Review article

Bioaccumulation of potentially toxic elements by submerged plants and biofilms: A critical review

Nan Geng[a,b], Yichao Wu[c], Ming Zhang[d], Daniel C.W. Tsang[e], Jörg Rinklebe[f,g], Yinfeng Xia[a,b], Debao Lu[a,b], Lifang Zhu[a], Kumuduni Niroshika Palansooriya[b], Ki-Hyun Kim[h,*], Yong Sik Ok[b,*]

[a] College of Water Conservancy and Environment Engineering, Zhejiang University of Water Resources and Electric Power, Hangzhou, China
[b] Korea Biochar Research Center, O-Jeong Eco-Resilience Institute (OJERI) & Division of Environmental Science and Ecological Engineering, Korea University, Seoul 02841, Republic of Korea
[c] State Key Laboratory of Agricultural Microbiology, College of Resources and Environment, Huazhong Agricultural University, Wuhan, China
[d] Department of Environmental Engineering, China Jiliang University, Hangzhou, China
[e] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China
[f] School of Architecture and Civil Engineering, Institute of Soil Engineering, Waste- and Water Science, Soil- and Groundwater-Management, Pauluskirchstraße 7, 42285 Wuppertal, Germany
[g] Department of Environment, Energy and Geoinformatics, Sejong University, Seoul, Republic of Korea
[h] Department of Civil and Environmental Engineering, Hanyang University, Seoul, Republic of Korea

ARTICLE INFO

ABSTRACT

The accumulation of potentially toxic elements (PTEs) in aquatic ecosystems has become a global concern, as PTEs may exert a wide range of toxicological impacts on aquatic organisms. Submerged plants and the micro-organisms attached to their surfaces, however, have displayed great potential as a means of coping with such pollution. Therefore, it is crucial to understand the transport pathways of PTEs across sediment and organisms as well as their accumulation mechanisms in the presence of submerged plants and their biofilms. The majority of previous studies have demonstrated that submerged plants and their biofilms are indicators of PTE pollution in the aquatic environment, yet relatively little is known about PTE accumulation in epiphytic biofilms. In this review, we describe the transport pathways of PTEs in the aquatic environment in order to offer remarkable insights into bioaccumulation mechanisms in submerged plants and their biofilms. Based on the literature cited in this review, the roles of epiphytic biofilms in bioaccumulation and as an indicator of ecosystem health are discussed.

1. Introduction

Large quantities of potentially toxic elements (PTEs) have been released into aquatic ecosystems with the rapid development of industry and agriculture. Most of the PTEs are potentially lethal and persistent, which can accumulate in the food chain and even exert adverse effects on aquatic organisms (Lu et al., 2015; Luo et al., 2018; Palansooriya, 2019). Currently, PTE pollution in aquatic ecosystems has become a global concern that warrants legislative attention (Islam et al., 2015; Abraham et al., 2017). As such, this problem has stimulated studies that investigate the diverse mechanisms regulating the transport, transformation, and fate of PTEs in water bodies (Dey and Paul, 2018; Meena et al., 2018).

PTEs in rivers and lakes come from domestic, industrial, and agricultural sources as well as atmospheric deposition (Elkady et al., 2015;

Kuriata-Potasznik et al., 2016; Yang, 2018). The aquatic environments ultimately serve as either a direct or indirect sink of various PTEs, which may be labile and vary between the particulate, dissolved, and biological phases (Tang et al., 2015; Zhang et al., 2017a). For example, PTEs can be released from the sediment to the water column when the sediment is disturbed by bioturbation or resuspension. Likewise, PTE levels may vary considerably depending on the conditions of an aquatic ecosystem, which can greatly complicate remediation efforts (Roberts, 2012; Du Laing et al., 2009a; Du Laing et al., 2009b).

There is a diverse range of PTEs in aquatic environments including cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), lead (Pb), nickel (Ni), zinc (Zn), and arsenic (As) (Sánchez-López et al., 2015; Lu et al., 2016; Rinklebe et al., 2016; Song et al., 2017). Although certain PTEs, such as Cu and Zn, are essential for the normal growth and development of many organisms, they can become toxic at excess levels.

Some PTEs, such as Hg, are even toxic at low concentrations that can inhibit the growth of aquatic organisms (Clemens and Ma, 2016; Azzam et al., 2016). It has been reported that Cd is highly bioavailable in aquatic environments, and it readily transfers between sediment and the water column (Nan et al., 2016; Alvarez et al., 2011). Upon absorption by a plant, Pb decreases seed germination and plant growth rates (Wang et al., 2016; Malar et al., 2014; Ahmad et al., 2012). Some PTEs, such as Cr, As, and manganese (Mn), may exist in multiple oxidation states, and express different chemical, toxicological, and epidemiological properties depending on environmental conditions. Although Cr(III) is essential to organisms, its oxidized form, Cr(VI), is highly toxic (Rajapaksha et al., 2018; Shanker et al., 2005).

Compared to physical and chemical remediation methodologies, bioremediation including phytoremediation and microbial remediation, is considered to be a more eco-friendly solution due to its cost-effectiveness, environmental sustainability, and limited impact on functioning, albeit contaminated, ecosystems (Ahmad et al., 2014; Rajapaksha et al., 2016: El-Naggar, 2018; Palansooriya, 2019). Submerged plants including *Elodea canadensis*, *Vallisneria natans* (Lour.) Hara, and *Myriophyllum spicatum* L. have significant tolerance to PTEs. Moreover, some of them, particularly *Lemna minor* and *Ceratophyllum demersum* L., have demonstrated the ability to significantly accumulate PTEs from polluted water (Chen et al., 2015; Török et al., 2015). The surfaces of submerged plants are usually coated with active biofilms, which consist of a complex combination of microorganisms, exudate polymers, absorbed nutrients and metabolites, and particulate materials (D'Acunto et al., 2016). These epiphytic biofilms mature within one week if there are sufficient nutrients (Hiraki et al., 2009). Biofilms have been found to exert effective control on PTE pollution in aquatic systems (Rene et al., 2016). Since they are polyanionic, biofilms can facilitate the biosorption of PTEs (D'Acunto et al., 2016; Bradney, 2019). In addition, some bacteria species can modify PTE sorption by increasing the surface area of the plants or root length, or promoting biofilm formation, which can potentially increase the bioavailability of PTEs (Antoniadis et al., 2017; Palansooriya, 2019).

Despite the increase in research on the accumulation of PTEs, relatively little is known about the mechanisms through which PTEs accumulate in epiphytic biofilms, which is an important system to consider in terms of site remediation. In this review, we offer some insight into the mechanisms controlling the fate and bioavailability of PTEs in aquatic environments and their bioaccumulation in submerged plants and biofilms. Finally, we provide a comprehensive descriptive model of the combined phytoremediation and microbial remediation for PTE pollution in aquatic systems.

2. Transport of PTEs from sediment to water

In aquatic environments, PTEs are commonly released into the water column from sediment pore water and the underlying sediments when the latter is agitated by bioturbation, or through water movement and diffusion (Kalnejais et al., 2010; Roberts, 2012; Wang et al., 2016) (Fig. 1). PTEs associated with resuspended particulates are slowly released into the surrounding water through desorption (Kalnejais et al., 2010). The degree of PTE release during resuspension is strongly influenced by the chemical speciation of PTEs, the concentration gradient of PTEs in the surrounding water, and the physicochemical properties of the sediment including particle size distribution (PSD), sulfide content, organic matter content, and the presence of iron (Fe) and Mn oxides (Du Laing et al., 2009b; Campana et al., 2013). Labile PTEs in the water column may be readily reabsorbed by finer suspended solids depending on their chemical speciation (Pourabadehei and Mulligan, 2016). Clay colloids are considered to be effective adsorbents for a wide range of PTEs. Organic matter, especially humic and fulvic acids, colloids, and synthetic organic substances also serve as reactive sorbents with the capacity to bind large amounts of PTEs (Carolin et al., 2017; Uluturhan et al., 2011). A recent study showed that clay minerals can

retain up to 1.0360 g Pb, 1.0029 g Hg, 0.5621 g Cd, 0.3269 g Zn, 0.3178 g Cu, and 0.1733 g Cr(III) for each 1 $cmol_c$/kg soil (Antoniadis et al., 2017).

Various PTEs can also be released into the water column due to changes in the background solution composition, such as the pH and the dissolved oxygen (DO) content at the water/sediment interface (El-Naggar et al., 2018b). Increases in DO content can increase the redox potential (Eh), under which conditions sulfides are oxidized and thermodynamically unstable PTE-sulfides dissolve; thus, the mobility of the associated PTEs in the sediment increases (De Jonge et al., 2012; Awad et al., 2018). PTEs in the pore water of the surface sediment are released into the water column where they undergo oxygen enrichment (Tang et al., 2016; Beiyuan et al., 2017). However, some PTEs (e.g., Ni, As) adsorb or bond with Fe−Mn oxides that result from higher Eh conditions. In addition, in another example, some PTEs, e.g., Pb, readily precipitate depending on the identity and relative concentrations of inorganic ligands including carbonates and phosphates (Antić-Mladenović et al., 2017; Shaheen et al., 2016; Vikrant, 2018).

3. Bioaccumulation mechanisms of PTEs by submerged plants and biofilms

Submerged plants and epiphytic biofilms have considerable potential to accumulate PTEs from the surrounding environment. The leaves and roots provide physical support for biofilms, which facilitate both facultative anaerobic and anaerobic microorganisms to absorb nutrients (Valipour et al., 2015). In addition to the nutrients required by living organisms, plants and biofilms also accumulate non-essential trace elements, e.g., Cd, Cr, and As (Ali et al., 2013). The epiphytic biofilms adsorb/absorb PTEs and transport them to the leaves. The interactions between rhizosphere-associated biofilms and plants enhance the overall PTE removal efficiency directly by increasing the trace element content in plants and indirectly by promoting the rhizome length and rhizome biomass (Carolin et al., 2017; Srivastava et al., 2015; Rajkumar et al., 2012). The physicochemical changes (e.g., the decomposition of nutrients, the increase in Eh) caused by the rhizosphere microbiome can alter PTE partitioning in the sediment to solubilize them and render them bioavailable (Mitch, 2002; Gupta et al., 2014). The accumulation of PTEs generally consists of fast, reversible PTE-binding (adsorption) followed by slow, irreversible ion-sequestration (absorption) (Keskinkan et al., 2003).

3.1. Submerged plants

Submerged plants have very thin cuticles through which PTEs in the surrounding water can readily pass (Prasad, 2007). Borisova et al. (2016) found that transfer from the water column across the cell membrane of leaves occurs in ascending order of $Ni^{2+} < Cu^{2+} < Zn^{2+} < Fe^{3+} < Mn^{2+}$, as the concentration of Ni in plants was usually much higher than that in the water in the study area. It also relates to the physiological roles of these elements in the metabolism of a plant. The absorption of PTEs in plants begins with entry into plants via plasma membrane transporters (Fig. 2). For example, various ZRT/IRT-like protein (ZIP) family transporters participate in Zn, Cd, and Ni uptake (Mizuno et al., 2005). In hyperaccumulators, the expression levels of ZIP transporters are not regulated by PTE availability. This property explains the extraordinary PTE uptake capability of hyperaccumulators (Assunção et al., 2001). PTEs and essential nutrients are chemically similar. For example, arsenate and selenite are chemically analogous to phosphate and sulphate, respectively. Therefore, the former can be readily absorbed (Rizwan et al., 2018). Studies have shown that As enters root cells via phosphate transporters, whereas sulfate transporters exhibit a high affinity for selenium (Se) (Meharg and Hartley-Whitaker, 2002; Shibagaki et al., 2002). Non-hyperaccumulators may sequester PTEs in vacuoles to prevent their translocation to the shoot following adsorption by cells
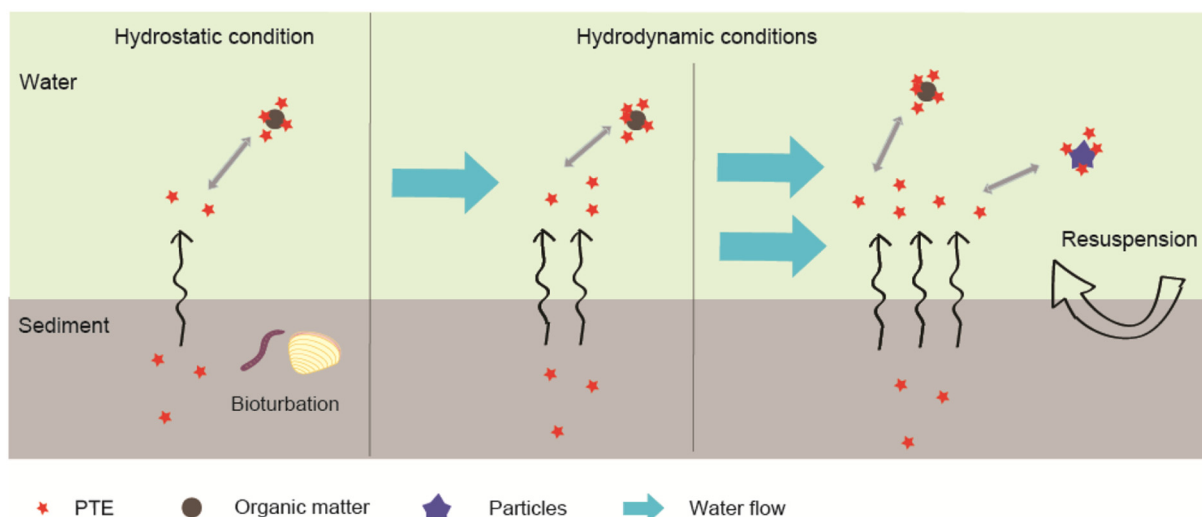
Fig. 1. Transport and transformation of PTEs in an aquatic environment under hydrostatic and hydrodynamic conditions.

(Rascio and Navari-Izzo, 2011; Rizwan, 2017). In contrast, hyper-accumulators have lower PTE sequestration rates in their roots and more efficient root-to-shoot PTE translocation than non-hyper-accumulators (Fig. 2).

To survive in metalliferous environments, aquatic plants have evolved various protective mechanisms against PTE cytotoxicity including access control, rapid translocation, efficient accumulation, and detoxification. Aqueous PTEs bind to cell walls, otherwise they are chelated by root exudates (e.g., macromolecular organic matter) (Salt et al., 2000; Ali et al., 2013). They are hindered from entering root cells in both of these cases. Hyperaccumulating plant species actively absorb PTEs from ambient environments. PTE concentrations in hyper-accumulators can be five orders of magnitude higher than those in the water column around them (Albers and Camardese, 1993; Usman et al., 2012). The bioconcentration factor (BCF) is used to indicate the capacity of species to accumulate elements from soil or water (Ladislas et al., 2012). However, the BCF may vary considerably among different PTE species within each aquatic plant genus. The study by Borisova et al. (2016) showed that the average BCF values of Cu^{2+}, Ni^{2+}, Zn^{2+}, Mn^{2+}, and Fe^{3+} in the leaves of *Ceratophyllum demersum* L. were 4901, 4592, 20,400, 95,804, and 9605, respectively.

Detoxification and sequestration determine the extent to which shoots can accumulate PTEs without phytotoxicity. Several proteins participate in PTE efflux processes, and play key roles in PTE homeostasis and tolerance including heavy metal-transporting ATPases (HMAs), natural resistance-associated macrophage proteins (Nramps), cation diffusion facilitator (CDF) family proteins, and multidrug and toxin efflux proteins (Clemens and Ma, 2016). The main detoxification mechanism includes PTE complexation and sequestration into inactive compartments, such as the epidermis, the vacuole, and the cuticle (Fig. 2). This process relies heavily on transporters like CDF to exclude PTEs from the cytoplasm. In addition to these transporters, recent studies found vesicular trafficking was also involved in metal deposition in the vacuole. PTE-enriched vesicles have been identified in plants, and may play a role in vacuolar sequestration (Dräxl et al., 2013). Moreover, the increased vacuolar volume by vesicle fusion may induce an electrochemical driving force to facilitate PTE transport (Sharma et al., 2016; Fan et al., 2011). PTE-binding ligands chelate PTEs and prevent free element cations from entering the cytoplasm. As PTEs can also induce oxidative stress, antioxidant enzymes are over-expressed in plants to maintain redox homeostasis (Verma and Dubey, 2003). When the PTE concentrations in plants are higher than the toxic threshold values, the plants may die and degrade over time. Then, the

PTEs will settle in the sediment or be released into the water column.

3.2. Biofilms

Various bacteria in aquatic environments can directly interact with certain elements and/or change their physicochemical properties (Table 1). Even the cell-walls of bacteria may retain PTEs through phosphoryl ligands, carboxyl groups, and other binding sites (Beveridge and Murray, 1980; Boyanov et al., 2003). Worms et al. (2006) described the physicochemical processes involved in PTE uptake by aquatic microorganisms. These elements first diffuse to the surface of the organism, then react with sites on their biological membranes (adsorption/desorption), where PTEs can be transported biologically (internalization). The processes of adsorption and uptake are quite complicated, and easily affected by various factors, such as electron acceptors, concentrations of PTEs, and Eh (Ayangbenro and Babalola, 2017). Bacteria exist primarily in association with biofilms, which consist mainly of closely associated microbial cells and extracellular polymeric substances (EPSs) (D'Acunto et al., 2016; Nocelli et al., 2016). While they are embedded in biofilms, sessile microbes have several advantages over their planktonic counterparts, including enhanced antimicrobial resistance, protection from predation, and intensive microbial interaction (Flemming et al., 2016).

Root exudates provide nutrients to sustain bacterial growth and the rhizosphere is a central point of biofilm formation Zhang et al., 2017b (). In general, rhizosphere biofilms are initiated by bacterial chemotaxis towards root exudates (Zhang et al., 2015). Bacterial migration rates towards the roots are highly correlated with the bacterial species and the type of secreted attractants. Once attached to the root surface, these bacteria gradually form microcolonies and develop a mature biofilm architecture. A recent study found that the formation of a rhizosphere microbial community is not a random process. Rather, it is specific to the functional and taxonomic traits of the bacteria (Yan et al., 2017). The members of rhizosphere biofilm communities have stronger interactions with PTEs than those observed in the bulk environment (Danhorn and Fuqua, 2007).

Potentially toxic elements can accumulate in biofilms via biosorption, bioprecipitation, intracellular accumulation, and redox immobilization (Edwards and Kjellerup, 2013). The polysaccharides, proteins, and DNA in the biofilm matrices serve as sinks for PTE biosorption. Various functional groups in biofilm matrices including carboxyls, hydroxyls, and phosphates contribute to their overall polyanionic charge and interact with positively charged PTE ions (Philippis
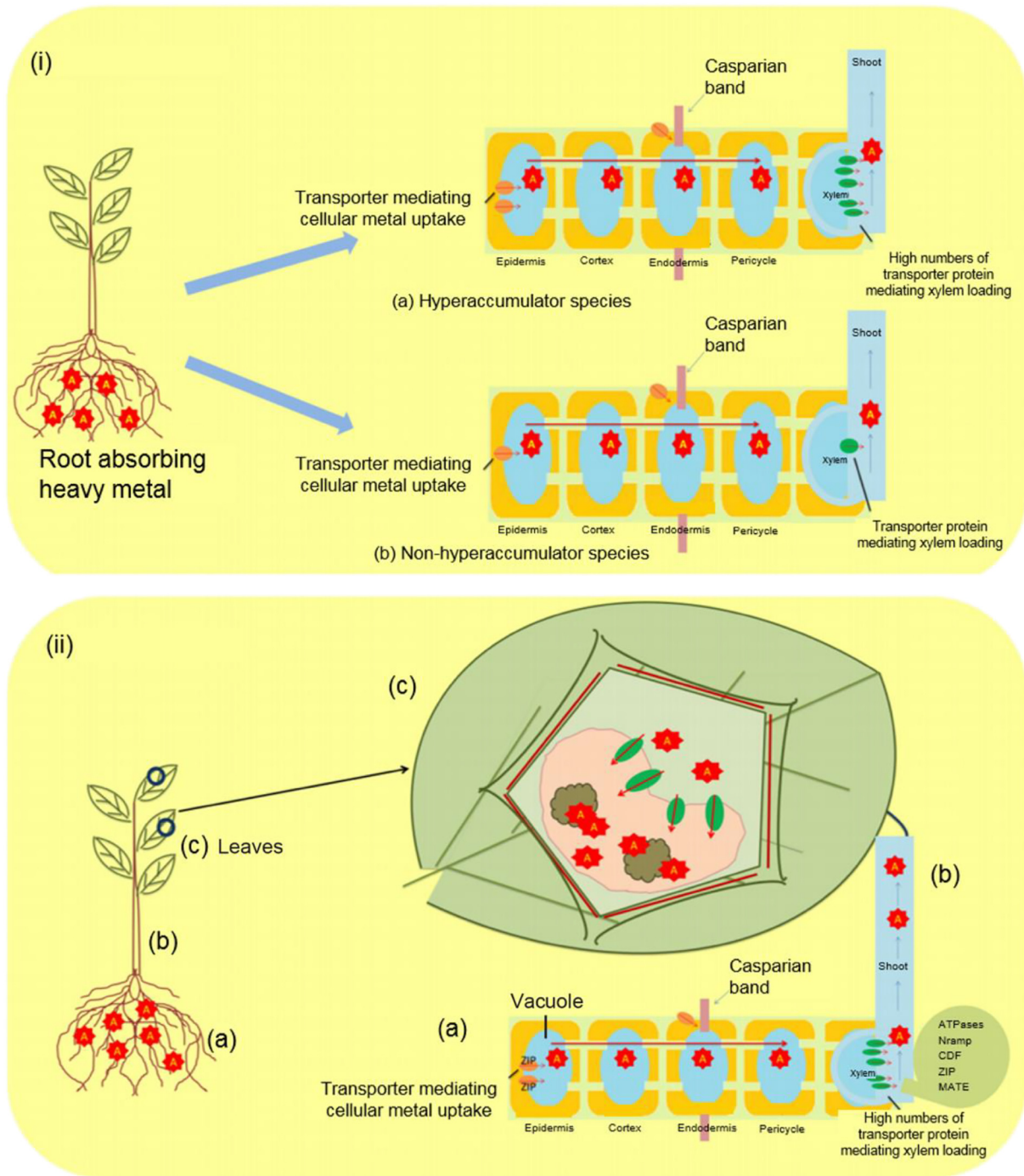
Fig. 2. Schematic diagram showing differential PTE accumulation mechanisms in hyperaccumulating (a) and non-hyperaccumulating (b) plants. (i) PTE uptake and translocation in normal plants. (ii) PTE translocation and detoxification in hyperaccumulators. A, PTE; Nramp, natural resistance-associated macrophage protein; CDF, cation diffusion facilitator family proteins; ZIP, zinc-iron permease family proteins; MATE, multidrug and toxin efflux proteins, multidrug and toxin efflux family proteins (Singh et al., 2016).

et al., 2011). Biofilms also create oxygen-limiting microenvironments for the bioreduction of redox sensitive PTEs. Selenium (Se), Cr, technetium (Tc), and U may be reduced to form less soluble species that are immobilized in biofilm matrices (Ahmed et al., 2012; Ng et al., 2013; Ding et al., 2014; Zheng et al., 2014). In a continuous-flow biofilm reactor, 56% of Cr(VI) was found to be immobilized in *Shewanella* biofilm after 56-h exposure (Ding et al., 2014). Oxidation can also occur inside biofilms and generate PTE oxides. For example, the nitrate-reducing *Acidovorax* sp. can readily oxidize Fe (II) to form insoluble magnetite in 2 days (Pantke et al., 2012).

Rhizosphere-associated biofilms can also promote PTE accumulation in plants. Rhizosphere biofilms secrete micronutrients and metabolites, e.g., antibiotics and phytohormones, that promote plant growth (Ramey et al., 2004; Muehe et al., 2015). For example, some *Bacillus subtilis* strains are capable of producing a broad spectrum of antibiotics that suppress root infections (Bais et al., 2004). Enhanced plant growth accelerates PTE accumulation in them. Biofilms also mobilize PTEs in the ambient environment. Siderophores and citrates secreted by bacteria can solubilize unavailable PTEs and facilitate their uptake (Gadd, 2000; Mishra et al., 2017). In natural environments, the contents of

Table 1
Species and functions of various bacterial genera that interact with PTEs in aquatic environments.

Species	Reported function of the bacteria	References
Micrococcus; Aspergillus	Effective for the removal of Cr (VI) and Ni (II)	(Congeevaram et al., 2007)
Bacillus; Arthrobacter	Effective for the removal of Cr	(Wang and Xiao, 1995; Dey and Paul, 2018)
Bacillus firmus	Effective for removal of Pb, Cu, and Zn	(Salehizadeh and Shojaosadati, 2003)
Bacillus cereus	Effective for removal of Pb and Cu ions	(Pan et al., 2007)
Escherichia coli	Effective for removal of Cr (VI), Cd (II), Fe (III), and Ni (II)	(Quintelas et al., 2009)
Pseudomonas aeruginosa	Effective for removal of Pb and Ni	(Gabr et al., 2008)
Geobacter	Reduce uranium (U) from a soluble state (U^{6+}) to an insoluble state (U^{4+})	(Lovley et al., 1991)
Klebsiella pneumoniae M426	Reduce Hg (II) to Hg (0) and Hg precipitation as insoluble Hg due to volatile thiol (H_2S)	(Sone et al., 2013)
Pseudomonas tolaasii RP23*; Pseudomonas fluorescens* RS9	Siderophore-producing bacteria (SPB) potentially support PTE uptake and reduce stress symptoms in plants	(Dell' Amico et al., 2005; Rajkumar et al., 2010)
Desulfobacterium autotrophicum	Sulfate-reducing bacteria (SRB) promote anaerobic biodegradation of complex substrates, such as petroleum hydrocarbons in sediments	(Cabral et al., 2016)
Thiobacillus	Sulfur-oxidizing bacteria (SOB) oxidize elemental sulfur to plant-available sulfate; decompose organic matter, and oxidize sulfide	(Vidyalakshmi et al., 2009).
Gallionella, Sideroxydans; Ferrovum myxofaciens; Albidiferax ferrireducens; Geobacter	Iron-oxidizing bacteria (FeOB) oxidize iron and retain metal in a high-metal environment	(Fabisch et al., 2016)

solubilized elements are determined by the competition of various organic chelators (Boiteau et al., 2018).

3.3. Factors affecting PTE accumulation efficiency

PTE uptake is significantly affected by chemical speciation and mobility in aqueous systems with the pH and Eh of a system playing a major role in determining PTE bioavailability Ahmad, 2017. Organic matter in the environment can also play an important role in controlling bioavailability through chelation reactions that increase PTE solubility (Du Laing et al., 2009a). The uptake rates of PTEs, such as Cr, Cu, and Mn, are negatively correlated with pH, but positively correlated with organic matter content (Zeng et al., 2011; Frohne et al., 2014; Frohne et al., 2015). The relative uptake efficiency of individual elements is also influenced by the presence of other PTEs in the system. Membrane transporters have preferential selectivity for various elements. For example, the Cd transfer rate by ZIP transporters is affected by the presence of Zn ions (Zhao et al., 2002). The plant growth status also affects PTE accumulation efficiency (Yu et al., 2015). When plant growth is impeded, its overall PTE removal rate is also limited. Therefore, plant growth promotion is a common strategy to enhance phytoremediation performance (Rajkumar et al., 2012; Ullah et al., 2015).

4. PTE pollution bioindicators

The PTE concentration in exposed organisms, which is accumulated from aquatic environments, not only defines PTE pollution levels, but also represents a moving time-averaged value for the relative biological availability of PTEs within a system area. Both submerged plants and their biofilms are suitable bioindicators of PTE pollution (Ladislas et al., 2012). Certain physiological responses (e.g., metallothionein production) or cell ultrastructure injury in organisms can also be used to assess PTE exposure and toxicity of the environment (Geng et al., 2015; Adrees et al., 2015).

4.1. Submerged plants as indicators of PTE pollution

Aquatic plants absorb PTEs and nutrients directly from both the sediment and the overlying water column. They can generally tolerate internal PTE concentrations that are several times greater than those found in the surrounding water (Materazzi et al., 2012; Shahid et al., 2017). The roots and the aboveground tissues of submerged plants are suitable for sampling and quantifying PTE content as an indicator of exposure history (Kurilenko and Osmolovskaya, 2007). Submerged plants are more reliable indicators of pollution than either emergent or floating plants, because their tissues remain submerged in the water column and underlying sediment at a fixed location (Rezania et al., 2016). Therefore, submerged plants are widely used as indicators in PTE toxicological monitoring programs for aquatic ecosystems with promising results. For example, Rai et al. (1996) found that concentrations of PTE in submerged plant tissues increased with PTE exposure in aquatic environments. Then, some submerged plants were used as bioindicators of river pollution, because there was a positive relationship between the PTE concentration in plants and that in the sediment and water (Harguinteguy et al., 2014; Harguinteguy et al., 2016). Fawzy et al. (2012) suggested that several species should be investigated together in order to identify the best bioindicator in their study with *Ceratophyllum demersum* L., *Echinochloa pyramidalis (Lam.) Hitchc. & Chase., Eichhornia crassipes (Mart.) Solms-Laub, Myriophyllum spicatum* L., *Phragmites australis (Cav.) Trin. ex Steud,* and *Typha dom*ing*ensis (Pers.) Poir. ex Steud*.

However, according to Gao et al. (2016), correlations between sedimentary and aquatic plant tissue PTE levels are difficult to establish. Xing et al. (2013) and Wang et al. (2014) found no significant correlations between submerged plants and their surrounding environments in the middle and lower reaches of the Yangtze River and Dianchi Lake in China. Plant growth rates may offset the accumulative effects and lessen the relationships between the PTE concentration in plant tissues and that in the sediment and water column due to the interactions occurring among various PTEs in plants and other confounding factors (Zhou et al., 2008). Furthermore, PTE accumulation may reduce plant growth rates and hinder further accumulation (Chibuike and Obiora, 2014). PTE biosorption is another factor that affects this relationship; it is fast and equilibrates within 20 min (Keskinkan et al., 2003). Nan et al. (2016) suggested that, when using aquatic organisms to assess PTE pollution, adsorbed elements should be removed to avoid the environmental influence, e.g., the hydrodynamic conditions, which could increase the content of adsorbed elements in aquatic organisms. In addition, there were strong interactions between accumulation and environmental variables, such as temperature, nutrients, pH, and oxidation state (Cattaneo et al., 1995; Rezania et al., 2016). All of these interactions should be considered in the planning and implementation of using plants as PTE pollution bioindicators.

4.2. Biofilms as indicators of PTE pollution

Microorganisms in biofilm are sensitive to the physiochemical conditions of their ambient environment. Bacterial composition, structure, and function may rapidly shift to resist or adapt to environmental contamination levels due to their short life cycles and genetic

Table 2
Indexes of biofilms and their indicative roles for PTE pollution and water health.

PTEs	Indexes of biofilms	Indicative roles	References
Cu, Cd, Pb	PTE concentrations in biofilms	PTEs pollution in water	(Fuchs et al., 1996)
Cu, Zn			(Mages et al., 2004)
As, Cd, Cu, Pb, Zn			(Rhea et al., 2006)
Cd			(Duong et al., 2008)
Zn, Cu, Pb	Biofilm bacterial populations or community composition	Water ecological health or PTEs contamination	(Ancion et al., 2010)
As, Cd, Cu, Zn			(Bouskill et al., 2010)
Zn, Cu, Pb	Bacterial and ciliate protozoa communities	Detrimental effects of PTEs on freshwater ecosystems	(Ancion et al., 2013)
Zn	Antioxidant enzyme activities (AEA) and PTE accumulation of biofilm	PTEs pollution in water	(Bonet et al., 2014)
Zn, Cu, Pb	Microbial DNA	Freshwater health	(Ancion et al., 2014)

variation (Yin et al., 2015; Barnhart et al., 2016; Moche et al., 2015). Therefore, biofilms have been successfully used as rapid indicators of environmental stress, such as PTE exposure (Table 2). For example, Mages et al. (2004) found that the concentrations of PTE in biofilm increased when the water was polluted. Duong et al. (2008) and Bonet et al. (2014) believe that the concentrations of PTE in biofilm are easier to detect than those in water, which also provide an early and sensitive indicator of metal pollution.

Despite the complexity of aquatic ecosystems, PTE concentrations in biofilms can indicate PTE pollution in the water column or the underlying sediment. In addition, biofilms are believed to accurately reflect the effects of PTEs on freshwater communities, as biofilms can immobilize the dissolved PTEs from water or sediment, and incorporate them into the food chain (Bhaskar and Bhosle, 2006). When PTEs accumulate in biofilm, chemical, physical, and physiological changes may occur to protect the resident cells (Harrison et al., 2007; Kang and Kirienko, 2018). However, some studies have not observed any correlation between the concentration of PTEs and the resistance of the bacterial community (Dean-Ross and Mills, 1989; Tian et al., 2015), which was attributed to the high pH of the river water that limited PTE toxicity. Furthermore, the redox status, dissolved organic carbon levels, the presence of other toxins, and a variety of other factors can affect the bioaccumulation of PTEs and the community composition of biofilms.

5. Conclusions

Submerged plants and epiphytic biofilms play an important role in aquatic systems because they help to mitigate PTE pollution. However, the extent of PTE transfer between biofilms and submerged plants remains unclear. In addition, the relationships between PTEs and different submerged plant species can vary considerably, so it is difficult for plants to be eligible PTE indicators. Therefore, further research is required to better understand the complex relationships between PTEs, epiphytic biofilms, and submerged plants in the aquatic environment, and their impact on PTE accumulation. Such studies should be comprehensive and accurate, and mass transfer, charge balance, and kinetics, as well as element cation binding reactions, should be considered. We also believe that epiphytic biofilms can serve as potential PTE indicators in aquatic environments. Therefore, the impact of PTEs on the diversity and structure of epiphytic biofilm communities in aquatic environments merits further investigation.

In summary, we offered a concise analysis of PTE transport processes from sediment to the water column, and then to biofilms and submerged plants. We summarized PTE bioaccumulation mechanisms in submerged plants and biofilms and discussed potential PTE indicators. To promote PTE bioremediation and application of bioindicators, future studies should be focused on the mechanistic elucidation of PTE accumulation and transport from biofilms to submerged plants in aquatic ecosystems.

Declaration of Competing Interest

None of the authors have any competing interests.

References

Abraham, J.S., Sripoorna, S., Choudhary, A., Toteja, R., Gupta, R., Makhija, S., Warren, A., 2017. Assessment of heavy metal toxicity in four species of freshwater ciliates (Spirotrichea:Ciliophora) from Delhi, India. Curr. Sci. 113, 2141. https://doi.org/10.18520/cs/v113/i11/2141-2150.

Adrees, M., Ali, S., Rizwan, M., Zia-ur-Rehman, M., Ibrahim, M., Abbas, F., Farid, M., Qayyum, M.F., Irshad, M.K., 2015. Mechanisms of silicon-mediated alleviation of heavy metal toxicity in plants: a review. Ecotoxicol. Environ. Saf. 119, 186–197. https://doi.org/10.1016/j.ecoenv.2015.05.011.

Ahmad, M., Soo Lee, S., Yang, J.E., Ro, H.-M., Han Lee, Y., Sik Ok, Y., 2012. Effects of soil dilution and amendments (mussel shell, cow bone, and biochar) on Pb availability and phytotoxicity in military shooting range soil. Ecotoxicol. Environ. Saf. 79, 225–231. https://doi.org/10.1016/j.ecoenv.2012.01.003.

Ahmad, M., Sang Soo Lee, Sung Eun Lee, Mohammad I. Al-Wabel, Daniel CW Tsang, and Yong Sik Ok, 2017. Biochar-induced changes in soil properties affected immobilization/mobilization of metals/metalloids in contaminated soils. Journal of soils and sediments 17 (3), 717–730. https://doi.org/10.1007/s11368-015-1339-4.

Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S., Ok, Y.S., 2014. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99, 19–33. https://doi.org/10.1016/j.chemosphere.2013.10.071.

Ahmed, B., Cao, B., McLean, J.S., Ica, T., Dohnalkova, A., Istanbullu, O., Paksoy, A., Fredrickson, J.K., Beyenal, H., 2012. Fe (III) reduction and U (VI) immobilization by Paenibacillus sp. 300A isolated from Hanford 300A subsurface sediments. Appl. Environ. Microbiol. 78 (22), 8001–8009 (AEM–01844).

Albers, P.H., Camardese, M.B., 1993. Effects of acidification on metal accumulation by aquatic plants and invertebrates. 1. Constructed wetlands. Environ. Toxicol. Chem. 12, 959–967. https://doi.org/10.1002/etc.5620120602.

Ali, H., Khan, E., Sajad, M.A., 2013. Phytoremediation of heavy metals—concepts and applications. Chemosphere 91, 869–881. https://doi.org/10.1016/j.chemosphere.2013.01.075.

Alvarez, M.B., Domini, C.E., Garrido, M., Lista, A.G., Fernández-Band, B.S., 2011. Single-step chemical extraction procedures and chemometrics for assessment of heavy metal behaviour in sediment samples from the Bahía Blanca estuary, Argentina. J. Soils Sediments 11, 657–666. https://doi.org/10.1007/s11368-011-0350-7.

Ancion, P.-Y., Lear, G., Lewis, G.D., 2010. Three common metal contaminants of urban runoff (Zn, Cu & Pb) accumulate in freshwater biofilm and modify embedded bacterial communities. Environ. Pollut. 158, 2738–2745. https://doi.org/10.1016/j.envpol.2010.04.013.

Ancion, P.-Y., Lear, G., Dopheide, A., Lewis, G.D., 2013. Metal concentrations in stream biofilm and sediments and their potential to explain biofilm microbial community structure. Environ. Pollut. 173, 117–124. https://doi.org/10.1016/j.envpol.2012.10.012.

Ancion, P.-Y., Lear, G., Neale, M., Roberts, K., Lewis, G.D., 2014. Using biofilm as a novel approach to assess stormwater treatment efficacy. Water Res. 49, 406–415. https://doi.org/10.1016/j.watres.2013.10.023.

Antić-Mladenović, S., Frohne, T., Kresović, M., Stärk, H.-J., Tomić, Z., Ličina, V., Rinklebe, J., 2017. Biogeochemistry of Ni and Pb in a periodically flooded arable soil: fractionation and redox-induced (im)mobilization. J. Environ. Manag. 186, 141–150. https://doi.org/10.1016/j.jenvman.2016.06.005. Biogeochemistry of trace elements in the environment.

Antoniadis, V., Levizou, E., Shaheen, S.M., Ok, Y.S., Sebastian, A., Baum, C., Prasad, M.N.V., Wenzel, W.W., Rinklebe, J., 2017. Trace elements in the soil-plant interface: phytoavailability, translocation, and phytoremediation–a review. Earth-Sci. Rev. 171, 621–645. https://doi.org/10.1016/j.earscirev.2017.06.005.

Assunção, A.G.L., Martins, P.D.C., Folter, S.D., Vooijs, R., Schat, H., Aarts, M.G.M., 2001. Elevated expression of metal transporter genes in three accessions of the metal hyperaccumulator Thlaspi caerulescens. Plant Cell Environ. 24, 217–226. https://doi.org/10.1111/j.1365-3040.2001.00666.x.

Awad, Y.M., Ok, Y.S., Abrigata, J., Beiyuan, J., Beckers, F., Tsang, D.C.W., Rinklebe, J., 2018. Pine sawdust biomass and biochars at different pyrolysis temperatures change soil redox processes. Sci. Total Environ. 625, 147–154. https://doi.org/10.1016/j.scitotenv.2017.12.194.

Ayangbenro, A., Babalola, O., 2017. A new strategy for heavy metal polluted environments: a review of microbial biosorbents. Int. J. Environ. Res. Public Health 14, 94. https://doi.org/10.3390/ijerph14010094.

Azzam, A.M., El-Wakeel, S.T., Mostafa, B.B., El-Shahat, M.F., 2016. Removal of Pb, Cd, Cu and Ni from aqueous solution using nano scale zero valent iron particles. J. Environ. Chem. Eng. 4, 2196–2206. https://doi.org/10.1016/j.jece.2016.03.048.

Bais, H.P., Fall, R., Vivanco, J.M., 2004. Biocontrol of *Bacillus subtilis* against infection of Arabidopsis roots by pseudomonas syringae is facilitated by biofilm formation and surfactin production. Plant Physiol. 134, 307–319.

Barnhart, E.P., Hornberger, M., Hwang, C., Dror, I., Bouskill, N., Short, T., Cain, D., Fields, M.W., 2016. Hyporheic microbial biofilms as indicators of heavy and rare earth metals in the Clark Fork Basin, Montana. AGU Fall Meet. Abstr. 53, B53K–06.

Beiyuan, J., Awad, Y.M., Beckers, F., Tsang, D.C.W., Ok, Y.S., Rinklebe, J., 2017. Mobility and phytoavailability of As and Pb in a contaminated soil using pine sawdust biochar under systematic change of redox conditions. Chemosphere 178, 110–118. https://doi.org/10.1016/j.chemosphere.2017.03.022.

Beveridge, T.J., Murray, R.G.E., 1980. Sites of metal deposition in the cell wall of *Bacillus subtilis*. J. Bacteriol. 141, 876–887. https://doi.org/10.1111/j.1574-6968.2001.tb10678.x.

Bhaskar, P.V., Bhosle, N.B., 2006. Bacterial extracellular polymeric substance (EPS): a carrier of heavy metals in the marine food-chain. Environ. Int., Marine Pollution and Ecotoxicology 32, 191–198. https://doi.org/10.1016/j.envint.2005.08.010.

Boiteau, R.M., Shaw, J.B., Pasa-Tolic, L., Koppenaal, D.W., Jansson, J.K., 2018. Micronutrient metal speciation is controlled by competitive organic chelation in grassland soils. Soil Biol. Biochem. 120, 283–291.

Bonet, B., Corcoll, N., Tlili, A., Morin, S., Guasch, H., 2014. Antioxidant enzyme activities in biofilms as biomarker of Zn pollution in a natural system: an active bio-monitoring study. Ecotoxicol. Environ. Saf. 103, 82–90. https://doi.org/10.1016/j.ecoenv.2013.11.007.

Borisova, G., Chukina, N., Maleva, M., Kumar, A., Prasad, M.N.V., 2016. Thiols as biomarkers of heavy metal tolerance in the aquatic macrophytes of Middle Urals, Russia. Int. J. Phytoremediation 18, 1037–1045. https://doi.org/10.1080/15226514.2016.1183572.

Bouskill, N.J., Barker-Finkel, J., Galloway, T.S., Handy, R.D., Ford, T.E., 2010. Temporal bacterial diversity associated with metal-contaminated river sediments. Ecotoxicology 19, 317–328. https://doi.org/10.1007/s10646-009-0414-2.

Boyanov, M.I., Kelly, S.D., Kemner, K.M., Bunker, B.A., Fein, J.B., 2003. Adsorption of cadmium *Bacillus subtilis* bacterial cell wall: a pH-dependent X-ray adsorption fine structure spectroscopy study. Geochim. Cosmochim. Ac. 67, 3299–3311. https://doi.org/10.1016/S0016-7037(02)01343-1.

Bradney, L., Wijesekara, H., Palansooriya, K.N., Obadamudalige, N., Bolan, N.S., Ok, Y.S., Rinklebe, J., Kim, K.H. and Kirkham, M.B.,, 2019. Particulate plastics as a vector for toxic trace-element uptake by aquatic and terrestrial organisms and human health risk. Environment International 131, 104937. https://doi.org/10.1016/j.envint.2019.104937.

Cabral, L., Júnior, G.V.L., Pereira de Sousa, S.T., Dias, A.C.F., Lira Cadete, L., Andreote, F.D., Hess, M., de Oliveira, V.M., 2016. Anthropogenic impact on mangrove sediments triggers differential responses in the heavy metals and antibiotic resistomes of microbial communities. Environ. Pollut. 216, 460–469. https://doi.org/10.1016/j.envpol.2016.05.078.

Campana, O., Blasco, J., Simpson, S.L., 2013. Demonstrating the appropriateness of developing sediment quality guidelines based on sediment geochemical properties. Environ. Sci. Technol. 47, 7483–7489. https://doi.org/10.1021/es4009272.

Carolin, C.F., Kumar, P.S., Saravanan, A., Joshiba, G.J., Naushad, M., 2017. Efficient techniques for the removal of toxic heavy metals from aquatic environment: a review. J. Environ. Chem. Eng. 5, 2782–2799. https://doi.org/10.1016/j.jece.2017.05.029.

Cattaneo, A., Méthot, G., Pinel-Alloul, B., Niyonsenga, T., Lapierre, L., 1995. Epiphyte size and taxonomy as biological indicators of ecological and toxicological factors in Lake Saint-François (Québec). Environ. Pollut. 87, 357–372. https://doi.org/10.1016/0269-7491(94)P4167-M.

Chen, G., Liu, X., Brookes, P.C., Xu, J., 2015. Opportunities for phytoremediation and bioindication of arsenic contaminated water using a submerged aquatic plant:Vallisneria natans (lour.) Hara. Int. J. Phytoremediation 17, 249–255. https://doi.org/10.1080/15226514.2014.883496.

Chibuike, G.U., Obiora, S.C., 2014. Heavy metal polluted soils: effect on plants and bioremediation methods [WWW document]. Appl. Environ. Soil Sci. https://doi.org/10.1155/2014/752708.

Clemens, S., Ma, J.F., 2016. Toxic heavy metal and metalloid accumulation in crop plants and foods. Annu. Rev. Plant Biol. 67, 489–512. https://doi.org/10.1146/annurev-arplant-043015-112301.

Congeevaram, S., Dhanarani, S., Park, J., Dexilin, M., Thamaraiselvi, K., 2007. Biosorption of chromium and nickel by heavy metal resistant fungal and bacterial isolates. J. Hazard. Mater. 146, 270–277. https://doi.org/10.1016/j.jhazmat.2006.12.017.

D'Acunto, B., Esposito, G., Frunzo, L., Mattei, M.R., Pirozzi, F., 2016. Mathematical modeling of heavy metal biosorption in multispecies biofilms. J. Environ. Eng. 142, C4015020. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001052.

Danhorn, T., Fuqua, C., 2007. Biofilm formation by plant-associated bacteria. Annu. Rev. Microbiol. 61, 401–422. https://doi.org/10.1146/annurev.micro.61.080706.093316.

De Jonge, M., Teuchies, J., Meire, P., Blust, R., Bervoets, L., 2012. The impact of increased oxygen conditions on metal-contaminated sediments part I: effects on redox status, sediment geochemistry and metal bioavailability. Water Res. 46, 2205–2214. https://doi.org/10.1016/j.watres.2012.01.052.

Dean-Ross, D., Mills, A.L., 1989. Bacterial community structure and function along a heavy metal gradient. Appl. Environ. Microbiol. 55, 2002–2009.

Dell' Amico, E., Cavalca, L., Andreoni, V., 2005. Analysis of rhizobacterial communities in perennial Graminaceae from polluted water meadow soil, and screening of metal-resistant, potentially plant growth-promoting bacteria. FEMS Microbiol. Ecol. 52, 153–162. https://doi.org/10.1016/j.femsec.2004.11.005.

Dey, S., Paul, A.K., 2018. Influence of metal ions on biofilm formation by Arthrobacter sp. SUK 1205 and evaluation of their Cr(VI) removal efficacy. Int. Biodeterior. Biodegrad. 132, 122–131. https://doi.org/10.1016/j.ibiod.2018.02.015.

Ding, Y., Peng, N., Du, Y., Ji, L., Cao, B., 2014. Disruption of putrescine biosynthesis in Shewanella oneidensis enhances biofilm cohesiveness and performance in Cr (VI) immobilization. Appl. Environ. Microbiol. 80, 1498–1506.

Dräxl, S., Müller, J., Li, W.B., Michalke, B., Scherb, H., Hense, B.A., Tschiersch, J., Kanter, U., Schäffner, A.R., 2013. Caesium accumulation in yeast and plants is selectively repressed by loss of the SNARE Sec22p/SEC22. Nat. Commun. 4, 2092.

Du Laing, G., Meers, E., Dewispelaere, M., Vandecasteele, B., Rinklebe, J., Tack, F.M.G., Verloo, M.G., 2009a. Heavy metal mobility in intertidal sediments of the Scheldt estuary: field monitoring. Sci. Total Environ. 407, 2919–2930. https://doi.org/10.1016/j.scitotenv.2008.12.024.

Du Laing, G., Rinklebe, J., Vandecasteele, B., Meers, E., Tack, F.M.G., 2009b. Trace metal behaviour in estuarine and riverine floodplain soils and sediments: a review. Sci. Total Environ. 407, 3972–3985. https://doi.org/10.1016/j.scitotenv.2008.07.025.

Duong, T.T., Morin, S., Herlory, O., Feurtet-Mazel, A., Coste, M., Boudou, A., 2008. Seasonal effects of cadmium accumulation in periphytic diatom communities of freshwater biofilms. Aquat. Toxicol. 90, 19–28. https://doi.org/10.1016/j.aquatox.2008.07.012.

Edwards, S.J., Kjellerup, B.V., 2013. Applications of biofilms in bioremediation and biotransformation of persistent organic pollutants, pharmaceuticals/personal care products, and heavy metals. Appl. Microbiol. Biotechnol. 97, 9909–9921. https://doi.org/10.1007/s00253-013-5216-z.

Elkady, A.A., Sweet, S.T., Wade, T.L., Klein, A.G., 2015. Distribution and assessment of heavy metals in the aquatic environment of Lake Manzala, Egypt. Ecol. Indic. 58, 445–457.

El-Naggar, A., Lee, S.S., Awad, Y.M., Yang, X., Ryu, C., Rizwan, M., Rinklebe, J., Tsang, D.C. and Ok, Y.S, 2018. Influence of soil properties and feedstocks on biochar potential for carbon mineralization and improvement of infertile soils. Geoderma 332, 100–108. https://doi.org/10.1016/j.geoderma.2018.06.017.

El-Naggar, A., Shaheen, S.M., Ok, Y.S., Rinklebe, J., 2018b. Biochar affects the dissolved and colloidal concentrations of Cd, Cu, Ni, and Zn and their phytoavailability and potential mobility in a mining soil under dynamic redox-conditions. Sci. Total Environ. 624, 1059–1071. https://doi.org/10.1016/j.scitotenv.2017.12.190.

Fabisch, M., Freyer, G., Johnson, C.A., Büchel, G., Akob, D.M., Neu, T.R., Küsel, K., 2016. Dominance of 'Gallionella capsiferriformans' and heavy metal association with Gallionella-like stalks in metal-rich pH 6 mine water discharge. Geobiology 14, 68–90. https://doi.org/10.1111/gbi.12162.

Fan, J.-L., Wei, X.-Z., Wan, L.-C., Zhang, L.-Y., Zhao, X.-Q., Liu, W.-Z., Hao, H.-Q., Zhang, H.-Y., 2011. Disarrangement of actin filaments and Ca2 + gradient by CdCl2 alters cell wall construction in Arabidopsis thaliana root hairs by inhibiting vesicular trafficking. J. Plant Physiol. 168, 1157–1167.

Fawzy, M.A., Badr, N.E., El-Khatib, A., Abo-El-Kassem, A., 2012. Heavy metal biomonitoring and phytoremediation potentialities of aquatic macrophytes in River Nile. Environ. Monit. Assess. 184, 1753–1771. https://doi.org/10.1007/s10661-011-2076-9.

Flemming, H.-C., Wingender, J., Szewzyk, U., Steinberg, P., Rice, S.A., Kjelleberg, S., 2016. Biofilms: an emergent form of bacterial life. Nat. Rev. Microbiol. 14, 563.

Frohne, T., Rinklebe, J., Diaz-Bone, R.A., 2014. Contamination of floodplain soils along the Wupper River, Germany, with As, Co, Cu, Ni, Sb, and Zn and the impact of pre-definite redox variations on the mobility of these elements. Soil Sediment Contam. Int. J. 23, 779–799. https://doi.org/10.1080/15320383.2014.872597.

Frohne, T., Diaz-Bone, R.A., Du Laing, G., Rinklebe, J., 2015. Impact of systematic change of redox potential on the leaching of Ba, Cr, Sr, and V from a riverine soil into water. J. Soils Sediments 15, 623–633. https://doi.org/10.1007/s11368-014-1036-8.

Fuchs, S., Haritopoulou, T., Wilhelmi, M., 1996. Biofilms in freshwater ecosystems and their use as a pollutant monitor. Water Sci. Technol. Lond. 34, 137–140.

Gabr, R.M., Hassan, S.H.A., Shoreit, A.A.M., 2008. Biosorption of lead and nickel by living and non-living cells of Pseudomonas aeruginosa ASU 6a. Int. Biodeterior. Biodegrad. 62, 195–203. https://doi.org/10.1016/j.ibiod.2008.01.008.

Gadd, G.M., 2000. Bioremedial potential of microbial mechanisms of metal mobilization and immobilization. Curr. Opin. Biotechnol. 11, 271–279. https://doi.org/10.1016/S0958-1669(00)00095-1.

Gao, J., Sun, X., Jiang, W., Wei, Y., Guo, J., Liu, Y., Zhang, K., 2016. Heavy metals in

sediments, soils, and aquatic plants from a secondary anabranch of the three gorges reservoir region, China. Environ. Sci. Pollut. Res. 23, 10415–10425. https://doi.org/10.1007/s11356-016-6587-3.

Geng, N., Wang, C., Wang, P., Qi, N., Ren, L., 2015. Cadmium accumulation and metallothionein response in the freshwater bivalve Corbicula fluminea under hydrodynamic conditions. Biol. Trace Elem. Res. 165, 222–232. https://doi.org/10.1007/s12011-015-0266-y.

Gupta, D.K., Chatterjee, S., Datta, S., Veer, V., Walther, C., 2014. Role of phosphate fertilizers in heavy metal uptake and detoxification of toxic metals. Chemosphere 108, 134–144. https://doi.org/10.1016/j.chemosphere.2014.01.030.

Harguinteguy, C.A., Cirelli, A.F., Pignata, M.L., 2014. Heavy metal accumulation in leaves of aquatic plant Stuckenia filiformis and its relationship with sediment and water in the Suquía river (Argentina). Microchem. J. 114, 111–118. https://doi.org/10.1016/j.microc.2013.12.010.

Harguinteguy, C.A., Noelia Cofré, M., Fernández-Cirelli, A., Luisa Pignata, M., 2016. The macrophytes Potamogeton pusillus L. and Myriophyllum aquaticum (Vell.) Verdc. as potential bioindicators of a river contaminated by heavy metals. Microchem. J. 124, 228–234. https://doi.org/10.1016/j.microc.2015.08.014.

Harrison, J.J., Ceri, H., Turner, R.J., 2007. Multimetal resistance and tolerance in microbial biofilms. Nat. Rev. Microbiol. 5, 928–938. https://doi.org/10.1038/nrmicro1774.

Hiraki, A., Tsuchiya, Y., Fukuda, Y., Yamamoyo, T., Kurniawan, A., Morisaki, H., 2009. Analysis of how a biofilm forms on the surface of the aquatic Macrophyte Phragmites australis. Microbes Environ. 24, 265–272. https://doi.org/10.1264/jsme2.ME09122.

Islam, M.S., Ahmed, M.K., Raknuzzaman, M., Habibullah-Al-Mamun, M., Islam, M.K., 2015. Heavy metal pollution in surface water and sediment: a preliminary assessment of an urban river in a developing country. Ecol. Indic. 48, 282–291.

Kalnejais, L.H., Martin, W.R., Bothner, M.H., 2010. The release of dissolved nutrients and metals from coastal sediments due to resuspension. Mar. Chem. 121, 224–235. https://doi.org/10.1016/j.marchem.2010.05.002.

Kang, D., Kirienko, N.V., 2018. Interdependence between iron acquisition and biofilm formation in Pseudomonas aeruginosa. J. Microbiol. 56, 449–457. https://doi.org/10.1007/s12275-018-8114-3.

Keskinkan, O., Goksu, M.Z.L., Yuceer, A., Basibuyuk, M., Forster, C.F., 2003. Heavy metal adsorption characteristics of a submerged aquatic plant (Myriophyllum spicatum). Process Biochem. 39, 179–183. https://doi.org/10.1016/S0032-9592(03)00045-1.

Kuriata-Potasznik, A., Szymczyk, S., Skwierawski, A., Glińska-Lewczuk, K., Cymes, I., 2016. Heavy metal contamination in the surface layer of bottom sediments in a flow-through lake: a case study of Lake Symsar in northern Poland. Water 8, 358. https://doi.org/10.3390/w8080358.

Kurilenko, V.V., Osmolovskaya, N.G., 2007. Bioindication role of higher plants in the diagnostics of aquatic ecosystems: case study of small water bodies in St. Petersburg. Water Resour 34, 718–724. https://doi.org/10.1134/S0097807807060140.

Ladislas, S., El-Mufleh, A., Gérente, C., Chazarenc, F., Andrès, Y., Béchet, B., 2012. Potential of aquatic Macrophytes as bioindicators of heavy metal pollution in urban stormwater runoff. Water Air Soil Pollut. 223, 877–888. https://doi.org/10.1007/s11270-011-0909-3.

Lovley, D.R., Phillips, E.J.P., Gorby, Y.A., Landa, E.R., 1991. Microbial reduction of uranium. Nature 350, 413–416. https://doi.org/10.1038/350413a0.

Lu, Y., Jenkins, A., Ferrier, R.C., Bailey, M., Gordon, I.J., Song, S., Huang, J., Jia, S., Zhang, F., Liu, X., Feng, Z., Zhang, Z., 2015. Addressing China's grand challenge of achieving food security while ensuring environmental sustainability. Sci. Adv. 1, e1400039. https://doi.org/10.1126/sciadv.1400039.

Lu, S., Ren, L., Fang, J., Ji, J., Liu, G., Zhang, J., Zhang, H., Luo, R., Lin, K., Fan, R., 2016. Trace elements are associated with urinary 8-hydroxy-2′-deoxyguanosine level: a case study of college students in Guangzhou, China. Environ. Sci. Pollut. Res. 23, 8484–8491.

Luo, J.-S., Huang, J., Zeng, D.-L., Peng, J.-S., Zhang, G.-B., Ma, H.-L., Guan, Y., Yi, H.-Y., Fu, Y.-L., Han, B., Lin, H.-X., Qian, Q., Gong, J.-M., 2018. A defensin-like protein drives cadmium efflux and allocation in rice. Nat. Commun. 9. https://doi.org/10.1038/s41467-018-03088-0.

Mages, M., Óvári, M., Tümpling, W. v, Kröpfl, K., 2004. Biofilms as bio-indicator for polluted waters? Anal. Bioanal. Chem. 378, 1095–1101. https://doi.org/10.1007/s00216-003-2291-5.

Malar, S., Shivendra Vikram, S., JC Favas, P., Perumal, V., 2014. Lead heavy metal toxicity induced changes on growth and antioxidative enzymes level in water hyacinths [Eichhornia crassipes (Mart.)]. Bot. Stud. 55, 54. https://doi.org/10.1186/s40529-014-0054-6.

Materazzi, S., Canepari, S., Aquili, S., 2012. Monitoring heavy metal pollution by aquatic plants. Environ. Sci. Pollut. Res. 19, 3292–3298. https://doi.org/10.1007/s11356-012-0846-8.

Meena, R.A.A., Sathishkumar, P., Ameen, F., Yusoff, A.R.M., Gu, F.L., 2018. Heavy metal pollution in immobile and mobile components of lentic ecosystems—a review. Environ. Sci. Pollut. Res. 25, 4134–4148. https://doi.org/10.1007/s11356-017-0966-2.

Meharg, A.A., Hartley-Whitaker, J., 2002. Arsenic uptake and metabolism in arsenic resistant and nonresistant plant species. New Phytol. 154, 29–43. https://doi.org/10.1046/j.1469-8137.2002.00363.x.

Mishra, J., Singh, R., Arora, N.K., 2017. Alleviation of heavy metal stress in plants and remediation of soil by rhizosphere microorganisms. Front. Microbiol. 8. https://doi.org/10.3389/fmicb.2017.01706.

Mitch, M.L., 2002. Phytoextraction of toxic metals: a review of biological mechanism. J. Environ. Qual. 31, 109–120.

Mizuno, T., Usui, K., Horie, K., Nosaka, S., Mizuno, N., Obata, H., 2005. Cloning of three ZIP/Nramp transporter genes from a Ni hyperaccumulator plant Thlaspi japonicum and their Ni2+−transport abilities. Plant Physiol. Biochem. 43, 793–801. https://doi.org/10.1016/j.plaphy.2005.07.006.

Moche, M., Gutknecht, J., Schulz, E., Langer, U., Rinklebe, J., 2015. Monthly dynamics of microbial community structure and their controlling factors in three floodplain soils. Soil Biol. Biochem. 90, 169–178.

Muehe, E.M., Weigold, P., Adaktylou, I.J., Planer-Friedrich, B., Kraemer, U., Kappler, A., Behrens, S., 2015. Rhizosphere microbial community composition affects cadmium and zinc uptake of the metal-hyperaccumulating plant Arabidopsis halleri. Appl. Environ. Microbiol. 81 (6), 2173–2181 (AEM–03359).

Nan, G., Peifang, W., Chao, W., Jun, H., Jin, Q., Lingzhan, M., 2016. Mechanisms of cadmium accumulation (adsorption and absorption) by the freshwater bivalve Corbicula fluminea under hydrodynamic conditions. Environ. Pollut. 212, 550–558. https://doi.org/10.1016/j.envpol.2016.01.091.

Ng, C.K., Sivakumar, K., Liu, X., Madhaiyan, M., Ji, L., Yang, L., Tang, C., Song, H., Kjelleberg, S., Cao, B., 2013. Influence of outer membrane c-type cytochromes on particle size and activity of extracellular nanoparticles produced by Shewanella oneidensis. Biotechnol. Bioeng. 110, 1831–1837. https://doi.org/10.1002/bit.24856.

Nocelli, N., Bogino, P., Banchio, E., Giordano, W., 2016. Roles of extracellular polysaccharides and biofilm formation in heavy metal resistance of rhizobia. Materials 9, 418. https://doi.org/10.3390/ma9060418.

Palansooriya, K.N., Ok, Y.S., Awad, Y.M., Lee, S.S., Sung, J.K., Koutsospyros, A. and Moon, D.H, 2019. Impacts of biochar application on upland agriculture: A review. Journal of environmental management 234, 52–64.

Palansooriya, K.N., Wong, J.T.F., Hashimoto, Y., Huang, L., Rinklebe, J., Chang, S.X., Bolan, N., Wang, H., Ok, Y.S, 2019. Response of microbial communities to biochar-amended soils: a critical review. Biochar 1 (1), 3–22.

Palansooriya, K.N., Yang, Y., Tsang, Y.F., Sarkar, B., Hou, D., Cao, X., Meers, E., Rinklebe, J., Kim, K.-H., Ok, Y.S., 2019. Occurrence of contaminants in drinking water sources and the potential of biochar for water quality improvement: A review. Critical Reviews in Environmental Science and Technology 1–63. https://doi.org/10.1080/10643389.2019.1629803.

Pan, J., Liu, R., Tang, H., 2007. Surface reaction of Bacillus cereus biomass and its biosorption for lead and copper ions. J. Environ. Sci. 19, 403–408. https://doi.org/10.1016/S1001-0742(07)60067-9.

Pantke, C., Obst, M., Benzerara, K., Morin, G., Ona-Nguema, G., Dippon, U., Kappler, A., 2012. Green rust formation during Fe(II) oxidation by the nitrate-reducing Acidovorax sp. strain BoFeN1. Environ. Sci. Technol. 46, 1439–1446. https://doi.org/10.1021/es2016457.

Philippis, R.D., Colica, G., Micheletti, E., 2011. Exopolysaccharide-producing cyanobacteria in heavy metal removal from water: molecular basis and practical applicability of the biosorption process. Appl. Microbiol. Biotechnol. 92, 697. https://doi.org/10.1007/s00253-011-3601-z.

Pourabadehei, M., Mulligan, C.N., 2016. Resuspension of sediment, a new approach for remediation of contaminated sediment. Environ. Pollut. 213, 63–75. https://doi.org/10.1016/j.envpol.2016.01.082.

Prasad, M.N.V., 2007. Aquatic plants for Phytotechnology. In: Environmental Bioremediation Technologies. Springer, Berlin, Heidelberg, pp. 259–274. https://doi.org/10.1007/978-3-540-34793-4_11.

Quintelas, C., Rocha, Z., Silva, B., Fonseca, B., Figueiredo, H., Tavares, T., 2009. Biosorptive performance of an Escherichia coli biofilm supported on zeolite NaY for the removal of Cr(VI), Cd(II), Fe(III) and Ni(II). Chem. Eng. J. 152, 110–115. https://doi.org/10.1016/j.cej.2009.03.039.

Rai, U.N., Sinha, S., Chandra, P., 1996. Metal biomonitoring in water resources of eastern Ghats, Koraput (Orissa), India by aquatic plants. Environ. Monit. Assess. 43, 125–137. https://doi.org/10.1007/BF00398603.

Rajapaksha, A.U., Chen, S.S., Tsang, D.C.W., Zhang, M., Vithanage, M., Mandal, S., Gao, B., Bolan, N.S., Ok, Y.S., 2016. Engineered/designer biochar for contaminant removal/immobilization from soil and water: potential and implication of biochar modification. Chemosphere 148, 276–291. https://doi.org/10.1016/j.chemosphere.2016.01.043.

Rajapaksha, A.U., Alam, M.S., Chen, N., Alessi, D.S., Igalavithana, A.D., Tsang, D.C.W., Ok, Y.S., 2018. Removal of hexavalent chromium in aqueous solutions using biochar: chemical and spectroscopic investigations. Sci. Total Environ. 625, 1567–1573. https://doi.org/10.1016/j.scitotenv.2017.12.195.

Rajkumar, M., Ae, N., Prasad, M.N.V., Freitas, H., 2010. Potential of siderophore-producing bacteria for improving heavy metal phytoextraction. Trends Biotechnol. 28, 142–149. https://doi.org/10.1016/j.tibtech.2009.12.002.

Rajkumar, M., Sandhya, S., Prasad, M.N.V., Freitas, H., 2012. Perspectives of plant-associated microbes in heavy metal phytoremediation. Biotechnol. Adv. 30, 1562–1574. https://doi.org/10.1016/j.biotechadv.2012.04.011. Special issue on ACB 2011.

Ramey, B.E., Koutsoudis, M., Bodman, S.B. von, Fuqua, C., 2004. Biofilm formation in plant–microbe associations. Curr. Opin. Microbiol., Growth and development 7, 602–609. https://doi.org/10.1016/j.mib.2004.10.014.

Rascio, N., Navari-Izzo, F., 2011. Heavy metal hyperaccumulating plants: how and why do they do it? And what makes them so interesting? Plant Sci. 180, 169–181. https://doi.org/10.1016/j.plantsci.2010.08.016.

Rene, E.R., Pakshirajan, K., Lens, P.N.L., 2016. Special issue on biofilm engineering for heavy-metal removal and recovery. J. Environ. Eng. 142, C2016001. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001168.

Rezania, S., Taib, S.M., Md Din, M.F., Dahalan, F.A., Kamyab, H., 2016. Comprehensive review on phytotechnology: heavy metals removal by diverse aquatic plants species from wastewater. J. Hazard. Mater. 318, 587–599. https://doi.org/10.1016/j.jhazmat.2016.07.053.

Rhea, D.T., Harper, D.D., Farag, A.M., Brumbaugh, W.G., 2006. Biomonitoring in the Boulder River watershed, Montana, USA: metal concentrations in biofilm and macroinvertebrates, and relations with macroinvertebrate assemblage. Environ. Monit.

Assess. 115, 381–393. https://doi.org/10.1007/s10661-006-7086-7.

Rinklebe, J., Shaheen, S.M., Yu, K., 2016. Release of As, Ba, Cd, Cu, Pb, and Sr under pre-definite redox conditions in different rice paddy soils originating from the U.S.A. and Asia. In: Geoderma, Integrated Management Strategies for Arsenic and Cadmium in Rice Paddy Environments. 270. pp. 21–32. https://doi.org/10.1016/j.geoderma.2015.10.011.

Rizwan, M., Ali, S., Adrees, M., Ibrahim, M., Tsang, D.C.W., Zia-ur-Rehman, M., Zahir, Z.A., Rinklebe, J., Tack, F.M.G., Ok, Y.S., 2017. A critical review on effects, tolerance mechanisms and management of cadmium in vegetables. Chemosphere 182, 90–105.

Rizwan, M., Ali, S., Zia ur Rehman, M., Rinklebe, J., Tsang, D.C.W., Bashir, A., Maqbool, A., Tack, F.M.G., Ok, Y.S., 2018. Cadmium phytoremediation potential of Brassica crop species: a review. Sci. Total Environ. 631–632, 1175–1191. https://doi.org/10.1016/j.scitotenv.2018.03.104.

Roberts, D.A., 2012. Causes and ecological effects of resuspended contaminated sediments (RCS) in marine environments. Environ. Int. 40, 230–243. https://doi.org/10.1016/j.envint.2011.11.013.

Salehizadeh, H., Shojaosadati, S.A., 2003. Removal of metal ions from aqueous solution by polysaccharide produced from Bacillus firmus. Water Res. 37, 4231–4235. https://doi.org/10.1016/S0043-1354(03)00418-4.

Salt, D.E., Kato, N., Kraemer, U., Smith, R.D., Raskin, I., 2000. The Role of Root Exudates in Nickel Hyperaccumulation and Tolerance in Accumulator and Non-accumulator Species of Thlaspi. US.

Sánchez-López, A.S., Carrillo-González, R., González-Chávez, M. del C.A., Rosas-Saito, G.H., Vangronsveld, J., 2015. Phytobarriers: plants capture particles containing potentially toxic elements originating from mine tailings in semiarid regions. Environ. Pollut. 205, 33–42. https://doi.org/10.1016/j.envpol.2015.05.010.

Shaheen, S.M., Rinklebe, J., Frohne, T., White, J.R., DeLaune, R.D., 2016. Redox effects on release kinetics of arsenic, cadmium, cobalt, and vanadium in Wax Lake Deltaic freshwater marsh soils. Chemosphere 150, 740–748. https://doi.org/10.1016/j.chemosphere.2015.12.043.

Shahid, M., Dumat, C., Khalid, S., Schreck, E., Xiong, T., Niazi, N.K., 2017. Foliar heavy metal uptake, toxicity and detoxification in plants: a comparison of foliar and root metal uptake. J. Hazard. Mater. 325, 36–58. https://doi.org/10.1016/j.jhazmat.2016.11.063.

Shanker, A.K., Cervantes, C., Loza-Tavera, H., Avudainayagam, S., 2005. Chromium toxicity in plants. Environ. Int. 31, 739–753. https://doi.org/10.1016/j.envint.2005.02.003.

Sharma, S.S., Dietz, K.-J., Mimura, T., 2016. Vacuolar compartmentalization as indispensable component of heavy metal detoxification in plants. Plant Cell Environ. 39, 1112–1126.

Shibagaki, N., Rose, A., McDermott, J.P., Fujiwara, T., Hayashi, H., Yoneyama, T., Davies, J.P., 2002. Selenate-resistant mutants of Arabidopsis thaliana identify Sultr1;2, a sulfate transporter required for efficient transport of sulfate into roots. Plant J. 29, 475–486. https://doi.org/10.1046/j.0960-7412.2001.01232.x.

Singh, S., Parihar, P., Singh, R., Singh, V.P., Prasad, S.M., 2016. Heavy metal tolerance in plants: role of transcriptomics, proteomics, metabolomics, and ionomics. Front. Plant Sci. 6. https://doi.org/10.3389/fpls.2015.01143.

Sone, Y., Mochizuki, Y., Koizawa, K., Nakamura, R., Pan-Hou, H., Itoh, T., Kiyono, M., 2013. Mercurial-resistance determinants in Pseudomonas strain K-62 plasmid pMR68. AMB Express 3, 41. https://doi.org/10.1186/2191-0855-3-41.

Song, X., Xu, L., Dai, Y., 2017. Yangtze River: The potential ecological risk of heavy metals in sediment from 1996 to 2012. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing, pp. 12030.

Srivastava, S., Agrawal, S., Mondal, M.K., 2015. A review on progress of heavy metal removal using adsorbents of microbial and plant origin. Environ. Sci. Pollut. Res. 22, 15386–15415. https://doi.org/10.1007/s11356-015-5278-9.

Tang, W., Zhang, H., Zhang, W., Shan, B., Zhu, X., Song, Z., 2015. Dynamics of heavy metals and phosphorus in the pore water of estuarine sediments following agricultural intensification in Chao Lake Valley. Environ. Sci. Pollut. Res. 22, 7948–7953. https://doi.org/10.1007/s11356-014-3945-x.

Tang, W., Duan, S., Shan, B., Zhang, H., Zhang, W., Zhao, Y., Zhang, C., 2016. Concentrations, diffusive fluxes and toxicity of heavy metals in pore water of the Fuyang River, Haihe Basin. Ecotoxicol. Environ. Saf. 127, 80–86. https://doi.org/10.1016/j.ecoenv.2016.01.013.

Tian, W., Zhang, Z., Hu, X., Tian, R., Zhang, J., Xiao, X., Xi, Y., 2015. Short-term changes in total heavy metal concentration and bacterial community composition after replicated and heavy application of pig manure-based compost in an organic vegetable production system. Biol. Fertil. Soils 51, 593–603. https://doi.org/10.1007/s00374-015-1005-4.

Török, A., Gulyás, Z., Szalai, G., Kocsy, G., Majdik, C., 2015. Phytoremediation capacity of aquatic plants is associated with the degree of phytochelatin polymerization. J. Hazard. Mater. 299, 371–378. https://doi.org/10.1016/j.jhazmat.2015.06.042.

Ullah, A., Heng, S., Munis, M.F.H., Fahad, S., Yang, X., 2015. Phytoremediation of heavy metals assisted by plant growth promoting (PGP) bacteria: a review. Environ. Exp. Bot. 117, 28–40.

Uluturhan, E., Kontas, A., Can, E., 2011. Sediment concentrations of heavy metals in the Homa lagoon (eastern Aegean Sea): assessment of contamination and ecological risks. Mar. Pollut. Bull. 62, 1989–1997. https://doi.org/10.1016/j.marpolbul.2011.06.019.

Usman, A.R.A., Lee, S.S., Awad, Y.M., Lim, K.J., Yang, J.E., Ok, Y.S., 2012. Soil pollution assessment and identification of hyperaccumulating plants in chromated copper arsenate (CCA) contaminated sites, Korea. Chemosphere 87, 872–878. https://doi.org/10.1016/j.chemosphere.2012.01.028.

Valipour, A., Raman, V.K., Ahn, Y.-H., 2015. Effectiveness of domestic wastewater treatment using a bio-hedge water hyacinth wetland system. Water 7, 329–347. https://doi.org/10.3390/w7010329.

Verma, S., Dubey, R.S., 2003. Lead toxicity induces lipid peroxidation and alters the activities of antioxidant enzymes in growing rice plants. Plant Sci. 164, 645–655. https://doi.org/10.1016/S0168-9452(03)00022-0.

Vidyalakshmi, R., Paranthaman, R., Bhakyaraj, R., 2009. Sulphur oxidizing bacteria and pulse nutrition- a review. World J. Agric. Sci. 5, 270–278.

Vikrant, K., Kim, K.-H., Ok, Y.S., Tsang, D.C.W., Tsang, Y.F., Giri, B.S., Singh, R.S., 2018. Engineered/designer biochar for the removal of phosphate in water and wastewater. Science of The Total Environment 616–617, 1242–1260. https://doi.org/10.1016/j.scitotenv.2017.10.193.

Wang, Y.-T., Xiao, C., 1995. Factors affecting hexavalent chromium reduction in pure cultures of bacteria. Water Res. 29, 2467–2474. https://doi.org/10.1016/0043-1354(95)00093-Z.

Wang, Z., Yao, L., Liu, G., Liu, W., 2014. Heavy metals in water, sediments and submerged macrophytes in ponds around the Dianchi Lake, China. Ecotoxicol. Environ. Saf. 107, 200–206. https://doi.org/10.1016/j.ecoenv.2014.06.002.

Wang, P.F., Geng, N., Wang, C., Qian, J., Hou, J., Qi, N., 2016. Evaluating the impact of long term hydrodynamic conditions on the release of metals from contaminated sediments in Taihu Lake, China. J. Environ. Inform. https://doi.org/10.3808/jei.201500318.

Worms, I., Simon, D.F., Hassler, C.S., Wilkinson, K.J., 2006. Bioavailability of trace metals to aquatic microorganisms: importance of chemical, biological and physical processes on biouptake. Biochimie 88, 1721–1731. https://doi.org/10.1016/j.biochi.2006.09.008.

Xing, W., Wu, H., Hao, B., Huang, W., Liu, G., 2013. Bioaccumulation of heavy metals by submerged Macrophytes: looking for hyperaccumulators in Eutrophic Lakes. Environ. Sci. Technol. 47, 4695–4703. https://doi.org/10.1021/es303923w.

Yan, Y., Kuramae, E.E., Hollander, M. de, Klinkhamer, P.G.L., Veen, J.A. van, 2017. Functional traits dominate the diversity-related selection of bacterial communities in the rhizosphere. ISME J 11, 56–66. https://doi.org/10.1038/ismej.2016.108.

Yang, X., Igalavithana, A.D., Oh, S.-E., Nam, H., Zhang, M., Wang, C.-H., Kwon, E.E., Tsang, D.C., Ok, Y.S., 2018. Characterization of bioenergy biochar and its utilization for metal/metalloid immobilization in contaminated soil. Science of The Total Environment 640, 704–713.

Yin, H., Niu, J., Ren, Y., Cong, J., Xiaoxia, Zhang, Fan, F., Xiao, Y., Xian, Zhang, Deng, J., Xie, M., He, Z., Zhou, J., Liang, Y., Liu, X., 2015. An integrated insight into the response of sedimentary microbial communities to heavy metal contamination. Sci. Rep. 5, 14266. https://doi.org/10.1038/srep14266.

Yu, C., Peng, X., Yan, H., Li, X., Zhou, Z., Yan, T., 2015. Phytoremediation ability of Solanum nigrum L. to Cd-contaminated soils with high levels of Cu, Zn, and Pb. Water Air Soil Pollut. 226, 157.

Zeng, F., Ali, S., Zhang, H., Ouyang, Y., Qiu, B., Wu, F., Zhang, G., 2011. The influence of pH and organic matter content in paddy soil on heavy metal availability and their uptake by rice plants. Environ. Pollut. 159, 84–91. https://doi.org/10.1016/j.envpol.2010.09.019.

Zhang, N., Yang, D., Wang, D., Miao, Y., Shao, J., Zhou, X., Xu, Z., Li, Q., Feng, H., Li, S., Shen, Q., Zhang, R., 2015. Whole transcriptomic analysis of the plant-beneficial rhizobacterium Bacillus amyloliquefaciens SQR9 during enhanced biofilm formation regulated by maize root exudates. BMC Genomics 16, 685. https://doi.org/10.1186/s12864-015-1825-5.

Zhang, J., Hua, P., Krebs, P., 2017a. Influences of land use and antecedent dry-weather period on pollution level and ecological risk of heavy metals in road-deposited sediment. Environ. Pollut. 228, 158–168. https://doi.org/10.1016/j.envpol.2017.05.029.

Zhang, R., Vivanco, J.M., Shen, Q., 2017b. The unseen rhizosphere root–soil–microbe interactions for crop production. Curr. Opin. Microbiol. 37, 8–14.

Zhao, F.-J., Hamon, R.E., Lombi, E., McLaughlin, M.J., McGrath, S.P., 2002. Characteristics of cadmium uptake in two contrasting ecotypes of the hyperaccumulator Thlaspi caerulescens. J. Exp. Bot. 53, 535–543. https://doi.org/10.1093/jexbot/53.368.535.

Zheng, S., Su, J., Wang, L., Yao, R., Wang, D., Deng, Y., Wang, R., Wang, G., Rensing, C., 2014. Selenite reduction by the obligate aerobic bacterium Comamonas testosteroni S44 isolated from a metal-contaminated soil. BMC Microbiol. 14, 204. https://doi.org/10.1186/s12866-014-0204-8.

Zhou, Q., Zhang, J., Fu, J., Shi, J., Jiang, G., 2008. Biomonitoring: an appealing tool for assessment of metal pollution in the aquatic ecosystem. Anal. Chim. Acta 606, 135–150. https://doi.org/10.1016/j.aca.2007.11.018.