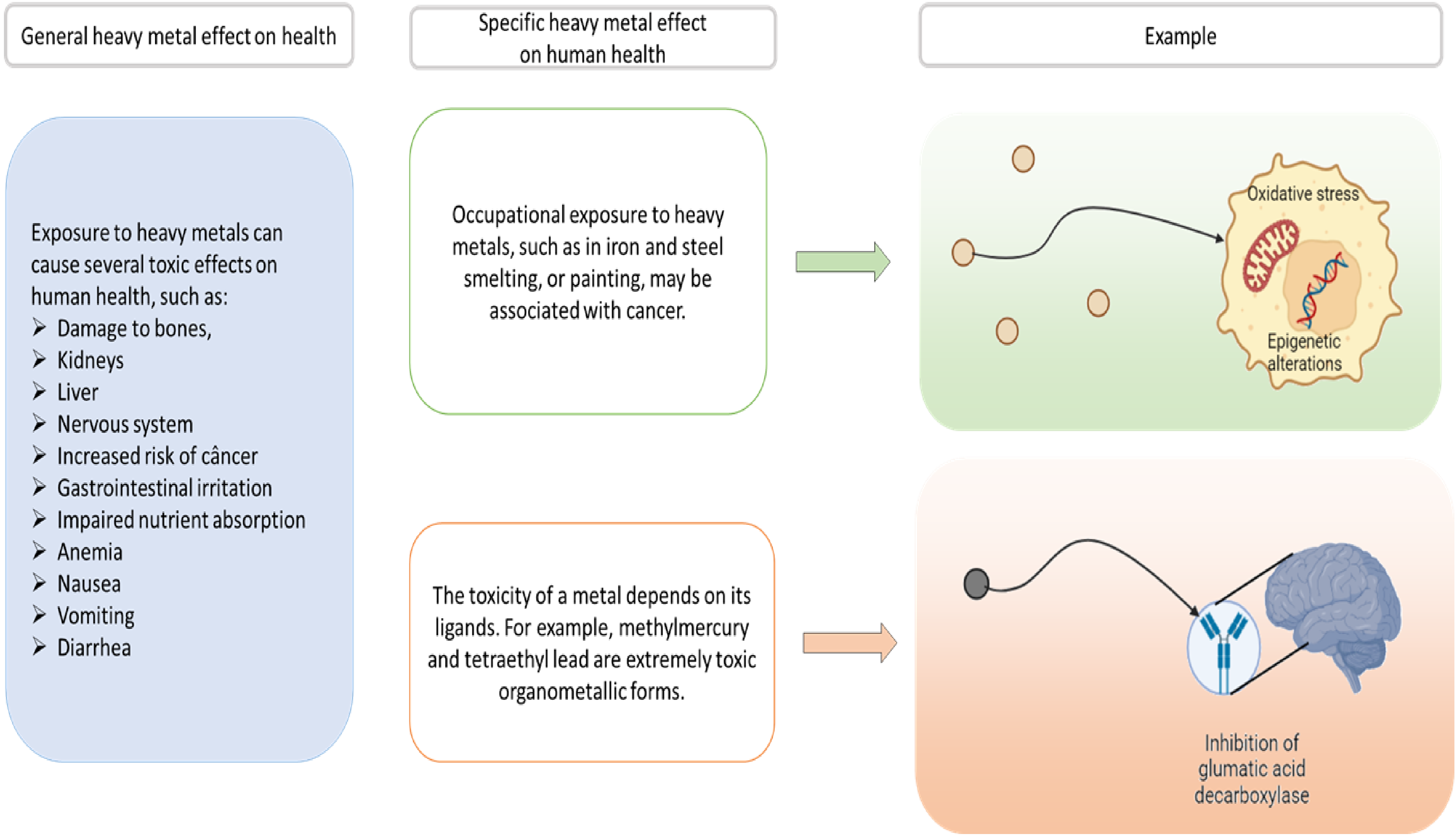
Dyes can cause genetic damage by breaking down DNA molecules in cells. This mutagenic behavior can lead to the development of cancer.

Some dyes, such as tartrazine, ponceau and sunset yellow, are azo dyes or yellow dyes that can cause allergies. Brilliant blue, erythrozine and indigo carmine are non-azod dyes that can also cause allergies.

Red dye 40, widely used in sweets, soft drinks and some cereals, can cause inflammatory bowel disease.

The toxic effects of metals (Figure 2) have always been classified as short-term and acute events. In recent years, long- and medium-term occurrences have been observed, where the relationships between the effects and the causes are subclinical and not very evident (El Messaoudi et al., 2024; Franco et al., 2024; Georgin et al., 2024b, 2024a). Due to the low specificity, these cases are difficult to distinguish, which corroborates the fact that they may be associated with contamination by other toxic compounds or even by interactions between contaminants. The level and degree of contamination is always related to the dose that can be distributed throughout the human organism. This ends up contaminating all organs, altering the metabolism of biochemical pathways as well as the cell membranes and organelles present there (Ciğeroğlu et al., 2024; Georgin et al., 2022b, 2023a, 2023c). Generally, most organisms can already be affected to a considerable level even with small doses of metals (as is the case with mercury) (Franco et al., 2022; Şenol et al., 2024). For survival, there are metals that are essential for the human body, however, these must be present in very low doses (micronutrients). Among them are iron (constituent of hemoglobin), zinc, cobalt and magnesium. When the dose of these metals exceeds the concentrations necessary for survival, they become dangerous and toxic. There are metals that do not occur naturally in any living organism, this group includes mercury, arsenic, lead, chromium and cadmium. In addition, this group does not exert any biochemical or nutritional activity, neither in plants nor in humans or animals. Because of this, when the organism is contaminated by these ions, even in low doses, the damage can be serious and permanent. Once present in the organism, its activity and metabolic pathways depend on its interaction with other chemical compounds and elements. For example, in the case of lead, assimilation tends to be greater in people who have a low intake of calcium, phosphates or iron. Zinc absorption can reduce copper absorption and protect against the toxic effects of lead and cadmium. Low phosphate intake can help to reduce the toxic effects of aluminum, which is generally not toxic to humans. In recent years, there has been a steady increase in the amount of these metals, and their toxic effects have caused permanent health problems. The level of toxic effects of chemical compounds will always depend on excretion, absorption, metabolism and distribution (Georgin et al., 2024b, 2024a; Manzar et al., 2024).

Figure 2. Potential damage to human health caused by heavy metals.



Exposure to heavy metals can cause several toxic effects on human health, such as:

- Damage to bones,
- Kidneys
- Liver
- Nervous system
- Increased risk of câncer
- Gastrointestinal irritation
- Impaired nutrient absorption
- Anemia
- Nausea
- Vomiting
- Diarrhea

Occupational exposure to heavy metals, such as in iron and steel smelting, or painting, may be associated with cancer.

The toxicity of a metal depends on its ligands. For example, methylmercury and tetraethyl lead are extremely toxic organometallic forms.

The level of toxic effects of metals depends on several factors, including the form of the metal, its toxicokinetics, the specific metal, its toxicodynamics, and the degree and period of exposure. Contact with metals by the world's population has become a global phenomenon, where the level of exposure will depend on the form, whether organic, inorganic, or elemental, as well as the different habitats in which we live and the foods we consume (Fu et al., 2012). Contamination can occur professionally or environmentally, and once exposed, the possible toxic effect involves three stages. The first corresponds to absorption and the route of entry; the second is related to distribution, transport, effect, and biotransformation; and the third stage is the route of elimination by the body. The form in which the metal occurs in each stage varies; it is generally associated with its favorable form, interactions with the physiological properties of the organs, and anatomical characteristics. Once present within the body, the metal ions encounter the sulfhydryl radical (a form of sulfur), leading to inhibition of enzyme activity (Naija and Yalcin, 2023). This compromises cellular transport, along with protein activity. Another point is that sulfur also helps to structure molecules, maintaining their three-dimensional shape (proteins). With the presence of a metal, the structure may present disulfide points, leading to structural changes. Hydrogen can also be displaced by binding to sulfur, which also leads to structural changes. If it is a plasma protein, this modification may not cause significant damage; however, if it is an enzyme, its metabolic activity may be reduced. Another toxic aspect is that heavy metals can block important functional groups present in molecules, including polynucleotides, enzymes, and the transport system for essential nutrients and ions. This can also alter the replacement of essential ions within cell sites (Eremeeva et al., 2023).

When analyzing the risk through exposure to these contaminants, other factors such as susceptibility, age, genetic variability, sex, exposure time, nutritional conditions, type and condition of exposure and socioeconomic status must also be analyzed; all of these must be considered for a realistic approximation (Bayuo et al., 2020). Heavy metals such as nickel (Ni), selenium (Se), lead (Pb), the metalloid arsenic (As), mercury (Hg), tin (Sn), cadmium (Cd), manganese (Mn) and chromium (Cr) are toxic to humans; however, various risk factors, such as those mentioned above, can make some individuals more susceptible than others, and many gaps involving this still remain unclear and require further investigation.

2.2 Bioaccumulation of organic compounds and metals

When the biomass used in water remediation is of living origin, it contains microbiological organisms, resulting in bioaccumulation. This process occurs together with the cultivation of the biomass of a microorganism close to the toxic metal to be remediated (Torres, 2020). For this step to be efficient, the culture medium must have the essential nutrients for the microorganisms, thus rapid growth is observed. At this point, the organisms carry out metabolic processes, activating the transport systems and leading to the accumulation of the pollutant inside their organism (Mustapha and Halimoon, 2015). This process is characterized by two stages, the first of which is when the metal is adsorbed into the cells. This stage is rapid and generally accompanies some interaction mechanisms, such as precipitation, electrostatic interaction, redox process, surface complexation or ion exchange. These types of mechanisms are generally reversible. The second stage is irreversible, slower and corresponds to the active transport of the pollutant into the cell (Derco and Vrana, 2018; Tang et al., 2015) . The occurrence of another stage will depend on the cell metabolism (Vidyashankar and Ravishankar, 2016). Once present inside the cell, the metal can be immobilized by the vacuole or even bind to other compounds, such as polysaccharides. Another aspect involves the transformation by the cells into other species with less toxicity potential, or when this transformation does not occur, expulsion may occur via the efflux system (Emami Moghaddam et al., 2018). The major variable responsible for the success of the process is the composition of the nutrient medium, which is responsible for growth and must contain numerous carbon sources (Wang, X. et al., 2019). Special attention should also be given to the selection of the species of microorganisms, using individuals that are highly resistant to the pollutants present in the environment, which leads to greater efficiency in the process (Das et al., 2016) Figure 3 describes the differences between biosorption and bioaccumulation, while Figure 4 shows a diagram of a living cell and the mechanisms that promote the entry of metals, along with the possible mechanisms of interactions involving biosorption on the cell surface.

Figure 3. Illustrative differences between biosorption and bioaccumulation (Adapted from (Tang et al., 2015)

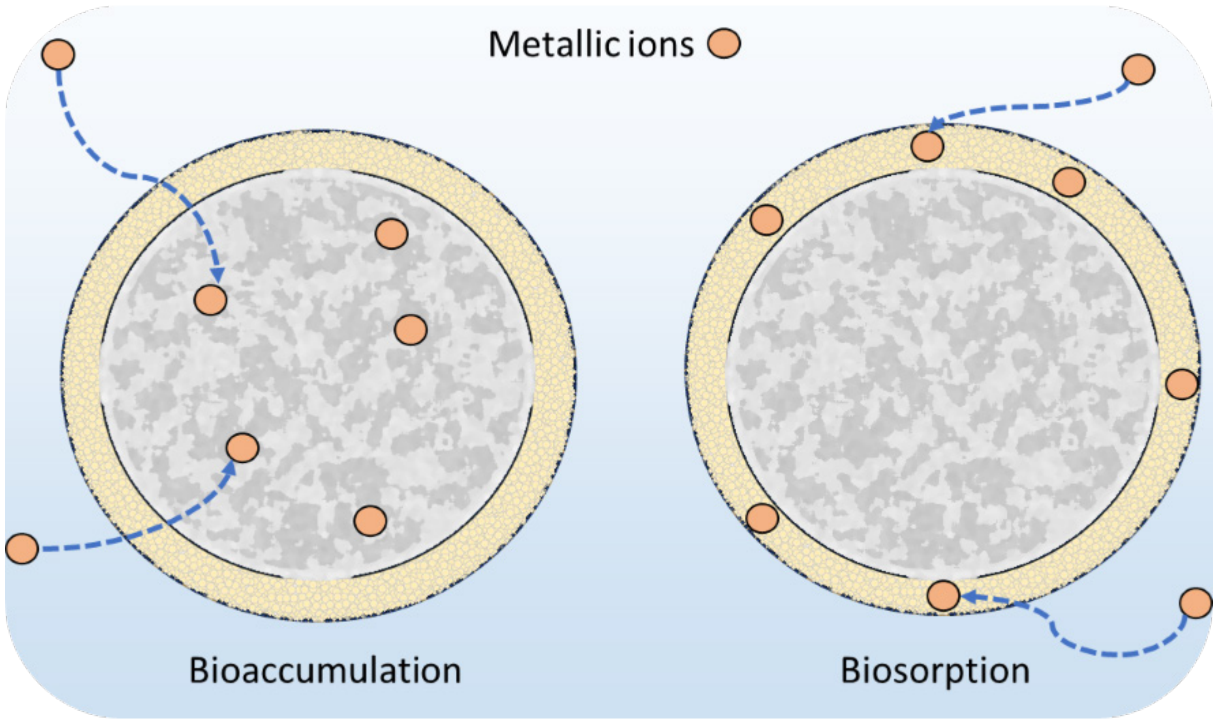
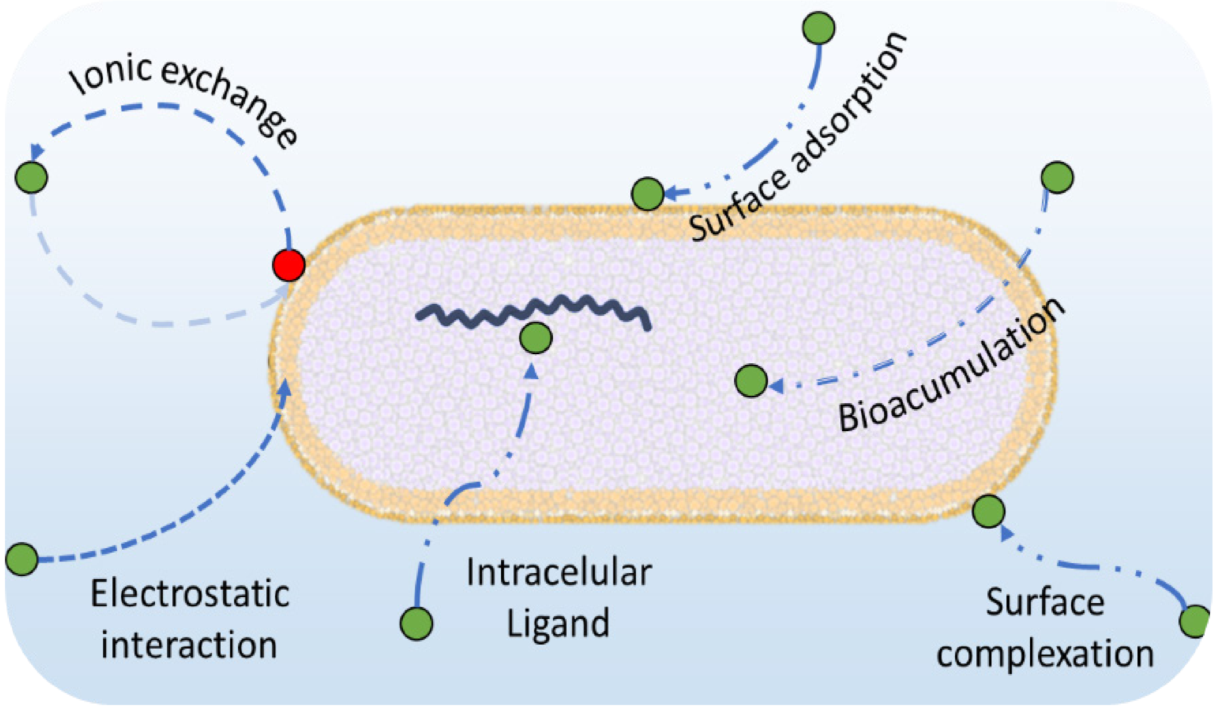


Figure 4. Possible forms of interactions involving the removal of metals via the use of microorganisms, adapted from (Ayangbenro, and Babalola, 2017).

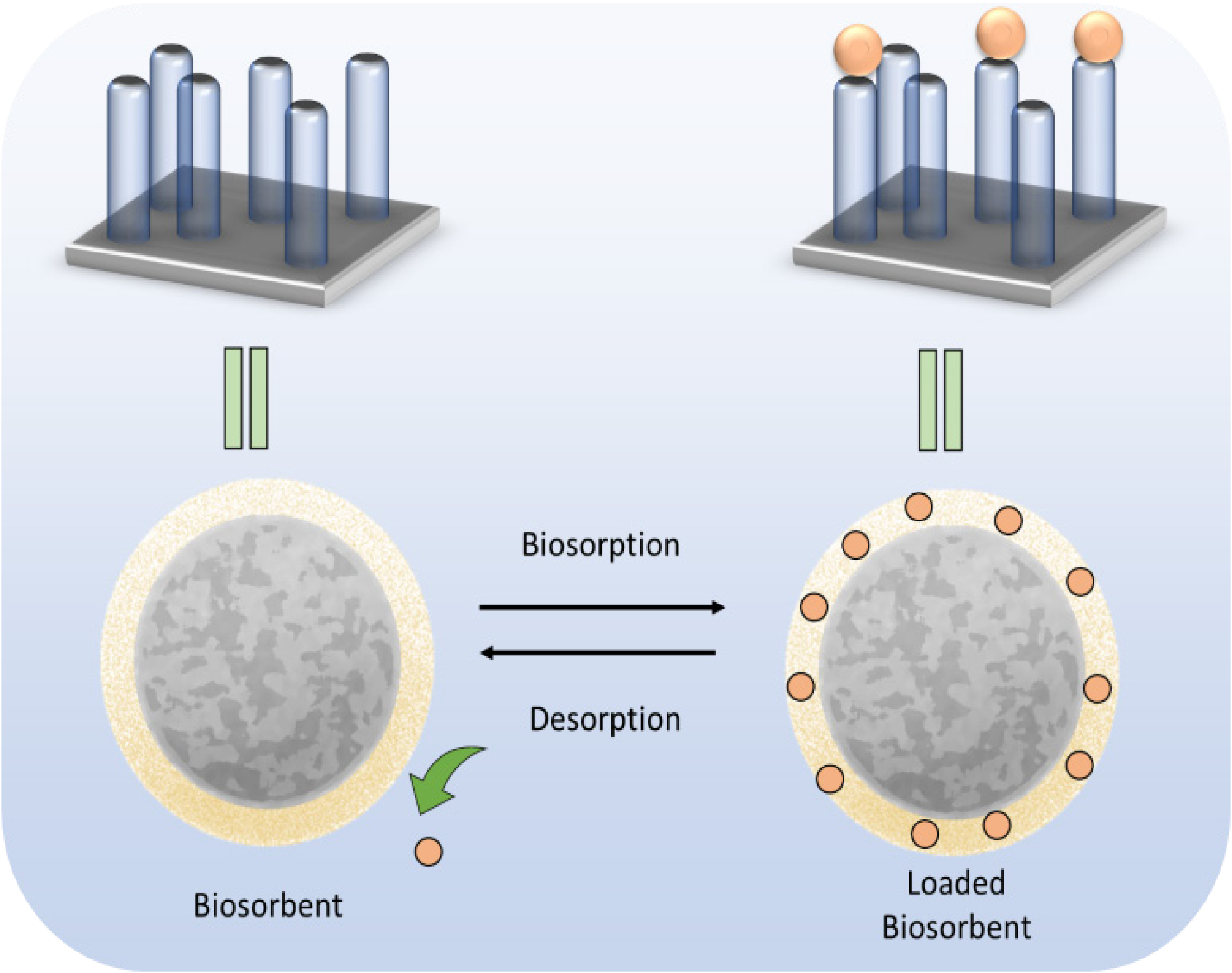


According to Figure 4, the cell wall of microorganisms acts as an ion exchange complex, due to the anionic characteristics and functional groups present, such as carboxyl, amino group, sulfate and phosphate, which will be responsible for the capture of adsorbed metal cations, promoting a series of electrostatic interactions and other processes (ion exchange, precipitation, bioaccumulation) (Ayangbenro, and Babalola, 2017).

2.3 Biosorption and desorption of organic compounds and metals

The transformation of biomass from waste into biosorbents has been analyzed by various studies that analyze the removal of organic pollutants and metals to the surface of the solid (adsorbent). The great advantage is the increase in the value of the waste added to the low synthesis cost and good adsorption capacity (Ojima et al., 2019). Adsorption also has as a positive aspect the operational design is not at all robust, unlike the use of living biomasses that require the presence of nutrients. Another aspect involves the possibility of reusing the biosorbent. It is important to emphasize that desorption requires the use of reagents and energy. Therefore, if the biosorbent is low-cost and abundant, this process is often unfeasible (Jacob et al., 2018). Due to all these advantages, researchers have been developing various methods supported by biosorption, many of which present removal effectiveness in addition to being an economically viable process that is also ecological and sustainable (de Freitas et al., 2019; Deniz and Tezel Ersanli, 2020). The favorable properties of a biosorbent are directly related to its efficiency in capturing the adsorbate on its surface. For this, it is desirable that it presents high selectivity and is easy to obtain, which corroborates its large-scale use (Salman and Abdul-Adel, 2015). Adsorption studies are generally aimed at remediating organic compounds such as herbicides, dyes, pesticides, and drugs such as antibiotics, because they can generate serious environmental problems even at low concentrations (Georgin et al., 2020; Sun et al., 2019). Adsorption is viable and can be used to replace some chemical and physical processes that are often inefficient when the adsorbate is in low concentration and are expensive (Dada et al., 2020). Biosorption is a viable process aimed at the use of a nanostructured system, aimed at removing high percentages of organic contaminants (Ezekoye et al., 2020; Sunsandee et al., 2020). Figure 5 illustrates the adsorption system of contaminants to the surface of the biomass, this occurs until saturation, where desorption then occurs, corresponding to the release of the adsorbate from the surface. This is possible in processes that involve physical interaction mechanisms with low energy and low specificity.

Figure 5. Illustration of the adsorbate adsorption/desorption processor on the biosorbent surface. Adapted from (Medhi et al., 2020)



In the case of precious adsorbates, which have some economic interest, as is the case of some metals such as platinum, gold and palladium, adsorption occurs with a bias towards recovering the adsorbates (Páez-Vélez et al., 2019; Tan et al., 2017). In these cases, desorption mechanisms are used to remove the compounds of interest from the surface of the solid, for which it is very important to correctly size the eluent choice (Bayuo et al., 2020; de Freitas et al., 2019). The chosen reagent must be low cost, guarantee intact binding capacity to the pollutant, be ecologically acceptable and be selective with the biosorbent.

2.4 Factors that alter the efficiency of the biosorption process

For the biosorbent to perform high removal, certain experimental parameters that influence the process must be carefully dimensioned (Ali Redha, 2020). Table 1 describes the parameters that influence and interfere with the performance of the adsorbent, and therefore must be controlled during adsorption.

Table 1. Parameters that interfere with the adsorption process of pollutants on the surface of biosorbents.

Factors	Aspects of interest
pH	In alkaline conditions, they can generate the formation of metal hydroxides, which also increases the anion charge, which can limit their use; The zero charge point of the material is important in order to obtain the optimum pH value; When the conditions of the environment are below the pH of the zero charge point, an increase in cations is observed on the surface of the adsorbent; On the other hand, when the pH is above the zero charge point, the negative charges are the majority on the surface of the biosorbent; Checking the pKa of the functional groups of the organic compounds is important to analyze the charges present and the interpretation of protonation.
Initial pollutant concentration	The initial concentration of the pollutant must overcome the resistance of mass transfer; When increasing the concentration of the adsorbate, the capacity also increases up to the saturation point; The opposite behavior is evidenced in removal, where it decreases with the increase in concentration, this occurs due to the reduction of active sites available on the surface of the biomass.
Biosorbent dosage	The amount of pollutant adsorbed per unit weight is high with a low dose of biosorbent; The amount adsorbed tends to be low when the concentration is high; The interaction site with a lower proportion of pollutant corroborates the number of unoccupied sites on the surface of the solid (biosorbent).

Temperature	Due to the increase in solubility, the increase in temperature tends to corroborate adsorption, being compatible with an endothermic system; There are studies that show that the increase in temperature does not favor adsorption, these are related to exothermic systems, and are compatible with lower energy consumption and consequently lower operating costs.
Contact time (kinetic studies)	The time required for maximum adsorption depends on the type of biosorbent and the type of adsorbate, and this value varies greatly throughout the literature. Short kinetic times corroborate with high affinity between the surface and the target pollutant; therefore, it requires less operational time and is more economically viable; Kinetic behavior generally presents stages, where the first is characterized by a high adsorption rate, closely related to the fact that the surface is unoccupied, corroborating the rapid accommodation of the contaminant molecules. In the second and third stages, the adsorption rate is considerably reduced until saturation. This occurs due to the difficulty of the molecules in finding a free site available on the surface of the biosorbent.
Stirring speed	Studies generally use agitation between 150 and 200 rpm, because an increase in agitation reduces the resistance to mass transfer, which corroborates with removal; A moderate agitation speed should be used in order to obtain suspension homogeneity, ensuring removal and not damaging the biomass; When using high rotations, it may corroborate with the occurrence of the vortex phenomenon. This is characterized by the loss of suspension homogeneity, leading to a reduction in the time during which the interaction between the pollutant and the solid occurs, which may negatively affect removal.
Available surface (biosorbent)	Generally, some modifications, such as treatments with strong acids, are carried out in order to alter the chemistry or physics of the biosorbent surface and increase removal. Natural biosorbents have the disadvantage of low surface area; carrying out additional treatments can increase this property, corroborating new pores for accommodation of the adsorbate; Increasing the dosage of biosorbent increases removal; however, this must be carefully sized, always in relation to the adsorption capacity. Excessive amounts of adsorbent generate economic losses and also make removal unfeasible, since they corroborate the phenomenon of particle agglomeration, making removal unfeasible.

2.5 Immobilized biosorbents

In order to increase pollutant removal at an industrial level, immobilized biomass is used. In the case of living biomass, cell freedom in continuous operation presents some limitations. These correspond to lower efficiency, loss of solid after regeneration, and difficulty in separating the solid and liquid phases (Ge et al., 2017; Xie et al., 2020). The advantages are related to the ease of collecting biomass and increased cell tolerance to extreme conditions (such as temperature and pH) (Vasilieva et al., 2016; Velkova et al., 2018). To immobilize the biosorbent in the liquid medium, it is possible to use some techniques and these can be chemical means or physical means (Ndaba et al., 2020). Table 2 highlights some of the most common methods used to immobilize microorganisms.

Table 2. Immobilization techniques for biomass with microbiological activity (Tan et al., 2017).

Method	Considerations
Adsorption	This is the simplest method used to immobilize microorganisms; Because it involves interactions of physical mechanisms, it is reversible; During the process, biomass may escape, corroborated by the weak interactions that occur.
Covalent bond	Due to the presence of covalent bonds, the stability of microorganisms during the process is high; The use of chemical reagents is related to the level of toxicity; After the process, a rapid decrease in microbial activity is observed.
Cross-linking	Macromolecules (of biological origin) are linked together through the presence of covalent bonds; Glutaraldehyde and bisdiazobenzidine are used as multifunctional reagents; Despite the versatility of the process, its control is difficult.
Encapsulation	The use of a polymeric gel of synthetic or natural origin is used to encapsulate the microorganisms; There is a limitation of the diffusion process due to the entrapment of the microorganisms (polymers).
Trapped in a matrix	This matrix that performs the trapping has high porosity and can be synthetic or even natural; The advantage of natural polymers is sustainability and a higher diffusion rate; Synthetic polymers have the advantage of being more stable; Mass transfer is limited; For the process to be successful, it is important that the carrier support has some characteristics, such as: favorable to mass transfer, high porosity in its structure, no inhibitory effect, low molecular weight, non-toxic and non-biodegradable in the experimental parameters used in the test; It is important that the matrix has a surface with irregularities that are favorable to colonization and with high physical, biological and chemical resistance.

3. Materials and methods

This literature review refers to the use of biosorbents for pollutant remediation, in order to support wastewater treatment. The entire manuscript was developed through a diverse analysis of recently published book chapters and articles. Both were verified in the scientific and engineering databases (Scopus, Ei compendex and Science direct). The methodology used comprises a systematic and integrative investigation. In this, the main effects that influence biosorption, the biosorbent materials used, the mechanisms of biosorption and the main wastewater pollutants were described. All these topics were described in a general and critical manner. The organization of the selected articles corresponds to the construction of tables organized into subgroups of biosorbents. The most relevant results obtained in each study are arranged within the tables, together with a discussion and critical analysis.

4. Results and discussion

4.1 Biosorption for removal of metal ions with living microorganisms

Table 3 includes several studies that used biomass of living microorganisms arranged in a liquid medium. Each of these studies analyzes the parameters and conditions of the medium used in the process and their respective removal/ adsorption capacity values.

Table 3. Main biosorbents used in the process of removing heavy metals by biosorption.

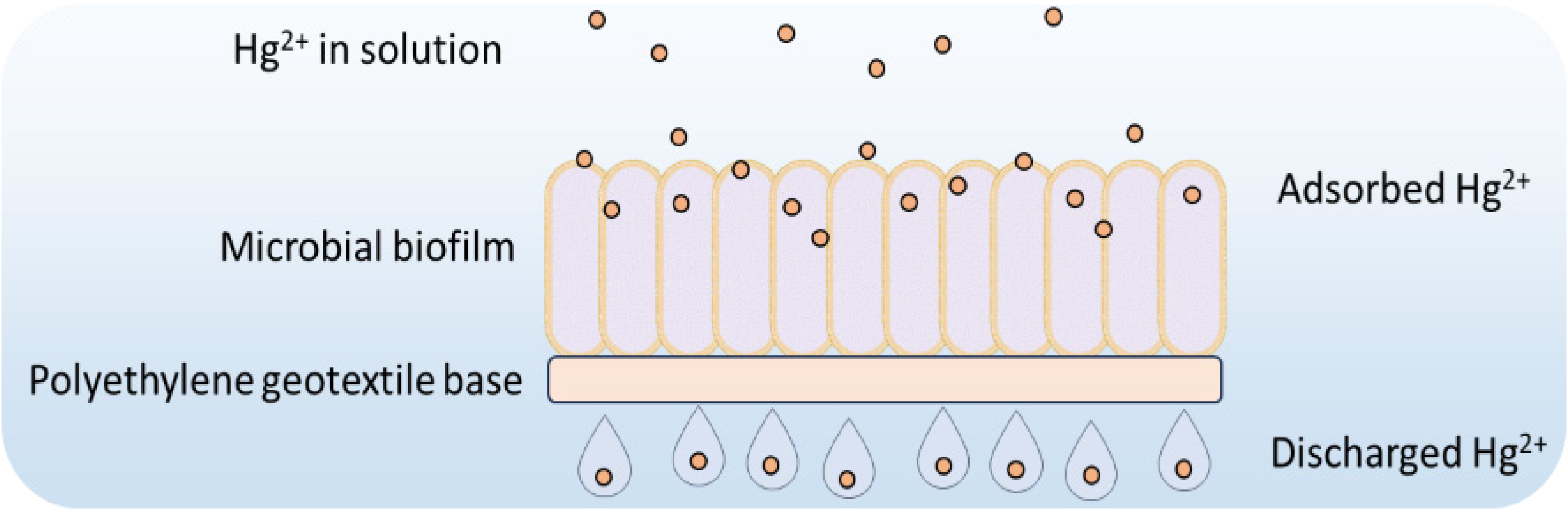
Biosorbent	Pollutant	R(%)/q_{max} (mg g^{-1})	Methodology used	Reference
Cyanobacteria *Synechococcus mundulus* (secreted substances)	Chrome (VI)	85%	Cyanobacteria were collected from a medium containing microalgae, and the secretion of polymeric substances was obtained through the use of gamma radiation. At a concentration of 100 mg L^{-1} of chromium, removal reached 85% after 48 hours of contact. The interactions of the metal cations with the anions on the surface of the biosorbent were possible due to the functional groups present in the proteins.	(Hussein et al., 2019)
Botryosphaeria rhodina (fungus)	Lanthanum (III)	100%	Lanthanum removal was analyzed using autoclaved fresh fungi and freeze-dried fungi. At pH levels between 5 and 7, maximum removal was observed for both materials. At pH 5, the removal of freeze-dried biomass was higher, being 100% for a concentration of 20 mg L^{-1} of metal. When the pH increased to 7, removal was 97%. Autoclaved biomass had removal rates of 87% and 97%, at pHs of 5 and 7, respectively. These results are due to high levels of H^+ protons in conditions close to 7, which compete with the positive groups of the metal, reducing removal.	(Giese et al., 2019)
Pseudomonas sp. (bacterium)	Cadmium (II)	92 mg g^{-1}	The effect of pH was analyzed on cadmium removal using dead and live Pseudomonas sp. For both biomasses, a pH of 7 was favorable for metal removal. With capacities of 92 and 63 mg g^{-1}, for live and dead biomass, respectively. Using low metal concentrations of 1 to 100 mg L^{-1}, the use of live biomass is promising for cadmium metal removal.	(Xu et al., 2020)
Microbial biofilm of bacteria	Mercury (II)	85%	At pH 5.5, mercury removal was maximum, reaching 85% through the application of biofilm. Removal was achieved in 120 min at a temperature of 298 K. The incubation time was 28 days using a low mercury concentration (1 mg L^{-1}). Increasing the metal concentration led to a decrease in biomass efficiency, where the greater occupation of the active sites led to inhibition of the interactions of the remaining adsorbates with the biomass.	(Fathollahi et al., 2020)
Bacillus amyloliquefaciens (bacterium)	Uranium (VI)	179 mg g^{-1}	The bacterial colonies were isolated and then placed in contact with 50 mg L^{-1} of uranium for remediation purposes. After a contact time of 3 hours and a pH of 6, the best adsorptive performance was obtained. The capacity of 179 mg g^{-1} demonstrated the high remediation potential of the species against radionuclide contamination.	(Liu, 2019)

Providencia sp. (bacterium)	Manganese (II)	291 mg g^{-1}	Bacterial colonies were collected from the soil and then isolated and used for manganese remediation. The good result of 291 mg g^{-1} capacity is related to the oxidation that occurred on the cell surface due to the presence of manganese ions. The interactions of the metal with the functional groups and the accumulated presence of manganese carbonate inside the cell were essential for the efficiency of the process. With the use of 150 mg L^{-1} of metal and at pH conditions of 7, the biosorbent showed complete saturation.	(Li et al., 2020)

As observed, biosorbents from living biomass showed good results against metal contamination. When analyzing the remediation of chromium (VI) using other biosorbents, it is observed that it is also compatible with other sources. The cultivation of the algae species Pseudopediastrum boryanum under optimal conditions using a photobioreactor was analyzed by removing chromium (VI) (Rani et al., 2019). Initially, the biomass was collected for subsequent drying and then used as a biosorbent, where the maximum removal was 70%; however, the adsorption capacity was low. The best results are highlighted in studies where the materials were synthesized in the laboratory using carbon nanotubes and graphene oxide, where the chromium (VI) capacities exceed values of 150 mg g-1 (Blagojev, 2019; Kulkarni et al., 2019). The disadvantage of using these adsorbents is the uncertainties surrounding their use and subsequent presence in the environment. In addition, they are not abundant and are more expensive when compared to biosorbents. The application of live biomass is associated with ideal conditions that must be rigorously maintained throughout the process in order to obtain high cellular metabolism, thus increasing the chances of efficiency (Escudero et al., 2018). Considering this aspect, conditions that present a high level of contamination can generate an environment that is not favorable to the growth and survival of microorganisms, which would lead to their death and operational failure (Zhang et al., 2020). Even if live biomass is not applied, it must be cultivated and stored under specific conditions in order to obtain a considerable volume of adsorbent for remediation tests. The number of tests must be compatible with the number of parameters to be analyzed. Despite the negative aspects, the application of living biomass has the potential for cellular bioaccumulation, which is not present in dead biomass. This allows its use in situ, less dependence on pH variation and less likelihood of generating secondary pollution with the emergence of intermediate compounds (Kalak et al., 2020). The use of living fungal biomass demonstrated high removal values for the metal lanthanum (III) (Giese, 2020). For the removal of the same metal, excellent results were also described with the use of living cells of the bacterial species Bacillus subtilis. In order to improve the properties of the material, it was subjected to chemical modification with sodium hydroxide (Ali and Bhakta, 2020). These cells were obtained from contaminated soil and stored under ideal conditions in the laboratory. After cultivation, the material was used to remove the metal. In other studies, sericin/alginate particles cross-linked by poly(vinyl alcohol) were synthesized and used to remove lanthanum (III) (Villen-Guzman et al., 2019). The adsorbent also achieved good removal, reaching 96%; however, since it is synthetic, it is not abundant in nature, so the use of chemical reagents is necessary to synthesize the material, which increases the cost of obtaining it. Therefore, the use of living material, or its mixture with dead material obtained in cultivation, as for the synthesis of new materials that require prior preparation, must go through prior procedures to obtain the material of interest for later use in adsorption tests. When choosing the adsorbent, the synthesis time to obtain it, the costs involved in the synthesis of modification, whether with inorganic or organic products, the costs of cultivation in the biomass, and all secondary pollution that may be generated during the process must be taken into account. In the case of lanthanum (III) remediation, it is important to compare the methods in order to select the ideal adsorbent. Here, factors such as saturation kinetic time and cost-benefit must be analyzed together.

In the case of cadmium (II) adsorption, a study analyzed and compared the removal using live biomass and dead biomass, both obtained from bacterial matter (Xu et al., 2020). The authors highlight that at low adsorbate concentrations, the live biomass was more efficient. The smallest part of the metal was bioaccumulated inside the cell, and the largest portion in the cell wall; maximum efficiency was obtained after 48 hours of operation. The plant species Sorghum bicolor was grown in a field and characterized in the laboratory in order to analyze its removal potential in line with its high surface porosity (Dinh et al., 2021). To optimize the results, the biomass underwent a modification with the use of thiourea, which corroborates the increase in the number of interactions between the pollutant and the biomass. However, the authors highlight a low adsorption capacity of only 17 mg g-1. One difference with the previous study is that the bioaccumulation mechanism is barely present in this study, which may justify the low performance. These performance discrepancies may be related to textural differences such as surface area and the types and numbers of functional groups present on the surface. Another point to be observed is that the adjustments to isotherm models were diversified between live and dead biomass. The Freundlich model corresponds to adjustments obtained by dead biomass, while the Langmuir model corresponds to adjustments obtained by live biomass. The first model corresponds to multilayer adsorption, causing a greater amount of pollutant to be retained on the cell surface, while the Langmuir model corresponds to a surface that adheres the pollutant through the formation of monolayers. Researchers synthesized a graphene oxide material covered with silica, the method of obtaining which used a toxic material, potassium permanganate (Wang et al., 2021). The initial test reported a capacity of only 42 mg g-1, which is lower than the study shown in Table 3. Another alternative for remediating metals is the application of microbial biofilms where the colonies of microorganisms are adhered to the surface in order to remediate mercury (Fathollahi et al., 2020). In this mechanism, part of the metal remains adhered to the biofilm together with the geotextile filter barrier that prevents the passage of the metal. Figure 6 demonstrates the mercury retention scheme in the biofilm containing a geotextile filter.

Figure 6. Biosorption process in a biofilm. Adapted from (Fathollahi et al., 2020).



Mercury removal was also analyzed using algae biomass, where its surface area and certain strategic functional groups were essential for removing the metal (Nishikawa et al., 2018). Under optimal conditions, removal reached 93% through a batch study and with free circulation of the liquid medium, conditions similar to the other study that used an immobilized membrane. It is worth noting here that the way the biomass is located during the process can create more obstacles to its future application in the treatment of real industrial waters. This is because collecting the adsorbent or free pollutant is more difficult, which generates wasted time and additional costs.

4.2 Application of the biosorption process for the removal of metal ions from agro-industrial waste

In addition to releasing large amounts of contaminants into their effluents, various industrial activities are also responsible for producing large volumes of waste or by-products that, in most processes, are not reused and are improperly deposited on land intended for such disposal. These areas generate contamination at the water table level due to leaching from infiltration that occurs during periods of rainfall, as well as atmospheric and visual contamination. These areas end up becoming uninhabitable since they generate odor and accumulate animals and insects. All these aspects corroborate the need to use these biomasses to capture pollutants, resulting in the circumvention of both existing problems. The literature presents a multitude of wastes, mainly of vegetable origin, that have been used to remove pollutants, especially dyes (Georgin et al., 2022a; Pang et al., 2020; Sellaoui et al., 2023; Yamil et al., 2021). When considering large-scale adsorption, the volume and availability of the solid are important, since in fixed bed conditions the amount of adsorbent required to fill the column is large. Industries are one of the major culprits of pollution, including dyes, which have physical and chemical properties that, depending on their composition, can be highly toxic, especially those used in the textile industry. Table 4 describes the waste biosorbents obtained from various industrial sectors, including alcoholic beverage producers, food producers, agricultural sectors and the timber sector. Among these sectors, the part originating from agro-industrial activities is the most analyzed and has shown excellent remediation results against heavy metal pollution. Thus, there is a significant range of agro-industrial wastes being used to remove metal ions in solution, regardless of their origin.

Table 4. Main agro-industrial waste used as biosorbents in the removal of pollutants in wastewater.

Biosorbent	Pollutant	R(%)/qmax (mg g-1)	Methodology used	Reference
Wood residue	Copper (II)	178 mg g-1	Sawdust is a common waste from the wood industry. It was collected and subjected to three preparation methods. The first sample was subjected to boiling, where the boiling of distilled water sought to eliminate possible components that were harmful to adsorption. Then, the solid was separated and dried by filtration. In the second, formaldehyde was mixed with the sawdust, then washed several times until neutral pH. In the third, the sawdust was treated with sulfuric acid, being diluted in distilled water after removing impurities and washed until neutral pH. The maximum capacities were obtained at pH 5.8, being: 98 mg g-1, 178 mg g-1 and 142 mg g-1, for the sample treated with boiling, followed by formaldehyde and finally sulfuric acid, respectively.	(Rani et al., 2019)
Beet peel	Chrome (VI)	30%	An agribusiness sector that generates tons of beet peel waste provided a sample for analysis in metal removal. The best performance was in acidic conditions. In these conditions, chromium is present in anionic form, while the surface presents a high number of protonated groups, corroborating electrostatic interactions. Removal was not very efficient, remaining at around 30%.	(Blagojev et al., 2019)
Waste from the beer industry	Nickel (II)	49%	The residues were obtained from beer industries and contained yeast. Nickel was better adsorbed at pH 5. The existence of a large number of negative charges in the adsorbent corroborated the interactions with metal cationic ions. Above pH 7, removal is not feasible due to the generation of hydroxides that inhibit electrostatic physical interaction. The maximum removal of 49% was observed at a concentration of 10 mg L^{-1}, for a temperature of 30°C and dosage of 4 g L^{-1}.	(Kulkarni et al., 2019)
Grape residue	Silver (I)	61 mg g^{-1}	Wineries produce a large volume of residue containing grape pomace, seeds and stems. The three residues were separated and analyzed, where the optimum dosage of 3 g L^{-1} and pH of 7 was ideal for both residues. The silver adsorption capacities were 41 mg g^{-1}, 61 mg g^{-1} and 46 mg g^{-1}, for the residues from grape skins, seeds and stems, respectively.	(Anastopoulos et al., 2019)
Residual biomass from polyglutamic acid production	Chrome (VI)	96 ± 0.45%	Waste generated by microbial fermentative production of polyglutamic acid. The bacteria *Bacilus subtilis* compose the biomass. It was used in an immobilized form in order to corroborate the separation of the aqueous solution. This also allowed greater efficiency, control and stability. The concentration of 200 mg L^{-1}, at pH 7, dosage of 2 g L^{-1} and saturation time of 60 min, obtained the highest removal efficiency.	(Zhang et al., 2020)
Elderberry pomace (*Sambucus nigra)*	Iron (III)	99%	A food industry generates a large volume of elderberry residue. A sample was analyzed for iron removal at a concentration of 2 to 22 mg L^{-1} for a dosage of 50 g L^{-1} of biosorbent. The best efficiency was 99%. This was possible using 100 g L^{-1} of adsorbent and in acidic conditions (pH = 2) and a concentration of 10.6 mg L^{-1}, with a maximum capacity of 33 mg g^{-1}. The organic groups allowed electrostatic interactions of the metal with the surface of the solid.	(Kalak et al., 2020)

4.3 Application of the biosorption process for the removal of metal ions using inactive microorganisms

Various materials that do not present microbiological activity were used to remove heavy metals. Table 5 describes the various experimental conditions used in the studies and the efficiency values.

Table 5. Examples of dead biosorbents used to remove metals in wastewater.

Biosorbent	Pollutant	R(%)/q_{max} (mg g^{-1})	Methodology used	Reference
Leaves of *Corchorus olitorious*	Zinc (II)	65%	Zinc was removed using a low-cost plant-based material. Maximum removal was achieved at pH 6, above which the removal rate decreased drastically. This is due to the generation of zinc hydroxide, which is insoluble in water. The highest removal rate was achieved at a concentration of 3 mg L^{-1} and a dosage of 2 mg L^{-1}. Above this value, particle agglomeration occurred and adsorption was severely impaired.	(Ali and Bhakta, 2020)
Lemon peel	Nickel (II)	36 mg g^{-1}	The residual lemon peels were obtained from three different locations, both were treated with sodium hydroxide and used for comparison in the removal of nickel. The removal was gradually increased up to a dosage of 5 g L^{-1}, after which agglomeration occurred and it was no longer possible to increase the removal. No differences in performance were observed between pH 2 and 6, therefore, the natural pH close to 5 was selected. The three biomasses did not present differences in capacities, with the maximum value of 36 mg g^{-1} obtained at a concentration of 200 mg L^{-1}.	(Villen-Guzman et al., 2019)
Orange peel	Lead (II)	47 mg g^{-1}	The orange peel showed high affinity for lead removal, since the maximum capacity was obtained with only 120 min of contact and with a pH of 5.5. The maximum concentration used of 80 mg L^{-1} obtained a capacity of 47 mg g^{-1} using approximately 0.1 g L^{-1} of adsorbent.	(Sharifpour et al., 2020)
Garlic peel	Iron, cerium and titanium	91, 84 e 83 mg g^{-1}	Iron, titanium and cerium ions were adsorbed on the surface of tungsten (VI) modified garlic peel. All optimum conditions occur at acidic conditions with pH less than 4. The maximum capacities were 91 mg g^{-1}, 84 mg g^{-1} and 83 mg g^{-1} at pH 2.5 for iron, cerium and titanium, respectively.	(Wang and Huang, 2020)
Brown seaweed	Cadmium (II)	0.75 mmol g^{-1}	Brown seaweed *Sargassum filipendula* was modified, where the maximum capacity of 0.75 mmol g-1 occurred at pH 3.5. The system is endothermic where the temperature rise to 50°C corroborated the adsorption of the metal.	(Nishikawa et al., 2018)

4.4 Application of the biosorption process for the removal of different organic pollutants

Organic pollutants represent a wide range of pollutants that constantly damage the environment and threaten the survival of future generations. In this sense, various biomasses with or without microbiological activity have begun to remove these contaminants. When it comes to removing organic molecules, the complexity is slightly higher when compared to metals, since the greater variety of chemical groups can make accommodation difficult, avoiding interactions with the surface of the solid. Table 6 describes various contaminants of organic origin that were remediated with biomasses under different experimental conditions.

Table 6. Examples of biosorbents used in the removal of organic compounds in wastewater.

Biosorbent	Pollutant	R(%)/ q_{max} (mg g^{-1})	Methodology used	Reference
Luffa cylindrica (vegetable sponge)	Phenol	28 mg g^{-1}	The material was initially separated into small fibers, then a sample was mixed with zinc nitrate (4% zinc and alternating current) and used in phenol remediation. Compared to other hybrid materials, the capacity of this material was superior, being 28 mg g^{-1} for a concentration of 30 mg L^{-1} of phenol. The modification increased the number of possible interaction sites.	(Mbarki et al., 2021)
Fungal-bacterial biofilm	Acetylsalicylic acid	292 mg g^{-1}	Two activated carbons were used to support a fungal-bacterial biofilm. The first is made from coconut fiber and the second is made from the bark of tree fruits (*Hymenaea stigonocarpa*). The combination of charcoal fibers from tree residue with the biofilm increased the adsorption power by approximately 57%. The one containing coconut charcoal obtained a smaller increase of 32% in the adsorption efficiency. The maximum capacity of the biofilm with charcoal obtained a maximum capacity of 292 mg g^{-1} value obtained in acidic conditions (pH=3.5).	(Bó et al., 2019)

Phaeocystis globosa (microalga)	Nonylphenol	66%	At a concentration of 1 mg L^{-1}, the microalgae with microbiological activity obtained an adsorption capacity of 441.8 µg L^{-1} for a 24-hour process time. This performance is equivalent to 43% removal efficiency. After 5 days, this value increased to 66%, using a concentration of 2.5 mg L^{-1}.	(Wang et al., 2019)
Scenedesmus obliquus (green microalga)	Salicylic Acid and Ibuprofen	63mg g^{-1} e 12mg g^{-1}	The adsorption of acid and drug on the surface of green microalgae corresponds to the pseudo-second order kinetic model and the Langmuir isotherm. The drug obtained the lowest removal performance with a capacity of 12 mg g^{-1}, much lower than that of the acid, which was 63 mg g^{-1}.	(Silva et al., 2020)
Moringa oleifera	Diuron (herbicide)	47%	The herbicide diuron was removed by applying fruit peels. Under basic conditions (pH=10), it was possible to generate negative charges on the adsorbent that adsorbed the diuron molecules with opposite charges. The mechanism was governed by hydrophobic interactions, for a maximum removal of 47% at a concentration of 5 mg L^{-1} of diuron.	(Wernke et al., 2020)
Ulva fasciata and *Sargassum dentifolium* (macroalgas)	Methylene blue	244 mg g^{-1}	Two different species of seaweed were used to remove methylene blue from solution, which were washed, dried and ground in a ball mill to obtain micro-scale size. The seaweed species *Ulva fasciata* achieved better results, removing 97% of 328 mg L^{-1} of methylene blue with a maximum adsorption capacity of 244 mg g^{-1}, while the species *Sargassum dentifolium* performed slightly worse, achieving the removal of 85.6% of 26 mg L^{-1} of methylene blue with a maximum adsorption capacity of 66.6 mg g^{-1}. The pH value showed no change in the results, so a value equal to 7.0 as the optimum pH was used.	(Moghazy et al., 2019)
Kappaphycus alvarezii, Gracilaria salicornia and *Gracilaria edulis* (macroalgas)	Rhodamine B	112 mg g^{-1}	In the adsorption of rhodamine B, three species of marine algae were used, which were washed, dried and ground to obtain powder form. They were tested under normal conditions and modified with ethanol. The maximum biosorption capacity found was 9 mg g^{-1} (KA), 11 mg g^{-1} (GS), 8 mg g^{-1} (GE), 112 mg g^{-1} (EKA), 105 mg g^{-1} (EGS) and 97 mg g^{-1} (EGE), respectively for the removal of RB from aqueous solutions. The best removal yield of rhodamine B was observed at pH value equal to 2.	(Selvakumar 2019)
Fucus vesiculosus (macroalga)	Eriochrome T and methylene blue	698 mg g^{-1} and 24 mg g^{-1}	The microalgae F. *vesiculosus* was applied to remove methylene blue and eriochrome T dyes. The biomass demonstrated a maximum biosorption capacity of 698 mg g$^{\square 1}$ for methylene blue and 24 mg g$^{\square 1}$ for eriochrome T. The kinetic evaluation indicated that the pseudo-second-order model was the most appropriate for the data obtained. The optimization of the model aimed to increase the efficiency in the removal of pollutants, resulting in 99% removal of methylene blue and 99% of eriochrome T.	(Lebron et al., 2021)

5. Recommendations and future perspectives

The recommendations in the area of adsorption using biosorbents are as follows: Diversification of Materials, that is, encouraging research and development of different types of biosorbents, including agro-industrial waste, microalgae and fungi, to increase efficiency in pollutant removal; Optimization of Operating Conditions, with the performance of systematic studies on operating conditions (pH, temperature, contact time) to maximize the adsorption efficiency of biosorbents; Economic Assessment, in this aspect, conducting cost-benefit analyses to assess the economic viability of using biosorbents compared to conventional treatment methods; more scalability studies, therefore, investigating the scalability of biosorption processes, from the laboratory to large-scale application, ensuring effectiveness in different contexts; Focusing on the reuse and regeneration of biosorbents after the adsorption process, contributing to sustainable practices; and multidisciplinary integration by promoting collaborations between different disciplines, such as biotechnology, chemistry and environmental engineering, to enrich research and innovation in the area. Future perspectives involve technological advances with the incorporation of new technologies, such as nanotechnology and biotechnology, which can enhance the effectiveness of biosorbents and open up new application possibilities. The development of smart biosorbents with materials that respond to changes in environmental conditions or that have adaptive properties can revolutionize adsorption. Researchers should conduct studies of adsorption mechanisms with further investigation of the interaction mechanisms between biosorbents and pollutants, allowing for more effective design of materials. The expansion of applications with a view to exploring the application of biosorbents in the removal of emerging pollutants, such as pharmaceutical micropollutants and industrial chemicals. Changes in the sphere of Public Policies and Regulations to support the formulation of public policies that encourage the use of biosorbents and promote more sustainable water treatment practices, and finally education and awareness, raising awareness about the importance of using biosorbents in wastewater treatment processes, engaging the academic community and the industrial sector. These recommendations and perspectives can help to boost research and development of biosorbents, promoting innovative and sustainable solutions for the treatment of pollutants in wastewater.

6. Conclusion

The literature review revealed encouraging results regarding innovations in the removal of pollutants from wastewater. Biosorption technology offers a variety of combinations for the use of different biomasses in the adsorption of contaminants. The effectiveness of the biomass should be weighed against the time required for the biosorption process, as well as the costs, availability and possibility of reuse. In this sense, biosorption is positioned as a promising alternative to conventional wastewater treatment methodologies. The data obtained indicate a high selectivity of biosorbents in the removal of several organic pollutants, including metal ions and dyes, through investigations on adsorption equilibrium and kinetics, which help in the understanding of the mechanisms underlying the biosorption process.

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