Wetland Flora of West Bengal for Phytoremediation: Physiological and Biotechnological Studies—A Review

19

Gouri Das and Ashwani Kumar

Abstract

Phytoremediation is a promising green technology for the remediation of various industrial effluents. Notably, aquatic plants are widely applied to remove dyes and toxic metals from polluted environments. Aquatic plants have attracted wide attention because of their low cost and high level of resource utilization and are promising green technology for the remediation of various industrial effluents. Water treatment, reuse, and reducing the nutrients loading to the aquatic environments are key ways to achieve sustainable aquaculture. A large number of plants are being used for phytoremediation. Water plants or hydrophytes are the most conspicuous and colorful element of any wetland system. In present investigation, the hydrophytes, phytoplanktons, and herbaceous plant life of the adjacent areas of Tapan Dighi in Dakshin Dinajpur District of West Bengal were explored, collected, and preserved. Altogether, 78 species under 37 families were observed during the study. Phytoplanktons, especially cyanobacteria and chlorophycean members (blue-green and green algae) showed rampant growth in late spring producing algal bloom. Macrophytes observed were of free-floating, rooted with floating leaves, submerged, and immersed with floating and submerged leaf types. Phytoremediation by aquatic macrophytes is a promising technology with higher efficiency. The data generated from the study will provide

---

G. Das (✉)
Department of Botany, Balurghat College, Balurghat, West Bengal, India

A. Kumar
Department of Botany, University of Rajasthan, Jaipur, India

S. Arora et al. (eds.), *Biotechnological Innovations for Environmental Bioremediation*, https://doi.org/10.1007/978-981-16-9001-3_19

a meaningful insight into the vegetation, phytoremediation, and ecosystem of the study area. Key issues of phytoremediation are reviewed.

Keywords

Hydrophytes · Phytoplankton · Phytoremediation · Tapandighi · Wetland

19.1 Introduction

With the development of industrialization and urbanization, the abundance of heavy metals in the environment has increased enormously during the past decades, which raised significant concerns throughout the world. Merian (1984) reported that emissions of the heavier elements chromium, nickel, and cobalt with their short atmospheric life cycle play a more overpowering role in waters and soils. Merian (1984) further suggested that natural weathering of rocks and soils is in the order of one-sixth of the total emissions for cobalt, chromium, nickel, and arsenic, but is relatively smaller for beryllium, selenium, and cadmium. Sebastian and Prasad (2014) studied cadmium minimization in rice. However, volcanic emissions are globally of very low significance. Increasing use of metal contaminated underground water for agricultural purposes (irrigation in rice and other crop fields) in the arsenic-affected areas, especially in Bangladesh and West Bengal (India), resulted in the increased concentration of pollutants, especially arsenic in freshwater systems, which could potentially lead to arsenic entering the human food chain (Rmalli et al. 2005; Beebout 2013). Many countries like India, Bangladesh, Taiwan, Argentina, Hungry, Mexico, and Chile have reported extensive arsenic contamination in their groundwater. Indiscriminate use of arsenical pesticides, geogenic sources, and anthropogenic activities like fossil fuel burning, mining, and natural minerals are the main source of arsenic contamination in the environment. Contamination in freshwater systems poses a health threat not only to the aquatic organisms but also to the humans. High levels of arsenic have been reported in a number of aquatic plants grown in contaminated water bodies. Contamination of rice with toxic heavy metals is especially a health concern in developing countries. Tripathi et al. (2007) studied Arsenic tolerance and remediation by plants. Alarcón-Herrera et al. (2013) reported that several million people around the world are currently exposed to excessive amounts of arsenic (As) and fluoride (F) in their drinking water. Das et al. (2022) reviewed efficacious bioremediation of heavy metals and radionuclides from wastewater employing aquatic macro- and microphytes.

A large number of azo dyes including Reactive Red 120 (RR120) are extensively used in fabric manufacturing due to low cost, ease of preparation, fastness, versatility, and intensity of the colors (Mathur and Kumar 2013, 2016; Rawat et al. 2016). Certain azo dyes contain chemical groups, which have a high affinity for metal ions (Balapure et al. 2015; Hussain et al. 2016). These enhanced properties provide a high degree of biological, chemical, and photocatalytic stability. Nevertheless, their resistance to break down due to time, exposure to sunlight, detergents, water, and microorganisms results in poor degradation in the environment (Solís et al. 2012). The dye removal using phytoremediation has demonstrated its potential to degrade many recalcitrant dyes. Phytoremediation, a plant-based green technology, includes several processes namely phytoextraction, phytodegradation, rhizofiltration, phytostabilization, and phytovolatilization. It has received increasing attention after the discovery of hyperaccumulating plants, which are able to accumulate, concentrate, and translocate high amounts of certain toxic elements in their aboveground/harvestable parts (Mathur and Kumar 2013). The water treatment, reuse, and reducing the nutrients loading to the aquatic environments are key ways to achieve sustainable aquaculture (Sarkheil and Safari 2020).

The usage of phytoremediation is a widely studied and applied technology using aquatic plants, and their associated microorganisms is an effective and environment-friendly method for water treatment (Mathur and Kumar 2013; Bokhari et al. 2019). Both terrestrial and aquatic plants can remediate contaminated soils and waters due to their high adaptive and hyperaccumulation capability (Patel and Sahoo 2020).

Wetlands, the earth's most important freshwater resource, perform some of the important functions including water storage, flood attenuation, recharge of groundwater, water purification, biogeochemical filtration, agriculture, fisheries, wildlife resource and habitat, transport, and recreation. Wetland ecosystem, which has phytoplankton, zooplankton, plant community in succession, microorganisms, migratory flocks, and many others, is the common biotic elements, and is the most fragile and biologically diverse ecosystem. The vegetation type of such water bodies thus plays a very crucial role in these functions in the long run. Aquatic plants are widely applied to remove dyes and toxic metals from polluted environments.

Aquatic macrophytes are defined as emergent, floating-leaved, or submerged macroscopic plant species with distinct roots and shoots. Rooted plants include submerged (e.g., family Hydrocharitaceae, Ceratophyllaceae) and emergent (e.g., family Potamogetonaceae, Ranunculaceae, and Cruciferae) members. A number of aquatic plant species have been investigated for the remediation of toxic contaminants such as As, Cu, Zn, Cr, Cd, Pb, and Hg. This review provides insight into the process of phytoremediation and possible sources native and invasive plants from Dakshin (South) Dinajpur for current and future use.

Dakshin (South) Dinajpur District is traditionally known as a district of wetlands. The district is dotted with numerous natural water bodies each having its influence on life and professional activities on the areas around the wetlands. The vegetation of the wetlands and adjacent areas, therefore, need to be peered into in depth. There is a complete lack of data concerning the plant community present in and around the wetland ecosystem for South Dinajpur. This study was carried out with an intention to generate awareness and information on phytoplankton and plants available in and around one of the water bodies with historical importance. The data generated from the study will be collated for rendering a meaningful insight into the vegetation and ecosystem of the study area. It will certainly create awareness among the incumbents about the vegetation pattern and diverse plant groups of the water body and the need to conserve the biodiversity of the water body and adjacent area. Map showing physiographic divisions of West Bengal is presented here. Source: https://www.researchgate.net/publication/275833658_River_systems_and_water_resources_of_West_Bengal_A_review/figures?lo=1. This figure was uploaded by Sunando Bandyopadhyay (Fig 19.1).

Plants growing in wetlands and water are technically called hydrophytes (Tiner 1999). Hydrophytes (plants with perennating rhizomes or winter buds) and helophytes (plants with buds at the bottom of the water or in the underlying soil) were the two types of cryptophytes (plants with dormant parts below ground), while other wetland plants were included in other life forms, such as phanerophytes (trees and shrubs) as envisaged by Vymazal (2007).

Life Forms Plants growing in wetlands and other moist soils may either be annuals or perennials. Many of the smaller and slender herbs are annuals. They flower, fruit, and disperse seeds and die in a single year. However, perennials have been growing for many years developing food storing woody structures such as rhizomes, corms, and stolons (Rao et al. 2008). Such plants provide a rich source of phytoremediation activities and have been used widely (Brunhoferova et al. 2021).

Growth Forms There have been many attempts to classify aquatic plants according to their growth forms. A classification based on the response of the plant to milieu for growth and development was suggested rather than directly on its morphology or the way it survives adverse conditions (Cook 1996). According to this, the different types of growth forms are ephydates—bottom-rooted with floating leaves, haptophyte—attached to but not penetrating the substrate, hyperhydate—emergent aquatics (lower parts almost always in water), plankton—free swimming below the water surface, pleustophyte—free-floating (at the water surface), rosulate—submerged, bottom-rooted, leaves in a rosette, tenagophyte—juvenile submerged, adult usually terrestrial, and vittate—submerged, bottom-rooted, leaves cauline. However, many species change their dependence on water in regions with differing climates or with different hydrological regimes. Such plants can have more than one life form.

Brunhoferova et al. (2021) studied a mixture of 27 micropollutants (pharmaceuticals, pesticides, herbicides, fungicides, and others) and their removal from aqueous solution by phytoremediation. Phytoremediation contributes to removal of micropollutants from wastewater in constructed wetlands. *Phragmites australis*, *Iris pseudacorus*, and *Lythrum salicaria* in hydroponic conditions indicated leading capability for micropollutant uptake in *Lythrum salicaria*.

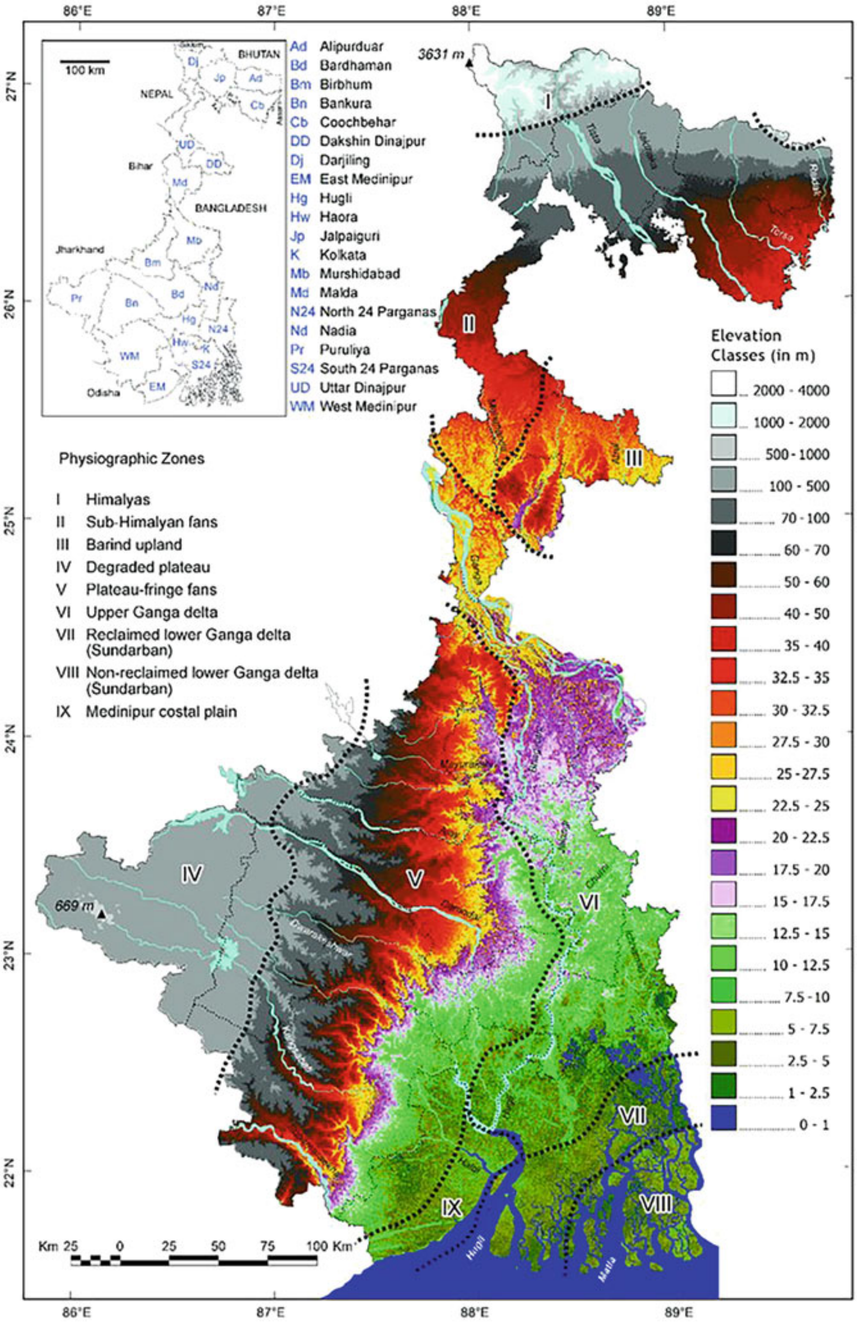

Fig. 19.1 West Bengal: physiographic divisions. Districts shown in this and most subsequent maps are identified in the inset. (Source: Spot-heights from Survey of India. Other elevations from Shuttle Radar Topography Mission data of 2000; https://www.researchgate.net/publication/275833658_River_systems_and_water_resources_of_West_Bengal_A_review/figures?lo=1. This figure was uploaded by Sunando Bandyopadhyay)

Huang et al. (2021) reported vermifilter combined with wetland plant (VFP) is an eco-friendly and sustainable approach for recycling excess sludge by joint action of earthworms, wetland plants, and microorganisms. However, the effects of wetland plants on sludge decomposition and involved microorganisms remain unclear. The wetland plants' species of *Acorus calamus* and *Epipremnum aureum* were separately planted on the surface layer of vermi-reactors by earthworms *Eisenia fetida*. Wetland plants could significantly ($P < 0.001$) enrich the eukaryotic population, rather than bacterial population (Huang et al. 2021).

19.2 Materials and Methods

The study was a random opportunistic survey visiting the wetland locality of Tapan Dighi. The area adjacent to Tapan Dighi was also studied floristically. In wetland, plants were collected from different wetland zones such as deep waters, shallow water, fringes, and other nearby moist soils around the water body. All the collected specimens, identified and unidentified, were pressed for herbaria using a dry method and are kept in the department. Fresh specimens were identified with the comparison from relevant documents, books, and regional and other floras.

19.2.1 Study Area

Down the ages, Tapan Dighi has been the cynosure of many events of political and social importance. Many myths still can be heard among the locals. The wetland, Tapandighi, is situated 14 km to the south of Bangadh, a place of historic interest, and is 30 km away from Balurghat, the district headquarter of Dakshin Dinajpur. As per measurements taken by Mr. Hamilton, during the early nineteenth century, it measures 1420 yards in length and 400 yards in width (Fig. 19.1a–d).

19.3 Results

19.3.1 Habit and Habitat

Tapan Dighi offers a very rich habitat for phytoplankton (Fig. 19.1c). It is seen in the form of smelly filamentous mats on the surface of water, and some unicellular algae and members of Cyanophyceae occur in late spring season, which reduce clarity of the water body and often appear green or golden blue in color.

19.3.2 Survey and Collection

The pond typically contains three broad categories of phytoplankton—filamentous phytoplankton, macroscopic multi-branched phytoplankton, and unicellular phytoplankton. Macroscopic filamentous phytoplankton is composed of long chains of cells attached to a substrate, like submerged or emergent vegetation, rocks, or bottom of the Dighi. The rampant growth of these benthic filamentous algae becomes visible at the surface. Benthic filamentous algae often break and float on the surface as dense mats. Members of filamentous blue-green algae and green algae develop into nuisance filamentous mats on the surface of Tapan Dighi.

A thorough survey of the vegetation of Tapan Dighi and adjacent areas was carried out, and specimens were collected, studied, and recorded (Tables 19.1 and 19.2). The plants collected were pressed, dried, and preserved following proper technique for herbarium sheet preparation. The identification was made following relevant floras and manuals (Das 2004; Ghosh et al. 2008). Some of the plants recorded here are already in use for phytoremediation, and possibility of other plants for phytoremediation is very bright as they purify the water of wetlands (see asteristics).

19.3.3 Identification

Table 19.1 List of plants collected from and around Tapandighi

Cryptogams		
Sl. No.	Name of the species	Family
1.	*Anabaena* sp.	Nostocaceae
2.	*Azolla pinnata* R.Br. (Robert Brown)	Salviniaceae
3.	*Cladophora* sp.	Chadophoraceae
4.	*Chara* sp.	Charophyceae
5.	*Hydrodictyon* sp.	Hydrodictyaceae
6.	*Microcystis* sp.	Microcystaceae
7.	*Nostoc* sp.	Nostocaceae
8.	*Oedogonium* sp.	Charophyceae
9.	*Oscillatoria* sp.	Oscillatoriaceae
10.	*Spirogyra* sp.	Zygnemataceae
11.	*Ulothrix* sp.	Ulotrichaceae

Table 19.2 List of plants collected from and around Tapandighi

Angiosperms		
Sl. No.	Name of the species	Family
Magnoliopsida		
1.	*Acalypha indica* L.	Euphorbiaceae
2.	*Achyranthes aspera* L.	Amaranthaceae
3.	*Ageratum conyzoides* L.	Asteraceae
4.	*Alternanthera sessilis* (L.) R.Br. ex DC.	Amaranthaceae
5.	*Amaranthus spinosus* L.	Amaranthaceae
6.	*Amaranthus viridis* L.	Amaranthaceae
7.	*Argemone mexicana* L.	Papaveraceae
8.	*Bidens pilosa* L.	Asteraceae
9.	*Cassia tora* L.	Fabaceae
10.	*Centella asiatica* (L.) Urb.	Apiaceae
11.	*Chromolaena odorata* (L.) R.M. King and H. Rob.	Asteraceae
12.	*Clerodendrum infortunatum* L.	Lamiaceae
13.	*Croton bonplandianum*, Baill.	Euphorbiaceae
14.	*Cyanthillium cinereum* (L.) H. Rob.	Asteraceae
15.	*Dentella repens* (L.) J.R. Forst. and G. Forst.	Rubiaceae
16.	*Dentella repens* var. *serpyllifolia* (Wall. ex Craib) Verdc.	Rubiaceae
17.	*Digitalis ciliaris* Ehrh.	Scrophulariaceae
18.	*Eclipta alba* (L.) Hassk.	Asteraceae
19.	*Emilia sonchifolia* (L.) DC. ex DC	Asteraceae
20.	*Enhydra fluctuans* Lour.	Asteraceae
21.	*Evolvulus nummularius* (L.) L.	Convolvulaceae
22.	*Glinus oppositifolius* (L.) Aug. DC.	Molluginaceae
23.	*Ipomoea carnea* Jacq.	Convolvulaceae
24.	*Leucas aspera* (Willd.) Link.	Lamiaceae
25.	*Ludwigia repens* J.R. Forst.	Onagraceae
26.	*Mikania micrantha* Kunth.	Asteraceae
27.	*Mimosa pudica* L.	Fabaceae
28.	*Nymphaea nouchali* Burm. f.	Nymphaeaceae
29.	*Parthenium hysterophorus* L.	Asteraceae
30.	*Persicaria hydropiper* (L.) Delarbre	Polygonaceae
31.	*Persicaria orientalis* (L.) Spach.	Polygonaceae
32.	*Phyllanthus niruri* L.	Phyllanthaceae
33.	*Ranunculus aquatilis* L.	Ranunculaceae
34.	*Rumex dentatus* L.	Polygonaceae
35.	*Scoparia dulcis* L.	Plantaginaceae
36.	*Scrophularia scorodonia* L.	Scrophulariaceae
37.	*Solanum torvum* Sw.	Solanaceae
38.	*Spermacoce ocymoides* Burm.f.	Rubiaceae
39.	*Suregada multiflora* (A.Juss.) Baill.	Euphorbiaceae
40.	*Trapa natans* var. *bispinosa* (Roxb.) Makino	Trapaceae
41.	*Tridax procumbens* (L.) L.	Asteraceae
42.	*Xanthium strumarium* L.	Asteraceae

Angiosperms

Sl. No.	Name of the species	Family
Liliopsida		
1.	*Alisma subcordatum* Raf.	Alismataceae
2.	*Colocasia esculenta* (L.) Schott.	Araceae
3.	*Commelina benghalensis* L.	Commelinaceae
4.	*Cymbopogon martinii* (Roxb.) Wats.	Poaceae
5.	*Cynodon dactylon* (L.) Pers.	Poaceae
6.	*Cynodon dactylon* (L.) Pers.	Poaceae
7.	*Cyperus halpan* L.	Cyperaceae
8.	*Cyperus rotundus* L.	Cyperaceae
9.	*Dactyloctanium aegyptium* (L.) Willd.	Poaceae
10.	*Eichhornia crassipes* (Mart.) Solms.	Pontederiaceae
11.	*Eleocharis acicularis* (L.) Roem. and Schult.	Cyperaceae
12.	*Eleocharis dulcis* (Burm.f.) Trin. ex Hensch.	Cyperaceae
13.	*Eleocharis parvula* (Roem. and Schult.) Link ex Bluff, Nees and Schauer	Cyperaceae
14.	*Eleusine indica* (L.) Gaertn.	Poaceae
15.	*Fimbristylis miliacea* (L.) Vahl	Cyperaceae
16.	*Hydrilla verticillata* (L. f.) Royle	Hydrocharitaceae
17.	*Imperata cylindrica* (L.) Beauv.	Poaceae
18.	*Lemna minor* L.	Lemnaceae
19.	*Panicum repens* L.	Poaceae
20.	*Pistia stratiotes* L.	Araceae
21.	*Potamogeton crispus* L.	Potamogetonaceae
22.	*Potamogeton epihydrus* Raf.	Potamogetonaceae
23.	*Saccharum spontaneum* L.	Poaceae
24.	*Sagittaria sagittifolia* L.	Alismataceae
25.	*Vallisneria spiralis* L.	Hydrocharitaceae

19.4 Phytoremediation

Irrigation of agricultural soils with wastewater results in elevated uptake of metals in crops affecting food quality and poses health risks to the consumers (Murtaza et al. 2015). Jallad (2015) analyzed different types of rice grains for heavy metal analysis and then compared the daily dietary intake of toxic metals for the general population in 29 different countries around the world. Efforts are being made to minimize uptake through roots and translocation to grains of toxic heavy metals, especially Cd in rice. Genetic engineering is used as an approach to achieve this goal, and some transgenic rice varieties have been developed to meet the challenge (Cai et al. 2015).

19.4.1 Textile Waste

Textile manufacturing releases potentially toxic compounds, such as synthetic dyes, into the environment. Uncontrolled use of such dyes can negatively affect human health and the ecological balance (de Oliveira et al. 2015). Aquatic pollution caused by dyes has increased together with the growth of activities using colorants such as the food, textile, leather, and agrochemical industries (Hernández-Zamora and Martínez-Jerónimo 2019).

19.4.1.1 Phycoremediation of Heavy Metals using Living Green Microalgae

Due to anthropogenic activities, the quantity of heavy metals in the environment has led to an increase in our exposure to the metals and, by consequence, an increase in heavy-metal-related diseases. Microalgae are generally endangered in aquatic ecosystems by the presence of hazardous materials like toxic metals. According to Javanbakht et al. (2014), the metals that are currently considered to be the most problematic are cadmium (Cd), copper (Cu), magnesium (Mn), chromium (Cr), lead (Pb) iron (Fe), zinc (Zn), mercury (Hg), and as these metals are toxic even in low concentrations. Microalgae have the potential to offer a new eco-friendly, efficient, and cost-effective solution to remove heavy metals from wastewater (Javanbakht et al. 2014).

Microalgae are ecologically important species in aquatic ecosystems due to their role as primary producers (Moorthy et al. 2020; Spain et al. 2021; Fig. 19.2). The textile-used, azo dye DB15, caused toxic effects of different magnitude on microalgae (Hernández-Zamora and Martínez-Jerónimo 2019). Textile dyes—Optilan yellow, Drimarene blue, and Lanasyn brown—cause toxicity to algal growth. However, high decolorization percentages achieved by *Chlorella vulgaris*, *Anabaena oryzae*, and Wollea *saccata* make them potential candidates for bioremediation and preprocessing to remove dyes from textile effluents. However, recently the most frequently used microalgae strains in the phycoremediation belong to the

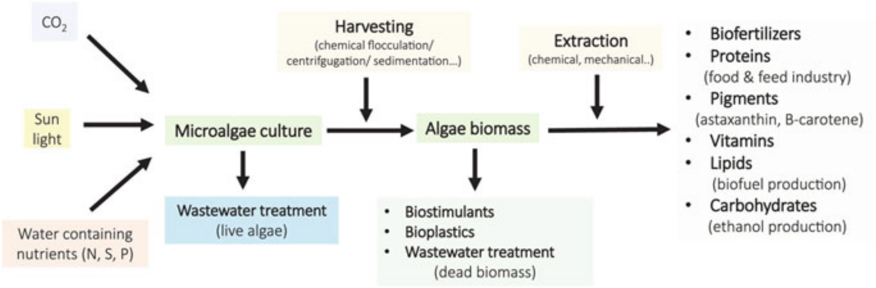

Fig. 19.2 Schematic view of the product value chain of microalgae. Source: Spain et al. (2021). Reproduced under license number 5124011229845 dated 8 August

Chlorophyta phylum, particularly species of genera *Chlorella* and *Scenedesmus* (Spain et al. 2021).

The application of living microalgae for the phycoremediation of HMs can include both extracellular and intracellular bioremediation strategies, and Danouche et al. (2021) reviewed the different steps like

1. Michalak et al. (2013) defined biosorption as the rapid and reversible binding of ions from aqueous solutions onto functional groups present on the surface of biomass. The biosorption process includes the mechanisms: precipitation, complexation, ion exchange, transport across cell membranes, and physical adsorption (Javanbakht et al. 2014). HM biosorption indicates the physicochemical property of the microalgae cell surface, which allows the HM ions from the solution to bind to the cell surface without involving cell metabolism. This nonmetabolic process is highly dependent on a variety of different parameters (e.g., pH, temperature, concentration, biosorbant dosage, or contact time), with the microalgal strain, the contact time, and the pH being the most important aspects (Spain et al. 2021). Microbial extracellular polymeric substances (EPS) can enhance the aggregation of soil particles and benefit plants by maintaining the moisture of the environment and trapping nutrients (Costa et al. 2018).
   However, the extracellular polymeric substances (EPS) formed by microalgae in response to stress conditions depend on cell metabolism. EPS are biosynthetic polymers composed mainly of polysaccharides, structural proteins, lipids, nucleic acids, enzymes, and other compounds such as humic acids (Flemming et al. 2000). Costa et al. (2018) suggested that advances in modern techniques such as high-throughput sequencing, controlled low-strength material (CLSM), nuclear magnetic resonance, scanning electron microscopy, and association with classic microbiology techniques will characterize and develop new EPS with efficient function in water and soil ecosystem.

   The microalgal cells can regulate EPS synthesis and can also change the properties of these biopolymers as required (Naveed et al. 2019; Ubando et al. 2021). Naveed et al. (2019) reported applications of microalgal EPS to the remediation of metal(loid) polluted environments. Ubando et al. (2021) identified the materials produced by microalgae to facilitate biosorption. Industries may benefit from adoption of microalgal biosorption of heavy metals to treat their affluents.

   Spectroscopic studies have shown that functional groups including carboxyl, hydroxyl, sulfate, sulfhydryl (thiol), phosphate, amino, amide, imine, thioether, phenol, carbonyl (ketone), imidazole, phosphonate, and phosphodiester have the properties to be involved in metal binding (Fig. 19.3). Modification of surface reactive sites via surface grafting and/or exchange of functional groups could be helpful to improve biosorbent capacity (Javanbakht et al. 2014).
2. The complexation with extracellular polymeric substances was released by microalgae in the extracellular environment under stress conditions. The chelation and the complexation of HMs with active groups of the cell surface of microalgae incorporate ions such as Na^+, K^+, Ca^{2+}, and Mg^{2+}, which can be

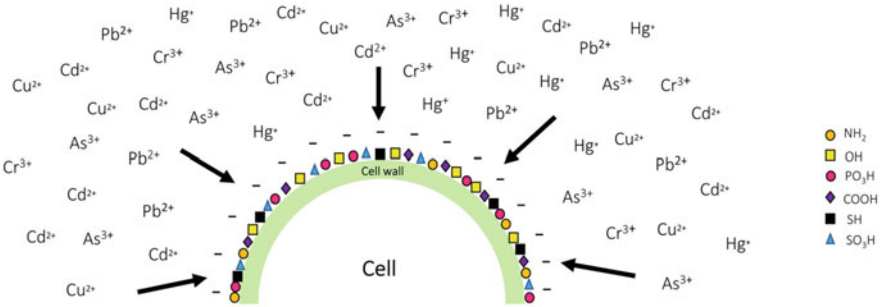

Fig. 19.3 Process of metal ions to the functional groups on the microalgal cell wall (adapted from Javanbakht et al. 2014) Source: Spain et al. (2021). Reproduced under license number 5124011229845 from RightsLink dated August 8

reversibly substituted by other toxic HMs ions in solution, via a process called ion exchange (Danouche et al. 2021). According to Monteiro et al. (2012) when concentration of metal in the extracellular environment is significantly higher than the intracellular concentration, cations can be transported by the negative charged groups of the cell surface to reach the intracellular compartment via active transport across the plasma membrane after binding to thiol molecules primarily cysteine.

3. In contrast to the biosorption process, bioaccumulation is a dependent metabolic pathway. Metal transporters are involved in the intracellular bioaccumulation of HMs
4. Generally, most of the HMs are hydrophilic, and their transport across the plasma membrane (lipophilic) is mediated mainly through a specific protein called as metal transporters. Main intracellular mechanisms include compartmentalization in cell organelles, enzymatic biotransformation, or photoreduction of HMs (Fig. 19.4) (see review Danouche et al. 2021). The sequestration of the MT-HM complex in particular cell organelles, especially vacuoles, chloroplasts, and mitochondria, has prompted researchers to develop hypotheses about metal bioaccumulation pathways for the associated tolerance mechanisms. Thereafter, several detoxification pathways can take place in intracellular compartments (Leong and Chang 2020).

Figure 19.4 summarizes the main pathways involved in the bioremediation and mitigation of HMs (Danouche et al. 2021).

19.4.1.2 Role of Microorganisms

García-García et al. (2016) suggested that bacteria, protists, and microalgae are able to compartmentalize heavy metal complexes into vacuoles, phytochelatin, and metallothionein biosynthesis, phosphate/polyphosphate metabolism; chloroplasts, and mitochondria. Recently, genetically engineered microorganisms with greater capacities and efficiencies for heavy metal recovery, recycling of heavy metals,

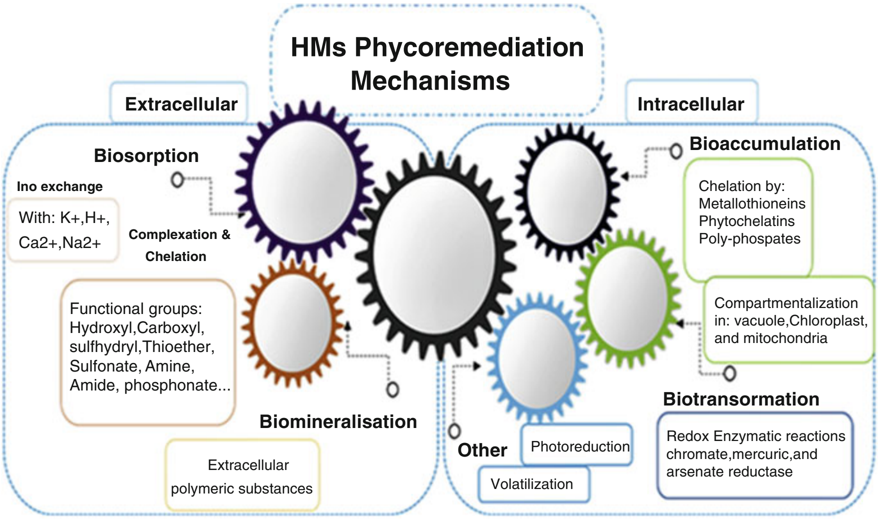

Fig. 19.4 HM-phytoremediation mechanisms (modified from (García-García et al. 2016; Kumar et al. 2015)). Source: Danouche et al. (2021). Reproduced with licence number 5234950808694 dated 23rd January 2022

biosensing of metal ions, and engineering of metalloenzymes have been developed. Microorganisms are the most favorable convertor of azo dyes in comparison with other applications due to their practicality, productivity, simplicity, and inexpensiveness (Islahuddin et al. 2017; Manogaran et al. 2021). The application of microorganisms in azo dye remediation is one of the most favorable processes in comparison with other applications due to its practicality, productivity, simplicity, and inexpensiveness.

19.4.2 Hyperaccumulating “Monilophytes” or Ferns

Water fern, *Azolla pinnata*, *Azolla caroliniana*, *A. filiculoides*, etc., are found to possess capacity of toxic element uptake (Zhang et al. 2008). *Azolla filiculoides* bioaccumulates As, Hg, and Cd as depicted by Rahman et al. (2008), Rai (2008), Rai and Tripathi et al. (2008).

Current application of the synthetic chemical controls and its constant repetitive applications have resulted in resistant mosquitoes and environmental pollution (Ravi et al. 2018). *Azolla pinnata* extracts have shown the potential for developing natural products against *Aedes aegypti* and *Aedes albopictus* mosquitoe dengue vectors (Ravi et al. 2021). Their experimental test showed that *A. pinnata* plant extracts can be used for *Aedes* adulticidal activities by impregnated paper method (method similarly used to test chemical insecticides). Three important chemical compounds from *A. pinnata* extracts have been isolated such as 1-(O-alpha-D-glucopyranosyl)

(1,3R,25R)-hexacosanetriol, pyridate, and nicotinamide N-oxide. These are bioactive compounds that are responsible for adulticidal and ovicidal activity in *Aedes* mosquitoes and at the same time inducing repellence toward the mosquitoes. All these chemicals have also been used against mosquito vectors such as *Culex pipiens* and *Anopheles* spp. as reported by Ravi et al. (2021).

19.4.3 The Hyperaccumulating Angiospermic Plants

The hyperaccumulating plants, the major tools for green technology, are known to accumulate, concentrate, and translocate high amounts of toxic elements present in the environment. In aquatic phytoremediation systems, aquatic plants can be either floating on the water surface or submerged into the water. The floating aquatic hyperaccumulating plants absorb or accumulate contaminants by its roots, while the submerged plants accumulate metals by their whole body. Some aquatic macrophytes, like *Eichhornia crassipes*, *Lemna gibba*, *L. minor*, *Pistia stratiotes*. *Hydrilla* verticillata, *Spirodela polyrhiza*, *Lepidium sativum*, *and Ipomoea aquatica*, are employed for phytoremediation. Nahar and Hoque (2021) reported use of floating aquatic macrophyte, water lettuce (*Pistia stratiotes* L), to improve eutrophic ecosystem.

19.4.4 Aquatic Macrophytes for Phytoremediation

Lemna minor L. has been found to be a potent toxic accumulator in aquatic ecosystems. The prominent contaminants in this case are As, Cu, Zn, and Hg (Alvarado et al. 2008; Kara 2004, 2005). According to Bokhari et al. (2019), macrophytes like swollen duckweed (*Lemna gibba* Linn.) lesser duckweed (*Lemna aequinoctialis* Welw.) can accumulate heavy metals (HMs) in its root and shoot systems up to 100 times higher concentration than a surrounding environment without any production of toxic symptoms.

19.5 Removal of Various Pollutants

19.5.1 Herbicides

Glyphosate (Gly) is the most widely used herbicide in the world as it has broad spectrum and nonselective activity. Its indiscriminate use results in risks of contamination of water bodies and can affect living organisms. Their indiscriminate use results in their accumulation of water bodies and can affect living organisms, especially sensitive or resistant nontarget plants (Dosnon-Olette et al. 2011; da Silva et al. 2020). da Silva et al. (2020) studied mechanisms and phytoremediation potential of the macrophyte *Salvinia biloba* (Fig. 19.5). da Silva et al. (2020) exposed *Salvinia biloba* to different concentrations of a Gly commercial formulation (Gly-CF) and a Gly analytical standard (Gly-AS) and evaluated the physiological

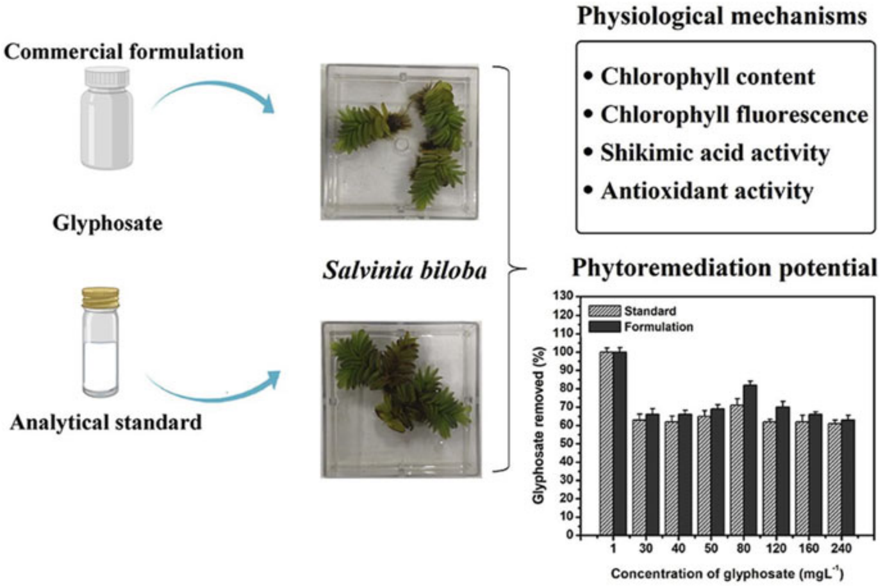

Fig. 19.5 Bioremediation using *Salvinia biloba*. Source: da Silva et al. (2020). Reproduced by License Number 5123010494525 License date Aug 6, 2021

mechanisms of the aquatic macrophyte. *S. biloba* may be a potential phytoremediation agent for low Gly concentrations, since 1 mg L^{-1} Gly was completely removed and exhibited low phytotoxicity (da Silva et al. 2020). Santiago (2020) also studied physiological mechanisms and phytoremediation potential of the macrophyte *Salvinia biloba* towards a commercial formulation.

Dosnon-Olette et al. (2011) focused on toxicity and phytoremediation potential of aquatic plants to remove phytosanitary products from contaminated water. *Lemna minor* (*L. minor*) could eliminate two herbicides isoproturon and glyphosate from their medium. Effect of *Salvinia molesta* on isolated and combined effects of glyphosate and its by-product aminomethylphosphonic acid was studied (Mendes et al. 2021). Kaushal and Mahajan (2021) studied phytoremediation ability of *Salvinia molesta* Mitchell and reported that it can be utilized for remediation of water bodies and wetlands contaminated with Direct Red 28 (DR28) dye wastewater in natural conditions.

Mendes et al. (2021) evaluated *Salvinia molesta* to remove glyphosate and its by-product aminomethylphosphonic acid (AMPA) from contaminated water.

Chen et al. (2019) reported herbicides (mesotrione and fomesafen) with long degradation cycles in water by water hyacinth (*Eichhornia crassipes*). They suggested that uptake by plants combined with degradation by plant-associated bacteria may be the dominant process in the removal of mesotrione and fomesafen by water hyacinth.

19.5.2 Pesticides

Only a small section of the microbiota has the ability to decompose and biotransform certain residual effluents, pesticides, and hydrocarbons (Bhattacharjee et al. 2020). Góngora-Echeverría et al. (2020) using a microbial consortium having *Pseudomonas nitroreducens* and *Ochrobactrum sp.* obtained highest degradations (>90%) of the five pesticides commonly used in Yucatan Mexico: atrazine, carbofuran, and glyphosate.

19.5.3 Heavy Metals

19.5.3.1 What are Heavy Metals?

According to Csuros and Csuros (2002), a heavy metal is defined as "a metal with a density greater than 5 g/cm^3 (i.e., specific gravity greater than 5)."Very recently, we have proposed a broader definition for the term, and heavy metals have been defined as "naturally occurring metals having atomic number greater than 20 and an elemental density greater than 5 g·cm^{-3}" (Ali and Khan 2018). According to Duffus (2002) "the term "heavy metals" is often used as a group name for metals and semimetals (metalloids) that have been associated with contamination and potential toxicity or ecotoxicity."

HMs can also be classified into three categories: (1) toxic HMs, such as Hg, Cr, Pb, Zn, Cu, Ni, Cd, As, Co, and Sn; (2) precious metals mainly including Ag, Au, Ru, Pt, and Pd; and (3) radionuclides HMs such as Ra, Th, and U. On the other hand, it is commonly recognized that nonessential HMs have varying degrees of toxicity toward microorganisms, animals, plants, and humans even at very low concentrations (Ali and Khan 2018; Ali et al. 2019). Five heavy metals namely arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and mercury (Hg) are carcinogenic and show toxicity even at trace amounts, posing threats to environmental ecology and human health (Leong and Chang 2020).

Examples of essential heavy metals are Mn, Fe, Cu, and Zn, while the heavy metals Cd, Pb, and Hg are toxic and are regarded as biologically nonessential (Ramírez 2013). The heavy metals Mn, Fe, Co, Ni, Cu, Zn, and Mo are micronutrients or trace elements for plants.

Hartl (2012) remarks that "metals, of natural or anthropogenic origin, are ubiquitous in the aquatic environment, and therefore understanding their behavior and interaction with aquatic organisms, particularly fishes, a major source of protein for human consumption, is of a great socio economic importance." Chronic exposure to heavy metals in the environment is a real threat to living organisms (Wieczorek-Dąbrowska et al. 2013).

19.5.3.2 Environmentally Relevant Most Hazardous HMs and Metalloids

Environmentally relevant most hazardous heavy metals and metalloids include Cr, Ni, Cu, Zn, Cd, Pb, Hg, and As. Vehicle traffic is among the major anthropogenic sources of heavy metals such as Cr, Zn, Cd, and Pb (Ferretti et al. 1995). During coal combustion, Cd, Pb, and As are partially volatile, while Hg is fully volatile. Phosphate fertilizers are particularly rich in toxic heavy metals. Fertilizers also usually contain significant contents of Cr (Krüger et al. 2017). The natural sources of Cd in the environment are volcanic action and weathering of rocks, whereas an anthropogenic source is nonferrous metal mining, especially processing of Pb-Zn ores (Wang et al. 2015a, b). Anthropogenic increases in Cd concentrations are also caused by excessive application of chemical fertilizers (Grant and Sheppard 2008). The two main pathways for transfer of toxic heavy metals from phosphate fertilizers to the human body are shown below (Dissanayake and Chandrajith 2009). Combustion of leaded gasoline is also a source of Pb in the environment. Although use of the tetraethyl lead as an antiknock agent in gasoline has been banned, it is still used in some developing regions of the world (Palaniappan and Karthikeyan 2009).

The soil-to-plant transfer of heavy metals is a very important step in the trophic transfer of such metals in food chains. Consumption of cereals contaminated with toxic heavy metals may cause risk to human health (Orisakwe et al. 2012). The translocation of heavy metals from roots of the rice plant to stem, leaves, and rice grains is of human health concern. Rice crop is especially susceptible to heavy metal contamination because it needs water during most of its growth period. The trace elements, Cd, Pb, Hg, and As, are ubiquitous in the environment with harmful effects on human health. Regarding their presence in rice as a public health concern, As is on top followed by Cd (Beebout 2013) Human intake of Cd has been reported to be highest through consumption of rice (Cai et al. 2015).

Aquatic macrophytes have been widely employed for in situ phytoremediation of cadmium (Cd)-polluted sediments (Yuan et al. 2021). Eelweed, *Vallisneria spiralis* L., can also degrade Cu, Cd, along with Hg as opined by Rai and Tripathi (2009). Bioaccumulation and toxicity of mercury in rooted submerged macrophyte, *Vallisneria spiralis*, *were* studied by Gupta and Chandra (1998). Dixit and Dhote (2010) suggested that *Hydrilla verticillata* commonly known as Esthwaite waterweed would be a good option for phytoremediation of contaminated water. Pb, Zn, and Cr are the contaminants, which are corrected by *Hydrilla verticillata.* Accumulation of heavy metals in water spinach (*Ipomoea aquatica*) cultivated in the Bangkok region showed As, Cd, Pb, Hg, Cu, and Zn as the major heavy metals.

Gothberg et al. (2002, 2004), Hu et al. (2008). The tolerance of plants to Cd is a scientific and interesting issue for phytoremediation. The absorption of Cd is mainly retained in the root of *E. crassipes*. It will be effective in remediating sites with moderate pollution (≤ 2 mg/L). Maine et al. (2004), enumerated the role of Water lettuce *Pistia stratiotes* in As, Cr, Pb, Ag, Cd, Cu, Hg, Ni, and Zn accumulation. Significant enrichments in agricultural soil for As, Pb, and Zn (in urban area), Cd, Cu, and Ni (in a copper mine area), higher availability detected in developing world, was ascribed to both lithogenic and anthropogenic elements (Balabanova et al. 2015). Availability of metals in a potentially polluted soil and their possible transfer and bioaccumulation in sorrel (*Rumex acetosa*), spinach (*Spinacia oleracea*), and common nettle (*Urtica dioica*) was examined (Balabanova et al. 2015). Measurement of eight potentially toxic elements (As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn) in sediment and plant tissues of *Typha latifolia* L. showed good phytostabilization capability of *Typha latifolia* L. for Cd, Cu, and Pb, and phytoextraction capacity for Zn (Haghnazar et al. 2021). Thus, phytoremediation using *Typha latifolia* L. could be a practical method for uptake and removal of potentially toxic elements from aquatic environments (Haghnazar et al. 2021).

Ameh et al. (2021) reported that *Ageratum conyzoides* Linn (ACL), *Desmodium velutinum* (DV), *Triumfetta rhomboidea* Jacq. (TRJ), *Gleichenia linearis* (Burns) (GL), *Selaginella myosurus* (SM), and *Sida linifolia juss.* excav. (SL) had potential as hyperaccumulators of nickel. *Eclipta alba* (L) Hassk (EAH) and *Triumfetta rhomboidea* Jacq were phytostabilizers for Pb. Most of the plants were found to be useful for phytoremediation of the soil.

19.6 Combination Treatment

Microbial-assisted phytoremediation and reclamation are both potential contaminated soil remediation technologies, but little is known about the combined application of the two technologies on real contaminated soils.

19.6.1 Macrophytes and Algae

Tabinda et al. (2019) used two macrophytes *Pistia stratiotes* and *Eichhornia crassipes* and an alga (*Oedogonium* sp.) were used to treat textile effluents rich in COD, BOD, dyes, and heavy metals (Pb, Fe, Cd, Cu). They reported that *Oedogonium sp*. was the best for COD removal and decolorization. However, *Eichhornia crassipes* was the best for BOD and heavy metal removal, while *Pistia stratiotes* was found to accumulate more concentrations of Pb and Fe (Tabinda et al. 2019). Bokhari et al. (2019) reported the heavy metal phytoextraction potential of swollen duckweed (*Lemna gibba* Linn.) and lesser duckweed (*Lemna aequinoctialis* Welw.) for removal of nickel (Ni), lead (Pb), and cadmium (Cd). Gul et al. (2019) assessed EDTA-assisted Pb and Cd phytoextraction potential of locally grown *Pelargonium hortorum* and *Pelargonium zonale*. They reported that overall, the performance of *P. hortorum* was better than that of *P. zonale* for EDTA-assisted phytoextraction of Pb and Cd (see also Manzoor et al. 2019) .

19.6.2 Macrophytes and Bacteria

The plant-associated bacteria to enhance the phytoremediation efficiency of the heavy metals from polluted water are an emerging area of research. Bacteria-assisted phytoremediation is cost-effective strategy and metal sequestration mechanism that hold high metal biosorption capacities.

Application of plant-microorganism-based environmental remediation is gaining momentum. The roles of plant root exudates and rhizosphere microorganisms in the remediation of ecology and environment have also been discussed (Yang et al.

2021). Yang et al. (2021) described the composition, secretion mechanism, and functions of root exudates and summarized the functions of root exudate in heavy metal absorption, allelopathy, interaction between roots and rhizosphere microorganisms, and changes in soil physical and chemical properties.

Casella et al. (1988) proposed that rhizobia can circumvent exposure to the heavy metal by entering the plant roots. They reported that the nodulated plants, grown in the presence of 10 ppm of chromium, had an increased nitrogenase activity compared to the control plants. However, the effect of metal toxicity on the interaction between legumes and rhizobia is not clear (Hao et al. 2014). Yuan et al. (2021) studied responses of rhizosphere bacteria and their interspecific interactions to phytoremediation.

Legumes are important for nitrogen cycling in the environment and agriculture, and they have been reported to be dominant species in metal contaminated soils (Hao et al. 2014). They reviewed the potential role of legume–rhizobia symbiosis in aiding phytoremediation of such soils. The rhizobia used for phytoremediation could act on metals directly by chelation, precipitation, transformation, biosorption, and accumulation. The plant growth-promoting (PGP) traits of rhizobia including nitrogen fixation, phosphorus solubilization, phytohormone synthesis, siderophore release, and production of ACC deaminase and the volatile compounds of acetoin and 2,3-butanediol may facilitate legume growth while lessening metal toxicity. Naturally resistant rhizobia or recombinant rhizobia and co-inoculation with other plant growth-promoting bacteria (PGPB) may further increase metal detoxification process.

Yuan et al. (2021) suggested phytoremediation of cadmium-contaminated sediment using *Hydrilla verticillata* and *Elodeacanadensis* harboring two rhizobacteria *Pedosphaeraceae* and *Parasegetibacter*. The results showed that a group of specialized sediment bacteria were assembled in the rhizosphere zones closely associated with different host macrophytes. They benefited from the nutrients supplied from macrophyte roots, and thus, more bacterial species survived in the highly Cd-contaminated sediments (50 mg kg^{-1}). Fang et al. (2021) studied the effects of *Vetiveria zizanioides* L and assisted by *Herbaspirillum* sp. p5-19 for soil improvement and phytoremediation of copper stress tolerance and enhancing the accumulation of Mn, Cu, Zn, and Cd by *Vetiveria zizanioides* L. in copper tailings. Meanwhile, photosynthetic pigment contents were enhanced in co-inoculation treatment (p5-19 with alien soil improvement). In addition, the malondialdehyde (MDA) content was decreased, and the activities of antioxidant enzymes such as ascorbate peroxidase (APX), superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) were increased in p5-19 treatment, thereby alleviating the oxidative stress. These results provided the basis for the change in phytoremediation ability of *V. zizanioides* after inoculation. It was concluded that p5-19 assisted with alien soil improvement was a potential strategy for enhancing phytoremediation ability in tailings.

19.7 Eutrophication in Water Bodies and Nutrient Removal.

Shuai et al. (2019) reported that increased nitrogen and phosphorus pollution causes eutrophication in water bodies (see also Walter et al. 2016). Compared to native plants, the invasive plants show much higher nutrient removal efficiency with their high nutrient uptake capacity and thereby helping in the water purification process (Prabakaran et al. 2019). Aquatic macrophytes, such as water lettuce (*Pistia stratiotes*), water hyacinth (*Eichhornia crassipes*), and duckweed (*Lemna minor*), are ideally suited. Zhou et al. (2016) tested four plants, e.g., for *Acorus calamus*, *Typha orientalis*, *Lemna minor*, *and Ceratophyllum demersum* for phytoremediation. The results showed that the concentration of total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD) decreased sharply at the beginning of the test but decreased later. The wetland plant species were more effective in reducing TN when used in combination than used alone, and the combination of *T. orientalis*, *L. minor and C. demersum* had the highest efficiency in removing TN. A thorough understanding of mainly the agronomic, biochemical, physiological, and genetic aspects of phytoremediation is essential to develop the technology as envisaged by the phytoremediation researchers. Shuai et al. (2019) suggested six plants, e.g., *Polygonum orientale*, *Juncus effusus*,, *Iris pseudocorus*, *Phragmites australis*, *Iris sanguinea*, and *Typha orientalis*, are suitable to remove excess of N and P nutrients from water. Xu et al. (2021) suggested two plants *Iris ensata* Thunb. and *Potamogeton malaianus* Miq for the removal of different concentrations of wastewater and the effect of pollutants on plant growth.

19.8 Genetic Engineering for Phytoremediation

Jha (2020) reported that natural hyperaccumulator plant species mostly suffer with limitations of having low biomass and have less efficiency for uptake, accumulation, and degradation of xenobiotics. Genetic engineering of plants can improve their capacity of phytoremediation. *Festuca arundinacea* Schreb (Tall fescue) shows huge potential for lead (Pb) phytoremediation and overexpression of *FaHSP17.8-CII* gene improved Pb phytoremediation efficiency in tall fescue (Wang et al. 2021). The genetic engineering strategy to obtain transgenic tall fescue overexpressing a class II (CII) *sHSP* gene *FaHSP17.8-CII* exhibited 36.3% and 46.6% higher shoot Pb accumulation relative to the WT grasses. Furthermore, according to Wang et al. (2021), overexpression of *FaHSP17.8-CII* improved the synthesis of chlorophyll and transcript abundance of *FapsbC*, *FapsbD*, and *FapsbE*, and alleviated the photoinhibition of PSII in tall fescue under Pb stress.

Danouche et al. (2021) reviewed the future perspectives of physicochemical and genetic approaches, which can be used for the phytoremediation process in terms of selectivity for a targeted metal, removal efficiency, or reduction in treatment time and cost. Danouche et al. (2021) reported surface engineering for a target metal biosorption by algal surface (Fig. 19.6). Yen et al. (2017) reported that *Chlorella vulgaris* strains have the potential to convert Cr(VI) to Cr(III) through an enzymatic

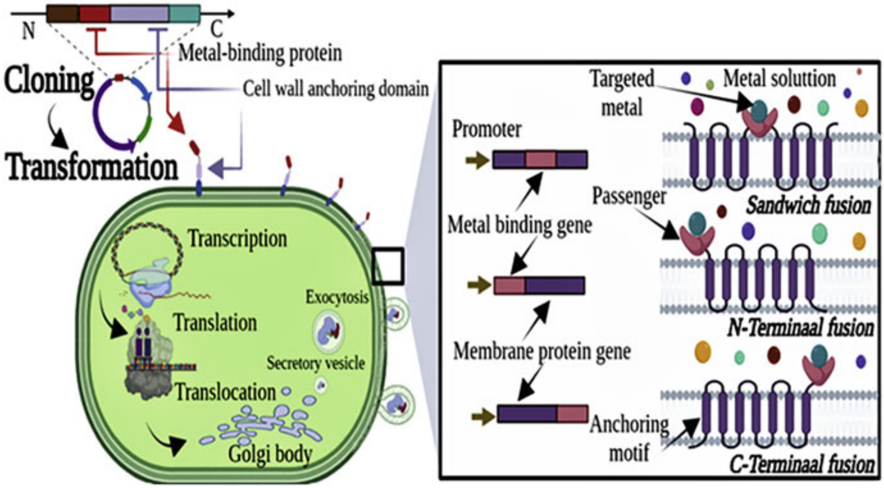

Fig. 19.6 Procedure of cell surface engineering for a target metal biosorption. Source: Danouche et al. (2021). Reproduced under licence number 5234950808694 dated 23rd January 2022

reaction catalyzed by the chromate reductase. Of the two predominant forms of chromium, Cr(III) has only about one-thousandth the toxicity of Cr(VI).

The arsenate reductase has also been found in the green microalgae *Chlamydomonas reinhardtii* (Yin et al. 2011) (Fig. 19.7). Figure 19.7 shows the pathways of biotransformation of As (V and III) by microalgae. Generally, As species are present in different cellular fractions of cells of microalgae including the lipid, cytosolic, cell membranes, and debris fractions. Recent studies have shown that algal strains can grow in 500–2000 mg/l of As waters and can remediate a substantial quantity by rewiring their cellular physiology (Arora et al. 2018). The detoxification pathway begins with the reduction of As(V) into As(III) form and ultimately conversion to a range of organoarsenicals such as arsenolipids, arsenosugars, arsenobetaine, and arsenoribosides (Arora et al. 2018).

Proposed biotransformation pathways of Cr(VI) developed from the finding of Deng et al. (2006), Lee et al. (2017), Rahman and Thomas (2021), Yen et al. (2017).

Artificial proteins can be created through genetic and protein engineering (Agapakis and Silver 2009). Danouche et al. (2021) illustrated the cell surface engineering procedure for a target metal biosorption. First, the coding DNA of the target metal-binding peptide or protein was obtained via whole sequence synthesis or PCR amplification from genomic or plasmid DNA. Next, it can be transformed to the host in the form of fusion of a protein under specific induction. The metal-binding protein/peptide can be displayed in the form of fusion of an anchor protein after transcription, translation, and translocation. The secretory vesicles encompassing the passenger and carrier proteins pass through the cell membrane and anchor the passenger proteins to the surface of the cell wall (Kuroda and Ueda 2011; Li and Tao 2013; Wang et al. 2021).

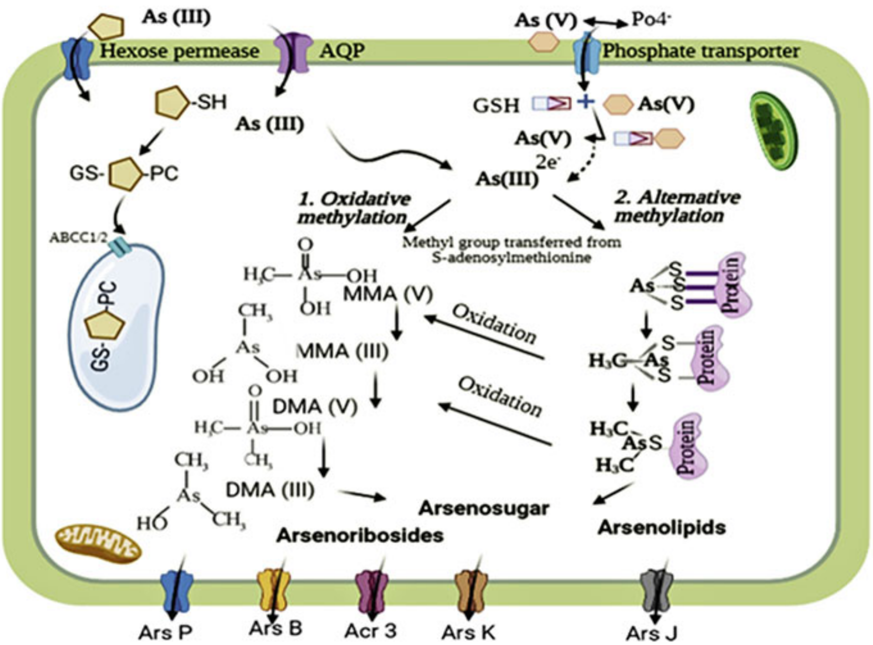

Fig. 19.7 Proposed biotransformation pathways of As (V and III) developed from Arora et al. (2018), Garbinski et al. (2019), Wang et al. (2015b). Source: Danouche et al. (2021). Reproduced under licence number 5234950808694 dated 23rd January 2022

19.9 Discussion

Aquatic ecosystems, both freshwater and marine, are vulnerable to pollution. Contamination of water resources by heavy metals adversely affects plants, animals, and human health (Rezania et al. 2005). Heavy metals are extremely toxic to aquatic organisms even at very low concentrations (Akif et al. 2002). These elements can cause significant histopathological alterations in tissues of aquatic organisms such as fish (Ahmed et al. 2014). The release of industrial effluents without treatment into the aquatic bodies is a major source of pollution of surface and groundwater water (Afzal et al. 2018). Pollution of water bodies with heavy metals is a worldwide problem because of the environmental persistence, bioaccumulation, and biomagnification in food chains and toxicity of these elements (Rajaei et al. 2012). Ecological and environmental problems including heavy metal pollution have received increasing concerns (Yang et al. 2021).

The As and F contamination results from water–rock interactions and may be accelerated by geothermal and mining activities, as well as by aquifer overexploitation. Although the individual toxic effects of As and F have been analyzed, there are few studies addressing their co-occurrences and water treatment options. Enrichment of F is generally related to fluorite dissolution, and it is also associated with high Cl, Br, and V concentrations. It is still urgent to develop technologies and methods capable of monitoring and removing both of these contaminants simultaneously from water. Alarcón-Herrera et al. (2013) suggested that As and F co-occurrence in groundwater is linked to volcanism, geothermal, and mining activities. As and F co-occurrence are particularly pronounced in arid and semi-arid regions. As and F are generally associated with high concentrations of Na^+ and $HCO3^-$. Technology is required to simultaneously remove As and F from drinking water.

Remediation of the polluted ecosystem is important to lessen the detrimental effects of discharge of pesticides and heavy discharge of industrial effluents on a long-term basis (Bhattacharjee et al. 2020). Chemical treatment of this discharge using electrochemical removal, ion exchange columns, alkaline precipitation, filtration, and membrane technologies are the currently available technologies for heavy metal removal. These conventional technologies are not economical and may produce adverse impacts on aquatic ecosystems. Phytoremediation of metals is a cost-effective "green" technology based on the use of specially selected metal-accumulating plants to remove toxic metals from soils and water (Rai 2008). It is a promising cleanup technology for contaminated soils, groundwater, and wastewater that is both low tech and low cost (Farid et al. 2014). Sequential phytoremediation with a mixture of plants was more effective than that relying only on a single plant species (Farid et al. 2014). Burges et al. (2018) suggested that since the emergence of phytoremediation, much research has focused on its development for (1) the removal of metals from soil and/or (2) the reduction in metal bioavailability, mobility, and ecotoxicity in soil. They further suggested that the combination of these phytotechnologies or phytomanagement provides certain benefits for the restoration of important ecosystem services, e.g., nutrient cycling, carbon storage, water flow regulation, erosion control, water purification, and fertility maintenance.

19.10 Conclusion

Heavy metals are non-degradable by any biological or physical process and are persistent in the soil for a long period, which pose a long-term threat for the environment (Suman et al. 2018). According to their role in biological systems, heavy metals can be grouped as essential and nonessential. Essential heavy metals such as Cu, Fe, Mn, Ni, and Zn are required for physiological and biochemical processes.

Aquatic macrophytes have been widely employed for in situ phytoremediation of heavy metals. Wetlands characteristically offer a varied degree of wetness, thereby supporting a diverse group of plants. In wetlands a number of plants carryout the function of phytoremediation. The local availability of water is seen to encourage transition between annual and perennial growth forms. Some of the algae in wetlands can be helpful in bioremediation. Microbial remediation is reported, but microbe plus plants are recent reports. Combination of bacteria and plants causes bioremediation. Applying lower group plants, like *Azolla* while the wetland supports plant diversity and conservation in the local ecological domain, a number of human needs are also catered to. Shrinkage of the waterline as evident in recent times is a result of rapid urbanization. However, a silver line has been seen with the currently ongoing process of revamping the entire water body by the State Government. This is heralded as a leap forward toward suitable management, welfare, and conservation of flora of Tapan Dighi.

Acknowledgement The author gratefully acknowledges the wholehearted co-operation extended by the local people, unstinted support, and encouragement received from the students of the Department of Botany, Balurghat College, for their assistance in field data collection, preservation, and herbaria preparation.

References

Afzal MS, Ashraf A, Nabeel M (2018) Characterization of industrial effluents and groundwater of Hattar industrial estate, Haripur. Adv Agric Environ Sci 1(2):70–77

Agapakis CM, Silver PA (2009) Synthetic biology: exploring and exploiting genetic modularity through the design of novel biological networks. Mol BioSyst 5:704–713

Ahmed MK, Parvin E, Islam MM, Akter MS, Khan S, Al-Mamun MH (2014) Lead- and cadmium-induced histopathological changes in gill, kidney and liver tissue of freshwater climbing perch *Anabas testudineus* (Bloch, 1792). Chem Ecol 30(6):532–540

Akif M, Khan AR, Sok K et al (2002) Textile effluents and their contribution towards aquatic pollution in the Kabul River (Pakistan). J Chem Soc Pak 24(2):106–111

Alarcón-Herrera MT, Bundschuh J, Nath B, Nicolli HB, Gutierrez M, Reyes-Gomez VM, Sracek OR (2013) Co-occurrence of arsenic and fluoride in groundwater of semi-arid regions in Latin America: genesis, mobility and remediation. J Hazard Mater 262:960–969

Ali H, Khan E (2018) What are heavy metals? Long-standing controversy over the scientific use of the term' heavy metals'-proposal of a comprehensive definition. Toxicol Environ Chem 100(1): 6–19

Ali H, Khan E, Ilahi I (2019) Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation chemistry. J Chem 2019: 6730305

Alvarado S, Guédez M, Lué-Merú MP, Nelson G, Alvaro A, Jesús AC, Gyula Z (2008) Arsenic removal from waters by bioremediation with the aquatic plants water hyacinth (*Eichhornia crassipes*) and lesser duckweed *(Lemna minor)*. Bioresour Technol 99:8436–8440

Ameh EG, Awulu DT, Akinde SB (2021) Phytoremediation tool for restoration of metal-polluted coal mine soil in Okaba, Nigeria: a hierarchical cluster approach. Environ Monit Assess 193(8): 514. https://doi.org/10.1007/s10661-021-09308-3

Arora N, Gulati K, Tripathi S, Pruthi V, Poluri KM (2018) Algae as a budding tool for mitigation of arsenic from aquatic systems. In: Hasanuzzaman M, Nahar K, Fujita M (eds) Mechanisms of arsenic toxicity and tolerance in plants. Springer, Singapore. https://doi.org/10.1007/978-981-13-1292-2_12

Balabanova B, Stafilov T, Bačeva K (2015) Bioavailability and bioaccumulation characterization of essential and heavy metals contents in *R. acetosa*, *S. oleracea* and U. dioica from copper polluted and referent areas. J Environ Health Sci Eng 13(1):2. https://doi.org/10.1186/s40201-015-0159-1

Balapure K, Bhatt N, Madamwar D (2015) Mineralization of reactive azo dyes present in simulated textile waste water using down flow microaerophilic fixed film bioreactor. Bioresour Technol 175:1–7

Beebout S (2013) Rice, health, and toxic metals, in Rice Today

Bhattacharjee G, Gohil N, Vaidh S, Joshi K, Vishwakarma GS, Singh V (2020) Microbial bioremediation of industrial effluents and pesticides. In: Pandey VC, Singh V (eds) Bioremediation of pollutants. Elsevier, London, pp 287–302

Bokhari SH, Mahmood-Ul-Hassan M, Ahmad M (2019) Phytoextraction of Ni, Pb and, Cd by duckweeds. Int J Phytoremediation 21(8):799–806. https://doi.org/10.1080/15226514.2019.1566882

Brunhoferova H, Venditti S, Schlienz M, Hansen J (2021) Removal of 27 micropollutants by selected wetland macrophytes in hydroponic conditions. Chemosphere 281:130980. https://doi.org/10.1016/j.chemosphere.2021.130980

Burges A, Alkorta I, Epelde L, Garbisu C (2018) From phytoremediation of soil contaminants to phytomanagement of ecosystem services in metal contaminated sites. Int J Phytoremediation 20(4):384–397. https://doi.org/10.1080/15226514.2017.1365340

Cai L-M, Xu Z-C, Qi J-Y, Feng Z-Z, Xiang T-S (2015) Assessment of exposure to heavy metals and health risks among residents near Tonglushan mine in Hubei, China. Chemosphere 127:127–135

Casella S, Stefania F, Fabrizio L, Andrea S (1988) Effect of cadmium, chromium and copper on symbiotic and free-living *Rhizobium leguminosarum* biovar *trifolii*. FEMS Microbiol Lett 49(3):343–347. https://doi.org/10.1111/j.1574-6968.1988.tb02754.x

Chen Z, Huang L, Song S, Zhang Y, Li Y, Tan H, Li X (2019) Enhanced disappearance of mesotrione and fomesafen by water hyacinth (*Eichhornia crassipes*) in water. Int J Phytoremediation 21(6):583–589. https://doi.org/10.1080/15226514.2018.1540543

Cook CDK (1996) Aquatic and wetland plants of India. Oxford University Press, New York

Costa OYA, Raaijmakers JM, Kuramae EE (2018) Microbial Extracellular Polymeric Substances: Ecological Function and Impact on Soil Aggregation. Front Microbiol 9:1636. https://doi.org/10.3389/fmicb.2018.01636

Csuros M, Csuros C (2002) Environmental sampling and analysis for metals. Lewis Publishers, Boca Raton

da Silva SJ, da Silva PM, Grillo R, Fiorucci AR, José de Arruda G, Santiago EF (2020) Physiological mechanisms and phytoremediation potential of the macrophyte *Salvinia biloba* towards a commercial formulation and an analytical standard of glyphosate. Chemosphere 259:127417. https://doi.org/10.1016/j.chemosphere.2020.127417

Danouche M, El Ghachtouli N, El Arroussi H (2021) Phycoremediation mechanisms of heavy metals using living green microalgae: physicochemical and molecular approaches for enhancing selectivity and removal capacity. Heliyon 16:e07609. https://doi.org/10.1016/j.heliyon.2021.e07609

Das AP (2004) Floristic studied in Darjeeling Hills. Bull Bot Surv India 43(1-4):1–18

Das S, Das S, Ghangrekar MM (2022) Efficacious bioremediation of heavy metals and radionuclides from wastewater employing aquatic macro- and microphytes. J Basic Microbiol. https://doi.org/10.1002/jobm.202100372. Epub ahead of print. PMID: 35014053

de Oliveira GA, de Lapuente J, Teixidó E, Porredón C, Borràs M, de Oliveira DP (2015) Textile dyes induce toxicity on zebrafish early life stages. Environ Toxicol Chem 35(2):429–434. https://doi.org/10.1002/etc.3202

Deng L, Wang H, Deng N (2006) Photoreduction of chromium (VI) in the presence of algae *Chlorella vulgaris*. J Hazard Mater 138(2):288–292

Dissanayake CB, Chandrajith R (2009) Phosphate mineral fertilizers, trace metals and human health. J Nat Sci 37(3):153–165

Dixit S, Dhote S (2010) Evaluation of uptake rate of heavy metals by *Eichhornia crassipes* and *Hydrilla verticillata*. Environ Monit Assess 169:367–374

Dosnon-Olette R, Couderchet M, Oturan MA, Oturan N, Eullaffroy P (2011) Potential use of Lemna minor for the phytoremediation of isoproturon and glyphosate. Int J Phytoremediation 13(6):601–612. https://doi.org/10.1080/15226514.2010.525549

Duffus JH (2002) Heavy metals a meaningless term? (IUPAC Technical Report). Pure Appl Chem 74(5):793–807

Fang Q, Huang T, Wang N, Ding Z, Sun Q (2021) Effects of Herbaspirillum sp. p5-19 assisted with alien soil improvement on the phytoremediation of copper tailings by *Vetiveria zizanioides* L. Environ Sci Pollut Res Int 27:15091

Farid M, Irshad M, Fawad M, Zeshan Ali A, Eneji E, Aurangzeb N, Mohammad A, Ali B (2014) Effect of cyclic phytoremediation with different wetland plants on municipal wastewater. Int J Phytoremediation 16(6):572–581. https://doi.org/10.1080/15226514.2013.798623

Ferretti M, Cenni E, Bussotti F, Batistoni P (1995) Vehicle-induced lead and cadmium contamination of roadside soil and plants in Italy. Chem Ecol 11(4):213–228

Flemming H-C, Wingender J, Mayer C, Korstgens V, Borchard W (2000) Cohesiveness in biofilm matrix polymers. In: Allison D, Gilbert P (eds) Symp soc gen microbiol. Cambridge University Press, Cambridge, pp 87–105

Garbinski LD, Rosen BP, Chen J (2019) Pathways of arsenic uptake and efflux. Environ Int 126: 585–597

García-García JD, Sánchez-Thomas R, Moreno-Sánchez R (2016) Bio-recovery of non-essential heavy metals by intra- and extracellular mechanisms in free-living microorganisms. Biotechnol Adv 34(5):859–873

Ghosh S, Ghora C, Murmu S (2008) Paschim banglar udvid. Bot Survey of India, Kolkata

Góngora-Echeverría VR, García-Escalante R, Rojas-Herrera R, Giácoman-Vallejos G, Ponce-Caballero C (2020) Pesticide bioremediation in liquid media using a microbial consortium and bacteria-pure strains isolated from a biomixture used in agricultural areas. Ecotoxicol Environ Saf 2020:110734. https://doi.org/10.1016/j.ecoenv.2020.110734

Gothberg A, Greger M, Bengtsson BE (2002) Accumulation of heavy metals in water spinach (Ipomoea aquatica) cultivated in the Bangkok region, Thailand. Environ Toxicol Chem 21: 1934–1939

Gothberg A, Greger M, Holm K, Bengtsson BE (2004) Influence of nutrient levels on uptake and effects of mercury, cadmium, and lead in water spinach. J Environ Qual 33:1247–1255

Grant CA, Sheppard SC (2008) Fertilizer impacts on cadmium availability in agricultural soils and crops. Hum Ecol Risk Assess 14(2):210–228

Gul I, Manzoor M, Silvestre J, Rizwan M, Hina K, Kallerhoff J, Arshad M (2019) EDTA-assisted phytoextraction of lead and cadmium by Pelargonium cultivars grown on spiked soil. Int J Phytoremediation 21(2):101–110

Gupta M, Chandra P (1998) Bioaccumulation and toxicity of mercury in rooted submerged macrophyte *Vallisneria spiralis*. Environ Pollut 103:327–332

Haghnazar H, Hudson-Edwards KA, Kumar V, Pourakbar M, Mahdavianpour M, Aghayani E (2021) Potentially toxic elements contamination in surface sediment and indigenous aquatic macrophytes of the Bahmanshir River, Iran: appraisal of phytoremediation capability. Chemosphere 285:131446. https://doi.org/10.1016/j.chemosphere.2021.131446

Hao X, Taghavi S, Xie P, Orbach MJ, Alwathnani HA, Rensing C, Gei (2014) Phytoremediation of heavy and transition metals aided by legume-rhizobia symbiosis. Int J Phytoremediation 16(2): 179–202. https://doi.org/10.1080/15226514.2013.773273

Hartl MGJ (2012) Book review homeostasis and toxicology of non-essential metals. J Fish Biol 83: 1476–1477

Hernández-Zamora M, Martínez-Jerónimo F (2019) Exposure to the azo dye direct blue 15 produces toxic effects on microalgae, cladocerans, and zebrafish embryos. Ecotoxicology 28(8):890–902. https://doi.org/10.1007/s10646-019-02087-1

Hu MH, Ao YS, Yang XE, Li TQ (2008) Treating eutrophic water for nutrient reduction using an aquatic macrophyte (Ipomoea aquatica Forsskal) in a deep flow technique system. Agric Water Manag 95:607–615

Huang K, Sang C, Guan M, Wu Y, Xia H, Chen Y, Nie C (2021) Performance and stratified microbial community of vermi-filter affected by *Acorus calamus* and *Epipremnum aureum* during recycling of concentrated excess sludge. Chemosphere 280:130609. https://doi.org/10.1016/j.chemosphere.2021.130609

Hussain G, Ather M, Khan MU, Saeed A, Saleem R, Shabir G, Channar PA (2016) Synthesis and characterization of chromium (III), iron (II), copper (II) complexes of 4-amino-1-(p-sulphophenyl)-3-methyl-5-pyrazolone based acid dyes and their applications on leather. Dyes Pigments 130:90–98

Islahuddin NK, Halmi MI, Manogaran M, Shukor MY (2017) Isolation and culture medium optimisation using one-factor-at-time and response surface methodology on the biodegradation of the azo-dye Amaranth. Bioremed Sci Technol Res 5:25–31

Jallad KN (2015) Heavy metal exposure from ingesting rice and its related potential hazardous health risks to humans. Environ Sci Pollut Res 22:15449–15458. https://doi.org/10.1007/s11356-015-4753-7

Javanbakht V, Alavi SA, Zilouei H (2014) Mechanisms of heavy metal removal using microorganisms as biosorbent. Water Sci Technol 69:1775–1787. https://doi.org/10.2166/wst.2013.718

Jha S (2020) 4-Progress, prospects, and challenges of genetic engineering in phytoremediation. In: Pandey VC, Singh V (eds) Bioremed of poll. Elsevier, London, pp 57–123. https://doi.org/10.1016/B978-0-12-819025-8.00004-1

Kara Y (2004) Bioaccumulation of copper from contaminated wastewater by using *Lemna minor*. Bull Environ Contam Toxicol 72:467–471

Kara Y (2005) Bioaccumulation of Cu, Zn and Ni from the wastewater by treated Nasturtium officinale. Int J Environ Sci Technol 2:63–67

Kaushal J, Mahajan P (2021) Kinetic evaluation for removal of an anionic diazo direct red 28 by using phytoremediation potential of salvinia molesta Mitchell. Bull Environ Contam Toxicol. https://doi.org/10.1007/s00128-021-03297-2

Kelly DJA, Budd K, Lefebvre DD (2007) Biotransformation of mercury in pH-stat cultures of eukaryotic freshwater algae. Arch Microbiol 2007:45–53

Krüger O, Fiedler F, Adam C, Vogel C, Senz R (2017) Determination of chromium (VI) in primary and secondary fertilizer and their respective precursors. Chemosphere 182:48–53

Kumar K, Dahms H-U, Won E-J, Lee J-S, Shin K-H (2015) Microalgae – a promising tool for heavy metal remediation. Ecotoxicol Environ Saf 113:329–352. https://doi.org/10.1016/j.ecoenv.2014.12.019

Kuroda K, Ueda M (2011) Molecular design of the microbial cell surface toward the recovery of metal ions. Curr Opin Biotechnol 22:427–433

Lee L, Hsu CY, Yen HW (2017) The effects of hydraulic retention time (HRT) on chromium (VI) reduction using autotrophic cultivation of *Chlorella vulgaris*. Bioprocess Biosyst Eng 40: 1725–1731

Leong YK, Chang J-S (2020) Bioremediation of heavy metals using microalgae: Recent advances and mechanisms. Bioresour Technol 303:122886. https://doi.org/10.1016/j.biortech.2020.122886

Li P, Tao H (2013) Cell surface engineering of microorganisms towards adsorption of heavy metals. Crit Rev Microbiol 41:140–149

Maine MA, Suñé NL, Lagger SC (2004) Chromium bioaccumulation: comparison of the capacity of two floating aquatic macrophytes. Water Res 38:1494–1501

Manogaran M, Yasid NA, Othman AR, Gunasekaran B, Halmi MIE, Shukor MYA (2021) Biodecolourisation of reactive red 120 as a sole carbon source by a bacterial consortium-toxicity assessment and statistical optimisation. Int J Environ Res Public Health 18(5):2424. https://doi.org/10.3390/ijerph18052424

Manzoor GM, Silvestre J, Rizwan M, Hina K, Kallerhoff J, Arshad M (2019) EDTA-assisted phytoextraction of lead and cadmium by *Pelargonium cultivars* grown on spiked soil. Int J Phytoremediation 21(2):101–110. https://doi.org/10.1080/15226514.2018.1474441

Mathur N, Kumar A (2013) Physico-chemical characterization of industrial effluents contaminated soil of sanganer. J Emerg Trends Eng Appl Sci 4(2):226–228

Mathur N, Kumar A (2016) Environmental pollution by textile industries causes and concern. In: Arya A, Basu SK (eds) Anthropogenic causes and concern. The Readers Paradise, New Delhi, pp 20–26

Mendes EJ, Malage L, Rocha DC, Kitamura RSA, Gomes SMA, Navarro-Silva MA, Gomes MP (2021) Isolated and combined effects of glyphosate and its by-product aminomethylphosphonic acid on the physiology and water remediation capacity of Salvinia molesta. J Hazard Mater 417: 125694. https://doi.org/10.1016/j.jhazmat.2021.125694

Merian (1984) Introduction on environmental chemistry and global cycles of chromium, nickel, cobalt beryllium, arsenic, cadmium and selenium, and their derivatives. Toxicol Environ Chem 8(1):9–38. https://doi.org/10.1080/02772248409357038

Michalak I, Chojnacka K, Witek-Krowiak A (2013) State of the art for the biosorption process – a review. Appl Biochem Biotechnol 170:1389–1416. https://doi.org/10.1007/s12010-013-0269-0

Monteiro CM, Castro PML, Malcata FX, Instituto I, Carlos A, Campos O, Maia C, Pedro P (2012) Metal uptake by microalgae: underlying mechanisms and practical applications. Biotechnol Prog 28:299–311

Moorthy KA, Govindarajan Rathi B, Shukla SP, Kumar K, Shree Bharti V (2020) Acute toxicity of textile dye Methylene blue on growth and metabolism of selected freshwater microalgae. Environ Toxicol Pharmacol 82:103552. https://doi.org/10.1016/j.etap.2020.103552

Murtaza G, Javed W, Hussain A, Wahid A, Murtaza B, Owens G (2015) Metal uptake via phosphate fertilizer and city sewage in cereal and legume crops in Pakistan. Environ Sci Pollut Res 22(12):9136–9147

Nahar K, Hoque S (2021) Phytoremediation to improve eutrophic ecosystem by the floating aquatic macrophyte, water lettuce (Pistia stratiotes L.) at lab scale. Egypt J Aquat Res 47(2):231–237. https://doi.org/10.1016/j.ejar.2021.05.003

Naveed S, Li C, Xinda L, Chen S, Yin B, Zhang C, Ge Y (2019) Microalgal extracellular polymeric substances and their interactions with metal(loid)s: a review. Crit Rev Environ Sci Technol 49(19):1769–1802. https://doi.org/10.1080/10643389.2019.1583052

Orisakwe OE, Nduka JK, Amadi CN, Dike DO, Bede O (2012) Heavy metals health risk assessment for population via consumption of food crops and fruits in Owerri, South Eastern, Nigeria. Chem Cent J 6(1):77

Palaniappan PR, Karthikeyan S (2009) Bioaccumulation and depuration of chromium in the selected organs and whole body tissues of freshwater fish *Cirrhinus mrigala* individually and in binary solutions with nickel. J Environ Sci 21(2):229–236

Patel HA, Sahoo S (2020) A review of water quality improvement with the help of aquatic macrophytes. Curr World Environ 15:3

Prabakaran K, Li J, Anandkumar A, Leng Z, Zou CB, Du D (2019) Managing environmental contamination through phytoremediation by invasive plants: a review. Ecol Eng 138:28–37

Rahman Z, Thomas L (2021) Chemical-assisted microbially mediated chromium (Cr) (VI) reduction under the influence of various electron donors, redox mediators, and other additives: an outlook on enhanced Cr(VI) removal. Front Microbiol 11:1–19

Rahman MA, Hasegawa H, Ueda K, Maki T, Okumura C, Rahman MM (2008) Arsenic accumulation in duckweed (*Spirodela polyrhiza* L.): a good option for phytoremediation. Chemosphere 69:493–499

Rai PK (2008) Heavy metal pollution in aquatic ecosystems and its phytoremediation using wetland plants: an ecosustainable approach. Int J Phytoremediation 10(2):133–160. https://doi.org/10.1080/15226510801913918

Rai PK, Tripathi BD (2009) Comparative assessment of *Azolla pinnata* and *Vallisneria spiralis* in Hg removal from G.B. Pant Sagar of Singrauli industrial region, India. Environ Monit Assess 148:75–84

Rajaei G, Mansouri B, Jahantigh H, Hamidian AH (2012) Metal concentrations in the water of Chah nimeh reservoirs in Zabol, Iran. Bull Environ Contam Toxicol 89(3):495–500

Ramírez R (2013) The gastropod Osilinus atrataas a bioindicator of Cd, Cu, Pb and Zn contamination in the coastal waters of the Canary Islands. Chem Ecol 29(3):208–220

Rao GR, Divaker K, Mesta S, Chandran MD, Ramachandra TV (2008) Wetland flora of Uttara Kannada. Environment education for ecosystem

Ravi R et al (2018) Evaluation of two different solvents for Azolla pinnata extracts on chemical compositions and larvicidal activity against Aedes albopictus (Diptera: Culicidae). J Chem. https://doi.org/10.1155/2018/7453816

Ravi R, Rajendran D, Oh WD, Mat Rasat MS, Hamzah Z, Ishak IH, Mohd Amin MF (2021) The potential use of Azolla pinnata as an alternative bio-insecticide. Sci Rep 10(1):19245. https://doi.org/10.1038/s41598-020-75054-0

Rawat D, Mishra V, Sharma RS (2016) Detoxification of azo dyes in the context of environmental processes. Chemosphere 155:591–605

Rezania S, Taib SM, Md Din MF, Dahalan FA, Kamyab H (2005) Comprehensive review on phytotechnology: heavy metals removal by diverse aquatic plants species from wastewater. J Hazard Mater 318:587–599

Rmalli A, Haris SW, Harrington PI, Ayub M (2005) A survey of arsenic in foodstuffs on sale in the United Kingdom and imported from Bangladesh. Sci Total Environ 337(1):23–30. https://doi.org/10.1016/j.scitotenv.2004.06.008

Santiago EF (2020) Physiological mechanisms and phytoremediation potential of the macrophyte Salvinia biloba towards a commercial formulation and an analytical standard of glyphosate. Chemosphere 259:127417. https://doi.org/10.1016/j.chemosphere.2020.127417

Sarkheil M, Safari O (2020) Phytoremediation of nutrients from water by aquatic floating duckweed (Lemna minor) in rearing of African cichlid (*Labidochromis lividus*) fingerlings. Environ Technol Innov 18:100747

Sebastian A, Prasad MNV (2014) Cadmium minimization in rice. Agron Sustainable Dev 34(1): 155–173

Shuai Y, Miao C, Song H, Huang Y, Chen W, He X (2019) Efficiency of nitrogen and phosphorus removal by six macrophytes from eutrophic water. Int J Phytoremediation 21(7):643–651. https://doi.org/10.1080/15226514.2018.1556582

Solís M, Solís A, Pérez HI, Manjarrez N, Flores M (2012) Microbial decolouration of azo dyes: a review. Process Biochem 47:1723–1748

Spain O, Plöhn M, Funk C (2021) The cell wall of green microalgae and its role in heavy metal removal. Physiol Plant 2021:1–10. https://doi.org/10.1111/ppl.13405

Suman J, Uhlik O, Viktorova J, Macek T (2018) Phytoextraction of heavy metals: a promising tool for clean-up of polluted environment? Front Plant Sci 9:1476. https://doi.org/10.3389/fpls.2018.01476

Tabinda AB, Arif RA, Yasar A, Baqir M, Rasheed R, Mahmood A, Iqbal A (2019) Treatment of textile effluents with *Pistia stratiotes*, *Eichhornia crassipes* and *Oedogonium sp*. Int J Phytoremediation 21(10):939–943. https://doi.org/10.1080/15226514.2019.1577354

Tiner RW (1999) Wetland Indicators: a guide to wetland identification, delineation, classification, and mapping. Lewis Publishers, Washington, DC

Tripathi RD, Srivastava S, Mishra S, Singh N, Tuli R, Gupta DK, Maathuis FJM (2007) Arsenic hazards: strategies for tolerance and remediation by plants. Trends Biotechnol 25:158–165

Tripathi RD, Mishra S, Srivastava S (2008) Role of aquatic macrophytes in arsenic phytoremediation in wetlands. Proc Natl Inst Sci 78:167–182

Ubando AT, Africa ADM, Maniquiz-Redillas MC, Culaba AB, Chen W-H, Chang J-S (2021) Microalgal biosorption of heavy metals: a comprehensive bibliometric review. J Hazard Mater 402:123431

Vymazal J (2007) Removal of nutrients in various types of constructed wetlands. Sci Total Environ 380:48–65

Walter K, Dodds, Val H, Smith (2016) Nitrogen, phosphorus, and eutrophication in streams. Inland Waters 6(2):155–164

Wang D, Dang Z, Feng H, Wang R (2015a) Distribution of anthropogenic cadmium and arsenic in arable land soils of Hainan, China. Toxicol Environ Chem 97(3-4):402–408

Wang Y, Cheng ZZ, Chen X, Zheng Q, Yang ZM (2015b) CrGNAT gene regulates excess copper accumulation and tolerance in Chlamydomonas reinhardtii. Plant Sci 240:120–129

Wang T, Amee M, Wang G, Xie Y, Hu T, Xu H (2021) FaHSP17.8-CII orchestrates lead tolerance and accumulation in shoots via enhancing antioxidant enzymatic response and PSII activity in tall fescue. Ecotoxicol Environ Saf 28:112568

Wieczorek-Dąbrowska M, Tomza-Marciniak A, Pilarczyk B, Balicka-Ramisz A (2013) Roe and red deer as bioindicators of heavy metals contamination in north-western Poland. Chem Ecol 29(2):100–110

Xu J, Liu J, Hu J (2021) Nitrogen and phosphorus removal in simulated wastewater by two aquatic plants. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-15206-5

Yang FL, Shi Y, Li B, Wang MT, Liao HY, Chen J, Huang J (2021) Status and prospects of the application of root exudates in the restoration of polluted or desertated soil. Ying Yong Sheng Tai Xue Bao 32(7):2623–2632

Yen H-W, Chen P-W, Hsu C-Y, Lee L (2017) The use of autotrophic Chlorella vulgaris in chromium (VI) reduction under different reduction conditions. J Taiwan Inst Chem Eng 74:1–6

Yin X, Wang L, Duan G, Sun G (2011) Characterization of arsenate transformation and identification of arsenate reductase in a green alga Chlamydomonas reinhardtii. J Environ Sci (China) 23 (7):1186–1193

Yuan Q, Wang P, Wang X, Hu B, Tao L (2021) Phytoremediation of cadmium-contaminated sediment using Hydrilla verticillata and Elodea canadensis harbor two same keystone rhizobacteria Pedosphaeraceae and Parasegetibacter. Chemosphere 286(1):131648

Zhang X, Zhao FJ, Huang Q, Williams PN, Sun GX, Zhu YG (2008) Arsenic uptake and speciation in the rootless duckweed Wolffia globosa. New Phytol 182:421–428

Zhou Y, Han YG, Zhang M, Li DJ, Wang CZ, Zhao Y, Lin P, Yang LL (2016) Purification efficiency of four different ecotypes of wetland plants on eutrophic water body. Ying Yong Sheng Tai Xue Bao 27(10):3353–3360

Dr. Gouri Das, Head, Department of Botany, has been teaching at Balurghat College, under the University of Gour Banga, West Bengal, India, since 2006, and did master's (1989), and doctoral (1996) degrees in Botany, with specialization in microbiology. Gouri has research interest in ethnobotany, microbiology, and plant pathology. She has carried out research on brown blight of tea and its biocontrol, river water microbiology and pollution assessment, health and drinking water-related issues of slum dwellers, diversity of forest macrofungi, and their impact on human health. She published a number of papers in national and international journals and authored articles as book chapters. Gouri was selected as a participant from India by the MEA of the People's Republic of China for the International Training Workshop at Virus-free Seedling Research Institute of Heilongjiang Academy of Agricultural Science, Heilongjiang, China, in 2017. She is a member of the Mycological Society of India and has 15 years of teaching experience. Gouri has been offered a certificate from the University of Leeds, England, UK, on Learning Online: Searching and Researching.

Dr. Ashwani Kumar Alexander von Humboldt Fellow (Germany), Professor *Emeritus*, Department of Botany, University of Rajasthan, Jaipur, India, researched photosynthetic apparatus in vitro and in vivo initially working with Professor Dr. K. H. Neumann at Institute of Plant Nutrition at Justus Liebig University Giessen, Germany, and subsequently with Professor Dr. Sven Schubert on physiology role of enzymes in salinity stress resistance with support from Alexander von Humboldt Fellowship. He served as JSPS visiting Professor, Japan, and guided 39 students for Ph.D. published 220 research papers and 23 books, served as President of the Indian Botanical Society 2019–2020 and currently President Society for Promotion of Plant Science for 2021–2022. Department of Botany and P.G. School of Biotechnology, University of Rajasthan, Jaipur 302004, India. E-mail: ashwanikumar214@gmail.com.