

Review

Biosorption: A Review of the Latest Advances

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Abstract: Biosorption is a variant of sorption techniques in which the sorbent is a material of biological origin. This technique is considered to be low cost and environmentally friendly, and it can be used to remove pollutants from aqueous solutions. The objective of this review is to report on the most significant recent works and most recent advances that have occurred in the last couple of years (2019–2020) in the field of biosorption. Biosorption of metals and organic compounds (dyes, antibiotics and other emerging contaminants) is considered in this review. In addition, the use and possibilities of different forms of biomass (live or dead, modified or immobilized) are also considered.

Keywords: biosorption; biomass; bioaccumulation; biocomposite; pollutants; metals; emerging organic contaminants; dyes

1. Introduction

Biosorption is a variant of the sorption techniques in which the sorbent is a material of biological origin. Today, biosorption is considered a simple, economical and environmentally friendly process that is used as an attractive alternative for removing pollutants. Within this context, biosorption is a general term that describes the removal of pollutants by their binding to a material of biological origin (biomass). There have been numerous biosorption studies in the last decade, and advances in this field have reinforced the interest in this technique to solve environmental pollution problems. The existing information on biosorption is abundant due to the large number of works that are published to test the validity of certain materials as biosorbents or to develop more complex hybrid materials that can be more efficient for this purpose. This review aims to evaluate the latest contributions (in the last couple of years: 2019–August 2020) in the field of biosorption. Although biosorption is a mechanism that also acts in soil decontamination, this review will focus on biosorption processes from aqueous solutions.

2. Biosorption: Generalities

The main element of a biosorption process is biomass. The term biomass is a very broad term that includes intact living cells and derived compounds of biological origin with different degrees of transformation (waste, charcoal, etc.). Taking this into account, the use of biological materials as sorbents has an important alternative: this biomass can be alive or dead. In the case of dead biomass, the pollutants passively (metabolism-independent) bind to this type of biomass through ionic, chemical or physical mechanisms (biosorption); however, with living biomass, the process is more complex because the metabolic activity of this biomass is added to the passive mechanisms. This metabolic activity allows the active transport of pollutants through the membrane into the cell interior. In this way, pollutants can accumulate inside the cell (bioaccumulation). Furthermore, since the enzymatic activity is preserved in living biomass, there is also the possibility that different enzymatic activities may alter the state of the pollutant (biodegradation and biotransformation).

Considering the previous information, the use of living biomass as a biosorbent would have more possibilities to remove a greater amount of pollutants, which constitutes an important advantage when

using this type of biomass. However, other advantages and disadvantages must be considered in the use of one type or another of biomass. Most applications focus on the use of dead biomass because toxicity related problems are avoided, no maintenance is required, this biomass can be stored for long periods without loss of effectiveness, regeneration is more feasible and it is possible to work on a greater range of environmental variables. In addition, this biomass can be cut and ground to obtain a suitable particle size. However, despite all these advantages of dead biomass, the use of living biomass can have an important advantage, since, as indicated above, the cells are metabolically active, so the pollutants can be incorporated into the cell interior increasing the efficiency of the process because bioaccumulation contributes to the initial biosorption process [1,2]. In this case, there would be a first step, independent of metabolism, in which the pollutant would bind to the cell surface (biosorption in the strict sense), and a second step, dependent on metabolism, in which the pollutant is transported through the cell membrane to the cell interior. At this step, it must be taken into account that some pollutants could also pass through the membrane by passive diffusion. In many cases, the term biosorption is used in a general way to include both steps when using living systems, although both steps are different.

Continuing with the advantages and disadvantages of living biomass, an additional advantage that active systems have is that there is also the possibility of biotransformation or biodegradation, increasing, in some cases, the ability to eliminate a higher amount of pollutant [3–7]. However, there are also disadvantages that can be attributed to the use of living biomass. Thus, it must be considered that to use living biomass it is necessary to have culture systems, nutrient supply and some method for cell harvesting, which makes the process more expensive. However, dead biomass can also have additional costs, since, in some cases, this type of biomass is chemically modified, carbonized or ground to make it more effective, which does not apply to living biomass. Additionally, living biomass is easier to separate from a reaction system.

In any case, an important aspect to consider in order to achieve the advantages of living biomass can be effective is to look for those organisms that show greater resistance to the toxic effects of the pollutant. Hence, this is a first step to optimize a biosorption/bioaccumulation process using living biomass. Strains more resistant to the target pollutant can have a greater removal capacity; a recent example is the use of a strain of *Pseudomonas* sp. with resistances to multiple heavy metals for cadmium removal; this resistant strain used as living biomass was more effective than the dead one [8]. In this sense, there is currently a growing interest in the use of microorganisms as base material to develop biosorbents due to their good sorption properties and resistance to the toxic effect of pollutants. Various species of fungi, bacteria, yeast and microalgae have been tested against many types of pollutants with very promising results [4,8–13].

In addition to biomass from microorganisms, as indicated above, a large number of materials have been evaluated as biosorbents to eliminate different pollutants, among the most recent are: agro-industrial waste materials [14], sludge [15,16], polysaccharides [17], plant-derived materials [18–20] and biopolymers [21]; although it is necessary to indicate that throughout the years of development of biosorption, a large number of biological materials of very diverse origin have been evaluated as possible biosorbents [22,23]. Many of these materials are considered as waste: for this reason, the use of these materials as biosorbents has a double advantage, on the one hand, a waste is used for an application, and therefore, its waste is reduced; on the other hand, this material is used to eliminate pollution with a possible low cost.

These biomaterials can be applied directly or immobilized on different supports. Recently, there has been an increase in the number of studies applying biomaterials packed in fixed-bed columns [24,25]. This technique offers advantages for practical applications of large-scale biosorption processes because it allows continuous work. Thus, to operate with these columns, the biomass must be immobilized, which is necessary when using biomass from microorganisms. A common alternative (which can even be used with living cells) is to immobilize the biosorbent in a calcium alginate matrix [6,26,27]. Immobilization allows the biomass to be retained in a reactor, reduces separation costs and increases the

mechanical resistance of the biomass. In this context, although biosorption/bioaccumulation techniques are usually simple, more complex systems have now been developed, forming biocomposite materials with new characteristics. These materials with polymeric structures allow to protect and maintain the viability of living systems, which makes it possible to take advantage of the highest efficiency of these systems. An example of this was the use of biomass from *Lysinibacillus sphaericus* CBAM5 immobilized in polycaprolactone microfibrinous mats and alginate microcapsules to capture gold from synthetic water samples [28]. Although the application of nanoparticles in the field of biosorption has been developing for a long time, more recently the application of magnetic nanoparticles as a support for the immobilization of microorganisms has also been assessed, as evidenced in the review by Giese et al. (2020) [29].

Another way to use biomass is by its chemical modification to increase the sorption capacity. These modifications alter the functional groups of the biomass and its surface topography favoring the binding of pollutants. Some examples have recently been published in which different modification methods are used, such as esterification, graft polymerization, coating, treatments with acids, alkalis, methanol, cationic surfactants, formaldehyde or triethyl phosphate and nitromethane [30–33]. Although these modifications apply to dead biomass, living biomass can also be modified, but in a very different way, by genetic modification, which allows the introduction of genes into the desired biomass that increase resistance to the toxic effect of certain pollutants, or that increase the uptake of the pollutant (several examples with metals have recently been published) [34–36].

Although biosorption alone is an effective technique, its flexibility allows coupling with other techniques. For example, biosorption allowed to replace expensive materials used in anodic oxidation processes with plant material [37]; in this way, hybrid materials are created increasing the efficiency of biosorption [38].

Since biosorption requires an interaction between the biomass and the pollutant (usually multiple interactions coexist), those factors that influence this interaction will influence the efficiency of the process. Interactions such as ion exchange, complexation/coordination, electrostatic interactions, chemisorption, physisorption, microprecipitation and reduction can be established in a biosorption process. Taking this into account, factors such as pH, temperature (thermodynamic studies), contact time, shaking speed, initial concentration of the pollutant or amount of biosorbent are well known and are evaluated to optimize the biosorption process [23]. However, there are other less studied factors that have an impact on the process—for example, the type and amount of functional groups in the biomass such as carboxyl, amino, phosphoryl or sulfonate and that influence the biosorption of some pollutants (mainly metals) [9,31,39], ionic strength [40], presence of dissolved organic matter that alters the absorption of metals [41] or the competition with other pollutants [40,42,43]. When using a living system, it is necessary to consider other factors such as the response to the possible toxicity of the pollutant [44,45].

It is evident that the nature of the biosorbent determines many of its physico-chemical properties, such as the type and quantity of functional groups, but there are other aspects that are also especially relevant in the process, such as surface area (increasing the surface area increases the contact of the sorbate with the sorbent), porosity (mesoporosity increases the biosorption capacity, while microporosity decreases it) or cell structures (different structures have different physico-chemical characteristics) [39,46,47]. The characterization of the material in terms of its morphology and composition are common in biosorption studies because they allow a more detailed description and provide information on the sorption mechanisms. Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDS) are methods commonly used for this purpose. Thermogravimetric test, elemental analysis, zeta potential and point of zero charge (pHzpc) measurement are alternative parameters that also provide information on the physico-chemical characteristics of the biosorbent. Recently, an electrokinetic method termed as dielectrophoresis (DEP) was applied for the characterization of biosorption [48].

Kinetic and isotherm models are used for the mathematical modeling of the biosorption processes. Traditionally, the most widely used kinetic models are pseudo-first order [49], pseudo-second order [50] and intraparticle [51]. From these models, different parameters are obtained that allow characterizing the speed of the process, time to reach equilibrium or even determine which stages of the process may be limiting. Currently there are other kinetic models that are being used and that are useful to characterize biosorption processes such as the kinetics Brouers-Sotolongo family model [38,52]. Regarding the isotherm models, the Langmuir [53] and Freundlich [54] models are still the most widely used.

The search and evaluation of new biosorbents is a current challenge in this field. These new biosorbents must be more efficient, economical and have good reusability through various application cycles. Although this last property is desired for many sorbents, in the case of biosorbents (used as dead biomass) it can be considered non-essential because, precisely, a property of these materials must be their low cost. Instead, it is important that these materials prove their worth under real application conditions.

Everything said above shows the great interest in applying biosorption-related techniques to solve pollution problems. However, the interest of biosorption goes beyond its usefulness as a pollutant remover: biosorption techniques even allow the recovery of some useful substances. Since many of the mechanisms involved in biosorption are reversible, there is the possibility of recovering the biosorbed materials, and at the same time regenerating the biosorbent. An example of this application is the rare-earths recovery: these high-value elements can be effectively recovered using biosorption techniques as an alternative to the conventional unit operations of extractive metallurgy [55].

Today, the validity of biosorption, with all its advantages, is more than demonstrated; the great challenge is to apply this technique to more real situations. In the vast majority of studies, the biosorption process is carried out in distilled water, where the pollutants to be tested are solubilized, and there are few examples where biomass is applied to more real situations [56,57].

3. Biosorption of Metals

Metal biosorption is among the most studied applications of this technique. In fact, the first applications of biosorption focused on metal removal [58,59]. For decades, metals have been a serious environmental problem due to human activity [60–62]. For this reason, the development of techniques that allow their removal has been a priority. Biosorption is a very effective, economical and environmentally friendly technique to remove these pollutants, and at present, different methods have been evaluated based on biosorption [22,63].

Ion exchange is the predominant mechanism for metal biosorption along with surface complexation and microprecipitation [46,55,64]. Various functional groups are involved in the biosorption of metals, carboxyl, hydroxyl, sulfate, phosphoryl and amino groups [31]. Because of this, pH has an important effect on the biosorption of metals. The pH affects the charge of these functional groups and, therefore, the amount of biosorbed metal. Since cationic species are among the predominant forms of most metals in aqueous solution, the more negative charge the biosorbent has, the greater the amount of biosorbed metal. For this reason, the most suitable pH range for metal biosorption is 7.0–8.0. At lower pHs, hydrogen ions and metal ions compete for binding sites; and at higher pHs, there is precipitation of metal ions in the form of hydroxides, reducing the amount of biosorbed metal. However, this behavior is different for the case of some metals whose predominant forms are anionic, such as chromium, arsenic or molybdenum, among others. In this case, acidic pHs (2.0–4.0) are the most favorable for increasing biosorption because at these pHs the biomass has a greater number of positive charges, which allows the attraction of anions.

Although pH is considered a key factor in this process, temperature also influences biosorption since this parameter affects the rate of reactions. Higher temperatures usually enhance biosorption rate due to the increase in surface activity and kinetic energy of sorbate [65]. However, its effect on the maximum amount of biosorbed metal is debatable. It is generally accepted that the increase in

temperature increases the maximum amount bioadsorbed, which occurs when the process is endothermic, and is due to various factors such as structural changes in the sorbent or breakdown of bonds between the sorbent molecules; however, there is also some exceptions, which take place when the process is exothermic. In this case, there is a decrease in biosorption capacity with an increase in temperature, possibly due to damage caused to the surface of the biosorbent [30,66,67]. With dead biomass, this effect of temperature is less apparent than with living biomass. With living biomass, as the temperature increases, the amount of bioadsorbed metal increases more appreciably than in the case of dead biomass [68,69]. The reason is the greater metabolic activity of living cells when the temperature increases until an optimum value, causing the metal to be incorporated in a higher amount into the cell interior. When the temperature exceeds the optimum value, the living material is damaged and the biosorption decreases to a greater extent in relation to the dead biomass [27]. Finally, an increase in ionic strength reduces the amount of bioadsorbed metal due to competition of other cations for the binding sites on the functional groups [70]. This is a major drawback when applying biosorbents in real effluents that are often characterized by complex concentrations of different cations.

Precisely, materials derived from biomass are characterized by offering a large and diverse number of functional groups that interact with metals (carboxyl, hydroxyl, sulfate, phosphoryl and amino groups, as indicated above), which explains the good performance of these materials as biosorbents in metal removal. Of special interest is biomass derived from algae because it has a relatively high adsorption efficiency of 1–10 g/L [71]. As an important additional property, biomass derived from microorganisms can be easily genetically modified to increase the biosorption capacity. This strategy is receiving a lot of attention recently to increase metal removal. Thus, the expression of the EC20 protein (a synthetic phytochelatin) on the surface of various bacteria was used in Pb, Zn, Cu, Cd, Mn, Ni and, recently, in Pt biosorption [34]. In the same way, the expression of a non-MT cadmium-binding protein from *Lentinula edodes* significantly enhanced the cadmium biosorption capacity of transgenic *Escherichia coli* [35]. The transformation of the wild-type *Saccharomyces cerevisiae* with two versions of a *Populus trichocarpa* gene (PtMT2b) coding for a metallothionein allowed an increase in the intracellular content of cadmium in relation to the wild strain [36].

Another aspect to take into account when applying biosorption to metal removal is that biosorption not only serves to remove these elements but also allows their recovery, which increases interest in this process [72]. This application can be extended to an industrial scale, for which the sorbent must have adequate properties. Precisely, one of the interesting properties of biomass is that it can be easily modified to adapt it to commercial and industrial uses [73].

Metal biosorption studies cover most commonly used metals, but metals considered non-essential are the ones that have received the most attention. Numerous studies on metal removal continue to be carried out today using different biosorbents.

3.1. Chromium (VI)

Chromium is the metal that has received the most attention lately for its removal through biosorption (Table 1).

Table 1. Recent chromium (VI) biosorption studies using different biomasses.

Biomass	Chromium Concentration (mg/L)	Contact Time (min)	Efficiency (mg/g)	Remarks	Reference
Waste biomass from polyglutamic acid production	50–400	60	2.39	Immobilized in sodium alginate	[74]
Date palm empty fruit bunch	50–250	120	70.49	Batch studies	[75]
<i>Datura stramonium</i> fruit	100–300	60	138.074	Carbonized form of sulfuric and phosphoric acid-treated biomass	[76]
<i>Halomonas</i> sp. DK4	50–250	2880	150.7	Batch studies	[77]
<i>Zhihengliuella</i> sp. ISTPL4	50–500	1440	49 ± 0.3	Calcite-based biocomposite biochar	[78]
Coconut fibers	100	20	87.38	Magnetized using magnetite nanoparticles	[14]
<i>Quercus crassipes</i> acorn shell	50–400	-	110.35	Fixed-bed column	[79]
<i>Leiotrametes flavida</i>	1000	1200	285	Live and heat-inactivated	[80]
<i>Sargassum horneri</i>	100–600	360	330.84	Polyethyleneimine-modified ultrasonic assisted acid hydrochar	[81]
<i>Pteris vittata</i>	100–250	120	166.7	Dead, unmodified	[82]
<i>Synechococcus mundulus</i>	75–175	2880	- 85.89% - Initial Cr(VI) concentration of 300 mg/L	Extruded polymeric substances secreted under the effect of 2-KGy gamma irradiation dose	[17]
<i>Agaricus campestris</i>	10–100	200	56.21	Unmodified dead biomass	[83]
<i>Pleurotus ostreatus</i>	10–150	22	- Living biomass: 169.84 - Dead biomass: 368.21	Living and dead biomass	[84]
<i>Pseudomonas</i> sp. strain DC-B3	10–135	420	25.64	Living cells	[85]
<i>Kodamaea transpacificca</i>	10–100	240	476.19	Cationic surfactant-modified living cells	[86]
<i>Parapedobacter</i> sp. ISTM3	10–200	15	33.78	Extracellular polymeric substances	[87]
<i>Eupatorium adenophorum</i>	10–300	60	28.011	Calcium alginate entrapped	[26]

As can be seen in this table, the biological materials that have been evaluated are very diverse and show very good efficiency. The strategies using these different biomasses were also very varied since they range from typical batch experiments to continuous flow systems, immobilization techniques or more sophisticated modifications of the biomass, which demonstrates the versatility of biosorption.

The main mechanisms involved in the biosorption of Cr(VI) are related to electrostatic attraction, surface complexation and heterogeneous redox reaction to form Cr(III) ions [75]. In addition, in chromium biosorption processes, it is necessary to consider that this metal, unlike most metals, is in the form of anions. This means that the behavior towards biosorbents is different. In this case, the range of pHs considered optimal to carry out biosorption is 2.0–3.0 [14,26]. At low pHs, the biomass surface is highly protonated, offering a large amount of positive charges that attract chromium anions. Obviously, this pH range cannot be used with living biomass; however, the biological activity of this type of biomass can compensate for this inconvenience, especially using resistant strains [85]. This behavior can be applied to other metals such as dysprosium [88], arsenic [89] or tungsten [20].

3.2. Cadmium (II)

Cadmium is among the metals that has received the most attention from the biosorption field. Today, there are still studies related to this non-essential metal. Thus, living and dead biomass of *Pseudomonas* sp. strain 375 was tested for cadmium removal. Living biomass was more effective (92.59 mg/g) than dead biomass (63.29 mg/g) [8]; it is a strain with great resistance to cadmium toxicity, and for this reason, the living form of this biomass surpassed the dead one in efficiency, demonstrating the interest in testing the use of living systems in this type of applications. Another example of the utility of using living systems was the application of *Pseudomonas chengduensis* strain MBR as living biomass. This strain was able to remove 100% of Cd(II) (with a high initial

concentration of 200 mg/L) due to a combination of biosorption and biotransformation. This strain has many functional genes related to heavy metal resistance in its genome which would explain this result [3].

In general, metal tolerant strains show better efficiencies in biosorption of these elements when living biomass is used; for example, living cells of a lead resistant strain of *Staphylococcus aureus* were more efficient for the biosorption of cadmium and lead than dead biomass [44]. This shows that it is very important to screen suitable strains for this purpose [90].

Unlike dead biomass, metabolically active cells can bioaccumulate metal inside the cell, which increases the amount of removed metal. At the same time, this type of biomass can transform the pollutant into non-toxic forms, which is important in practical applications. A similar result was obtained with a cadmium-tolerant bacterium, *Enterobacter ludwigii* LY6: the cadmium chloride removal rate of this strain with a treatment of 100 mg/L of cadmium chloride reached 56.0 %. In this strain, the expression of several genes closely related to bacterial cadmium tolerance and biosorption increased with the increase in the cadmium concentration [91]. Taking this into account, genetic modification is also a very useful tool to achieve resistant strains that can be used as living biomass, and therefore, with better biosorption capacity. Several examples show the effectiveness of this strategy. The deletion of the *crpA* gene (P-type ATPase) in the fungus *Aspegillus nidulans* showed 2.7 times higher cadmium biosorption capacity [92]. A transgenic yeast that expressed a metallothionein gene from *Populus trichocarpa* had higher intracellular Cd than the wild strain [36]. Through genetic engineering, a plant cadmium and zinc transporter (*AtHMA4*) was also used as a transgene to increase tolerance to these metals and the biosorption capacity of *Chlamydomonas reinhardtii* [93].

Most studies indicate that the tightly bound cadmium on the cell wall plays a major role in Cd²⁺ adsorption [8,90]. Thus, cadmium biosorption studies with the *Simplicillium chinense* QD10 strain [94] and with *Shewanella putrefaciens* [95] used as living cells suggested that the cell wall components were the primary interactive targets for this metal. Cadmium sulfide nanoparticles can also form on the cell surface, which contributes to the excellent tolerance to this metal of *E. ludwigii* LY6 [91]. Additionally, on the cell surface, the exopolysaccharides (EPS) might be the main means of cadmium adsorption by some strains [91].

Another recently used approach to increase the efficiency of cadmium removal was the use of grapefruit (*Citrus paradisi*) peel treated with Ca²⁺ or Mg²⁺. Through these modifications, increases of 46.3 and 27%, respectively, were achieved in the amount of cadmium removed by this biomass, demonstrating that this residue with a simple modification can be useful as a cadmium biosorbent [96]. A novel composite, which was synthesized by *Bacillus* sp. K1 loaded onto Fe₃O₄ biochars, presented a 230% increase in the capacity to remove cadmium compared to raw magnetic biochar [89]. This is one more demonstration of the importance of materials of biological origin in sorption processes.

The *Pediococcus pentosaceus* FB145 and FB181 strains, which can be considered as probiotic microorganisms, were suggested as potent biosorbents for preventing cadmium toxicity and reducing its absorption into the human body [97]—one more utility of biosorption, in this case, directly related to human health.

3.3. Lead (II)

Lead is another non-essential element that recently attracted greater attention from the field of biosorption. A new proposal to improve the biosorption of this element by fungal biomass was developed using the biomass of *Phanerochaete chrysosporium* with an intracellular mineral scaffold. The intracellular mineral scaffold of this functionalized biomass served as an internal metal container exhibiting high biosorption efficiency for Pb(II) and Cd(II) ions [98]. A comparative study using different biomass of microorganisms (*Pseudomonas putida* I3, *Microbacterium* sp. OLJ1 and *Talaromyces amestolkiae*) showed that the different cell structure had a clear influence on the efficiency of lead biosorption. The most efficient biomass was *Pseudomonas putida* I3 with 345.02 mg/g. These biosorbents were tested

in real wastewater, revealing that these biosorbents possessed good environmental adaptability and great potential for the removal of trace heavy metals from wastewater in practical application [46].

Live and dead biomass of a highly Pb(II) resistant (up to 2200 mg/L) bacterium (*Bacillus xiamenensis*) were also tested for biosorption of this ion. The maximum Pb(II) uptake was 216.75 and 207.4 mg/g for live and dead biomass, respectively [99]. Again, the living and active biomass of a resistant strain showed better performance (intracellular accumulation of lead ions was detected). Living and dead biomass of a (Pb)-resistant bacterium, *Staphylococcus hominis* strain AMB-2 was also evaluated for lead and cadmium removal. Living biomass exhibited more biosorption of metals than dead biomass in both single and binary systems; moreover, lead had a higher affinity for the binding sites on the biomass surface [44]. However, a different result was obtained using living and dead biomass of *Rhodococcus* sp. HX-2. In this case, the dead biomass was more effective. The maximum biosorption capacities were 88.74 and 125.5 mg/g for live and dead biosorbents, respectively. In this case, Pb(II) adhered to the surface of dead biosorbents more easily than to the surface of live biosorbents [68]. The characteristics of the cell surface also affect the amount of lead removed because, in addition to biosorption, this ion can be mineralized [100].

Biomass from the *Simplicillium chinense* fungus strain QD10 had a maximum biosorption capacity of 57.8 mg/g. In this strain, the lead biosorption was predominantly adsorbed by extracellular polymeric substances [101].

Other biomasses that were also recently tested for lead biosorption were *Moringa oleifera* leaves (maximum biosorption of 45.83 mg/g) [102] and the lactic acid bacterium *Lactobacillus brevis* used as living biomass with a maximum biosorption of 53.63 mg/g [69]. Cotton (*Gossypium hirsutum*) shell powder was used as a biosorbent for the treatment of synthetic Pb-contaminated water. This biomass reached a biosorption capacity of 9.6 mg/g [103].

3.4. Mercury (II)

Mercury is another of the non-essential elements that recently had some study from the point of view of biosorption. Different tests show the application of this technique to remove this metal. A biopolymer consisted of proteins, carbohydrates and nucleic acids from waste activated sludge was evaluated. This biopolymer had a maximum adsorption capacity up to 477.0 mg Hg(II)/g [21]. Algal biomass (*Chlorella vulgaris* UTEX 2714) was also tested for remove Hg(II). This biomass used as dead biomass presented a rapid kinetics of adsorption (90 min) and with a capacity of 42 mg/g [104]. In addition, this biomass presented a good regeneration: this property is important for a biosorption process to be viable.

Living systems were also recently used to remove mercury. Living biofilm, developed on a non-woven polypropylene and polyethylene geotextile was tested. This biomass removed 13.34 mg/g in 28 days [105].

3.5. Uranium (VI)

Uranium is another element that has recently received attention from the field of biosorption. This metal is a major health problem; therefore, the development of applications for its removal shows considerable interest. Different biomasses have recently been successfully evaluated for this purpose; of these biomasses stands out *Saccharomyces cerevisiae*. Dead biomass of this yeast removed uranium efficiently due to the large number of functional groups that this biomass presents [31]. This same species, immobilized by a new method based on saturated boric acid-alginate calcium cross-linking, had a biosorption capacity of 113.4 $\mu\text{mol/g}$ [106].

Living biomass of the resistant bacterium, *Bacillus amyloliquefaciens* had a maximum uptake capacity of 179.5 mg/g [45]. Similarly, biomass from the macrophytes *Pistia stratiotes* and *Lemna* sp. presented a maximum uranium sorption capacity of 2.86×10^{-2} and 6.81×10^{-1} mmol/g, respectively, with an optimum contact time of 60 min [107].

Sorbent modification has been a widely used method to increase the efficiency of uranium removal. This method is also applicable when biomass is used. Tri-amidoxime modified marine fungus material had a uranium biosorption capacity of 584.60 mg/g with good regeneration performance. The unmodified biomass originally had a capacity of only 15.46 mg/g [108]. The macroporous ion-imprinted chitosan foams showed an adsorption capacity of 248.9–253.6 mg/g. This modification of chitosan increased the number of active sites, mainly amine and hydroxyl groups, increasing the coordination with U(VI) [109].

Including uranium, the biosorption technique has recently been shown to be useful for removing metals from radioactive liquid organic waste. Rice and coffee husks (raw and chemically activated) were examined regarding their capacity to remove U(total), ^{241}Am and ^{137}Cs , demonstrating that these materials can be used for the treatment of this waste [110].

3.6. Copper (II)

Despite the fact that copper is an essential element, when its concentration is high, it is potentially toxic. This generates the need to develop procedures for its elimination from natural environments. Biosorption proves to be a very useful tool for this purpose. Several biosorbents have recently been evaluated to remove this metal. Biomass from the ornamental herb *Thevetia peruviana* had a biosorption capacity of 187.51 mg/g, far superior to other biomass or pretreated materials [19]. A new *Alcanivorax* sp. VBW004, resistant to copper toxicity, isolated from the shallow hydrothermal vent (Azores, Portugal) was evaluated for biosorption of this metal. This live biomass, cultured with 100 mg/mL of copper, reduced the concentration of this metal by 39.5 % after 48 h. Genetic studies revealed that this strain has copper detoxification genes [111]. This fact shows once again that living biomass with adequate characteristics can be superior to dead biomass.

Immobilization was also recently used for copper biosorption. Alginate-immobilized cells (living biomass) of the bacteria *Azotobacter nigricans* NEWG-1 was able to remove a percentage of copper of $82.35 \pm 2.81\%$ after 6 h and with an initial copper concentration of 200 mg/L [112]. The biomass of the *Aspergillus australensis* fungus was also used in immobilized form. In this case, commercial samples of a textile made of 100% polyester were used as an immobilization matrix, living and dead biomass were compared. In this study, it was observed that an active biosorption process took place, resulting in a higher copper removal compared to a passive process [11]. Another example of an immobilized system is the use of biomass from sugar beet shreds in a fixed-bed column. This process was optimized to remove copper using Box-Behnken experimental design with concentration and pH of the inlet solution and adsorbent dosage as independent variables [24].

Other biomasses that were also tested to assess copper biosorption were *Chlorella pyrenoidosa*, reaching 0.48 mmol/g [41] and *Ochrobactrum* MT180101: in this strain, there were several mechanisms involved in the biosorption of this metal: surface biosorption, extracellular chelation and bienzyme-mediated biotransformation, which supposes a superior efficiency in the copper biosorption [5]. The commercial biomass of the yeast *Saccharomyces cerevisiae* Perlage® BB with a maximum biosorption capacity of 4.73 mg/g [113], dead biomass of *Penicillium ochrochloron* with an average biosorption capacity of 7.53 mg/g [114], *Sargassum filipendula* [42] and alginate-based biosorbent produced from seaweed *Sargassum* sp. with a maximum biosorption capacity of 1.64 mmol/g [70] are recent examples of different biomasses that have been evaluated to determine their capacity as copper biosorbents.

3.7. Other Metals

Other metals that have recently been studied from the point of view of biosorption are shown in Table 2.

Table 2. Examples of other metals that have recently been studied for their removal through applications related to biosorption.

Metal	Biomass	Remarks	Reference
Zinc	Leaves of <i>Corchorus olitorius</i>	Biosorption capacity of 11.63 mg/g in 120 min	[115]
	<i>Streptomyces</i> K11	- Living biomass - Maximum biosorption capacity of 0.75 mmol/g	[65]
	Rape straw powders	- Different parts were evaluated - The maximum biosorption capacity obtained reached 36.74 mg/g	[116]
Antimony	<i>Rhodotorula mucilaginosa</i> Strain DJHN070401	- Living cells - Providing that living cells not only improved the removal efficiency in the presence of metabolic inhibitors but also prevented intracellular Sb(III) being re-released into the environment	[9]
Gold	<i>Lysinibacillus sphaericus</i> CBAM5	- Biocomposite materials - Cells immobilized in Polycaprolactone (PCL) microfibrinous mats and alginate microcapsules	[28]
Arsenic	<i>Sarcodia suiaeand</i>	External factors affecting algal metabolism and thus metal-accumulation mechanisms were studied	[67]
	<i>Pseudomonas aeruginosa</i> AT-01 Strain	Remediation efficiency at 2 h of incubation was 97.92 % with an initial As concentration of 10 mg/L	[117]
Manganese	<i>Providencia</i> sp. LLDRA6	- Mn(II) precipitation on the cell surface - Oxidation of Mn(II) into BioMnOx on the cell surface - Intracellular accumulation	[118]
Platinum	<i>Escherichia coli</i>	- EC20 protein fused to the <i>E. coli</i> cell surface using an InaKN-based display - Maximum adsorption capacity of 239.92 mg/g	[34]
	Lemon peel	Maximum adsorption capacity of 36.74 mg/g	[33]
Nickel	<i>Phanerochaete chrysosporium</i>	- Living cells - Maximum biosorption capacity of 46.50 mg/g	[119]
	Surface-engineered <i>Saccharomyces cerevisiae</i> EBY100	Biosorption capacity of 2.603 ± 0.004 g/g	[120]
	Industrial waste brewery sludge	Biosorption capacity of 7.874 mg/g	[15]
	Alginate-based biosorbent produced from <i>Sargassum</i> sp.	Maximum biosorption capacity of 1.147 mmol/g	[70]
Lithium	<i>Fucus vesiculosus</i>	- Simultaneous biosorption of Cd(II), Ni(II) and Pb(II) - Maximum biosorption capacity of 70.1 mg/g for Ni(II)	[66]
	<i>Aspergillus versicolor</i> and <i>Kluyveromyces marxianus</i>	Maximum biosorption capacities of 347.9 and 409.2 µmol/g for <i>A. versicolor</i> and <i>K. marxianus</i> , respectively	[47]
Cesium	<i>Haematococcus pluvialis</i> and <i>Chlorella vulgaris</i>	Cesium accumulation through the potassium transport channel	[121]
Dysprosium	<i>Mangifera indica</i>	- Raw and surface-modified bark powder - Maximum adsorption capacity of 55.04 mg/g	[88]
Tungstate	Garlic peel	- Modified by loading with Fe(III), Ti(IV) and Ce(III) through a cation exchange process - Maximum adsorption capacity of 91.5 mg/g with Fe	[20]
Lanthanum and samarium	<i>Botryosphaeria rhodina</i> MAMB-05	- Living and dead biomass	[122]
Iron	Elderberry (<i>Sambucus nigra</i>) pomace	- Fe (III) - Maximum biosorption capacity of 33.25 mg/g	[123]
	<i>Bacillus subtilis</i>	- Fe(II) - Living cells - Maximum biosorption capacity of 7.25 mg/g	[124]

4. Biosorption of Organic Compounds

Today, many organic compounds produce undesired effects in natural ecosystems, and some are considered very toxic to humans. Many of these are part of the so-called persistent organic pollutants (POPs) such as pesticides, insecticides, organochlorines, herbicides and polychlorinated biphenyls (PCBs). Although many of these compounds have been known and used for a long time, some are of recent development, and others have been discovered in the environment due to the progress of analytical techniques: these compounds have been called emerging organic contaminants (EOCs) [125,126]. Because these compounds cause serious problems in ecosystems even at low concentrations, it is necessary to develop techniques for their elimination. Physico-chemical techniques are sometimes not effective, they are more expensive and they can also generate additional problems.

In this context, biosorption is an alternative that avoids these inconveniences and for this reason is being increasingly developed to remove this type of substance. This is demonstrated by the number of studies that have recently been carried out to use biosorption in the elimination of these compounds.

The process is performed in a similar way to metal biosorption and, in general, the factors affecting efficiency are the same, although the response to them shows differences that must be studied in each case. Unlike metals, the complexity of these compounds, in terms of their composition, means that they may have different functional groups capable of presenting very different charge values and with different degrees of ionization depending on the pH of the solution. For this reason, the optimization of this parameter is of great importance, and the optimization values obtained for compounds with different nature show greater diversity than in the case of metals.

Furthermore, these compounds may have different degrees of hydrophobicity and reactivity, which have an effect on the process. Although hydrophobic compounds are not readily soluble in water, such compounds can interact with the biosorbent particles through hydrophobic interaction or can even cross the cell membranes when using living biomass. Therefore, this type of compounds can also be removed by biosorption.

In relation to temperature, its effect is contradictory, and generally the adsorption effectiveness increases with increasing temperature (endothermic process) [56,127]. However, there are results with some organic compounds whose effect was the opposite, indicating in these cases that the biosorption process was exothermic [128]. Finally, the ionic strength of the solution also modifies the biosorption capacity of organic compounds, although its effect seems to be less relevant than in the case of metals. A high concentration of salts is necessary for a significant decrease in the biosorption of these compounds to occur, although this effect is less studied than in the case of metals.

Some examples of organic compounds that have recently been studied will be reviewed in the following sections.

4.1. Antibiotics

Antibiotics are found today in relatively high amounts in ecosystems due to their increasing use. In fact, many studies have been carried out to examine the possibilities of biosorption for the removal of antibiotics. Recently, new articles confirm this use. An example of this is the antibiotic dicloxacillin, biosorption studies with this antibiotic that were performed with Indian almond (*Terminalia catappa*) leaf biomass. The maximum adsorption capacity was 71.94 mg/g. The optimal pH for this biosorption was 6.0. For the intermolecular interaction such as hydrogen bonds, van der Waals forces could be the main interaction for the dicloxacillin and the surface properties of this biosorbent [129]. Four sulfonamide antibiotics were also recently investigated. Extracellular polymeric substances (EPS) extracted from *Klebsiella* sp. J1 were used for this purpose and with efficiencies that reached 142.86 mg/g. In this case, the hydrophobic interaction between EPS and sulfonamides seemed to dominate the adsorption process. There was the maximum proportion of sulfonamides at molecular states when the solution pH was 4.0–5.0, and the molecular states of sulfonamides were favorable for hydrophobic groups to effectively play a role during adsorption process [130].

Biomass from *Dialium guineense* seed waste was modified with sodium hydroxide and tested as biosorbent for ciprofloxacin. This biomass, modified in this way, exhibited a maximum uptake capacity of 120.34 mg/g at pH = 6.0, higher than some reported adsorbents for this antibiotic [131]. Another antibiotic that was recently evaluated for its elimination by biosorption was oxytetracycline. This antibiotic was effectively removed using a reed-based-beads biosorbent (an enhanced adsorbent from Tunisian reed). The maximum biosorption capacity obtained was 15.78 mg/g at pH = 6.0. In this experiment, an initial mixture of 165.54 $\mu\text{mol/L}$ of oxytetracycline and 362.16 $\mu\text{mol/L}$ of Cd(II) was used, demonstrating the effectiveness of this material to simultaneously remove two pollutants. The biosorption of Cd(II) cations took place through electrostatic attraction between them and the biosorbent, and the biosorption of oxytetracycline could take place via π - π stacking, as well as hydrophobic interactions [52].

4.2. Dyes

Today, dyes are one of the main pollutants. They are produced in large quantities due to their widespread use, and for this reason, they can be released into natural environments. The release of these types of compounds causes serious problems to natural ecosystems due to their toxicity, carcinogenicity and because they also impart an intense color to the waters (even at very low concentrations) and, in addition, they are considered recalcitrant compounds. Therefore, effective treatments are necessary to remove these compounds from the waters. Biosorption is an excellent alternative to conventional methods. In fact, many papers have been published on the removal of these pollutants by biosorption, and recently, dyes continue to dominate biosorption applications.

The cationic dye methylene blue is one of the most widely used dyes in the industry, and for this reason, there is a wide variety of biosorbents that have been evaluated for the elimination of this dye. In recent years, there are also various examples of these proposals, in which both modified and unmodified biomass are used. Thus, coconut waste, chemically modified with acrylic and polyacrylic acids, has been utilized for the removal of this dye. With these modifications, the maximum sorption capacity reached was 138.88 mg/g at pH = 10.0 using the acrylic acid. The sorption mechanism is mainly based on electrostatic interaction and on Lewis acid-base interaction [30]. *Cortaderia selloana* flower spikes transformed into nanomagnetic particles reached a maximum removal capacity of this dye of 119.05 mg/g at pH = 6.0 and through electrostatic interactions [132].

However, unmodified biomass methods are still the most widely used to remove methylene blue. Recently, it has been made possible to find many examples of this. Brewer's spent grain has recently been used with a maximum adsorbed amount of methylene blue of 284.75 mg/g at pH = 11.0. A possible adsorption mechanism involves electrostatic interaction, electron donors and electron acceptors, hydrogen bonds and π - π dispersion [133]. Biomass obtained from weeds (*Cyanthium cinereum* and *Paspalum maritimum*) was also evaluated to eliminate this dye, the maximum absorption capacities obtained were 56.18 and 76.34 mg/g, respectively [134]. *Fucus vesiculosus* dead biomass was also used to remove this dye, presenting a maximum biosorption capacity of 698.48 mg/g at pH = 6.0 by a physical biosorption mechanism related to a cation exchange process between the dye and biomass functional groups, releasing protons (H^+) to the system [135]. Biomass from *Bifurcaria bifurcata* was also applied to remove this dye with a maximum biosorption capacity of 2744.5 mg/g in only 15 min. The best adsorption efficiency was obtained at pH = 5.6 due to electrostatic interaction [136]. In these examples, although the biomasses of these macroalgae were clearly higher, it is necessary to consider that the brewer's spent grain is a byproduct of the brewing industry produced in large quantities and with few ecological disposal options; in addition, weeds are abundant and with few applications. This shows that the choice of a certain biosorbent depends on many factors that must be evaluated together. The search for new biosorbents is essential to achieve this objective. An interesting example of this is the application of the biomass from brazilian berry seeds (*Eugenia uniflora*) to remove this dye in conditions closer to reality using two different simulated effluents with a color removal greater than 70%. This material had a biosorption capacity of 189.6 mg/g at pH = 8.0 and presents OH groups that can perform hydrogen and electrostatic bonds with methylene blue [56]. Other macroalgae also recently used as biomass were *Ulva fasciata* that reached a maximum adsorption capacity of 244 mg/g and *Sargassum dentifolium* with only 66.6 mg/g. In both cases, it was determined that the biosorption of methylene blue was independent of pH [12].

Crystal violet is another cationic dye that has recently received attention for biosorption. Powdered seeds of the araticum fruit (*Annona crassiflora*) were used in the biosorption of this dye with a maximum biosorption capacity of 300.96 mg/g in 120 min at pH = 7.5. Electrostatic interaction played an important role in the biosorption process of this dye since a pH higher than the zero charge point of the biosorbent (7.2) causes the surface of this material to be negatively charged due to its deprotonation, which favored an increase in its biosorption capacity because crystal violet is a cationic dye, and therefore, interaction with a negative charge on the surface increases the amount of dye biosorbed [18]. Biomass from *Diaporthe schini* (new fungus recently discovered) reached a maximum

biosorption capacity of 642.3 mg/g. This biomass was also evaluated in a simulated effluent with a considerable reduction in the color [137]. Finally, as a more sophisticated option, water dispersible Fe₃O₄/Chitosan/Glutaraldehyde nanocomposites (superparamagnetic) were also tested, in this case with a maximum biosorption capacity of 105.47 mg/g. Electrostatic interaction between the negative charge of the biosorbent surface and the positive charge of the dye would explain why this maximum capacity took place at pH 11.0. Although the maximum removal capacity was lower than the previous cases, the advantage of this technique is its ease and rapid separation from samples, allowing a reusability up to at least ten cycles [138].

The discarded seed biomass from pepper (*Capsicum annuum*) was tested to remove Basic red 46 dye. Taguchi DoE methodology was employed to optimize the process reaching a dye removal performance of 92.1 mg/g at pH = 8.0 [139].

Biomass derived from macroalgae was also evaluated to remove the Rhodamine B dye. The macroalgae used were *Kappaphycus alvarezii*, *Gracilaria salicornia* and *Gracilaria edulis*, both in native form and ethanol modified. The maximum biosorption capacity determined as 9.84, 11.03, 8.96, 112.35, 105.26 and 97.08 mg/g at pH = 2.0, respectively. At this low pH, there is an increase in the protonation effect on the surface of these materials resulting in a higher biosorption capacity. The modified biomass was more efficient [140].

Anionic dyes are the other group of dyes that also have a multitude of applications, and for this reason, they are also an environmental problem. These types of dyes have also recently been studied as applications in the field of biosorption. Thus, the removal of tartrazine yellow was evaluated using brewer's spent grain as biomass; the maximum adsorbed amount was 26.18 mg/g at pH = 2.0. This adsorption involves electrostatic attraction, π - π interaction and multilayer formation of dye [133]. Reactive Blue 19 using dead biomass of the brown marine alga *Bifurcaria bifurcata*, with a maximum adsorbed amount of 88.7 mg/g in only 15 min at pH = 1.0. At this very low pH, the concentration of H₃O⁺ was high enough to allow the protonation of sulfonate groups of this dye, which favors the interaction between the dye and the functional groups of the biomass [136]. Eriochrome black T is another example of an anionic dye recently studied for its elimination by biosorption; in this case, using dead biomass of *Fucus vesiculosus* and with a maximum biosorption capacity of 24.31 mg/g at pH < 4.0. Van der Waals interaction was the main interaction mechanism between this dye and biomass [135]. Biomass from *Ocimum gratissimum* leaves was tested for the indigo carmine dye biosorption. This biomass obtained a maximum biosorption capacity of 77.52 mg/g, confirming that this capacity was superior to that of other sorbents used to remove this dye. Since this dye is anionic, the most favorable adsorption occurred at pH 2.0 because the surface of this biosorbent is positively charged [128]. Direct Fast Scarlet 4BS was successfully removed using dead biomass from *Enteromorpha prolifera* with a maximum sorption capacity of 318.87 mg/g also at pH 2.0. The adsorption mechanism involved hydrogen bonding, electrostatic attraction and bonding and hydrophobic and van der Waals interaction [127]. Finally, Reactive Red 120, using immobilized biomass of *Pseudomonas guariconensis* in a Ca-Ag biocarrier matrix, was efficiently eliminated. In this case, since the biomass was alive, in addition to biosorption, biodegradation occurred. Toxic reactive dye was converted into non-toxic compounds. The immobilized bacterial cells exhibited 87% uptake of this dye, whereas the non-immobilized bacterial cells exhibited a maximum uptake of 37% [6].

Anionic dyes are better adsorbed at low pHs—that is, at pHs below the zero-charge point of the biosorbent—because under this condition, the surface of the biosorbent acquires positive charge.

4.3. Other Organic Pollutants

Other organic pollutants of interest have also been treated using biosorption as the primary removal technique. Table 3 shows some examples of the most recently studied organic pollutants.

Table 3. Examples of other organic pollutants that have recently been evaluated for their removal using biosorption.

Pollutant	Biomass	Efficiency	Remarks	Reference
Phenol	<i>Luffa cylindrica</i>	28.9 mg/g	Hybrid material with 4% Zn ²⁺	[38]
Sterols	<i>Aspergillus fumigatus</i> strain LSD-1	303.03–909.09 mg/g	Living and dead biomass	[141]
Propranolol hydrochloride	<i>Sargassum filipendula</i>	1.94 mmol/g	Remaining biomass of alginate extraction	[142]
Acetylsalicylic acid	Biosorption onto fungal-bacterial biofilm supported on two types of activated carbons	292.4 ± 2.01 mg/g	Batch and fixed-bed experiments	[143]
Nonylphenol	Microalgae	74.18–92.12% in 120h with initial concentration 1 mg/L	Living biomass	[7]
17 alpha-ethinylestradiol alone and along with estrone	Yeast biomass from ethanol industry	24.50 ± 0.07 and 0.80 ± 0.07 mg/g	An associative/competitive sorption process between both compounds	[40]
Salicylic acid	<i>Scenedesmus obliquus</i>	63 mg/g	- Batch experiments - Dead biomass	[144]
Diuron	<i>Moringa oleifera</i>	5.76 mg/g	Fixed-bed column	[25]
Ibuprofen	<i>Scenedesmus obliquus</i>	11.9 mg/g	- Batch experiments - Dead biomass	[144]
Triclosan	<i>Phaeodactylum tricornutum</i>	12.97–13.03 mg/g	- Seawater - Living and dead biomass and photodegradation	[10]

As can be seen in this table, the nature of the organic compounds is very varied, which is indicative of the enormous possibilities that biosorption techniques have for the removal of this type of pollutant. In addition, these examples reflect the flexibility of biosorption techniques since, in the same way as for other pollutants, biomass can be alive or dead, in batch or in fixed-bed experiments, but it is noteworthy that even this technique can be coupled to an alternating current system that allows increasing the speed of biosorption [38]. However, the removal capacity that some of these sorbents have is far from that achieved with commercial sorbents such as activated carbon. Although the comparison data are scarce, the values obtained indicate the need to search for biomaterials with greater capacity—for example, the biomass of *Scenedesmus obliquus* had a maximum removal capacity of salicylic acid and ibuprofen of 63 and 11.9 mg/g, respectively; instead in the same conditions, activated carbon had 250 and 147 mg/g [144].

5. Conclusions and Future Perspectives

As can be seen, the field of biosorption continues to offer very promising results for the elimination of pollutants. It is a technology that presents a great diversity of options and combinations, demonstrating great flexibility for its application. It is difficult to limit the studies that try to reveal the properties of any material for use in biosorption. The reason for this is obvious: the amount of possible materials (living or dead) is enormous. These studies must continue to progress because without a material with adequate properties, biosorption cannot be competitive. However, it is not only necessary to determine the properties of a possible material but also to evaluate it compared to others already established as sorbents (commercial sorbents), and therefore, conclude that this new material is a better alternative. There are still steps to be taken for biosorbents to be fully accepted. Currently, there are several challenges of biosorption: the development of large-scale procedures, greater commercialization and, in general, its application in real conditions. Although the advantages of this type of sorbent are evident (mainly cost), few biosorbents are currently marketed for their use [22]. The application of biosorption at the industrial scale has not been yet well exploited, and this constitutes another of the weaknesses that biosorption must face. Still, the vast majority of biosorption applications focus on laboratory studies. All these studies make possible the current knowledge about biosorption that is enough to provide a solid base that allows its use to be extended. However, this process is not widely used in industry.

An important reason that can explain these weaknesses is that biosorbents, in their natural state, tend to have a lower removal capacity than traditional or conventional sorbents such as activated carbons, zeolites or ion exchange resins. However, it is difficult to ascertain this fact because at present there are still few studies in which a biosorbent is compared with commercial sorbents under the same conditions [145,146]. Perhaps, the fact of thinking that a biosorbent may be less effective than the traditional ones could be counterproductive to achieve that biosorbents climb positions, because the true capacity of these materials will remain unknown. The fact that the matrices used in the experiments have different physicochemical properties does not help much in improving the perception of biosorption, since this makes it difficult to compare biosorbents to obtain the one with the highest affinity for a pollutant. A certain standardization could be interesting to solve this aspect.

In any case, if the above is true and biosorbents lack the necessary efficiency, this would imply the need to modify them to achieve greater efficiency. It would be desirable if the biosorbents had, at least, characteristics comparable in efficiency to the commercial ones. There are several alternatives that can improve the effectiveness of biosorbents, ranging from chemical or physical modifications to the use of nanomaterials [29,63,73]. Chemical or physical modifications applies mainly to dead biomass. However, these alternatives would increase the cost of the final product, and the resulting material could be even less eco-friendly, reducing the virtues of biomaterials. In this context, it is interesting not to forget the use of living biomass to improve the effectiveness of a pollutant removal process. Despite the advantages attributed to dead biomass, the properties of living biomass for application as biosorbents have not yet been adequately exploited or even better studied. Many studies indicate that the use of living biomass is more efficient than dead biomass, and living biomass is used without modification. The cost of the production and maintenance of living biomass is among the problems attributed to the use of this type of biomass; however, there are organisms that can be cultivated intensively and with low cost [147]. Macrophytes, microorganisms such as microalgae or some species of bacteria offer very promising results. Studies in this direction should continue.

Immobilization is another key mechanism to improve biosorption processes. It is also a fundamental mechanism for the application of biosorbents on an industrial scale. At present, different proposals are still being evaluated to solve the practical problems of immobilization, especially when living biomass is used [106]. In fact, there has been an increase in the number of studies using immobilized living biomass, perhaps because for many industrial applications, the use of living biomass is preferable. The support for this biomass is being increasingly perfected, as well as the search for the most suitable living biomass for each case, which is essential to ensure that a biosorbent can be successful in its application. An example of this improvement is an alternative that is being exploited by combining nanoparticles with biomass. Microbial cells immobilized on magnetic nanoparticles is a relevant new technique applied to obtain new biosorbents, which has several advantages [29]. However, it is necessary to recognize that the cost of these biocomposite materials can be uncompetitive, as well as an option that can be considered not very eco-friendly. In any case, living biomass immobilization techniques must continue to be refined, seeking more natural and cheaper supports.

Another weakness of biosorption is that many biosorption studies use synthetic wastewater or solutions in distilled water, which does not take into account the behavior of these sorbents with different competitors or with physicochemical parameters that can differ considerably in real conditions. The evaluation of biosorbents in real situations would provide more information and would allow a more adequate assessment of the possibilities of this technique. For this reason, future research should be directed in this direction.

Finally, it is hoped that in the future, as the weaknesses are resolved, biosorption will find its place in industry and in separation technologies.

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