



Review article

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



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ARTICLE INFO

Handling Editor: John Seaman

Keywords:

Potentially toxic element
Submerged plant
Biofilm
Bioaccumulation
Indicator species

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.

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<https://doi.org/10.1016/j.envint.2019.105015>

Received 19 November 2018; Received in revised form 10 July 2019; Accepted 11 July 2019

Available online 29 July 2019

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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 spiralis* (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'Acunio 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'Acunio 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) (Keskinan 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 $\text{Ni}^{2+} < \text{Cu}^{2+} < \text{Zn}^{2+} < \text{Fe}^{3+} < \text{Mn}^{2+}$, 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 hyper-accumulators, 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

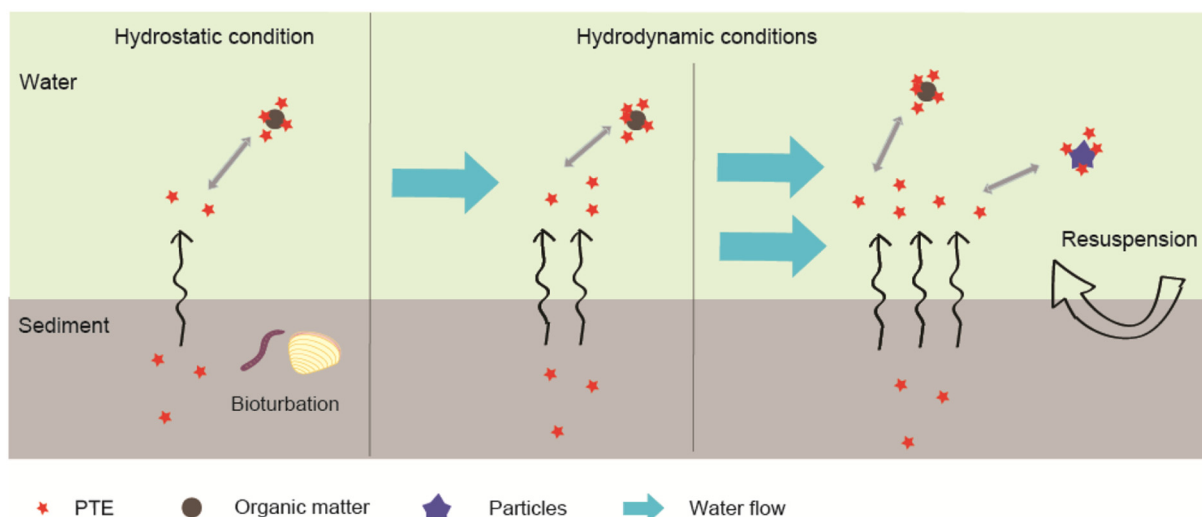


Fig. 1. Transport and transformation of PTEs in an aquatic environment under hydrostatic and hydrodynamic conditions.

(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 (Ladislav 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'Acunzio 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

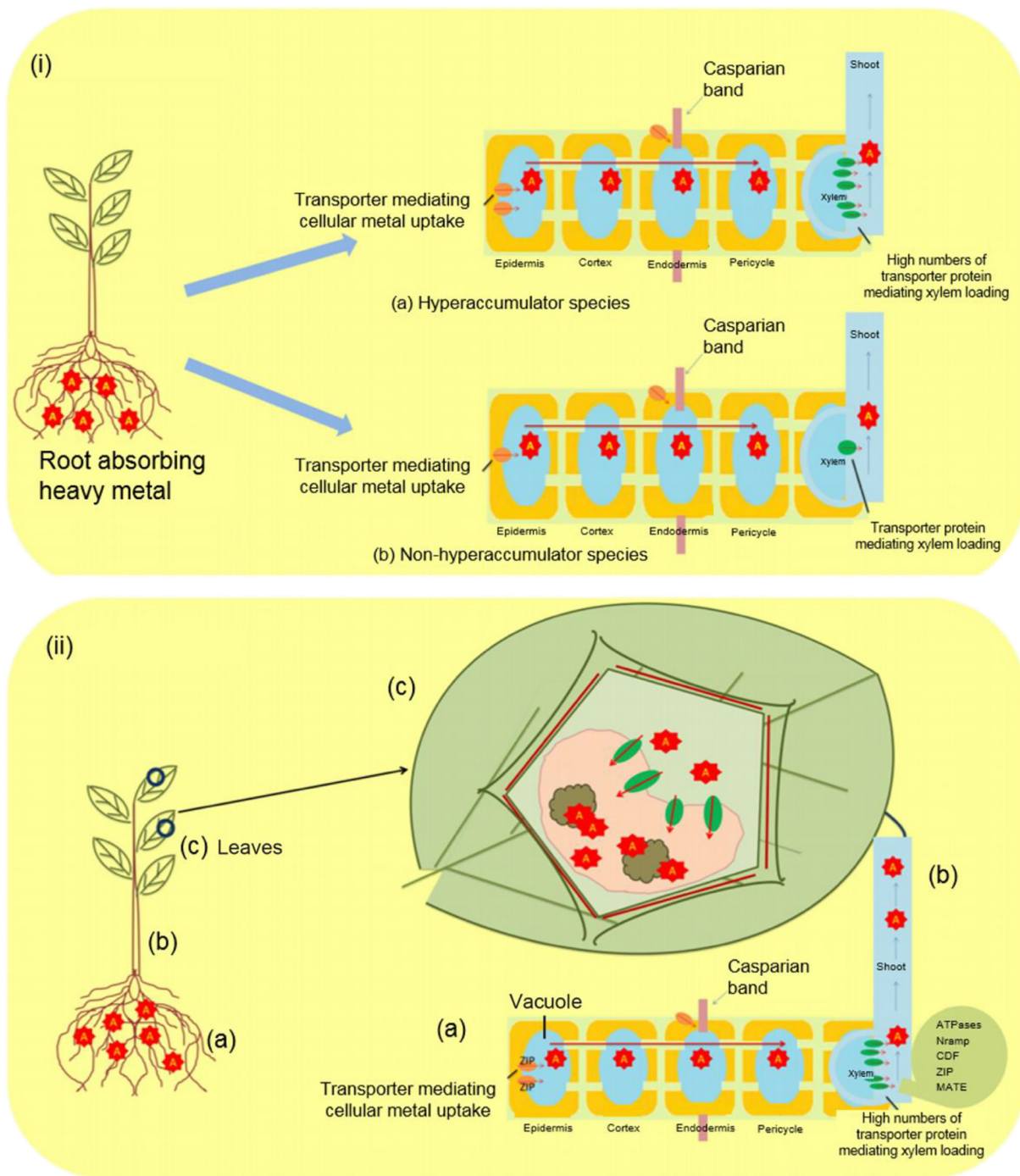


Fig. 2. Schematic diagram showing differential PTE accumulation mechanisms in hyperaccumulating (a) and non-hyperaccumulating (b) plants. (i) PTE uptake and translocation in normal plants. (ii) PTE translocation and detoxification in hyperaccumulators. A, PTE; Nramp, natural resistance-associated macrophage 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
<i>Micrococcus</i> ; <i>Aspergillus</i> <i>Bacillus</i> ; <i>Arthrobacter</i>	Effective for the removal of Cr (VI) and Ni (II) Effective for the removal of Cr	(Congeevaram et al., 2007) (Wang and Xiao, 1995; Dey and Paul, 2018)
<i>Bacillus firmus</i> <i>Bacillus cereus</i> <i>Escherichia coli</i> <i>Pseudomonas aeruginosa</i> <i>Geobacter</i> <i>Klebsiella pneumoniae</i> M426	Effective for removal of Pb, Cu, and Zn Effective for removal of Pb and Cu ions Effective for removal of Cr (VI), Cd (II), Fe (III), and Ni (II) Effective for removal of Pb and Ni Reduce uranium (U) from a soluble state (U^{6+}) to an insoluble state (U^{4+}) Reduce Hg (II) to Hg (0) and Hg precipitation as insoluble Hg due to volatile thiol (H_2S)	(Salehizadeh and Shojaosadati, 2003) (Pan et al., 2007) (Quintelas et al., 2009) (Gabr et al., 2008) (Lovley et al., 1991) (Sone et al., 2013)
<i>Pseudomonas tolaasii</i> RP23; <i>Pseudomonas fluorescens</i> RS9	Siderophore-producing bacteria (SPB) potentially support PTE uptake and reduce stress symptoms in plants	(Dell' Amico et al., 2005; Rajkumar et al., 2010)
<i>Desulfobacterium autotrophicum</i>	Sulfate-reducing bacteria (SRB) promote anaerobic biodegradation of complex substrates, such as petroleum hydrocarbons in sediments	(Cabral et al., 2016)
<i>Thiobacillus</i>	Sulfur-oxidizing bacteria (SOB) oxidize elemental sulfur to plant-available sulfate; decompose organic matter, and oxidize sulfide	(Vidyalakshmi et al., 2009).
<i>Gallionella</i> , <i>Sideroxydans</i> ; <i>Ferroplasma myxofaciens</i> ; <i>Albidiferax ferrireducens</i> ; <i>Geobacter</i>	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 (Ladislav 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 domingensis* (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 (Keskinan 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 Cu, Zn As, Cd, Cu, Pb, Zn Cd	PTE concentrations in biofilms	PTEs pollution in water	(Fuchs et al., 1996) (Mages et al., 2004) (Rhea et al., 2006) (Duong et al., 2008)
Zn, Cu, Pb As, Cd, Cu, Zn	Biofilm bacterial populations or community composition	Water ecological health or PTEs contamination	(Ancion et al., 2010) (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.

Acknowledgements

This study was supported by a Korea University Grant, the Natural Science Foundation of Zhejiang Province [No. LHY19E090003], the Natural Science Foundation of Zhejiang Province [No. LQ18E090002], the National Natural Science Foundation of China [No. 41702247], and the National Key Research and Development Program of China [No. 2016YFC0402502]. Ki-Hyun Kim acknowledges the support made by a grant from the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (Grant No: 2016R1E1A1A01940995).

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