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Adsorption Applications for Environmental Sustainability

Kingsley Eghonghon Ukhurebor, Uyiosa Osagie Aigbe and Robert Birundu Onyancha

Chapter 9

The use of biosorbents derived from invasive plants for environmental remediation

W O Egboduku, T Egboduku, J O Emegha and O Imarhiagbe

Unlike organic pollutants, heavy metals are persistent environmental contaminants that cannot be biodegraded. While chemical/physical methods can facilitate the removal of these substances, there is an increasing demand to embrace eco-friendly alternatives for remediation purposes. There is evidence to suggest that invasive-plant-derived biosorbents can effectively remove contaminants, including toxic metals, from the environment. Biosorbents can be either natural or altered. The utilization of common invasive plants as biosorbent sources for bioremediation is explored in this chapter. This approach could prove crucial in mitigating the adverse impact of these species on the environment, thereby promoting a waste-to-wealth strategy.

9.1 Introduction

Environmental remediation involves the removal of contaminants or pollutants from the environment, which includes water and soil [1]. The purpose of such remediation is more than just eliminating pollutants, as it includes protecting people and the environment from harm. Studies of exposure routes have highlighted the hazardous effects of contaminants including fine particles, heavy metals, and emissions from decommissioned petrochemical facilities. Moreover, there is a growing understanding of the degradation and reuptake of pollutants as well as intricate phase transformation procedures; for instance, those that take place between the soil–water or air–surface water interfaces [1]. In the process of environmental remediation, an essential step is to analyze and improve the quality of the three main ecological compartments. The goal is to minimize pollution levels by establishing acceptable limits for specific land uses. This can be achieved through risk characterization that includes evaluating hazard, exposure, and dose–response

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factors [2]. The impact of industrialization and technological progress on human civilization is significant, yet their effects have contributed to a decline in water quality [3]. Numerous published studies have illustrated that approximately one billion individuals globally lack access to potable drinking water [4]. The improper disposal of a vast array of organic and inorganic substances such as pharmaceuticals, hydrocarbons, heavy metals, and textile dyes is the primary cause of this situation. The contamination caused by heavy metals in water sources is particularly concerning because even low levels of these metals can induce reactive oxygen species, resulting in cytotoxicity [1, 5]. One example of the significant negative effects that can occur due to prolonged exposure to a particular substance is arsenic. Consumption of this element at a level of more than 0.05 mg l^{-1} over an extended period can lead to acute symptoms such as chronic respiratory disorders, sensory loss, skin discoloration, and even skin cancer, as documented by [5]. Similarly, the growth in industries involved in dye production has led to elevated quantities of wastewater containing more than 10 000 dyes, which has intensified the concentration levels of colored effluents present within it [1]. The presence of pollutants in water bodies can lead to reduced aesthetic quality and hinder light penetration, causing disruption within the aquatic ecosystem. As part of an attempt to address this issue sustainably, biosorbents are gaining popularity as a means of removing toxic organic compounds or heavy metals [5]. These sorbent materials are derived from various sources, such as bacterial biomass, yeasts, and fungi with fibrous structures along with by-products generated by the food and pharmaceutical production industries, which include agricultural wastes comprised mainly of polysaccharides—all of which contribute towards environmental remediation efforts [1]. Every biomaterial should display exceptional biosorption proficiency and attraction towards all organic compounds and inorganic ions. Examples of some essential bioadsorbents include fungi, notably the filamentous species of *Alternaria*, *Aspergillus*, *Rhizopus*, and *Penicillium* along with yeast strains such as *Saccharomyces cerevisiae* and *Saccharomyces carlsbergensis* [1].

Microorganisms, which are commonly utilized in the food and pharmaceutical sectors, generate a surplus of waste that can be accessed at no or low cost. In addition, algae serve as an effective biosorbent source. Red, green, and brown algae have potential for use as biosorbents; among them, brown algae such as *Chlorella vulgaris* have proven to be particularly proficient [1, 5].

9.2 Categories of biosorbents

Several biomaterials derived from bryophytes, fungi, bacteria, or environmental waste are known to adsorb heavy metals and other pollutants. This chapter uses two significant categories of biosorbents for environmental remediation [6].

1. **Natural biosorbents:** natural biosorbents are mainly obtained from living organisms. The cells of living plants and other organisms take up toxic substances such as heavy metals by bioaccumulation. Toxic substances are also removed by dead cells by biosorption (table 9.1).

Table 9.1. Summary of the types of biosorbents and their sources.

Categories of biosorbents	Examples
1 Natural Fungi	- *Aspergillus fumigates* - *Aspergillus niger* - *Aspergillus flavus* - *Rhizopus oryzae* - *Rhizopus nigricans* - *Rhizopus stolonifer*
Algae	- *Pithophora* sp. - *Scenedesmus spinosus* - *Spirogyra hyaline* - *Nannochloropsis oculata* - *Chlorella vulgaris* - *Auxenochlorella protothecoides* - *Sargassum polycystum*
Bacterial	- *Micrococcus luteus* - *Enterobacter cloacae* - *Shewanella oneidensis* - *Bacillus cereus* - *Geobacter sulfurreducens* - *Bacillus subtilis*
Plants	- Stems of *Musa acuminata* and *Musa paradisiaca* (banana) - Pectins from *Beta vulgaris* (sugar beet) - The stem bark of *Acacia leucocephala* (acacia) - Leaves, seeds, and roots of *Nympheae lotus* (water lily) - Leaves, seeds, and roots of *Eichhornia crassipes* (water hyacinth) - Leaves, seeds, and roots of *Santalum album* (sandalwood) - Powdered leaf of *Utricularia aurea* (bladderwort) - Biomass of *Momordica charantia* (bitter melon) - Leaves of *Azadirachta indica* (neem) - Leaves of *Magnifera indica* (mango) - Leaves of *Cajanus cajan* (pigeon pea)
Agricultural wastes	- Husk of *Oriza sativa* (rice) - Peels of *Punica granatum* (pomegranate) - Charcoal husk of *Arachis hypogaea* (peanut)
2 Modified	- Fly ash or coal ash - Biochar produced from the husk of *O. sativa* (rice) - Biochar from the peduncle of *Musa paradisiaca* (banana) - Biochar produced from wheat straw pellets - Husk of *A. hypogaea* (peanut) treated with NaOH - Biochar obtained from the peels of *Cucumis melo* (dew melon) - Biochar obtained from *Phoenix dactylifera* (date palm)

Table 9.2. The production process of invasive plant biochars and their operating conditions.

IPB production process	Conditions	Temperature (°C)	Time	Pressure	Biochar yield
Slow pyrolysis	- Absence of oxygen - Moisture content < 15%–20% - Heating rate < 10 °C min^{-1}	300–800	>60 min	1 atm	30%–55%
Fast pyrolysis	- Absence of oxygen - Moisture content < 15%–20% - Heating rate ⩾ 200 °C min^{-1}	450–600	~0.02	1 atm	10–25
Gasification	- Low oxygen supply - Moisture content 10%–20% - Heating rate ~100 °C min^{-1}	750–1000	0.2–0.4	1–3 atm	14–25
Hydrothermal carbonization (HTC)	Moisture content 75%–90%	180–300	5–240	1–200	50–80
Torrefaction	- Absence of oxygen - Moisture content < 10% - Heating rate < 50 °C min^{-1}	200–300	15–60	1	70–80

2. **Modified biosorbents:** modified biosorbents are adsorbents that are chemically characterized. They are usually synthesized from other living organisms (see table 9.1).

9.3 Biosorbents derived from invasive plants

Invasive plants are part of the global ecosystem [7]. Although they are known to cause ecological or economic harm in new environments, i.e. those that they are not indigenous to, several scientists have reported the use of invasive plants for environmental remediation [7]. Invasive plants possess remarkable adaptability and an exceptional capability to spread swiftly. As such, it is crucial to find sustainable approaches that can alleviate their adverse effects on the indigenous ecosystem. Several methods have been suggested to check the invasion of alien plants; some of these include chemical, biological, and alternative controls [8]. Although these approaches have enduring outcomes when put into practice, they still demand significant labor and material resources. Consequently, there is a need to identify a more economical, effective, and sustainable way to address the issues of invasive plants. One plausible suggestion is to use them as biosorbents—emerging materials for environmental protection [9]. According to research

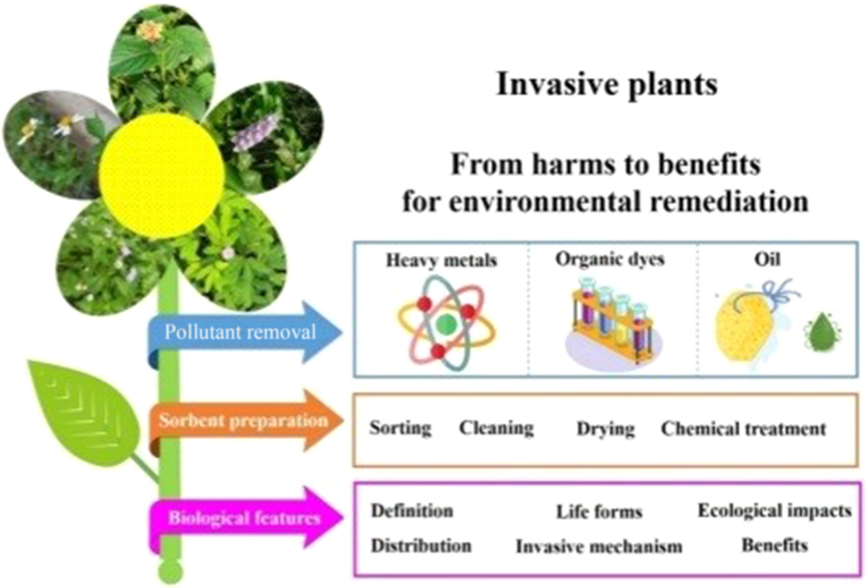

Figure 9.1. The conversion of invasive plants into biosorbents for environmental remediation. Reprinted by permission from Springer Nature [3], Copyright (2021).

findings, the creation of biosorbents from plants that have invaded an ecosystem can aid in reducing the ecological harm caused by biological invasions. The process of producing biochar using invasive plant species as a source material presents a viable approach for managing waste and curtailing the spread of such invasive vegetation [10]. Consequently, this technique offers promise in addressing the problems associated with invasive plants. Yang *et al* [11] reported that *Eichhornia crassipes*, *Solidago canadensis*, and *Alternanthera philoxeroides* have been identified as effective feedstocks for producing biochar and have potential applications as biosorbents in environmental remediation efforts. The invasive plants most currently used as biosorbents and biochars are *Eichhornia crassipes* (water hyacinth), *Eupatorium adenophorum* (cotton weed), *Spartina alterniflora* (smooth cord grass), *Alternanthera philoxeroides* (alligator weed), and *Solidago canadensis* L. (Canadian goldenrod) [3, 12]. The herbaceous nature of these invasive plants makes them readily available and abundant. Their stems possess numerous vascular bundles of small size, and adjacent to those are multiple thin-walled cells. This composition is favorable for manufacturing biochars which have increased porosity and a substantial specific surface area [13]. Table 9.2 shows biosorbents derived from some invasive plants and locations where they are used, while figure 9.1 shows the conversion of invasive plants into biosorbents for environmental remediation as adapted from [3].

9.4 The production of biosorbents/biochars from invasive plants

Pyrolysis is a chemical process of biomass breakdown that happens in the absence of oxygen. The term pyrolysis comes from two Greek words: 'pyro' meaning fire and 'lysis' which refers to decay or disintegration into fundamental components [14]. The conditions involved in pyrolysis, such as temperature, heating rate, etc. significantly affect the physicochemical properties of biochar. In the process of thermal decomposition, carbohydrates such as hemicellulose, cellulose, and lignin are subjected to cross-linking, depolymerization, and cleavage at distinct temperatures, which results in the formation of three forms of output: solid, liquid, and gas. The preparation of biochar through pyrolysis offers cost-effectiveness and the inherent benefits of a straightforward approach [11]. The process of pyrolysis, which involves heating organic matter in a nonreactive atmosphere, is intricate and comprises both simultaneous and successive reactions. The breakdown of the long chains of carbon, hydrogen, and oxygen compounds present in biomass occurs between 350 °C–550 °C and 700 °C–800 °C in the absence of air/oxygen. This results in the formation of smaller molecules such as gases, condensable vapors (tars and oils), and solid charcoal under pyrolytic conditions. Pyrolysis can mainly be categorized into three different types: conventional, fast, or flash, depending on various operational factors. This indicates that this procedure offers multifaceted operations with diverse product yields based on their different characteristics due to the various setups used for optimization purposes during its application [11]. These classifications depend on factors such as the biomass particle size, solid residence time, heating rate, and temperature (table 9.2).

1. **Conventional pyrolysis:** pyrolysis has been utilized for millennia to improve the production of charcoal by employing low temperatures and heating rates. The traditional method features a long vapor residence time (5–30 min), resulting in continuous reactions among the vapor-phase components, leading to solid char and other liquids [15]. However, this conventional pyrolysis technique is not ideal for producing biochar because it suffers from technical deficiencies such as high residence times that cause primary product cracking during slow pyrolysis, which can negatively impact both the yield and the quality of the resulting biochar [16, 17].
2. **Fast pyrolysis:** in the fast pyrolysis process, biomass belonging to a particular plant is heated rapidly without oxygen at extremely high temperatures. According to research based on weight, this method produces oily products or other forms of liquids that amount to approximately 60%–75%. This output consists of biochar solids which make up about 15%–25% and a gaseous phase accounting for around 10%–20%. The ratio varies depending on the type of feedstock used in production. Specifically, when it comes to liquid yield from biomass sources, optimal results are achieved through low temperature settings with high heating rates and short residence times. The fast pyrolysis method is characterized by an accelerated heating rate and efficient heat transfer, resulting in prompt vapor cooling with minimal time for vapor to remain. This technology can be comparatively inexpensive to

implement and has high energy efficacy, particularly when applied on a small scale, surpassing those of other processes [18].

3. **Flash pyrolysis:** A potentially advantageous approach to generating biochar from plant biomass is through the rapid pyrolysis technique. This method involves quick devolatilization in an inert atmosphere, speedy heating of particles, high reaction temperatures ranging between 450 °C and 1000 °C, and a gas residency time that does not exceed one second. However, this process presents some technological challenges which include oil solids produced as well as an increase in viscosity over time due to the char's catalytic effect; moreover, the thermal stability of the oil and its propensity for corrosiveness remain disappointing [14].

In addition to pyrolysis, alternative techniques for obtaining biochar from various sources include gasification, hydrothermal carbonization, and torrefaction. The process of gasification differs from pyrolysis in that it involves an oxidizing agent and is typically used to generate syngas consisting of H_2, CO, CO_2, and CH_4. Biochar is often regarded as a secondary output, which has led to minimal exploration of its production optimization. Torrefaction has emerged as a promising method for generating biochar. This strategy involves removing the moisture content, carbon dioxide, and oxygen from biomass at temperatures ranging from 200 °C to 300 °C in anaerobic conditions. Polymerized saccharides are broken down in this process, resulting in an insoluble product with a low O/C ratio that repels water effectively. The gradual temperature increase during torrefaction makes it a form of gentle pyrolysis treatment commonly applied to achieve torrefied products in operational processes.

However, in academic discourse, torrefaction is not considered a highly favorable approach toward biochar manufacturing. This holds true even though it achieves comparatively greater product yields of 70–80 wt.%. Its inadequacy stems from the presence of substantial volatile components retained by the biomass during the torrefaction process and also from its failure to meet the desired physical and chemical attributes necessary for producing high-quality biochar (e.g. $O/C > 0.4$). As such, torrefaction has more often been utilized as an initial step for removing moisture content from feedstock, for densification purposes, or for enhancing a material's fragility [19]. Table 9.2 shows and compares the described biochar production processes' operating conditions and biochar yields.

The use of invasive plant-derived biosorbents has provided a beneficial pathway that can be used to produce high-quality biochar for various applications [19]. The utilization of invasive plants as raw materials in the production of biochar/biosorbent presents a promising solution that can reinforce both environmental and economic sustainability. In view of their unique morphology, invasive plant species possess inherent advantages in terms of biomass structure and texture, which can be harnessed to enhance the structural properties of biochar products. For instance, water hyacinth is characterized by its hollow architecture that confers excellent initial structural features to biochar preparations. Table 9.3 shows a list of

Table 9.3. Invasive plants and their uses in environmental remediation.

Invasive plant	Production method	Modification	Characteristics	Uses	References
Ambrosia artemisiifolia L.	Pyrolysis/350 °C–550 °C/120 min		High pH value (alkaline)	Adsorption of Cd(II) and Pb (II)	[20]
Conyza canadensis	Pyrolysis/350 °C–550 °C/120 min		High pH value (alkaline)	Adsorption of Cd(II) and Pb (II)	[20]
Acacia auriculiformis	Pyrolysis/500 °C/120 min	—	—	Removal of dyes from water	[3]
Ailanthus excelsa				Removal of dyes from water	[3]
Ambrosia trifida L.	Pyrolysis/700 °C/180 min		Aromatic, low polarity	Adsorption of trichloroethylene in water	[11]
Solidago canadensis L.	Pyrolysis/700 °C/240 min	Ca/Al hydrotalcite or hydroxylapatite modification		Adsorption of Eu(III) in water	[21]
Eichhornia crassipes	Pyrolysis/550 °C/60 min	Impregnated with phase-change materials (PCMs)	High porosity, high carbon content, good thermal conductivity	Storage of energy	[22]
E. crassipes	Pyrolysis/700 °C/120 min	Modified with metal oxide (Fe)	Large apertures, nanoparticles of Fe_3O_4 aggregate to form a cluster	Gasification of coal wastewater, degradation of 2,4,6-trichlorophenol	[23]
E. crassipes	Pyrolysis/<700 °C	Modification with metal oxide (Mn)	Rich in Mn-OH groups	Adsorption of heavy metals in water	[25].
E. crassipes	Pyrolysis/500 °C/180 min	Modification with KOH	Large number of heteroatoms, developed carbon nanonetwork	Energy storage	[24].
E. crassipes	Pyrolysis/250 °C/60 min	Modification with metal oxide (Fe)	Magnetic, more surface activity sites	Adsorption of As(V) in water	[25].
E. crassipes	Pyrolysis/400 °C/180 min	Modification with metal oxide (Fe)	Magnetic, presence of more OH groups	Adsorption of Cr (VI) in water	[26]
Prosopis juliflora	Pyrolysis/400 °C/60 min	Modification with KOH	Large number of heteroatoms	Energy storage	[27]

Eupatorium adenophorum	HTC/220 °C/60 min	Modification with HNO_3	More functional groups, more pores	Adsorption of Pb(II) in water	[28]
E. adenophorum	Pyrolysis/600 °C/120 min	Modification with Fe and Ni	Increased surface functional groups	Removal of 2,4,6-trichlorophenol from water	[29]
Spartina alterniflora	Pyrolysis/350 °C/120 min	—	Many oxygen functional groups	Adsorption of Cd in soil	[30]
Alternanthera philoxeroides	Pyrolysis/450 °C/120 min	Modification with H_2O_2	Oxygen-containing functional groups	Adsorption of metformin hydrochloride in water	[31]
A. philoxeroides	Pyrolysis		Rich microporous structure	Adsorption of rhodamine B in water	[32]
Sicyos angulatus	Pyrolysis/700 °C/120 min	Activated with steam for 45 min	Increased pore volume	Adsorption of sulfamethoazine (SMT) in water	[11].
Lantana camara	Pyrolysis/500 °C/240 min	—	High ash content	Used to reduce soil acidity	[11]
Pistia stratioles	Pyrolysis/400 °C–700 °C/180 min	Nitrogen doped	Large pore structure, graphene structure, rich functional groups	Adsorption of phthalate esters in water	[33]
E. crassipes		Treated with NaOH		Removal of heavy metals from water	[3]
Acorus calamus		Treated with HCl and NaOH		Adsorption of ions	[3]
Undaria pinnatifda	Pyrolysis	Treated with $CaCl_2$		Adsorption of ions	[3]
Imperata cylindrica		Treated with NaOH	Large particle size	Adsorption of Cu(II) in water	[3]
E. crassipes		Treated with 10% EDTA		Adsorption of Co(II)	[3]

invasive plants that can be used to produce biosorbents for environmental remediation, including their production methods.

9.5 Preparing biosorbents from invasive plants

Although little work has been done on the preparation of biosorbents from invasive plants, a few scientists have been able to describe methods that might be efficient for this task. Anandrao and Rhesma [34] prepared biosorbents from *Ailanthus excelsa* by first drying the stalk and washing it with distilled water to remove impurities. The dried particles were then crushed and soaked with concentrated H_2SO_4 and kept for 6 h in a fume cupboard. After 6 h, the mixture was thoroughly washed with cold water to completely remove the H_2SO_4, producing a sulphonated carbon which was then used for the adsorption of methylene blue. Generally, biosorbents can be prepared from plants through the following process (figure 9.2):

- **Collecting invasive plants:** in this stage, the invasive plants are contained, and their parts (stems, flowers, rhizomes, leaves, bark, etc.) are harvested, which are then referred to as 'explants.'
- **Processing stage:** the explants undergo sorting and washing with distilled water or ethanol to eliminate impurities. Through this process, contaminants and pathogens are removed, while some endogenous inorganic matter that can hinder adsorption is discarded along with them.
- **Drying:** the explants are subsequently dehydrated to eliminate moisture content through exposure to solar light or by using an oven at a temperature range of 50 °C–105 °C.

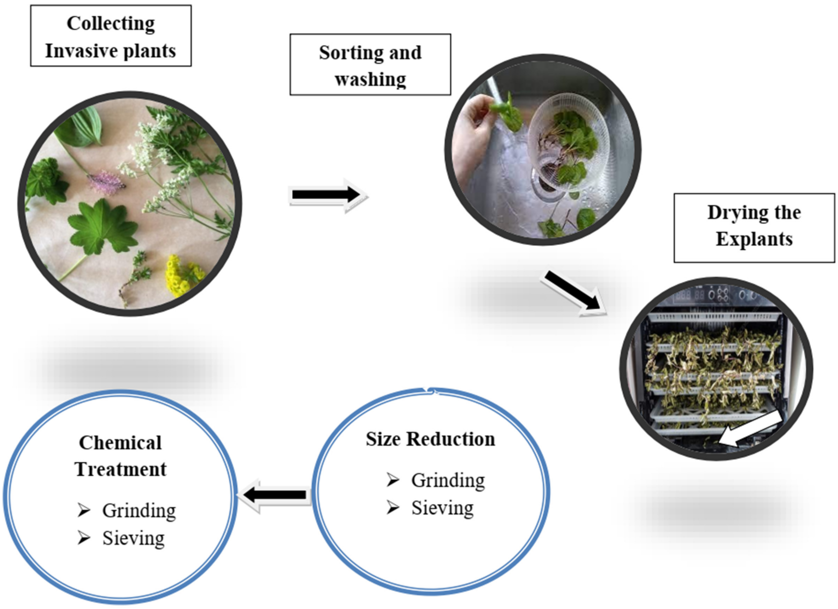

Figure 9.2. Preparation of biosorbents from invasive plants.

- **Reduction in size**: before a sieve is used to collect small particles, dried explants undergo size reduction through chopping or grinding. The main objective of this process is to increase the surface areas of adsorbents and reduce the diffusion path length for biosorbents. The result is an increase in the interactions between materials and pollutants, which enhances effectiveness [3]. The impact of explants' size reduction has been examined by scientists. In a study conducted by Khamparia and Jaspal [35], it was observed that the efficacy of rhodamine B elimination through adsorption on *Argemone mexicana* seed-based adsorbents increased considerably upon reducing the particle size from 710 to 300 μ. This stage is crucial in order to efficiently remove pollutants via the process of adsorption.
- **Chemical treatment:** chemical pretreatments play a significant role in the breakdown of lignin and cellulose within biomass or explants. This process facilitates an increase in surface area and porosity, thereby enhancing the adsorption of contaminants by biosorbents. Various chemicals, such as acids, bases, and oxidizers, are frequently utilized for this purpose [3]. Several sources have documented the analysis of chemical procedures carried out on alien plant explants. One such study conducted by Shooto [36] investigated the influence of hydrochloric acid and sodium hydroxide on the amounts of Cr and Pb heavy metal ions adsorbed by a biosorbent produced from rhizomes belonging to the *Acorus calamus* species. According to Shooto [36], the surface area of raw biomass can be increased through chemical treatment, and acid and base treatments result in an increase from 5.78 to 9.98 $cm^2\ g^{-1}$ and a near doubling, respectively. The study found that while both biosorbents had a higher adsorption capacity for Pb than for Cr, NaOH was the most effective modifier, followed by HCl. Specifically, upon treatment with an alkaline solution, the adsorption capacities of the biosorbent for Cr and Pb were found to increase by more than 10 $mg\ g^{-1}$ as compared to its untreated counterpart. In essence, chemical modifications lead to a favorable outcome in terms of reducing soluble organic compounds, which ultimately enhances pollutant removal efficiency.

9.6 The mechanism of biosorption

The term biosorption pertains to the non-active absorption of harmful substances by inanimate, lifeless, or biogenic materials [6]. Biosorption is a metabolic process that occurs outside of the cell membrane and involves various mechanisms for pollutant absorption, which may differ depending on the biomass applied. The physicochemical processes that underlie biosorption include absorption, adsorption, ion exchange, surface complexation, and precipitation. This spontaneous process does not rely on microorganisms' metabolisms to occur. Biosorbents are frequently utilized in biotechnology applications, as they enable the separation of organic or inorganic substances from solutions; this principle has also gained relevance with respect to environmental protection efforts.

The physicochemical characteristics of the metals and biosorbents and the process parameters influence the mechanisms of biosorption. Biosorbents derived from living organisms (microbes or plants) accumulate metals in capillaries and spaces of the cell walls and membranes when exposed to a concentration gradient [6]. The surfaces of biosorbents bear critical functional groups, viz. hydroxyls, sulfydryls, ketones, amines, carboxyls, and imidazoles, which help to facilitate the biosorption processes of specific metal ions [37]. The functional groups induce the detachment of metals from their typical binding sites, leading to a modification in the oxidation state of metallic ions and subsequently mitigating their harmful effects [38]. Nevertheless, there are various additional variables, such as the acidity level of the polluted environment, the arrangement of the biosorbents' structure, and thermal conditions that impact the performance of biosorbents. Zhang *et al* [39] stated that negatively charged biosorbents work best in sites contaminated with cationic metallic species. The optimum pH range is between 7.0 and 8.0. At lower pH values, competitive binding of hydrogen ions and metal ions ensues. At higher pH values, metals precipitate as hydroxides. Sites polluted with anionic metallic species such as chromium, arsenic, and molybdenum are best remediated at acidic pH values, i.e. 2.0–4.0 (figure 9.3 as adapted from [3]). High temperatures have also been discovered to drive biosorption by increasing the surface activity of biosorbents and the kinetic energy of the heavy metals to be absorbed [6].

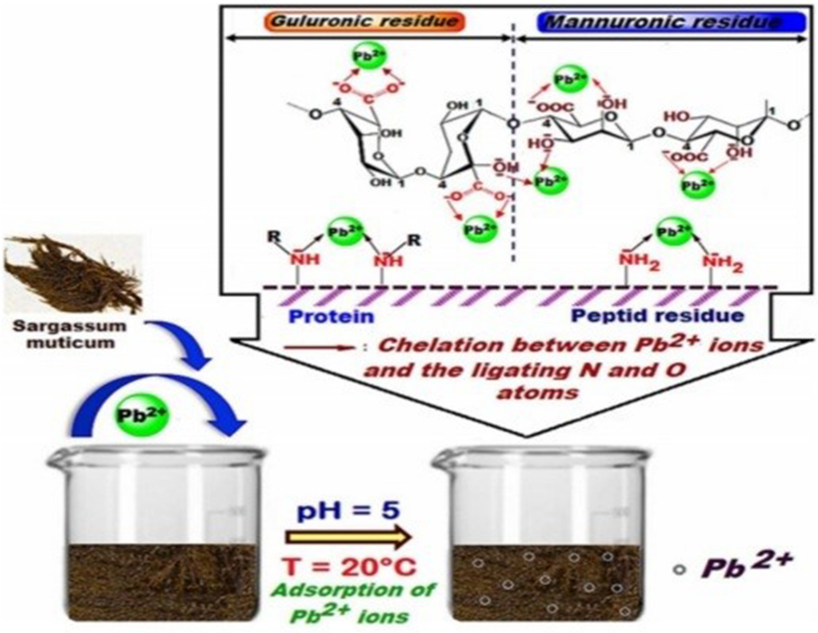

Figure 9.3. The adsorption mechanism of heavy metals by *Sargassum muticum*;lead was used in a case study. Adapted by permission from Springer Nature [3], Copyright (2021).

9.7 Conclusions

Invasive plants are generally known to be harmful to the environment. Nevertheless, these natural resources are versatile and can be used for various purposes such as food, medication, ornamental displays, and environmental remediation. In particular, they can address ecological concerns associated with the management of invasive species by serving as biosorbents. The chapter offered an overview of the different types of biosorbents classified according to their sources. Biosorbents can be extracted from invasive plants and subsequently chemically treated to introduce functional groups into them that can create biochar when modified. Such biosorbents have become useful materials for environmental healing purposes. Scientists remain keen to explore innovative applications of environmentally friendly techniques in order to use bioresources productively while also conserving nature. The use of invasive species for environmental reasons presents a promising solution with which to mitigate the detrimental effects of their proliferation on natural habitats. In addition, this approach addresses potential health hazards associated with ecosystem contamination. Various studies have documented cases in which non-native species efficiently acted as biosorbents in purifying contaminated areas. Notably, water hyacinths demonstrated exceptional capacity in absorbing heavy metals and storing energy from water sources, among numerous other examples described in the research literature.

Moreover, by utilizing biosorbents obtained from invasive plant species, researchers aim to improve their effectiveness in meeting environmental protection standards. A sustainable technique for a greener future with diverse combination options and the potential for application and research commercialization can be achieved through the ongoing development of biosorbents derived from such sources.

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