



# Invasive plants as biosorbents for environmental remediation: a review

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## Abstract

Water contamination is an environmental burden for the next generations, calling for advanced methods such as adsorption to remove pollutants. For instance, unwanted biowaste and invasive plants can be converted into biosorbents for environmental remediation. This would partly solve the negative effects of invasive plants, estimated at 120 billion dollars in the USA. Here we review the distribution, impact, and use of invasive plants for water treatment, with emphasis on the preparation of biosorbents and removal of pollutants such as cadmium, lead, copper, zinc, nickel, mercury, chromate, synthetic dyes, and fossil fuels. Those biosorbents can remove 90–99% heavy metals from aqueous solutions. High adsorption capacities of 476.190 mg/g for synthetic dyes and 211 g/g for diesel oils have been observed. We also discuss the regeneration of these biosorbents.

**Keywords** Invasive plants · Biosorbents · Water treatment · Heavy metal ions · Synthetic dyes · Oil removal

## Introduction

Industrialization and technological advancements play a considerable role in the civilization of mankind, but their repercussions are the water quality deterioration. Several

publications indicated that about one billion people did not have access to clean water worldwide and this figure would incline in tune with human development (Tauqeer et al. 2021). Besides, water contamination could enhance the growth of aquatic pathogens such as harmful microbes, especially coronavirus that causes the coronavirus 2019 (COVID-19) pandemic (Sharma et al. 2020). The major culprit for such phenomenon stems from the inappropriate disposal of a wide spectrum of organic and inorganic compounds including textile dyes, heavy metals, pharmaceuticals, and hydrocarbons (Islam et al. 2021). Among the contaminants, water pollutions caused by heavy metals are alarming because just low concentrations of them could trigger the reactive oxygen species that lead to cytotoxicity. For example, long-term excess exposure to arsenic, which means overconsuming 0.05 mg/L, could express acute symptoms such as chronic respiratory disorders, sensory loss, skin discoloration, and finally skin cancer (Sodhi et al. 2019). Likewise, with the development of dye production industries, over 10,000 dyes have been expelled, the concentration of color effluents in wastewater has increased greatly (Islam et al. 2021). These contaminants not only diminish the aesthetic value of the water bodies but also interfere with the penetration of light into the water, thereby leading to disturbances in the aquatic ecosystem. Particularly, recalcitrant

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dyes are mostly constituted by complex aromatic structures that make them carcinogenic and obstruct their biodegradation (Nguyen et al. 2021a). Therefore, discovering practical treatments to discard such toxic pollutants is considered the need-of-the-hour commission of humans.

Disparate methods have been exploited for water purification such as coagulation, oxidative-reductive degradation, Fenton process, membrane separation, ultrafiltration, reverse osmosis, and photocatalysis (Janani et al. 2022). These processes are costly, complicated, time and energy consuming, skilled personnel, and especially create amine residues in the sludge. In the last decade, adsorption is evaluated as a promising alternative because it is the most efficient and thus most applied in water treatment (Wang et al. 2021a). However, it is the nature of the adsorbent that affect directly to the removal efficiency of pollutants. In fact, thousands of adsorbents from available sources have been recommended in the literature to remove contaminants, for instance, clay minerals, biomass, materials from agricultural wastes, and by-products (Akpomie and Conradie 2020). Biomass-based adsorbents have gained considerable attention thanks to their availability in huge quantities in most places worldwide, environmental friendliness, and demanding simple pretreatment and preparation (Mpatani et al. 2021). In particular, the use of waste biomass from invasive species as adsorbent materials for the removal of pollutants from aqueous streams could decrease their threat, in harmony with the circular economy (Ahmed et al. 2020; Lian et al. 2020).

Plant biological invasion is considered the second alarming peril to biodiversity overtaken by habitat alteration. After invading areas outside their original natural regions, either deliberately or unintentionally, invasive species damage the function of bioecosystems, the structure, and also the dynamics of other populations. The strong reproduction, fast propagation, significant tolerance, and high adaptability of exotic plants support such ecological change (Paz-Kagan et al. 2019). For instance, the aquatic weed *Eichhornia crassipes*, commonly called water hyacinth, could flourish over 200 kg per ha each day (Huang et al. 2021), and 125 tons per surface ha in half of a year (Istirokhatun et al. 2015). Globally, its living form covered over 4 million hectares of wetlands, consequently, threatening the aquatic survival of other organisms and causing serious human issues such as mosquito-borne malaria, and the disturbance of the water transport network (Nguyen et al. 2021e). Moreover, invasive plants are also associated with human well-being, including jeopardizing the integrity of agricultural systems, the balance of the economy, and public health. Take the USA as an example, it was estimated an economic loss of 120 billion dollars yearly driven by such exotic plants (Duenas et al. 2018). In Africa, an invasive cactus, *Opuntia stricta*, was recorded to make a loss of 500 to 1000 US dollars per household annually by damaging the cultivated crops (Shackleton

et al. 2017; Sileshi et al. 2019). *Lantana camara*, a shrub with attractive flowers and had been utilized as ornamental, invaded almost all Indian pasture lands with a total area of 13.2 million ha. To control this aggressive weed, a cost of 70 US dollars for each ha was needed (Negi et al. 2019). Another highly noxious plant, *Ambrosia artemisiifolia*, was documented that induced pollen-borne allergy for about 13 million European and imposed economic costs of around 7.5 billion Euro each year (Schaffner et al. 2020). Because of their serious impacts on ecology and the economy, there is an urge for finding effective approaches to manage the invasive plants and utilize them as beneficial biomass sources.

Currently, the common disposal methods of exotic weed are usually manual eradication and chemical removal. Such processes produce an abundance of biomass waste, consequently, pose an increasing burden to the ecosystem. In fact, several researches have taken advantage of their great tolerance and stronger growth traits for phytoremediation (Prabakaran et al. 2019; Rezanian et al. 2019; Mustafa and Hayder 2021). However, this method requires great human and financial resources, performance may be seasonal, limits to several pollutants, and generates secondary wastes after treatment (Odoh et al. 2019). Thus, there is a shift in attention to the conversion of invasive plants to biosorbents for the decontamination of pollutants. Recently, Feng et al. (2021) have summarized the potential of exotic plants for biochar productions and their added value. Several other adsorbents for pollutants removal from invasive species were well reported such as activated carbons (Bouhamidi et al. 2017; Al-Musawi et al. 2021), nanoparticles (Durairaj et al. 2019; Davarnejad et al. 2020), composites (Wang et al. 2020a; Ren et al. 2021a), and aerogels (Yang et al. 2018; Cui et al. 2021). Although these materials are quite efficient, they necessitate so further preparations, chemicals, time, and energy that they are relatively not suitable for large-scale applications. Conversely, raw biomass-waste materials are gained attention due to their simple preparation, low cost, eco-friendly, and biodegradable characteristics (Shooto 2020; Acosta-Rodríguez et al. 2021).

Regardless of several publications on the utilization of invasive plants biomass for medicines, phytoremediation, and biochar production, it lacks a comprehensive review that mentions the use of invasive plants as biosorbents for environmental remediation. To the best of our knowledge, this is the first review covering all aspects from the distribution, harmful properties, the biological traits, invasive mechanisms to potential applications of invasive plants in water treatment. This study spotlights the viability of such biosorbents for the treatment of many kinds of pollutants such as heavy metal, organic dyes, and oils. Therefore, the present review is systematically organized in three key sections: (i) biological traits and harms of invasive plants; (ii) insights into the preparation of biosorbents from invasive

species; (iii) utilizations of invasive plant-based biosorbents for removal of heavy metals, organic dyes, and oils (Fig. 1). We briefly discuss the knowledge gaps and future directions of invasive plant-based adsorbents to orientate further researches, and their practical large-scale applications.

## Biological characteristics of invasive plants

### Anthropocentric definition

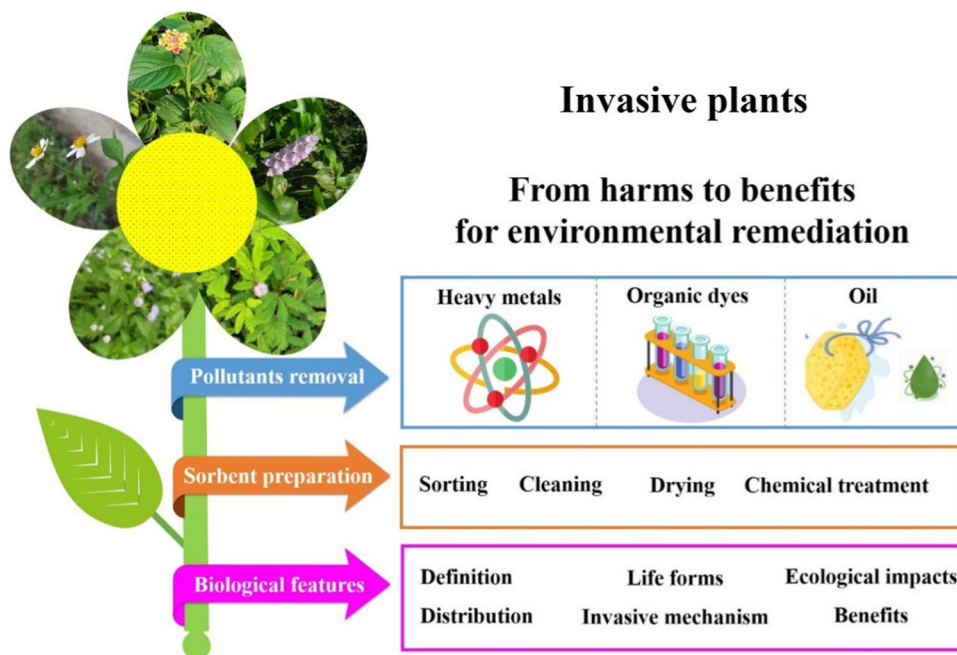
Hinging on the demography, the influence, and especially the genesis of species to definite what the invasive plant is. However, there are more common usages of the term “invasive” for the one which is both non-native and harmful for the economy and environment or even on human health (Russell and Blackburn 2017). For example, *Opuntia stricta* was originally grown as ornamental and fencing function in various places. After escaping cultivation and invading conserved regions, it causes many problems such as mitigating fodder production, jeopardizing public health, hindering human transportation, and influencing livestock (Witt et al. 2020). Pyšek et al. (2012) estimated there were 167 invasive species that resided in 49 plant families associated with the feedback of the resident biomes. These authors concluded that it lacked the universal measurement of influence and significantly depended on the observed context. On the other hand, Shackleton et al. (2019) overviewed relevant researches focusing on 66 invasive species. The data showed that 48% of species were attributed to having both advantages and disadvantages on local livelihoods including

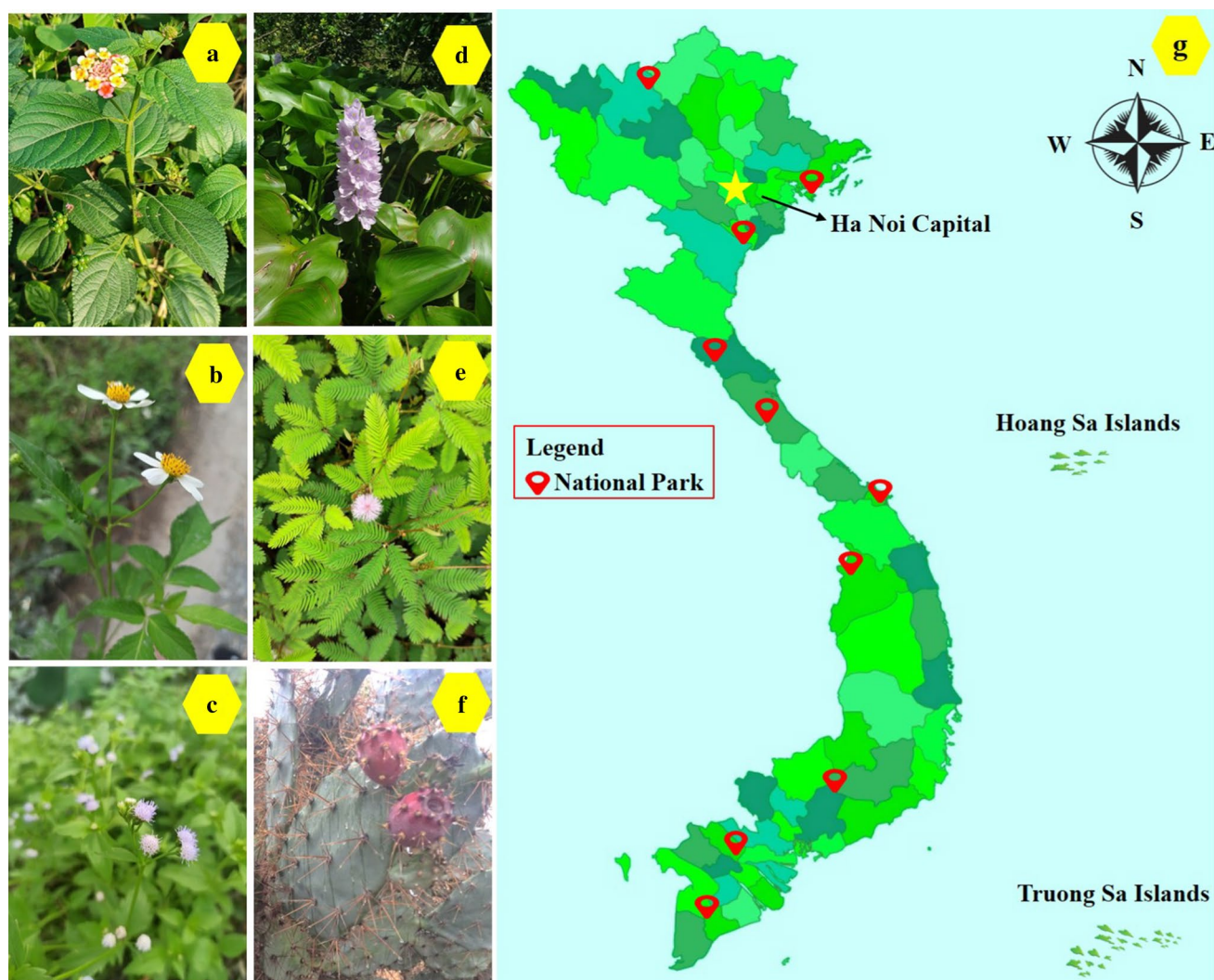
*Lantana camara*, while nearly 37% of them created major costs such as *Opuntia stricta* and *Chromolaena odorata*. Other representatives of invasive plants are illustrated in Fig. 2 based on the result of Tan et al. (2012) conducted in the national parks of Vietnam.

### Classification and habitat distribution of invasive plants

Invasive species commonly flourish in unusual habitats rich in resources, and thus, they have high biodiversity and wide distribution. Their extraordinary multitude of species, from aquatic weeds (e.g., *Eichhornia crassipes*, *Pistia stratiotes*) to grasses, small (e.g., *Poa annua*, *Cynodon dactylon*) and large (e.g., *Phragmites australis*, *Sorghum halepense*), forbs and herbs (e.g., *Lythrum salicaria*, *Centaurea solstitialis*), vines (e.g., *Celastrus orbiculatus*, *Rosa multiflora*), shrubs (e.g., *Mimosa pigra*, *Lantana camara*) and trees (e.g., *Pinus ponderosa*, *Castilla elastic*) (Albrecht et al. 2021). Mallick et al. (2019) reported that there were 132 genera in 165 taxa of invasive plants in the City of Odisha, India. Among, herbs were prevalent than other life forms, which accounted for 69% of the total recorded plant species. The proportion for trees, shrubs, and vines was 14, 13, and 3%, respectively. This could be explained that herbaceous plants not only possess more tolerant capacity to harsh conditions but also have tremendous viability in any environment. Weidlich et al. (2020) gathered information on exotic plant species in bio-ecological restoration from 372 articles in the first twenty years of the twenty-first century and analyzed their distribution. This systematic review showed that there were

**Fig. 1** Conversion of biomass from harmful invasive plants into beneficial biosorbents for environmental remediation. The biosorbent preparation experiences some stages such as collecting, cleaning, drying, and treatment. Biosorbents derived from invasive plants can be used to remove heavy metals, organic dyes, and oils. This development remedies wastewaters and contributes to the prevention of powerful invasion of exotic plants





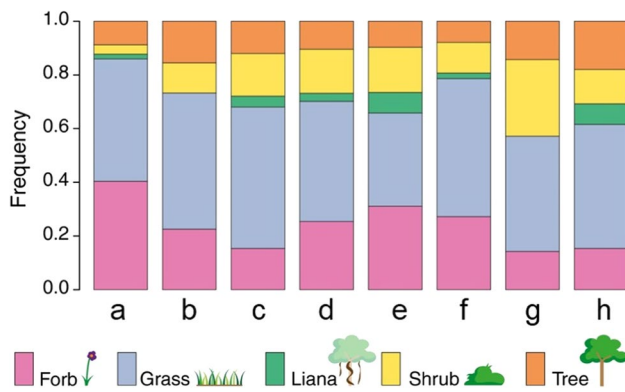
**Fig. 2** Invasive plants including *Lantana camara* (a), *Bidens pilosa* (b), *Chromolaena odorata* (c), *Eichhornia crassipes* (d), *Mimosa pigra* (e), *Opuntia stricta* (f), and their geographical distribution in national conservation parks in Vietnam (g)

10 researched biomes (Fig. 3). Regardless of what kind of biome, the major groups managed in restoration programs were relatively identical in terms of ratio. Nearly half of the species were exotic grasses that almost belong to Poaceae family, indicating that this invasive life form became a global issue. Forbs were recorded as the second most ubiquitous, followed by shrubs, trees, and lianas.

### Mechanism of plant invasion

Thousands of exotic species have been sent to native ecosystems over the world, either deliberately or unintentionally. The successful invasive reasons are complicated and need to be studied in the specific context of each species. Overall, such success comprises some main features related to wide bio-ecological demands and tolerances, r-selected life histories, broad geographical scopes, evolution from high

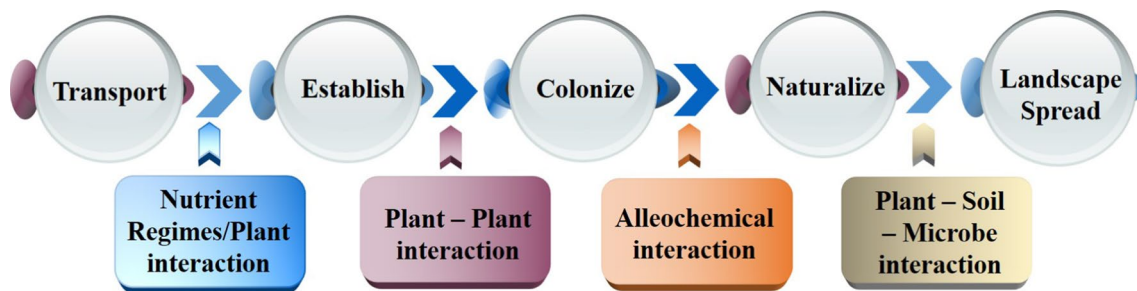
diverse regions as well as anthropogenic or disturbed native environments (Jose et al. 2013). In terms of ecological process, allelopathy is fundamentally one that active secondary compounds play a critical role in biotic interference. This approach helps invasive species modify the invaded regions to improve their competitiveness (Pinzone et al. 2018). For instance, essential oil from the rhizomes of *Hedychium coronarium* was demonstrated to have phytotoxic effect on the germination of resident plants (Costa et al. 2019). Zheng et al. (2015) hypothesized that *Chromolaena odorata* could secrete a phenolic compound called odoratin. Such allelochemical joined in the defense of soil-borne pathogens and other enemy resistance of this invasive weed, thus paving the way for its colonization. Allelopathy was demonstrated as one of the most ubiquitous invasion mechanisms throughout the vascular plant phylogeny which accounted for roughly 51% of non-native species in the surveyed database. Thus,



**Fig. 3** Proportion of exotic plants by growth forms—forb, grass, liana, shrub, and tree—that are controlled in restoration sites including **a** Chaparral, **b** Desert, **c** Savanna, **d** Temperature coniferous forest, **e** temperature deciduous forest, **f** Temperature grassland, **g** Tropical dry forest, and **h** Tropical rain forest. Accordingly, the distribution of major exotic species in various restoration sites was insignificantly different. Mean  $\pm$  standard deviation of five biomes could be shown:  $46.0 \pm 5.8\%$  grass,  $24.1 \pm 9.0\%$  forb,  $14.6 \pm 7.1\%$  shrub,  $12.1 \pm 3.5\%$  tree, and  $3.2 \pm 3.1\%$  liana. Reproduced with the permission of Wiley Online Library from reference (Weidlich et al. 2020)

allelopathy is considered to significantly influence the native ecosystems worldwide and deserves more attention (Kalisz et al. 2021).

In addition, efficient resource uptake and use is another approach for plant invasion. For example, *Bromus tectorum* could defeat other native plants thanks to its capacity to take advantage of an increase in nitrogen in soil (Morris et al. 2016). Figure 4 illustrates the common mechanism of biological invasion of plants in a new habitat. This process comprises five stages, from transporting to spreading in the landscape, which depends on the patterns of disturbance, biomes composition, and the interactions with environmental factors (Paz-Kagan et al. 2019). By understanding such



**Fig. 4** Mechanism of biological invasion of plants in new habitats. Biological invasion disrupts interactions of indigenous species. (i) Nutrient regime is the first indication of new invasive transportation. (ii) Invasive plants tend to proliferate well in their regions, directly affect local species interactions. (iii) To consolidate colonization, they secrete allelochemicals into ambient environment, thereby exerting

progress, people could generate effective strategies to either counter or limit the expansion of these exotic species.

### Impacts of invasive plants

Biological invasion of the plant is a well-perceived stimulator of ecological alternation globally. Such change relates to the function of bioecosystems, the structure, and also the dynamics of other populations. For example, the strong invasion of a shrub called *Rhododendron ponticum* facilitates the safety of a nocturnal rodent from the threat of its major predator—the tawny owl. However, the vigorous growth of this invasive weed restrains the development of native food plants, and hence lowers local food availability (Malo et al. 2013). There is a shift to negative impacts of biological invasion since it generates catastrophe on genes, populations, native communities, and thus loss of biodiversity. Munoz and Cavieres (2019) uncovered that *Taraxacum officinale*, an invasive weed, was attributed to change plant–pollinator networks when co-existing with native species. In terms of the impact on native flora communities, the exotic herb *Leucanthemum vulgare* was found to decrease the species richness severely at larger temporal scales (Ahmad et al. 2019). Another non-native weed, *Oenothera drummondii* was discovered to affect more negatively in inland areas in comparison with the foredune areas (Gallego-Fernandez et al. 2019). Therefore, the ecological impacts of biological invasion fluctuate from the standard of each native species to whole biosphere patterns and processes.

Invasive plants are also associated with human well-being, including jeopardizing the integrity of agricultural systems, the balance of the economy, and public health. Indeed, *Ambrosia trifida*, normally known as giant ragweed, has been recognized as not only a harmful factor for reducing crop yields but relating to serious allergic symptoms for people (Park et al. 2012). Another highly noxious

detrimental physiological effects on the growth and reproduction of native species. (iv) Naturalization signs a profound change in the distribution of plant, soil, and microbe. (v) With many strong functional traits, invasive plants spread various landscapes to complete a biological invasion and initiate a new cycle

ragweed, *Ambrosia artemisiifolia*, was documented that induced pollen-borne allergy for about 13 million European and imposed economic costs of around 7.5 billion Euro each year (Schaffner et al. 2020). Moreover, this exotic herb caused a loss of 30% to sunflower and maize production yields and had the potential to lower the soybean biomass up to 70% (Savić et al. 2021). In Africa, an invasive cactus, *Opuntia stricta*, was estimated to create a loss of 500 to 1000 US dollars per household annually by damaging the cultivated crops. An economic loss of about one billion US dollars in the agricultural field was caused by total non-indigenous invaders in the African continent (Shackleton et al. 2017; Sileshi et al. 2019). Also, several invasive plants impose an impact on humans via the alteration of water quality. Pejchar and Mooney (2009) reported that the invasion of genus *Tamarix* leads to a tremendous loss of water up to 3 billion cubic meters equivalent to around 70 million US dollars. Other invasive plants influence on public health by elevating the growth of pathogen populations. For example, Virginia deer takes advantage of invaded regions by non-native shrub *Lonicera maackii* as a food source. However, this animal is reported to carry northeastern water tick that causes tick-borne ehrlichiosis for humans. Other cases that benefited from invasive vascular plants are recorded as the vectors of pathogens, such as scrub typhus, Lyme disease, Hantavirus, malaria, trypanosomiasis, and spotted fever (Stewart et al. 2021).

On the other hand, there are some added potential facets of invasive plants, such as food sources, ornamental benefits, cosmetics, utilizations in vector bone control, medicine, bioenergy, and green synthesis of materials (Nguyen et al. 2021d). For instance, the extraction of flowering plant *Lantana camara* could be applied as mosquito repellent (Sharma et al. 2021). Recently, this invasive shrub has been proved to have manifold medicinal properties, including fungicidal, insecticidal, and strongly antibacterial against *E. coli*, *P. aeruginosa*, *Bacillus subtilis* (Arunkumar et al. 2019). Apart from the original use as a garden ornamental, *Lantana camara* biomass has been used to produce biopesticides, fertilizers, pulps, paper fibers, bioenergies, fuelwoods, honey plants, and cosmetics (Negi et al. 2019). A representative of aquatic weed, water hyacinth (*Eichhornia crassipes*) has been applied for the production of ethanol, biodiesel, biohydrogen and developing supercapacitors. Interestingly, there are more and more studies laid emphasis on this species as adsorbents including phytoremediation for removal of heavy metals, organic compounds, and other pollutants (Guna et al. 2017). In brief, the economic benefits and positive contribution of invasive plants could outweigh their disadvantages; thus, it requires more researches on cost–benefit examinations tailoring solutions for its effective management.

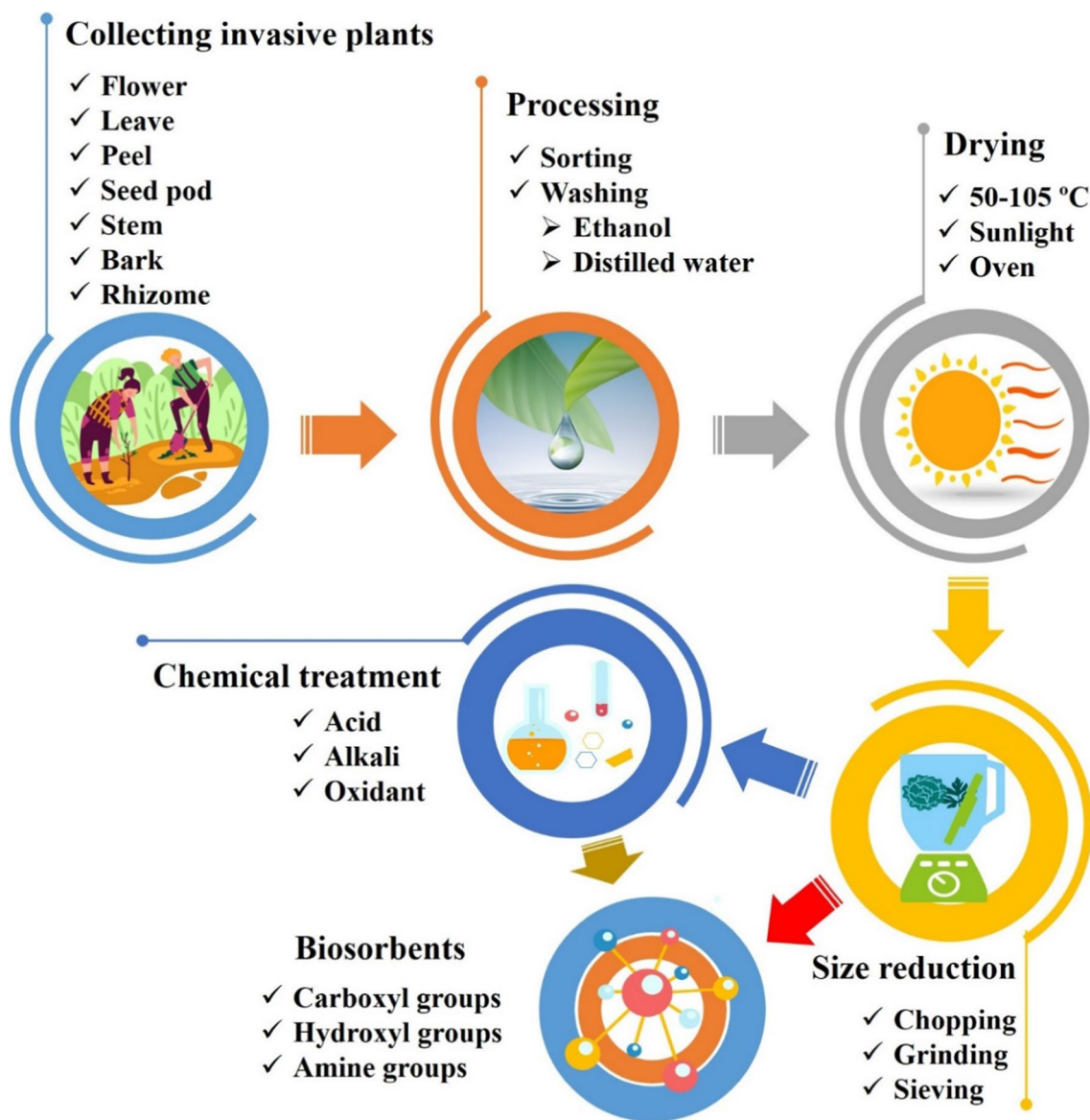
## Conversion of invasive plants into biosorbents

### Preparation procedure

Some invasive plants can contain many toxic compounds that trigger poisonous effects on humans such as skin inflammation and fester. Hence, the procedure of detoxification is required before they can be next proceeded. Attaining the invasive plant-based raw biomass, there are overall four main steps as illustrated in Fig. 5. Initially, the invasive plants are collected from their landscapes, and they could be the aboveground biomass like leaves, stems, flowers, bark or underground biomass like rhizomes or the whole plant. Then, the explants are sorted and washed to remove dirties. Next, they are commonly desiccated under solar light or by oven at temperatures from 50–105 °C to remove the moisture content. The dried materials are subjected to size reduction by chopping or grinding before using a sieve to obtain small size particles. Most of the previous publications ended at this step and the adsorbents were stored or used directly for further studies. However, more studies applied additional steps to enhance the adsorption capacity of the materials by chemical pretreatment. The detailed procedure of each technique will be discussed in the next sections.

### Cleaning the biomass

Washing biomass not only removes the impurities, pathogen borne agents but also discards some endogenic inorganics that affect the adsorption process. Johnson et al. (2019) identified fourteen species of insects including ant, fly, wasp, bee, and beetle that were considered the visitors of exotic weed *Fallopia japonica*. Many of them were proved to be vectors transmitting pathogens during plant–insect interactions. Indeed, it was documented that fungal pathogens including *Bipolaris* species causing foliar blight in an aggressive invasive grass, *Microstegium vimineum* (Flory et al. 2011). On the other hand, apart from the structural carbohydrates and lignin, invasive plant biomass also comprises extraneous ingredients including inorganics. These molecules exist in various forms, such as alkali metals, alkaline earth metals, transition metals, and non-metals (Dahou et al. 2021). While such elements only account for negligible proportion, they could be dissolved in the polluted solutions and thus lower the biosorption capacity of raw biomass (Amrhar et al. 2021). Regardless of the little concern or even lack in the material preparation method, the explants could be generally washed by distilled water at ambient temperature before drying



**Fig. 5** Preparation of biosorbents from invasive plants. Many invasive plant parts can be collected, including flowers, leaves, roots, etc., for the next processing stage. Drying procedure of invasive biomass

can be carried out under solar light to remove moisture. To enhance surface area and surface chemistry, the dried samples are ground and treated by chemical agents such as acid, or alkali

(Bansal et al. 2021). In brief, making the materials cleaner seems to be a straightforward step but plays an important role in the fabrication of biosorbents.

**Grinding the biomass**

Size reduction in biomass contributes significantly to the efficiency of pollutants removal of biosorbents. This step is approached by using a hammer mill (Rigueto et al. 2020) or a domestic mixer (Tounsadi et al. 2015) with initial chopping. Then, the sieves are applied to categorize the material by appropriate size for either further investigation or utilization. The underlying aim of reducing feedstock size is to

enhance the surface areas of the adsorbents and shorten the diffusion path of them, in order words, increase the interactions of materials and pollutants (Nguyen et al. 2021b). For example, Hossain et al. (2012) investigated the effect of three different particle sizes of garden grass raw biomass on copper removal. The authors concluded that the adsorption capacity rose from approximately 6 to 11.17 mg/g when diminishing the particle size more than a half from 150 µm. Similarly, Khamparia and Jaspal (2016) found that the removal efficiency of Rhodamine B by *Argemone mexicana* seed-based adsorbent inclined significantly in tune with the decrease in the particles size from 710 to 300 µm. Regardless of the fact that size reduction demands a noticeable amount of resources and cost

for scale-up investigation, this step is essential for an effective discard of contaminants by adsorption.

## Chemical pretreatment

Invasive plant biomass has recalcitrant traits due to its intrinsic complicated structures. Indeed, most biomass tissues built up by cellulose, hemicellulose, and lignin possess numerous complex bonds and functional groups (Wang et al. 2021b). Chemical pretreatments contribute relatively to the disruption of the lignocellulose biomass, thus helping the treated materials increase surface area and porosity. These improvements then facilitate the adsorption capacity of biosorbents for pollutants removal. Frequently, acids, bases, and oxidizing agents are utilized as chemicals for such purposes (Sheng et al. 2021). Raw biomass would experience hydrolysis reaction during the treatment with dilute acid, e.g., oxalic acid, hydrochloric acid (HCl), or alkali, typically sodium hydroxide (NaOH). The acid could break down interchain bonds of hemicellulose while the base solution helps to decrease lignin proportion (Mallesht et al. 2020). To sum up, the chemical modifiers benefit biomass by reducing soluble organic compounds and improving the pollutants elimination efficiency.

Several publications reported the investigation of chemical treatments on invasive plant biomass. For example, Shooto (2020) examined the effects of HCl and NaOH on the adsorption of Cr(VI) and Pb(II) heavy metal ions of biosorbent derived from *Acorus calamus* rhizome. The authors found that such treatment helps increase the surface area of raw biomass from 5.78 to 9.98 cm<sup>2</sup>/g by acid treatment and nearly twofold by base treatment. Although both biosorbents have the adsorption capacity for Pb(II) higher than Cr(VI), the overall trend illustrated that NaOH acted the best modifier, followed by HCl. In particular, the maximum removal of adsorbent for Cr(VI) and Pb(II) treated by alkaline solution inclined over 10 mg/g compared with pristine biomass. Similarly, Ye et al. (2010) used NaOH to treat rice husk and the treated adsorbent showed significantly higher elimination of Cd(II) than natural one. However, chemical pretreatments have some disadvantages related to costs of chemicals, facilities, and demanding further drying processes (Jönsson and Martín 2016). Thus, evaluation of the efficiency of such modifications on various exotic plants should be more concerned.

## Removal of heavy metal ions by invasive plants

### Occurrence of heavy metal ions

The term heavy metal implies a metallic element toxic that cause a poisonous level at low concentrations (Gemed

et al. 2021; Lisak 2021). Their occurrence in nature can be detected through metal corrosion, soil erosion, or releasing heavy metals from ore mining (Malik et al. 2019). Over the past decades, the presence of heavy metal ions in aqueous media such as groundwater, surface water, and seawater has been alarmingly serious (Lim et al. 2018; Liu et al. 2019a; Karaouzas et al. 2021). For example, Chowdhury et al. (2016) reported the co-exposure of a large amount of lead, arsenic, cadmium, copper, etc., in the drinking water from taps and plumbing pipes inside the building. Sibál and Espino (2018) investigated the occurrence and analytical determination of heavy metals in many lakes in Asian countries. Palansooriya et al. (2020) overviewed the recent occurrence of many kinds of contaminants including heavy metals co-existing in drinking water sources. These contaminations are mainly due to human activities since the discharge of heavy metal ions is occurred during the production of batteries, fertilizers, metallurgical industries, and electronic devices without pretreatment (Rathi et al. 2021).

Literatures reports adverse effects of heavy metal ions as carcinogenic substrates, or toxic agents against neurons (Fu and Xi 2020; Qasem et al. 2021). Many metals, such as lead, mercury and cadmium, cause cardiovascular diseases and cancer mortalities which result in adverse effects on human health as well as aquatic creatures (Vareda et al. 2019; Ajiboye et al. 2021). As a result, the removal of heavy metal ions is an urgent task. Nowadays, a number of techniques involving chemical precipitation, ionic exchange, membrane filtration and ultrafiltration have been adopted to treat the pollution of heavy metal ions (Carolin et al. 2017; Vasseghian et al. 2021). However, the main disadvantages of these techniques are high cost, time consuming procedures, and complex operations (Qin et al. 2020). Adsorption technique using biosorbents is highly recommended because it offers a wide range of advantages such as eco-friendliness, high performance, and simple procedure (Karaouzas et al. 2021). The use of invasive plants as biosorbents for the removal of heavy metal ions may meet these critical requirements.

### Plausible adsorption mechanism of heavy metal ions

The use of biosorbents from invasive plants is very beneficial because they exhibit the efficient and eco-friendly sequestration of cadmium (Ayuba et al. 2019). With the constitution of many chemical groups such as hydroxyl, amine, and carboxyl, these adsorbents can have high affinity to heavy metal cations (Pyrzynska 2019). According to Table 1, many works pointed out that some of the underlying mechanisms of metal cations adsorption are ionic exchange, and electrostatic attraction. The former relies on the formation of chelation and sequestration between divalent, trivalent metal



**Table 1** Adsorption performance of biosorbents from invasive plants for the treatment of heavy metal ions

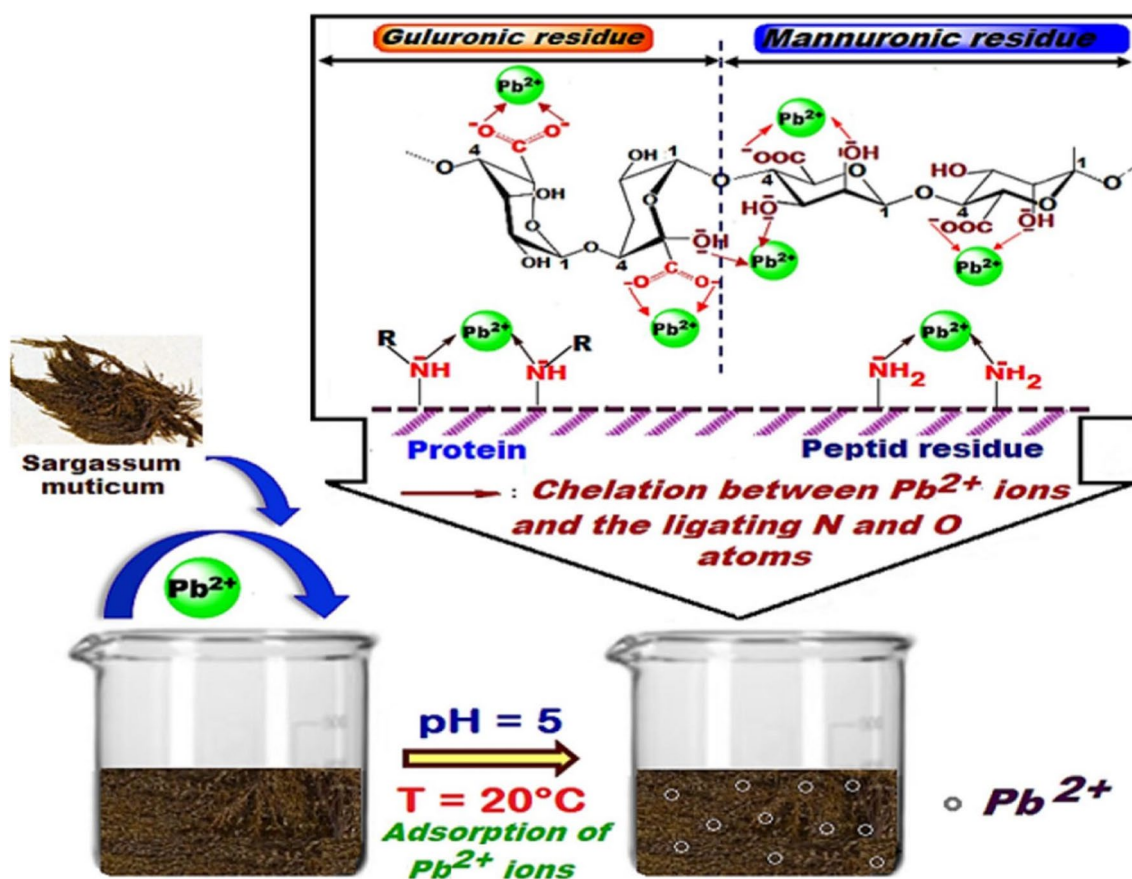
Plant	Part	Biosorbent features	Target metals	pH	Adsorption results	Adsorption mechanism	Refs.
<i>Arundo donax</i> L.	Leaf	Particle size: 750 µm	Cd(II)	5.5	27.9 mg/g	Electrostatic attraction, chemical reaction	(Ammari 2014)
<i>Cyperus papyrus</i>	Stem	Treated with H <sub>2</sub> O <sub>2</sub> and NaOH	Cd(II)	3.5	0.028–5.97 mg/g at 24 °C	Monolayer chemisorption	(Bakyayita et al. 2015)
<i>Eichhornia crassipes</i>	Whole	Treated with NaOH, particle size: 2000 µm	Cd(II)	5	12.4 mg/g at 25 °C	Ionic exchange, electrostatic interaction, complexation	(Saraswat and Rai 2010)
<i>Eichhornia crassipes</i>	Whole	Not reported	Cd(II)	4.84	12.60 mg/g	Ionic exchange	(Mahamadi and Nharingo 2010)
<i>Glebeionia coronaria</i>	Stem	Particle size: < 160 µm, surface area: 1.741 m <sup>2</sup> /g, point of zero charge: 6.5	Cd(II)	6.5	18.31 mg/g at 25 °C	Electrostatic interaction, ionic sorbent–sorbate interaction	(Tounsadi et al. 2015)
<i>Diplotaxis harra</i>	Stem	Particle size: < 160 µm, surface area: 1.612 m <sup>2</sup> /g, point of zero charge: 6.29	Cd(II)	7.5	25.24 mg/g at 25 °C	Electrostatic interaction, ionic sorbent–sorbate interaction	(Tounsadi et al. 2015)
<i>Undaria pinnatifida</i> (brown algae invasive species)	Whole	Treated with CaCl <sub>2</sub> , particle size: 10–16 mesh; surface area: 0.3 m <sup>2</sup> /g	Cd(II)	3	121.4 mg/g at 20 °C	Ionic exchange, complexation, coordination, and micro-precipitation	(Cazón et al. 2013)
<i>Acorus calamus</i>	Rhizome	Treated by HCl and NaOH, particle size: 800–1000 µm, surface area: 9.98 m <sup>2</sup> /g for biosorbent treated with HCl, and 11.65 m <sup>2</sup> /g for biosorbent treated with NaOH	Pb(II)	7–8.5	76.12 mg/g for biosorbent treated with HCl, and 88.08 mg/g for biosorbent treated with NaOH	Electrostatic interaction, reduction, and anionic adsorption	(Shooto 2020)
<i>Cyperus papyrus</i>	Stem	Treated with H <sub>2</sub> O <sub>2</sub> and NaOH	Pb(II)	4.5	0.732–1.231 mg/g at 24 °C	Monolayer chemisorption	(Bakyayita et al. 2015)
<i>Eichhornia crassipes</i>	Whole	Treated with HNO <sub>3</sub> , particle size: 2.5 mm	Pb(II)	4.84	26.32 mg/g for Pb(II)	Ionic exchange	(Mahamadi and Nharingo 2010)
<i>Eupatorium adenophorum</i>	Whole	Particle size: 40–60 mesh	Pb(II)	5.0	2.236 mg/g at 26 °C	Chemisorption or chemical adsorption	(Guo et al. 2009)
<i>Prosopis juliflora</i>	Seedpod	Particle size: 100 mesh	Pb(II)	6.0	40.322 mg/g at 28 °C	Chemisorption, ionic exchange	(Jayaram and Prasad 2009)
<i>Prosopis juliflora</i>	Seedpod	Particle size: 75–150 µm	Pb(II)	6.0	1.4 mg/g at 27 °C	Monolayer chemisorption	(Gautam et al. 2020)
<i>Moringa oleifera</i>	Seed	Particle size: 75–150 µm	Pb(II)	6.0	5.6 mg/g at 25 °C	Monolayer chemisorption	(Gautam et al. 2020)
<i>Sargassum muticum</i> Seaweed	Whole	Particle size: 500 µm	Pb(II)	5.0	76 mg/g at 25 °C	Chelation	(Hannachi and Hafidh 2020)
<i>Alternanthera philoxeroides</i> (Mart.) Griseb	Whole	Particle size: < 125 µm	Cr(VI)	2.0	17.71 mg/g, at 20 °C	Monolayer chemisorption, ion exchange, chelation	(Wang and Qin 2006)
<i>Acorus calamus</i>	Rhizome	Treated by HCl and NaOH, particle size: 800–1000 µm, surface area: 9.98 m <sup>2</sup> /g for biosorbent treated with HCl, and 11.65 m <sup>2</sup> /g for biosorbent treated with NaOH	Cr(VI)	1.0	<i>Acorus calamus</i> treated by acid: 21.93 mg/g, <i>Acorus calamus</i> treated by base: 24.48 mg/g	Electrostatic interaction, reduction and anionic adsorption (fraction of Cr(VI) is reduced to Cr(III) by electrons donating functional groups on the biomaterial surface)	(Shooto 2020)

Table 1 (continued)

Plant	Part	Biosorbent features	Target metals	pH	Adsorption results	Adsorption mechanism	Refs.
<i>Eichhornia crassipes</i>	Whole	Treated with NaOH, particle size: 2000 µm	Cr(VI)	2.0	5.6 mg/g at 25 °C	Ion exchange, electrostatic interaction, complexation	(Saraswat and Rai 2010)
<i>Eupatorium adenophorum</i>	Stem	Particle size: 60 mesh	Cr(VI)	1.0	89.22 mg/g at 308 K, 99.9% of Cr(VI) removal	(i) Electrostatic interaction (via binding of Cr(VI) with positively charged biomass surface), (ii) reduction in Cr(VI) to Cr(III); (iii) electronic repulsion or complexation of Cr(III) to release Cr(III) ions	(Song et al. 2016)
<i>Phragmites australis</i>	Whole	Particle size: < 250 µm	Cr(VI)	5.0	21.32 mg/g at 25 °C	Electrostatic interactions, reduction and chelation or complexation with the functional groups of adsorbents	(Mahmoud et al. 2021)
<i>Ziziphus spina-christi</i>	Whole	Particle size: < 250 µm	Cr(VI)	4.0	15.5 mg/g at 25 °C	Electrostatic interactions, reduction and chelation or complexation	(Mahmoud et al. 2021)
<i>Melaleuca diosmifolia</i>	Leaf	Particle size: 500 µm; surface area: 0.99 m <sup>2</sup> /g	Cr(VI)	7.0	62.5 mg/g at 24 °C	Adsorption-coupled reduction	(Kuppasamy et al. 2016a)
<i>Sargassum muticum</i> Seaweed	Whole	Particle size: 125–250 µm	Cr(VI)	2.0	196.1 mg/g at 20 °C	Ionic exchange, surface complexation and electrostatic attraction	(Bermúdez et al. 2012)
<i>Alternanthera philoxeroides</i>	Whole	Particle size: < 125 µm	Zn(II)	4.0	18.57 mg/g at 20 °C	Monolayer chemisorption, ion exchange, chelation	(Wang and Qin 2006)
<i>Cyperus Rotundus</i>	Whole	Surface area: 1.027 m <sup>2</sup> /g, pore volume: 9.035 cm <sup>3</sup> /g, point of zero charge: 5.0, and particle size: 150–330 µm	Zn(II)	8.0	208 mg/g at 30 °C	Electrostatic attraction	(Ramesh et al. 2013)
<i>Centaura nicaeensis</i>	Flower	Surface area: 0.76 m <sup>2</sup> /g, and particle size: 400 µm	Zn(II)	2.0	13.86 mg/g at 25 °C	Electrostatic interactions	(Dhouibi et al. 2020)
<i>Eichhornia crassipes</i>	Whole	Treated with NaOH, and particle size: 2000 µm	Zn(II)	6.0	9.3 mg/g at 25 °C	Ion exchange, electrostatic interaction, complexation	(Saraswat and Rai 2010)
<i>Undaria pinnatifida</i> (brown algae invasive species)	Whole	Treated with CaCl <sub>2</sub> . Size: 10–16 mesh, surface area: 0.3 m <sup>2</sup> /g	Zn(II)	4.0	100.0 mg/g at 20 °C	Ionic exchange, complexation, coordination, and micro-precipitation	(Cazón et al. 2013)
<i>Cyperus Rotundus</i>	Whole	Particle size: 150–330 µm; surface area: 1.027 m <sup>2</sup> /g, pore volume: 9.035 cm <sup>3</sup> /g, point of zero charge: 5.0	Cu(II)	6.0	500 mg/g at 30 °C	Electrostatic attraction	(Ramesh et al. 2013)
<i>Centaura nicaeensis</i>	Flower	Particle size: 400 µm, surface area: 0.76 m <sup>2</sup> /g	Cu(II)	4.0	24.53 mg/g at room temperature	Electrostatic interactions	(Dhouibi et al. 2020)

Table 1 (continued)

Plant	Part	Biosorbent features	Target metals	pH	Adsorption results	Adsorption mechanism	Refs.
<i>Imperata cylindrica</i>	Leaf	Treated with NaOH, particle size: 180–355 $\mu\text{m}$ , point of zero charge: 7.34	Cu(II)	5.0	11.64 mg/g at 310 K	Monolayer chemisorption, film diffusion	(Hanafiah et al. 2009)
<i>Eichhornia crassipes</i>	Whole	Treated with 10% EDTA	Co(II)	5.0	20.0 mg/g at 28 °C, 100% of Co(II) was removed the industrial samples	Electrostatic interactions caused by carboxyl, hydroxyl, amino, or sulfonic groups on biosorbent	(Acosta-Rodríguez et al. 2021)
<i>Glebionis coronaria</i>	Stem	Particle size: < 160 $\mu\text{m}$ , surface area: 1.741 $\text{m}^2/\text{g}$ , point of zero charge: 6.5	Co(II)	6.5	24.52 mg/g at 25 °C	Electrostatic interaction, ionic sorbent–sorbate interaction	(Tounsadi et al. 2015)
<i>Diplotaxis harra</i>	Stem	Particle size: < 160 $\mu\text{m}$ , surface area: 1.612 $\text{m}^2/\text{g}$ , point of zero charge: 6.29	Co(II)	7.5	33.02 mg/g at 25 °C	Electrostatic interaction, ionic sorbent–sorbate interaction	(Tounsadi et al. 2015)
<i>Alternanthera philoxeroides</i> (Mart.) Griseb	Whole	Particle size: < 125 $\mu\text{m}$	Ni(II)	4.0	9.73 mg/g at 20 °C	Monolayer chemisorption, ion exchange, chelation	(Wang and Qin 2006)
<i>Cyperus laevigatus</i>	Leaf	Particle size: 40–50 mesh	Se(IV)	2.0	110.5 mg/g at 25 °C, optimized by response surface methodology	Not reported	(Badr et al. 2020)
<i>Undaria pinnatifida</i> Seaweed	Whole	Treated with $\text{CaCl}_2$ , particle size: 10–16 mesh	Hg(II)	7.0	161.2 mmol/g at 20 °C	Electrostatic attraction	(Plaza et al. 2011)
<i>Undaria pinnatifida</i> (brown algae invasive species)	Whole	Particle size: 5000–1000 $\mu\text{m}$	Cs(I)		146.19 mg/g	Ionic exchange through carboxyl, sulfate, amine groups were involved in the adsorption process	(Hu et al. 2020)
<i>Undaria pinnatifida</i>	Whole	Particle size: 5000–1000 $\mu\text{m}$	Sr(II)		190.13 mg/g	Ionic exchange	(Hu et al. 2020)



**Fig. 6** Proposed mechanism for the adsorption of lead heavy metal ions over *Sargassum muticum* (Japanese wireweed) biosorbent. Here, several functional groups, e.g., amine, carboxyl, and hydroxyl, on the surface of the biosorbent are attributable to the protein or peptide residues of invasive plants. They may play a vital role in the chelation of

heavy metals with N and O atoms on surface functional groups. The sequestration of heavy metals over biosorbents can also be induced by electrostatic interactions. Reprinted with the permission of Elsevier from the reference (Hannachi and Hafidh 2020)

cations with adjacent carboxyl, hydroxyl, and amine groups on the biosorbent structure (Fig. 6). Such affinity leads to the stable coordination complexation of metallic compounds to release the protons ( $H^+$ ) or cations (e.g.,  $Na^+$ ,  $K^+$ ) into the solutions (Wong et al. 2014). The latter mechanism relies on the formation of electrostatic attraction between positively charged metal cations and negatively charged surface of the biosorbent (Saleh and Ali 2018; Verma et al. 2020; Peng et al. 2021). This may enhance the immobilization and sequestration of heavy metal ions in the structure of the biosorbent.

## Cadmium

Cadmium (Cd) presents as one of the most toxic non-biodegradable heavy metals in the aqueous media and soils (Peng et al. 2021). Cadmium is often detected in many kinds of industrial effluents, pigment production, and metal refining activities (Zhang et al. 2021). This element is also responsible for detrimental effects such as kidney damage, lung

insufficiency, cancer diseases, and deficiency of bones and blood (Luo et al. 2018). According to the World Health Organization, the permissible concentration of cadmium in drinking water is extremely low, at  $5 \times 10^{-3}$  mg/L (Pyrzynska 2019). Because of the high toxicity, and environmental accumulation, the removal of cadmium from the aqueous matrixes has been received great attention (Brião et al. 2020; Khan et al. 2020; Feng et al. 2022).

Many works reported the adsorption performance of biosorbents from invasive plants for the removal of cadmium ions (Table 1). Indeed, Tounsadi et al. (2015) discovered that the biosorbents from *Diplotaxis harra* and *Glebionis coronaria* plant stems can remove Cd(II) ions efficiently. In this study, pH points between 6.5 and 7.5 were found to acquire the maximum adsorption of 18.31 mg/g at 25 °C. Among inorganic ions,  $Al^{3+}$  showed the strongest inhibition due to its high affinity to Cd(II) ions. They indicated that functional groups on the surface of the *Diplotaxis harra* and *Glebionis coronaria* might participate in Cd(II) biosorption. Ammari (2014) reported the use of *Arundo donax* reed leaves for the

treatment of Cd(II) in the aqueous solutions. They optimized the condition for the highest Cd(II) removal efficiency of 97% and monolayer adsorption capacity of 27.9 mg/g under the dosage of 3.5 g/L, at pH 5.5.

To enhance the removal efficiency and adsorption capacity, the chemical modification of biosorbents from invasive plants was suggested (Bakyayita et al. 2015). The chemicals are often used such as NaOH, KOH, CaCl<sub>2</sub>, K<sub>2</sub>CO<sub>3</sub>, HCl, and so forth. As treated with these chemicals, the surface of biosorbents can be modified with many functional groups which link to the improvement of adsorption (Saraswat and Rai 2010). For example, Cazón et al. (2013) used *Undaria pinnatifida*—a brown alga invasive species for the preparation of biosorbent. They demonstrated that the biomass treated with CaCl<sub>2</sub> gave very high adsorption capacity (121.4 mg/g) to Cd(II) at pH 3. This outcome is explained due to the participation of many possible mechanisms such as ionic exchange, complexation, coordination, and micro-precipitation. At the same trend, Bakyayita et al. (2015) found the enormous improvement of adsorption capacity of *Cyperus papyrus* stem biosorbent from 0.028 mg/g to 5.97 mg/g after the modification with NaOH. However, the use of chemicals for biomass modification should be limited to ensure critical green strategies.

## Lead

As similar to cadmium, lead (Pb) also presents as toxic non-biodegradable heavy metal (Ajiboye et al. 2021). The previous works listed many detrimental impacts of lead exposure on human health, involving serious damages to the nervous system, liver, and reproductive organisms (Ghorbani et al. 2020; Qasem et al. 2021; Vasseghian et al. 2021). Lead also links to several adverse effects on the intelligence quotient degrees and physical growths in children (Kuang et al. 2020; Naranjo et al. 2020). Over the decades, lead can be released from the environment through human activities such as transportation, agriculture, ceramic, and battery productions (Ramos-Guivar et al. 2021). The presence of lead in wastewater is impactful because it can cause long-term accumulation and enter the human body through the food chains and contaminated water (O'Connor et al. 2020; Jarvis and Fawell 2021). As a result, the treatment of lead from the aqueous solution is an urgent requirement.

*Eupatorium adenophorum* is a highly growing species that invades wide tropical and subtropical areas in Asia and Africa (Zhu et al. 2021). It strongly hampers the germination and growth of native plants, causing severe ecological damages (Liu et al. 2021). Some works utilized the biomass of this species for environmental remediation. For example, Guo et al. (2009) employed the adsorption of lead ions by the biosorbents based on *Eupatorium adenophorum* stems. In this study, the authors found the optimum

pH for Pb(II) adsorption at 5.0 to reach the high removal efficiencies (84–90%). From the thermodynamic parameters such as Gibbs free energy and enthalpy, the authors made a deduction about the nature of spontaneous and endothermic biosorption of Pb(II) over *Eupatorium adenophorum* stems. Many invasive plants such as *Prosopis juliflora* and *Moringa oleifera* are locally prevalent in Uttar Pradesh, India. They are rapidly grown, drought-resistant, strongly invasive, and harmful to local plants. Taking advantage of available biomass sources, many studies have used them as green adsorbents for the removal of lead. Indeed, Gautam et al. (2020) reported the good outcomes of lead adsorption with capacity (1.4–5.6 mg/g) and efficiency (72–86%) at pH 6.0 using the above biosorbents. However, their adsorption performance was generally low, and the reusable property was not reported yet. Many kinds of invasive biomass treated with HNO<sub>3</sub>, CaCl<sub>2</sub>, HCl or NaOH gave clear improvements (26.32–76.12 mg/g), but there needs to be more investigated in further studies (Mahamadi and Nharingo 2010; Shooto 2020).

## Chromium

Chromium is one of the potentially toxic and carcinogenic heavy metals prevalently present in industrial wastewater because it is related to anthropogenic activities such as metal cleaning, plating, mining industries (Peng and Guo 2020). According to World Health Organization, the permissible concentration of total chromium in drinking water is recommended at 0.05 mg/L (Vaiopoulou and Gikas 2020). Although trivalent Cr(III) is the most prevalent chromium present in water, Cr(VI) offers a higher degree of carcinogenicity, mobility, and toxicity (Jobby et al. 2018; Tumolo et al. 2020). Cr(VI) exposure possibly results in many serious health hazards such as skin irritations, kidney dysfunction, or lung carcinoma (Bakshi and Panigrahi 2018; Vareda et al. 2019; Coetzee et al. 2020). As a result, the practical treatment of Cr(VI) pollution is of greater interest than Cr(III).

In general, the pH condition strongly affects the adsorption process of hexavalent chromium anions (Mitra et al. 2017). It was suggested that the removal of Cr(VI) should often be employed under the acidic solution conditions (pH 1–4). This finding may be the role of several interactions that influence the mechanism of chromium anions over the biosorbents. Indeed, Song et al. (2016) pointed out three stages of proposed mechanisms including (i) electrostatic interaction via binding of Cr(VI) anions with positively charged biomass surface, (ii) reduction in Cr(VI) to Cr(III), and (iii) electronic repulsion or complexation of Cr(III) to release Cr(III) ions. Mahmoud et al. (2021) also agreed with this hypothesis since they demonstrated the main role of electrostatic interactions, reduction and chelation or

complexation between Cr(VI), and the functional groups of the biosorbent.

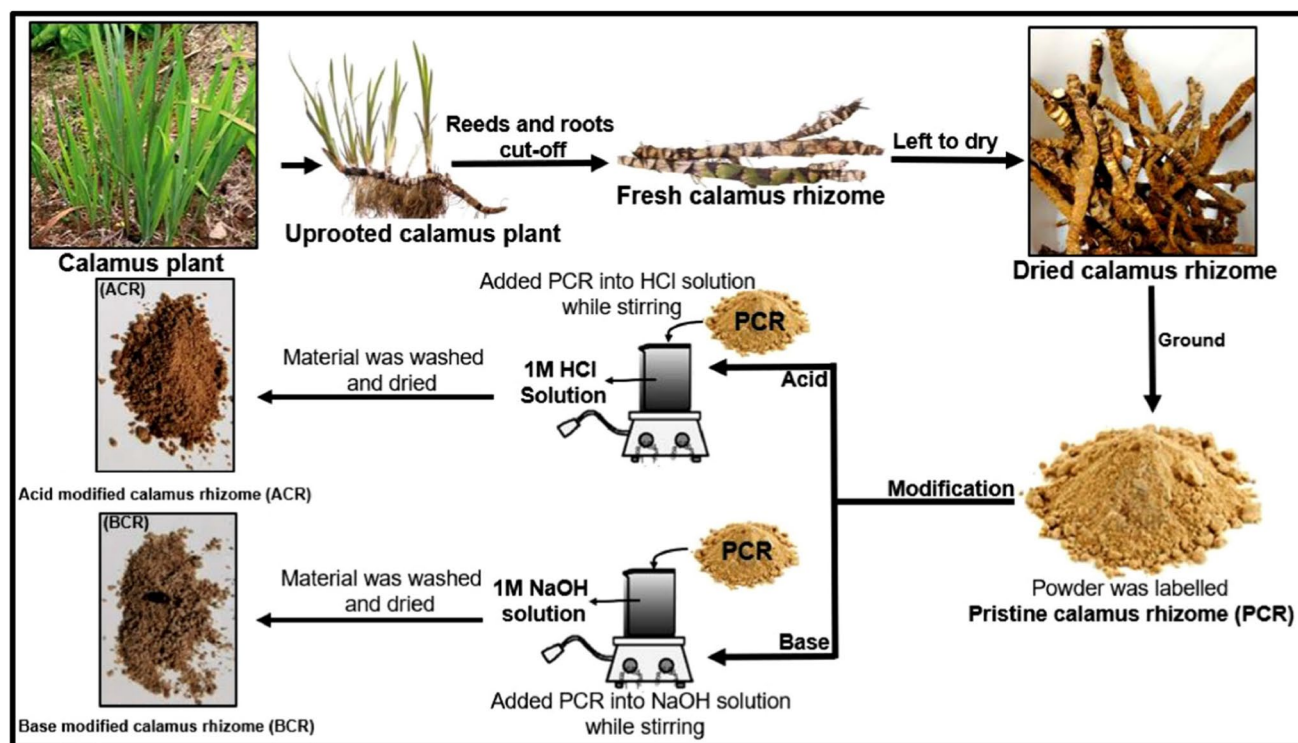
There are many works that demonstrated the potential of invasive plants as biosorbents to remove Cr(VI) from water. For example, Kuppusamy et al. (2016a) used the dried *Melaleuca diosmifolia* leaves to remove Cr(VI) at 24 °C with high uptake capacity (62.5 mg/g). Song et al. (2016) investigated the performance of *Eupatorium adenophorum* stems for the adsorption of Cr(VI) at very acidic solution (pH 1). As a result, 99% of Cr(VI) could be removed by this biosorbent. Recently, Shooto (2020) treated *Acorus calamus* rhizomes through chemical modification with HCl or NaOH (Fig. 7) to obtain a higher surface area (9.98–11.65 m<sup>2</sup>/g). The diversity of surface functional groups such as carboxyl groups (–COOH), hydroxyl groups (–OH) belonging to lignocellulose, and carbonyl groups (–C=O) on the treated biosorbents was detected using Fourier transform infrared spectroscopy. As a result, the authors found that the modification with alkaline agent gave a better adsorption performance than the cases modified with acidic agent or without any modification. More interestingly, the *Acorus calamus* rhizome biosorbents could be recycled at least three times without any significant decrease in the final cycle.

Considering the continuous adsorption mode, the fixed bed column is more appropriate in the scale-up industrial

treatment for chromium anions. Inspired by this fact, Nithya et al. (2020) reported the removal of Cr(VI) anions using chemically modified *Lantana camara* biosorbent (Fig. 8a). In their study, H<sub>2</sub>SO<sub>4</sub> with the ratio of 1:1 by weight was used to modify the surface of adsorbent. The fixed bed study was optimized with three parameters including Cr(VI) concentration, flow rate of the Cr(VI) solution, and bed height. The findings revealed that the fixed bed adsorption capacity was highly reached, at 362.8 mg/g. More importantly, the biosorbent could be easily desorbed by 0.4 N NaOH solution at the flow rate of 4 mL/min. The regeneration efficiency of the reused fixed column was reported with three cycles (Fig. 8b). To sum up, these results indicated the great potential of invasive plant biosorbents for the treatment of hexavalent chromium ions.

## Zinc

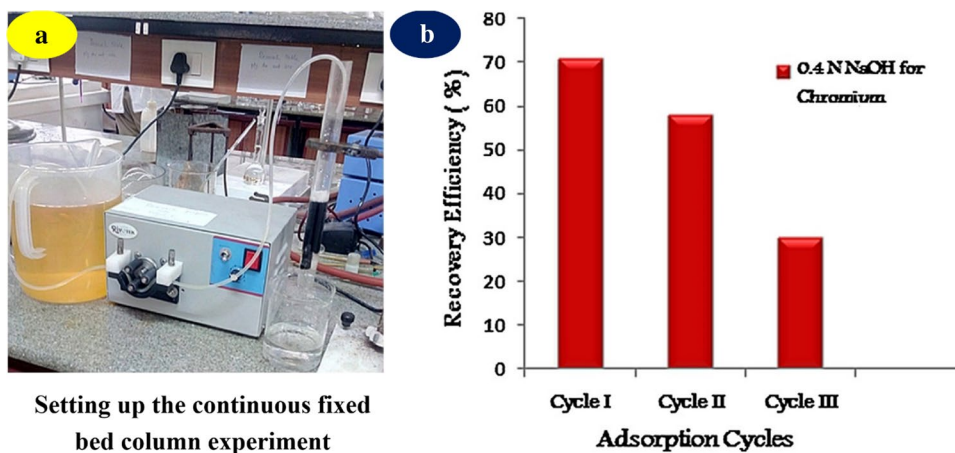
Zinc (Zn) is an essential micronutrient element that engages in the biochemical and physiological processes of living tissues (Gombart et al. 2020). The fundamental role of zinc has been admitted in boosting the immune system to reduce the risk of infection against pathogens such as the coronavirus disease 2019 (COVID-19) pandemic (Gasmi et al. 2020; Gorji and Khaleghi Ghadiri



**Fig. 7** Synthesis of *Acorus calamus* rhizome biosorbents. Here, the rhizomes were firstly washed, pretreated, dried, and ground. Subsequently, HCl or NaOH solution was immersed to treat the surface of

rhizomes powder. Reprinted with the permission of Elsevier from the reference (Shooto 2020)

**Fig. 8** Setting up the continuous fixed bed column (a), and the regeneration experiments of H<sub>2</sub>SO<sub>4</sub> modified *Lantana camara* biosorbent for the removal of Cr(VI) anions (b). Here, 0.4 N NaOH was used as an eluent solvent for desorbing Cr(VI) at the rate of 4 mL/min. The high regeneration efficiency could be still obtained after three cycles, and the final cycle gave an efficiency of about 30%. Reprinted with the permission of Elsevier from the reference (Nithya et al. 2020)



2021). Among the heavy metals, zinc also exhibits as one of the most benign metal elements (Wang et al. 2018). According to World Health Organization, the permissible concentrations of zinc in surface water, groundwater, and drinking water are recommended as 0.01, 0.05, and 3 mg/L, respectively (Ngabura et al. 2018). However, the presence of zinc and its inorganic compounds is increasingly prevalent in industrial effluents (Hołtra and Zamorska-Wojdyła 2020). Many fabric, wood, metal mining, and batteries production industries often discharge a large amount of zinc into the aqueous matrixes (Chen et al. 2019). The health issues including skin inflammations, fevers, irritability, and vomiting have been reported due to zinc exposure (Wei et al. 2021). Considering as a renewable biomass resource, the invasive plant may, therefore, be a good choice to handle the contamination of zinc from wastewater bodies (Turkmen Koc et al. 2021).

Zinc adsorption was often studied in competition with other heavy metals such as cadmium and chromium. Saraswat and Rai (2010) studied the use of *Eichhornia crassipes* dead biosorbent for the simultaneous removal of Zn(II), Cd(II), and Cr(VI) ions. It was pointed out that maximum adsorption capacity at 25 °C followed by Cd(II) > Zn(II) > Cr(VI). They suggested that the main mechanism of ion exchange and electrostatic interaction controlled this simultaneous adsorption. Apart from batch mode, the flow mode of heavy metals adsorption was also investigated since it exhibits more applicability. Cazón et al. (2013) reported the biosorption on *Undaria pinnatifida* plant for simultaneous removal of zinc and cadmium ions. They found that there was not nearly adsorption competition in the bicomponent system. By using Fourier transform infrared spectroscopy analysis, carboxylic groups containing nitrogen and sulfur were found to contribute significantly to Zn(II) and Cd(II) adsorption.

### Copper

Over the centuries, copper (Cu) has been widely used in ordinary activities as well as advanced applications such as photovoltaic cells and phytotherapies (Barsova et al. 2019). This element belongs to a group of essential micronutrients for multiple activities such as photosynthesis, metabolism, and reproduction processes in living organisms (Rehman et al. 2019). However, the exceeding discharge of copper and its compounds into the water and soil environments by anthropogenic activities has resulted in many imperative risks to human health and aquatic animals (Tang et al. 2019; Vardhan et al. 2019). The pollution of copper should be addressed by several green approaches including biosorption (Al-Saydeh et al. 2017; Krstić et al. 2018). Using invasive plants as bioremediators for the removal of copper may be one of the efficient solutions.

Ramesh et al. (2013) reported the very high maximum copper adsorption capacity (up to 500 mg/g at 30 °C) obtained by *Cyperus rotundus* biosorbent. In this study, they found the optimum dose of biosorbent and equilibrium time was 1.0 g/L, and 30 min, respectively. Considering waste reuse as a critical green approach, Dhouibi et al. (2020) have successfully optimized the simultaneous adsorption of copper and zinc over *Centaurea nicaeensis* residue after hydrodistillation process. The authors found the best fittings ( $R^2 \geq 0.99$ ) of experimental data with kinetic and isotherm models were pseudo-first-order and Sips equations, respectively. Moreover, the optimal conditions of operating parameters such as pH, temperature, and biosorbent dose were undertaken through response surface methodology. By using Minitab statistical software, the highest percentages of copper and zinc removal efficiency were obtained, at 92% and 82%, respectively. This result suggested the good adoption of response surface

methodology as a powerful tool for the effective optimization of metal adsorptive removal.

## Cobalt

Cobalt (Co) and its alloys are widely used in the production of electronic devices, ceramic products, and ferromagnetic materials (Taka et al. 2018; Abbas et al. 2021). It has a common radioisotope ( $^{60}\text{Co}$ ), which is frequently applied for radiotherapy and many industrial applications, such as leveling devices and thickness gauges (Nayl et al. 2020). Although cobalt is a micronutrient essential for animal and plant growth, its exposure at high concentrations can lead to many serious influences on human health, involving vomiting, pneumonia, heart failure, and so forth (Zhuang et al. 2018). The occurrence of cobalt pollution is mainly originated from many human activities, especially ore mining, electroplating, and battery manufacturing (Liu et al. 2019b). According to World Health Organization, the permissible concentration of Co(II) ions in drinking water is very low, at 0.05 mg/L (Islam et al. 2018). Because cobalt reflects high toxicity and bio-accumulative nature, the treatment of cobalt pollution in water is very necessary.

With many advantages of low-cost production and local availability, invasive plants can be great biosorbents for the elimination of cobalt from wastewater. Indeed, Tounsadi et al. (2015) undertook the simple and rapid cobalt removal procedure by using *Glebionis coronaria* and *Diplotaxis harra* stems. After 120 min of adsorption, about 60% of Co(II) was removed from the solutions at a dose of 10 g/L at room temperature (25 °C). Very recently, Acosta-Rodríguez et al. (2021) enhanced the cobalt removal efficiency up to 100% in the practical industrial samples using water hyacinth (*Eichhornia crassipes*) as a robust biosorbent. To obtain such promising results, water hyacinth biomass was treated with 10% ethylenediaminetetraacetic acid. In vivo experiment, the authors reported a lower removal of 17.3% after four weeks of incubation through the phytoremediation pathway. Consequently, invasive plants can become high-value, but zero-cost biosorbents for the removal of cobalt. At present, more studies should focus on the treatment of heavy metals in such ways.

## Other heavy metals

Apart from the treatment of above mentioned heavy metal ions, the biosorbents from the invasive plants can remove a range of toxic metals such as nickel, selenium, mercury, cesium, and strontium ions (Table 1). *Undaria pinnatifida* is known as seaweed which is present in the sea environment. After being treated with  $\text{CaCl}_2$ , the biosorbents from this species could remove Hg(II) from water (Plaza et al. 2011). In addition, Hu et al. (2020) reported the potential

of a marine brown alga invasive species, namely *Undaria pinnatifida* for the treatment of cesium ( $\text{Cs}^+$ ) and strontium ( $\text{Sr}^{2+}$ ) ions. They also applied the molecular dynamics simulation for the prediction of interaction between alginate and  $\text{Sr}^{2+}$  cations. The results of isotherm titration calorimetry exhibited a high competition between  $\text{Sr}^{2+}$  and alginate on marine algae. The maximum adsorption capacity values were reached at 146.2–190.1 mg/g, which may be attributable to the ionic exchange between metal ions with functional groups of marine algae. By the optimization using response surface methodology with  $2^4$  factorial experimental design, Badr et al. (2020) obtained the maximum selenium uptake value of 110.5 mg/g at 25 °C. Accordingly, the authors investigated the effect of process parameters on the uptake of Se(IV) over *Cyperus laevigatus* biomass and found their optimized points at initial concentration (400 mg/L), contact time (8 h), biosorbents dose (1 g/L), and pH 2. From the encouraging adsorption results, the biosorbents from invasive plants can be good materials for the treatment of heavy metal ions.

## Removal of synthetic dyes by invasive plants

### Occurrence of synthetic dyes

One of the first discovered synthetic dyes was mauveine by William Perkin in 1865 (Tkaczyk et al. 2020). Over the past centuries, the revolution of synthetic dyes has globally extended to many fields such as textile, food, beverage, printing, paper, and so forth (Bulgariu et al. 2019; Benkhaya et al. 2020). Up to now, over 100,000 synthetic organic dyes have been produced and available commercially worldwide (Tkaczyk et al. 2020). The global value of dyes and pigments market in 2021 is estimated at 36.4 billion dollars by Grand View Research Inc., United States. Although some are highly safe to be used in the color food, beverage, cosmetic, and pharmaceutical industries, a major number of organic dyes are underestimated as emergent contaminants in the aquatic media (Hassan and Carr 2018). This is attributable to their highly stable and non-biodegradable structure, which is not easy for treatment using chemical, physical and biological methods (Tran et al. 2019). Moreover, due to the highly visible and accumulative ability, the existence of synthetic dyes can lead to the blockage of solar light into water (Saya et al. 2021). The photosynthetic performance of aquatic plants and organisms can be therefore lessened. Many works have also indicated that the organic dyes are potentially teratogenic, carcinogenic, and mutagenic compounds, posing serious threats to human health as well as to marine life (Jun et al. 2020; Tkaczyk et al. 2020; Saya et al. 2021). To solve these problems, the proper treatments of synthetic organic dyes are required. Among the current



techniques, adsorption offers high performance, eco-friendliness, and effectiveness for the removal of emergent pollutants including synthetic organic dyes (Tran et al. 2020a, c; Dang et al. 2021). This section will discuss some plausible dye adsorption mechanisms as well as the adsorptive treatment using invasive plants as low-cost biosorbents.

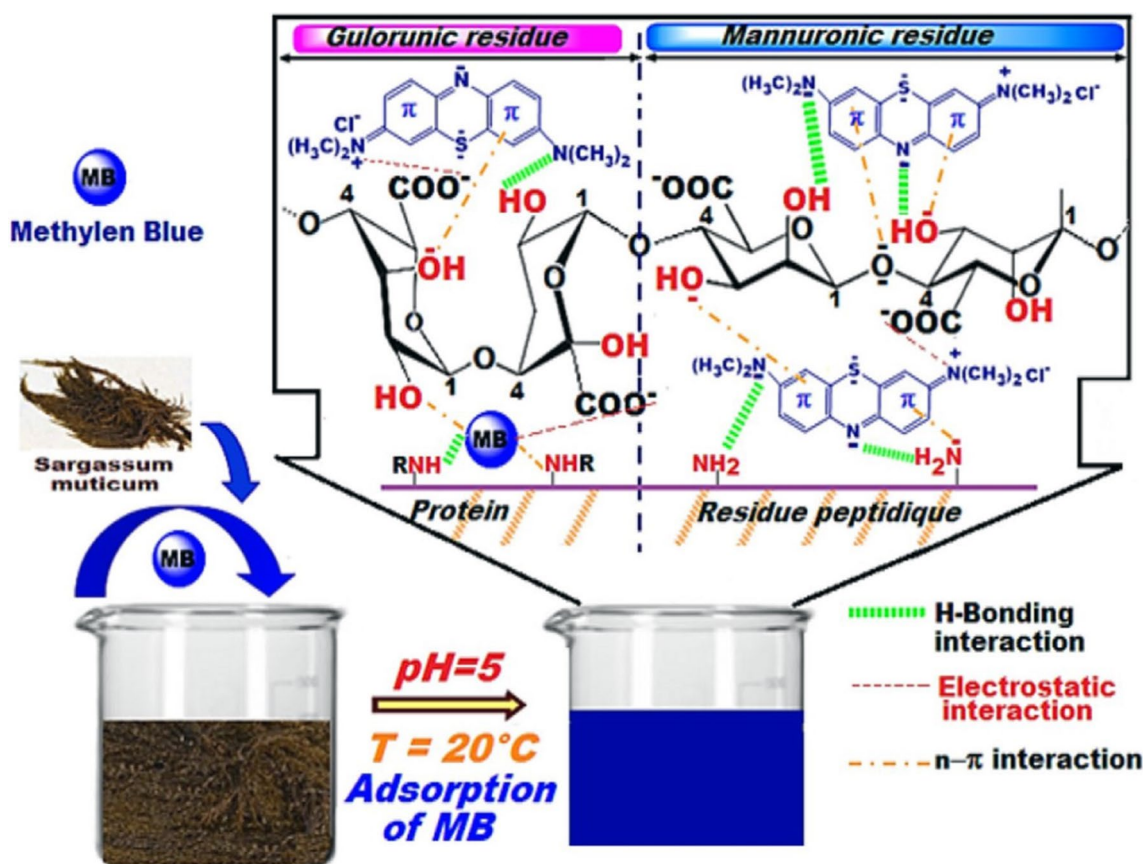
### Plausible adsorption mechanism of synthetic dyes

In general, chemisorption is the common mechanism based on the interaction of functional groups on the synthetic dyes and the surface of biosorbents (Ali 2018; Khadir et al. 2020). It is found that biosorbents from invasive plants can possess many biosubstrates such as cellulose, hemicellulose, polysaccharides, and so forth (Feng et al. 2021). These macro-compounds supply many hydroxyl, ketone, and amine groups that can interact with the synthetic dye molecules during the chemisorption (Stavrinou et al. 2018). Specifically, the presence of functional groups such as amine, carboxyl, and hydroxyl on the surface of biosorbent may take main responsibility for the hydrogen bonding, electrostatic, and  $n-\pi$  interactions with organic dye molecules (Fig. 9).

A large number of relevant studies have proposed the main mechanisms take responsibility for the sequestration of the synthetic dyes onto biosorbents (Table 2). To have more insights into the removal of heavy metal ions over biosorbents from invasive plants, the following section will discuss their adsorption performance and controlling mechanisms.

### Methylene blue

Methylene blue ( $C_{16}H_{18}N_3SCl$ ) is a cationic and thiazine dye (Bayomie et al. 2020). It was first synthesized in 1876 by Heinrich Caro and was widely used as a synthetic dye for the textile industry (Mashkooor and Nasar 2020). Some physicochemical properties of methylene blue include solid crystals and maximum light absorption at around 665 nm (Tran et al. 2020d; Nguyen et al. 2021c). Methylene blue has been thoroughly studied in both positive and negative effects. Acting as a synthetic textile dye, it exhibits as one of the most common colorings and staining agents (Ahmad et al. 2020). Consequently, a large amount of this textile dye is yearly discharged in the environment without the proper treatment (Santoso et al. 2020). Exposure to methylene blue



**Fig. 9** Proposed mechanism for the adsorption of organic dyes over the biosorbent. Here, the presence of functional groups, e.g., amine, carboxyl, and hydroxyl, on the surface of biosorbent may take main

responsibility for the hydrogen bonding, electrostatic, and  $n-\pi$  interactions with organic dye molecules. Reprinted with the permission of Elsevier from the reference (Hannachi and Hafidh 2020)

**Table 2** Adsorption performance of biosorbents from invasive plants for the treatment of organic dyes

Plant	Part	Biosorbent features	Target dyes	pH	Uptake capacity	Adsorption mechanism	Refs.
<i>Sargassum muticum</i> seaweed	Whole	Particle size: 100–500 $\mu\text{m}$ , point of zero charge: 5.45	Methylene blue	1–11	142.87 mg/g at 25 °C	Electrostatic interaction, hydrogen bonding, hydrophobic–hydrophobic interaction	(Atouani et al. 2019)
<i>Sargassum muticum</i> seaweed	Whole	Particle size: 500 $\mu\text{m}$	Methylene blue	5.0	92 mg/g at 25 °C	Electrostatic attractions, hydrogen bonding, n– $\pi$ electron donor–acceptor interactions	(Hannachi and Hafidh 2020)
<i>Lantana camara</i>	Stem	Treated with oxalic acid, particle size: 250–350 $\mu\text{m}$	Methylene blue	4.84	Raw and modified biosorbents: 23.25–111.12 mg/g, respectively, at 30 °C	Film diffusion, ionic exchange, chemical interaction	(Banerjee et al. 2016)
<i>Ailanthus Excelsa</i>	Leaf	Particle size: 150–600 $\mu\text{m}$ , point of zero charge: 7.6	Methylene blue	10.0	18.867 mg/g at 27 °C	Electrostatic interaction	(Bansal et al. 2021)
<i>Calotropis gigantea</i>	Seedpod	Particle size: 250–400 $\mu\text{m}$	Methylene blue	6.0	8.36 mg/g at 21 °C	Electrostatic interaction	(Ammar et al. 2021)
<i>Juncus effusus</i>	Whole	Not reported	Methylene blue	11.0	117.93 mg/g at 35 °C	Monolayer chemisorption, $\pi$ – $\pi$ stacking interactions, mesopore-filling, intra-particle diffusion	(Liu et al. 2016)
<i>Imperata cylindrica</i>	Whole	Treated with boiling distilled water, particle size: 125–150 $\mu\text{m}$	Methylene blue	8.46	27.40 mg/g at 26 °C, optimized by response surface methodology	Monolayer chemisorption	(Su et al. 2014)
<i>Glebionis coronaria</i>	Stem	Particle size: 120 $\mu\text{m}$ , surface area: 1.741 $\text{m}^2/\text{g}$ , point of zero charge: 6.5	Methylene blue	11.0	258.76 mg/g at 25 °C	Not reported	(Tounsadi et al. 2016)
<i>Diplotaxis harra</i>	Stem	Particle size: 120 $\mu\text{m}$ , surface area: 1.612 $\text{m}^2/\text{g}$ , point of zero charge: 6.29	Methylene blue	11.0	185.59 mg/g at 25 °C	Not reported	(Tounsadi et al. 2016)
<i>Cortaderia selloana</i>	Flower spike	Not reported	Methylene blue	Not reported	34.48 mg/g at 25 °C	Monolayer chemisorption	(Jia et al. 2017)
<i>Melaleuca diosmifolia</i>	Leaf	Particle size: 500 $\mu\text{m}$ , surface area: 0.99 $\text{m}^2/\text{g}$	Methylene blue	10.0	119.05 mg/g at 24 °C	Electrostatic interaction	(Kuppusamy et al. 2016b)
<i>Carpobrotus edulis</i>	Whole	Particle size: <250 $\mu\text{m}$	Crystal violet	2–11	17.70 mg/g at 23 °C	Not reported	(Dabagh et al. 2021)
<i>Acacia mearnsii</i>	Bark	Treated with acetone and sulfuric acid and removed tannins, surface area: 4.867 $\text{m}^2/\text{g}$	Crystal violet	10.0	280 mg/g at 30 °C	Not reported	(Silva et al. 2018)
<i>Cyperus Rotundus</i>	Whole	Particle size: 150–300 $\mu\text{m}$ , point of zero charge: 5.6	Crystal violet	8.0	84.13 mg/g at 20 °C	Electrostatic interaction	(Suyambo and Srikrishnaperumal 2014)

Table 2 (continued)

Plant	Part	Biosorbent features	Target dyes	pH	Uptake capacity	Adsorption mechanism	Refs.
<i>Centaurea nicaeensis</i>	Stem	Point of zero charge: 9	Crystal violet	10.1	476.190 mg/g at 25 °C, regeneration: eleven cycles, first: 98.3% and final > 90%, ethanol as eluent solvent	hydrogen bonding	(Naderi et al. 2018)
<i>Glebionis coronaria</i>	Stem	Particle size: 120 µm, surface area: 1.741 m <sup>2</sup> /g, point of zero charge: 6.5	Malachite green	11.0	117.32 mg/g at 25 °C	Not reported	(Tounsadi et al. 2016)
<i>Diplotaxis harra</i>	Stem	Particle size: 120 µm, surface area: 1.612 m <sup>2</sup> /g, point of zero charge: 6.29	Malachite green	11.0	64.37 mg/g at 25 °C	Not reported	(Tounsadi et al. 2016)
<i>Typha angustifolia</i>	Leaf	Particle size: 1250–2000 µm	Malachite green	8.0	75.27 mg/g at 35 °C	Chemical interactions	(Guechi and Hamdaoui 2013)
<i>Melaleuca diosmifolia</i>	Leaf	Particle size: 500 µm, surface area: 0.99 m <sup>2</sup> /g	Malachite green	2.0	116.28 mg/g at 24 °C	Electrostatic interaction	(Kuppusamy et al. 2016b)
<i>Lantana camara</i>	Stem	Treated with oxalic acid, particle size: 250–350 µm	Rhodamine B	4.84	34.24 mg/g at 30 °C	Film diffusion, ionic exchange, chemical interaction	(Banerjee et al. 2016)
<i>Trapa natans</i>	Peel	Particle size: 85–75 mesh, point of zero charge: 5.8	Rhodamine B	7.0	3.0 mg/g at 30 °C	Liquid-film, intra-particle diffusions	(Khan et al. 2013)
<i>Trapa natans</i>	Chestnut shell	Treated with 0.2 M NaOH, surface area: 1.127 m <sup>2</sup> /g, pore volume: 0.0067 cm <sup>3</sup> /g, pore radius: 1.09 nm	Rhodamine B	8.0	136.46 mg/g, and 90.36% removal, regeneration study: five consecutive cycle, methanol as a green eluent	Electrostatic attraction, van der Waals force, H-bonding, and π–π stacking	(Qaiyum et al. 2021)
<i>Lantana camara</i>	Whole	Particle size: 44 mesh, surface area: 123 m <sup>2</sup> /g, pore volume: 0.07 cm <sup>3</sup> /g, point of zero charge: 6.2	Alizarin red S	2.0	0.507 mg/g, sixth regeneration cycle, the adsorption remained at 70.2%, desorption by 0.1 M NaOH	Electrostatic attraction	(Gautam et al. 2014)
<i>Cyperus Rotundus</i>	Whole	Treated with HCl, particle size: 1000–2000 µm	Acid orange 7	7.0	35.69 mg/g at 20 °C	Not reported	(Azarpira and Balarak 2016)
<i>Eichhornia crassipes</i>	Root	Particle size: 2–20 mesh, surface area: 8.07 m <sup>2</sup> /g	Red reactive dye	2.0	43.28 mg/g at 30 °C, 95% of dye removal for 110 min	Monolayer chemisorption	(Rigueto et al. 2020)
<i>Melaleuca diosmifolia</i>	Leaf	Particle size: 500 µm, surface area: 0.99 m <sup>2</sup> /g	Acridine orange	2.0	126.58 mg/g at 24 °C	Electrostatic interaction	(Kuppusamy et al. 2016b)
<i>Melaleuca diosmifolia</i>	Leaf	Particle size: 500 µm, surface area: 0.99 m <sup>2</sup> /g	Eriochrome black T	2.0	94.34 mg/g at 24 °C	Electrostatic interaction	(Kuppusamy et al. 2016b)

can cause many inharmonious impacts on human health and the aquatic environment (Din et al. 2021). Indeed, Din et al. (2021) revealed that methylene blue is considered a potentially carcinogenic pollutant, and toxic agent with many general symptoms such as high blood pressure, skin irritation, vomiting, headache, and fever. The removal of methylene blue dye using low-cost biosorbents is therefore highly recommended.

Su et al. (2014) optimized the removal process of methylene blue by *Imperata cylindrica* using the response surface methodology. They obtained very good removal performance (99.09%) under the optimum conditions such as time of 40 min, pH 9, and dose of 1.0 g/L. Moreover, equilibrium isotherm adhered best to Langmuir model, which exhibited the monolayer behavior of adsorption process. Banerjee et al. (2016) reported the potential of *Lantana camara* stems treated by oxalic acid for the removal of methylene blue dye in both batch and continuous flow modes. In this research, the modified *Lantana camara* gave maximum adsorption capacity value at 111.12 mg/g, which was approximately fourfolds higher than that of raw biosorbent. With the fixed bed depth of modified *Lantana camara* at 15 cm, the highest removal efficiency for methylene blue was obtained at 94%. Sulfuric acid was also found as an efficient desorbing solvent for this fixed bed. Atouani et al. (2019) found that *Sargassum muticum* seaweed can adsorb methylene blue in the pH-independent condition. More importantly, the dye uptake capacity was very high, 142.87 mg/g at 25 °C. The authors assumed the main role of electrostatic, hydrogen bonding, hydrophobic–hydrophobic interactions in the enhancement of adsorption process.

### Crystal violet

Crystal violet ( $C_{25}N_3H_{30}Cl$ ) is known as hexamethyl pararosaniline chloride and a compound of triarylmethane (Putri et al. 2020). It is commonly used as a histological stain as well as in the textile industry (Sacco et al. 2018). In general, exposure to crystal violet can cause many severe environmental problems such as the reduction in water quality (Tran et al. 2020b). Crystal violet can cause eye burn that leads to permanent eye damage (Zhou et al. 2014). It was reported that the concentration of crystal violet at 1  $\mu\text{g/L}$  can be harmful and possibly mutagenic to human bodies (Fabryanty et al. 2017). Therefore, the removal of crystal violet from the aquatic matrix has been of enormous interest.

*Cyperus rotundus* is known as purple nutsedge mostly distributed in Africa. This species notably diminishes crop yields due to its superior competition with local plants (Samra et al. 2021). However, it can be utilized to convert effortlessly into effective biosorbents. Suyamboo and Srikrishnaperumal (2014) studied the crystal violet biosorption potential of *Cyperus rotundus* invasive plant. Through

the batch experimental setup, they obtained an adsorption capacity of 84.13 mg/g at 20 °C. Moreover, it was proved that the biosorption was thermodynamically a spontaneous and exothermic process. Naderi et al. (2018) applied the powerful and efficient statistical tools based on artificial neural network and simulated annealing for predicting and optimizing the biosorption of crystal violet dye. Under the optimized conditions, the dye adsorption capacity was extremely high, 476.190 mg/g at room temperature. More interestingly, the *Centaurea nicaeensis* stem-based biosorbent could remove 98.3% of crystal violet from water. The regeneration study could also endure up to eleven cycles without any significant decrease in the removal efficiency at the final cycle (> 90%). It can be consequently concluded that *Centaurea nicaeensis* invasive plant is an ideal biosorbent for the treatment of synthetic dyes from the wastewater.

### Malachite green

Malachite green ( $C_{23}H_{25}ClN_2$ ) is a triphenylmethane dye used globally for therapeutic treatment in aquaculture against fungal and protozoan infections in fish (Zhou et al. 2019). Although it is no longer authorized for medicinal usage in food-producing animals in many European Union countries, the illegal consumption of malachite green still extends worldwide (Ma et al. 2020). This may be attributable to its low production cost and high efficacy against parasites and fungal diseases. However, several works reported that the bioaccumulation of malachite green its primary metabolites can be potentially hazardous to the health of humans and other organisms (Zhou et al. 2019; Ma et al. 2020; Ren et al. 2021b). Indeed, exposure to malachite green dye brings many adverse effects such as carcinogenic and genotoxic risks (Tewari et al. 2018; Teymori et al. 2019). Because a large amount of the residue exists in the aquaculture activities, it is important to remove the malachite green dye from the aquatic water.

*Typha angustifolia* is a perennial macrophyte aquatic herb with the characteristics of fast growth and high productivity (Xiong et al. 2021). This aggressive invasive plant often found in the wetlands, sedge meadows, and river banks. Guechi and Hamdaoui (2013) used the cattail leaves of *Typha angustifolia* as a biosorbent for the malachite green treatment with the uptake capacity of 75.27 mg/g at 35 °C. Tounsadi et al. (2016) reported the usage of stems from *Glebionis coronaria* and *Diplotaxis harra* for the removal of malachite green from wastewater. They found that the biosorption was best favorable at pH 11 and 25 °C. Under these conditions, the adsorption capacity values were measured at between 64.37 mg/g and 117.32 mg/g. Equilibrium data were fitted best with nonlinear Redlich–Peterson equation. However, the plausible mechanisms of malachite green

adsorption over *Glebionis coronaria* and *Diplotaxis harra* have not been reported yet.

## Rhodamine B

Rhodamine B ( $C_{28}H_{31}ClN_2O_3$ ) is a xanthene dye, which is used as a water tracer fluorescent for the direction of flow and transport (Wang et al. 2020b). This dye stands an extensive value in the textile industries due to the low production cost, high stability, and non-biodegradability (Worathitanon et al. 2019). It is still controversial whether Rhodamine B is a carcinogenic and neurotoxic agent to human health (Al-Buriahi et al. 2022). Although many countries ban the use of Rhodamine B as textile colorant, it is prevalently present in most water sources because of the illegal utilization (Al-Gheethi et al. 2022). As a result, Rhodamine B seriously affects the water quality and photosynthesis of aquatic creatures (Bhat et al. 2020). Taking advantage of invasive plants as low-cost biosorbents for the removal of Rhodamine B dye is very beneficial for environmental remediation.

*Trapa natans* is a typical floating-leaved aquatic plant that strongly competes for light, nutrients, and spaces with other aquatic species (Dodd et al. 2021). It also reduces the quality of local water and threatens the ecological balance of the habitat (Yuan et al. 2021). In an effort to mitigate the adverse effects of this species, Khan et al. (2013) used *Trapa natans* as biosorbent to treat Rhodamine B dye. The adsorption could be performed under mild conditions such as pH 7.0 and contact time of 20–120 min. However, the maximum adsorption capacity measured from Langmuir isotherm model was relatively low, only 3.0 mg/g at 30 °C. Very recently, Qaiyum et al. (2021) significantly improved the adsorption efficiency of *Trapa natans* chestnut shells by modifying with 0.2 M NaOH. The excellent adsorption capacity and removal efficiency were obtained at 136.46 mg/g, and 90.36%, respectively. Considering the better adsorption results than those obtained by Khan et al. (2013), the authors explained that alkaline treatment considerably lessens the amount of lignocellulosic inherent in the *Trapa natans* shells. Therefore, the NaOH activation enhanced the stability of biosorbent compared with the raw material. Moreover, electrostatic attraction, van der Waals force, H-bonding, and  $\pi$ - $\pi$  stacking were proposed as the main mechanism for the adsorption of Rhodamine B dye over the *Trapa natans* biomass.

## Other synthetic dyes

Some synthetic dyes including alizarin red, acid orange, red reactive dye, acridine orange, and eriochrome black can be efficiently treated by biosorbents from invasive plants (Table 2). For example, Gautam et al. (2014) used *Lantana camara* for removing alizarin red with the capacity

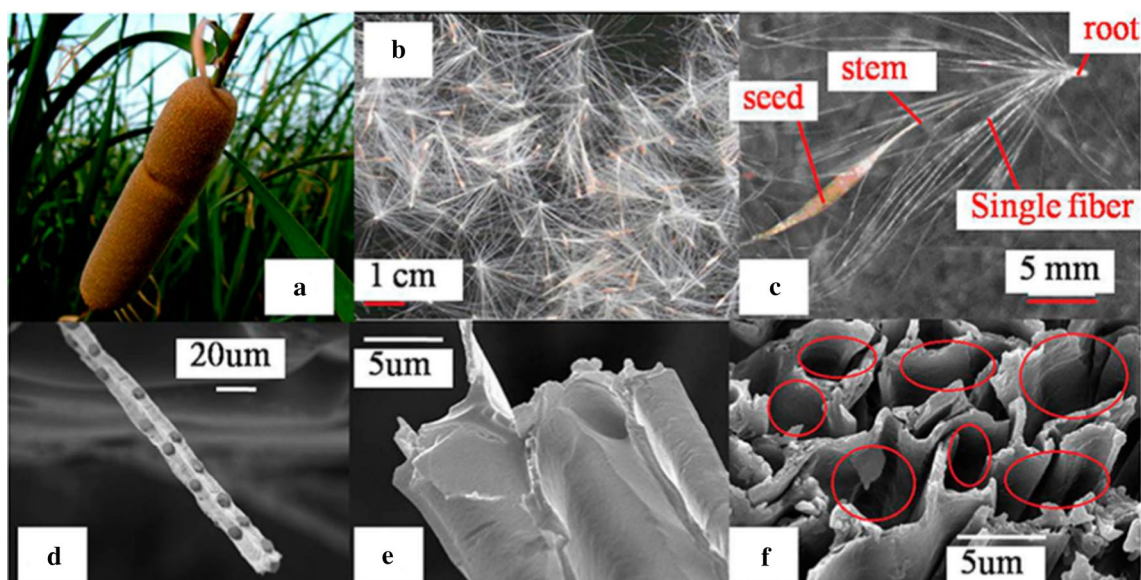
of 0.507 mg/g. The biosorbent exhibited high recyclability up to six cycles using 0.1 M NaOH as desorbing solvent. Kuppusamy et al. (2016b) demonstrated the multifunctional application of *Melaleuca diosmifolia* leaves for the treatment of both acid orange and red reactive dye. They performed the adsorption process at pH 2 and obtained high capacity, at 94.34–126.58 mg/g. Electrostatic interaction was ascribed to controlling the adsorption of these dyes onto *Melaleuca diosmifolia*-based adsorbent. Moreover, some food dyes such as tartrazine can be easily treated by biosorbent and the activated carbon derived from *Moringa oleifera seeds* (Reck et al. 2018).

The biosorbents derived from invasive plants have demonstrated their potential for the remediation of heavy metal ions, synthetic organic dyes, and oil recovery (Rathi et al. 2021; Saheed et al. 2021; Saravanan et al. 2021). However, there are very few studies that investigated these biosorbents for the treatment of many emergent pollutants such as pharmaceutical drugs, pesticides, and other organic compounds. It is expected that future researches will extend the potential of invasive plants to address these aspects.

## Removal of oils by invasive plants

Nowadays, oil spillage phenomena have posed a considerable threat to not only aquatic ecosystems but also the whole biosphere. Adsorbents from biomass receive more concerns to resolve such problems thanks to their biodegradability and cost-effectiveness. Apart from agricultural waste that is pretty well documented, invasive plants appear to be a promising source of natural fibers for the oil recovery system (Lv et al. 2018). For example, fibers isolated from fruit of cattail (*Typha*), a genus of dominated noxious weed, were noticed for their possibility of oil removal (Fig. 10). Each gram of this bulk material could uptake 13.4 g of motor oil and 14.6 g of vegetable fats. It was the exclusive bamboo-shaped framework of cattail fiber providing vacancy and thus high surface area enabling the oil adsorption process (Cui et al. 2014). Moreover, such structure was outstanding for oil retention to prevent the leak of treated oil during the recovery. Truly, Cao et al. (2016) estimated that nearly 90% of adsorbed oil was retained even after a day of dripping. The other contributors to this effectiveness were low density ( $617.8 \text{ kg m}^{-3}$ ) and the wax covering the surface of cattail fiber that accounted for 11.5% of Soxhlet extraction (Wu et al. 2021). Consequently, cattail natural fibers are expected as environmentally friendly and effective biomass for the fabrication of oil biosorbents.

There are other sources of fiber based oil adsorbents derived from invasive plants. For example, the ones derived from the stem of *Arundo donax* were so microstructural that could uptake the amount of commercial oil up to fivefold



**Fig. 10** Photographs of **a** Mature cattail stalk, and **b** Cattail tufts. Scanning electron microscope microphotographical images of **c** Cattail tuft, **d** Longitudinal section of cattail fiber, **e** Cross section of cattail fiber, and **f** Cross section of the cattail fiber. Cattail fibers have a down-like structure, including root, stem, seed, and several fibers.

They possess four-dimensional open spaces with an average length of  $7.9 \pm 1.2$  mm. With exceptionally hydrophobic and oleophilic features, cattail fibers could adsorb up to 12–26 g oils (engine, vegetable and used oils) per gram of fibers. Reproduced with the permission of Taylor & Francis from reference (Cao et al. 2016)

their weight. In particular, 300–2500  $\mu\text{m}$  long fibers showed porous orthotropic morphology but distinct adsorption capacity to different pollutant viscosity. The result showed that the smaller these fibers were, the better oil uptake in high viscosity liquid that contained one kind of oil, such as kerosene, pump oil, virgin naphtha, and crude oil (Fiore et al. 2019). The milkweed (*Asclepias syriaca*) floss had a superhydrophobic trait and hollow structure occupying 90% of its total volume. Such characteristics along with high

wax content were beneficial to the oil adsorption capacity of these fibers which was over 100 g/g of engine oil (Panahi et al. 2020). Table 3 illustrates typical natural fibers derived from invasive plants, their characteristics in terms of the average diameter, length, the percentage of wax content, and their adsorption capacity for several types of oils. Briefly, the conversion of noxious biomass into oil biosorbents could be a great potential for sustainable development and environmental protection.

**Table 3** Adsorption performance of biosorbents from invasive plants for the treatment of oils

Plant	Part	Material features			Oil type	Adsorption capacity (g/g)	Refs.
		Diameter ( $\mu\text{m}$ )	Length ( $\mu\text{m}$ )	Wax Content (%)			
<i>Arundo donax</i>	Stem	100–800	300–2500	Not reported	Kerosene,	46.1	(Fiore et al. 2019)
<i>Arundo donax</i>	Stem	100–800	300–2500	Not reported	Virgin naphtha	50.5	(Fiore et al. 2019)
<i>Arundo donax</i>	Stem	100–800	300–2500	Not reported	Pump oil,	61.0	(Fiore et al. 2019)
<i>Arundo donax</i>	Stem	100–800	300–2500	Not reported	Crude oil	51.7	(Fiore et al. 2019)
<i>Calotropis gigantea</i>	Seed	30.4	Not reported	1.8–3	Rapeseed oil	41.7	(Zheng et al. 2016)
<i>Calotropis gigantea</i>	Seed	30.4	Not reported	1.8–3	Paraffin oil	37.6	(Zheng et al. 2016)
<i>Typha</i>	Fruit	10–17	7900	11.5	Engine oil	13.4	(Cao et al. 2016)
<i>Typha</i>	Fruit	10–17	7900	11.5	Vegetable oil	14.6	(Cao et al. 2016)
<i>Urtica dioica</i>	Stem	3.94	6500	0.52	Engine oil	19.29	(Viju and Thilagavathi 2019)
<i>Urtica dioica</i>	Stem	3.94	6500	0.52	Crude oil	22.39	(Viju and Thilagavathi 2019)
<i>Asclepias syriaca</i>	Seed	24	2700	2–3	Engine oil	126	(Panahi et al. 2020)
<i>Populus nigra</i>	Seed	3–12	4000	4–9	Diesel	211	(Likon et al. 2013)

## Perspective

Although plant biological invasion is considered an alarming peril to biodiversity and the ecosystem, it can be seen that they are potential sources for various applications. In fact, invasive plants are widely distributed, have strong tolerance and aggressive development. Although there are some detrimental effects on the ecology, economy, and human health of such species, they are exploited as animal feed, food source, ornamental, and traditional medicine (Feng et al. 2021). Because of their abundant biomass, several exotic species have exhibited added values for paper production (Starešinič et al. 2021) and cosmetics (Nguyen et al. 2021d). In particular, they are great sources for producing energies such as bio-oils, biodiesels, and biogases (Van Meerbeek et al. 2015). In terms of generating materials, this biomass could be converted into biochars (Feng et al. 2021), activated carbons (Bouhamidi et al. 2017; Al-Musawi et al. 2021), nanoparticles (Duraij et al. 2019; Davarnejad et al. 2020), composites (Wang et al. 2020a; Ren et al. 2021a), and aerogels (Yang et al. 2018; Cui et al. 2021).

The use of waste biomass from invasive species as adsorbent materials for the removal of pollutants from aqueous streams could decrease their threat, in harmony with the circular economy. It is imperative that the distribution and total biomass of exotic weeds requires more updated and precise data worldwide. The collection and conservation of such sources need more concerns to secure the quality of raw biomass. Moreover, most studies about such biosorbents have been investigated in synthetic aqueous solutions. In fact, the actual treated environment is considered more complicated than that in the simulated laboratories. Therefore, it requires more in situ investigations to examine the actual influence of biosorbents on the habit including microbial community and other aquatic organisms. Such endeavors could facilitate invasive plant-based adsorbents to large-scale applications, especially for industrial ones. The following areas should be more involved to enhance this purpose for environmental remediation:

1. As invasive plants are widely distributed and have strong development, the clear statistic data of the classification, biological features, and their biomass should be continuously updated. The comparison of the exotic plants for phytoremediation and conversion to biosorbents needs to be gained more interest to find the best method managing and utilizing them.
2. Future studies are needed to increase the extent of invasive plant biomass on carbon, capture, and sequestration. The long-term influences on soil and aquatic environ-

ment of such materials require more patterns and evaluations.

3. Mathematic models including the adsorption factors on simultaneous or several pollutants uptake should be concentrated to elucidate the kinetics and competitive mechanisms. Besides, the application of several advanced optimization software such as response surface methodology should be exploited to shorten the experimental progress. These facilitate the applications of biosorbents in large-scale expected more effective results.
4. The experiments mentioned in this work have been mostly conducted in batch systems that are different from the actual environment. Therefore, more investigation on invasive plant-based biosorbents for pollutants removal in continuous systems are required. Also, the evaluation of economic aspects should be considered apart from technical ones to acknowledge the ultimate cost.
5. Attention should be paid to the reuse of invasive plant-based adsorbents over various cycles to avoid solid wastes. The further utilization of recycled materials should be tested after regeneration and desorption studies for sustainable treatment.
6. The modification of invasive plant-based adsorbents such as physical, chemical, and composite fabrication should be further investigated to improve the removal of contaminants. Besides, eco-friendly modified chemicals should be exploited for such modifications to limit secondary contamination.

## Conclusion

The review presented the distribution as well as harmful impacts of invasive plants and implicated their potential as low-cost and biodegradable biosorbents. The biosorbents from invasive plants possess many functional groups that make them ideal materials for removing heavy metals, organic dyes, and oil pollutants. The invasive biomass pretreatment and chemical modification were also assessed to improve the adsorption performance. Other characteristics of particle size, surface areas, and pore volume of biosorbents are significantly connected to their performance in the adsorption process. Several plausible mechanisms for pollutants treatment were proposed to have insight into the role of chemisorption, electrostatic interaction, ionic exchange, chelation, hydrophobic, and  $\pi$ - $\pi$  stacking interactions. Besides, the desorption and regeneration processes have been also mentioned to elucidate the practical value of biosorbents from invasive plants. Several prospects of invasive plant-based adsorbents for environmental

remediation, and knowledge gaps are pinpointed for further studies.

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**Data availability** The authors declare that all data and materials support their published claims and comply with field standards.

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## Declarations

**Conflict of interest** The authors declare that there are no conflicts of interest.

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