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Effects of vegetations on the removal of contaminants in aquatic environments: A review*

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Abstract: This paper reviews the removal of contaminants including nutrients, metals and organic pollutants by vegetations in aquatic environments. The removal efficiencies are considered with respect to 16, 19 and 14 kinds of different aquatic plants, respectively in three tables. Due to different characteristics, the removal effects of plants on contaminants from the overlying water differ greatly. The vegetation can improve the water quality mainly through two ways: (1) to adsorb and absorb pollutants from water, (2) to prevent pollutants from releasing from sediment. The contaminant removal mechanisms of vegetations and related physical, chemical and biological effects are discussed. The effects of vegetations on the contaminant removal are found to depend on the environmental conditions, the number and the type of plants, the nature and the chemical structure of the pollutants. In addition, the contaminant release and removal by vegetations under hydrodynamic conditions is specially addressed. Further research directions are suggested.

Key words: vegetation, nutrient, metal, organic pollutant, removal, hydrodynamic condition

Introduction

Aquatic environments are directly or indirectly taken as the recipients of potentially toxic liquids and solids from domestic, agricultural and industrial wastes[1,2]. Pollutants may accumulate in the overlying water, the pore water, the sediments and the vegetation[3], and they can be divided into three classes: the nutrient nutrients, the metals and the organic pollutants. The vegetation is one of the important components and plays a key role in aquatic environments. As primary producers, the vegetations supply food for the first consumers in trophic chains[4]. Meanwhile, the vegetations also provide habitats and refuges for periphyton[5], zooplankton[6], other invertebrate species[7], and vertebrate species[8]. The aquatic plants play key functions in biochemical cycles through the organic carbon production, the nutrient mobilization and the transfer of other trace elements[9]. They directly influence the hydrology and the sediment dynamics of freshwater ecosystems through their effects on the water flow[10,11] and the particle resuspension or settlement[12,13].

Plants require nutrients for their growth and reproduction, and the rooted plants take up nutrients primarily through their root systems. Many kinds of plants are very productive, a considerable amount of nutrients can be bound in their biomass[14,15]. However, excess nutrients lead to eutrophication, which is very harmful to aquatic ecosystems. The aquatic plants for the removal of nutrients are mainly applied in rivers[16], lakes[17] and constructed wetlands[18]. The appropriate macrophytes are planted in the water body absorbing nitrogen and phosphorus effectively[19,20]. And the water eutrophication level can be lowered through the phytoremediation technology. There, a timely harvest is very important, the amount of nutrients removed via harvesting could involve a substantial part of

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Table 1 Removal efficiency (%) of nutrients with vegetations in aquatic environments

Location[Ref.]	Vegetation	Removal efficiency (%)			
		TN	NO_3^--N	NH_4^+-N	
Australia[36]	*Phragmites australis*	16.00		62.00	
China[37]	*Acorus calamus*	46.00-68.00			
	Cyperus flabelliformis	53.00-76.00			
	Canna indica	49.00-67.00			
	Iris tectorum	36.00-53.00			
	Scirpus validus	46.00-61.00			
Germany[38]	*Phragmites australis*	48.00-93.80		74.00-93.70	
Mauritius[39]	*Eichhornia crassipes*			99.60	
	Hydrocotyle umbellata			99.00	
	Pistia stratiotes			99.20	
Korea[40]	*Trapa japonica*	80.00-99.00			
Taiwan Island[41]	*Ipomoea aquatica*	74.49-94.93			
USA[42]	*Scirpus californicus*	19.00-31.00	60.00-88.00	40.00-62.00	
USA[43]	*Ipomoea aquatica*		84.00	38.00	
		TP	TDP	PP	PO_4^{3-}-P
Australia[36]	*Phragmites australis*				17.00
China[44]	*Ceratophyllum demersum*	91.75	90.93	97.92	
	Elodea canadensis	84.71	86.09	87.20	
	Myriophyllum spicatum	68.29	71.36	49.47	
	Vallisneria spiralis	84.63	89.51	54.69	
China[37]	*Acorus calamus*	27.30-47.60			
	Cyperus flabelliformis	40.50-62.50			
	Canna indica	37.80-59.50			
	Iris tectorum	21.80-34.50			
	Scirpus validus	27.10-46.00			
Germany[38]	*Phragmites australis*	60.50-95.80	74.00-93.70	74.00-93.70	
Mauritius[39]	*Eichhornia crassipes*	98.50			96.50
	Hydrocotyle umbellata	71.30			60.90
	Pistia stratiotes	64.20			48.50
Korea[40]	*Trapa japonica*	81.00-97.00			
USA[42]	*Scirpus californicus*	39.00-62.00			40.00-67.00
USA[43]	*Ipomoea aquatica*				83.00

the inflow load[21]. If the plants are not harvested, most of the nutrients from the biomass would return to the water during the decomposition process. On the other hand, the harvested plants can be used properly to bring about certain economic benefits.

The pollution of the environment with toxic metals is an issue of considerable public interest over the past few decades. Heavy metals release into aquatic systems generally as particulate matter, and they eventually settle down and become incorporated into sediments[22]. The surface sediment therefore is the most important reservoir or sink of metals and other pollutants in aquatic environments. The sediment-bound pollutants can be taken up by rooted aquatic macrophytes and other aquatic organisms[23,24]. Some plants can enrich one or several metals[25]. These plants can accumulate metals in a concentration 10^5 times greater than that in the associated water[26], and therefore have been used for metal removal from a variety of sources. Plants as hyper-accumulators can tolerate, take up and translocate high levels of certain metals that would be toxic to most organisms. In recent years, the metal removal by various macrophytes becomes more and more prevalent, especially by using constructed wetlands[27-29].

Persistent organic pollutants (POPs) present in aquatic environments may be immobilized in sediments or accumulated by aquatic organisms. Hydrocarbons can become dangerous especially if they enter the food chain, since several of the more persistent compounds, as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) are carcinogenic[30]. Unlike inorganic pollutants, such as heavy metals, the hydrocarbons can be transformed and degraded mainly by biological processes, resulting sometimes to mineralization[31]. The plant uptake and degradation of organic pollutants is an important process for removing contaminants. The vegetation has been applied successfully for *in situ* treatments of sediment and water in sites contaminated by organic pollutants[32,33]. This popular remediation method is cost-effective, aesthetically pleasing, and suitable for large areas and over long period of time.

Remediation of pollutants in aquatic environments is a big project. The estimated costs for the clean-up of contaminated sites with conventional physical and chemical techniques are enormous. Moreover, the traditional techniques not eliminate but only transfer the pollutants to other places. By means of phytoremediation, these problems can be solved. However, the effects of vegetations on the contaminant removal and the mechanisms are still inadequately studied, especially under different hydrodynamic conditions. This paper reviews the removal effects and the mechanisms of vegetation for nutrients, metals and organic pollutants in aquatic environments. Some new suggestions are made for future researches.

1. Effects of vegetation on nutrient removal

1.1 *Removal effect*

Nitrogen and phosphorus[34,35] nutrients are considered as “pollution” when they reach toxic levels in the receiving water bodies, and promote toxin-producing cyanobacteria, and facilitate algal biomass growth causing eutrophication. Vegetations affect the nutrient levels in water not only by restraining the release of nutrients from sediment but also by adsorbing nutrients from water and sediment. Aquatic vegetations can effectively absorb numerous nutrients in the growth process, transfering inorganic nutrients into plant materials. Water quality can be purified after harvesting the mature vegetations. Aquatic vegetations have mostly a positive effect on the removal of nutrients such as total nitrogen (TN), ammonia nitrogen (NH_4^+-N), total phosphorus (TP) and orthophosphate (PO_4^{3-}-P). Table 1 shows the removal efficiency of nutrients with vegetations in aquatic environments. In this table, 16 typical aquatic plants, including emergent, floating and submerged plants, are selected to analyze the removal efficiency of nutrients. In general, submerged plants have a better effect on the removal of phosphorus, while emergent plants absorb nitrogen more effectively. From the results, the removal rates of phosphorus and nitrogen by floating plants seem to be similar. *Phragmites australis*, *Ceratophyllum demersum* and *Eichhornia crassipes* are typical species which adsorb nutrients efficaciously in aquatic environments.

1.2 *Influencing factors*

In aquatic environments, the species and the planting patterns of vegetations, the nutrient levels and the external conditions (temperature, pH value, light, microorganism, etc.) all affect the removal efficiency of nutrients[45]. The vegetation specie is the primary factor influencing the phytoremediation effects for contaminated water. Because of different growth rates, the vegetations have different nutrient needs and absorptive capacities. For example, if our main concern is to remove nitrogen (denitrification), the selected plants should have to provide large roots of adhesion interface and strong oxygen transfer capacity for microorganisms, and when the reduction of nitrogen and phosphorus mainly rely on vegetation adsorptions, we need selective vegetations with abilities of fast growth and good enrichment. Mei et al.[37] studied six emergent plants and pointed out that the removal efficiency of total nitrogen (TN) and total phosphorus (TP) from water is in the following order: *Cyperus flabelliformis* > *Canna indica* > *Acorus calamus* > *Scirpus validus* > *Iris tectorum*. Sooknah and Wilkie[39] found that the removal effect of three floating plants for ammonia nitrogen (NH_4^+-H), TP and orthophosphate (PO_4^{3-}-P) is in the following order: *Eichhornia crassipes* > *Hydrocotyle umbellate* > *Pistia stratiotes*. Gao et al.[44] observed five submerged plants adsorbing TP, total dissolved phosphorus (TDP) and particulate phosphorus (PP) and obtained the order of removal capacity as: *Ceratophyllum demersum* > *Elodea canadensis* > *Vallisneria spiralis* > *Myriophyllum spicatum*.

It is reported that multiple plants can purify water quality better than a single plant due to their more reasonable species diversity, which makes it easier to maintain a long-term stability of the ecological system[46]. Although the overall efficiency of water purification could be improved by multiple plants, the multiple planting may result in a competition between plants to inhibit the growth of each other. For example, the removal efficiency of TN and TP obtained by emergent-floating plants[40] is high than emergent-floating-submerged plants[42]. Hence, it is important to plant the right vegetations. Aquatic plants have a certain tolerance range of pollutants, and in this range, the removal rates of nitrogen and phosphorus increase with the elevated nitrogen and phosphorus concentrations. Körner et al.[47] studied the removal effect of nitrogen and phosphorus by *Lemna minor* in sewage, and analyzed the relationship between the initial nitrogen, the phosphorus concentrations and the nutrient degradation rates. It is shown that the degradation rates of nitrogen and phosphorus increase with the decrease of the initial nitrogen and phosphorus concentrations. When the initial phosphorus concentration is decreased to a certain level, the phosphorus becomes a limiting factor to the growth of plants, causing a fast removal of phosphorus from water. Although the aquatic plants can absorb a large number of nutrients, the nutrients have a reaction on the plant growth. The excess nutrients make the aquatic plants exposed to a toxic stress.

The external conditions, such as the temperature, the pH value, the light and the microorganism, will also affect the phytoremediation. The temperature is the key factor that influences the vegetation purification efficiency. Generally speaking, plants grow luxuriantly in a higher water temperature and the large production consumes more nutrients. According to the study of *Spirodela polyrrhiza*[48], a low water temperature leads to the reduction of the abilities of the cell growth, the synthesis and the absorption. The normal mechanism of plant growth might be damaged, so the eutrophic water might be unable to purify. The growth of the aquatic plants, especially, the submerged plants, is influenced by the pH value significantly. In alkaline water body, the alkali-resistant aquatic plants (*Vallisneria spiralis*, *Myriophyllum*, etc.) become the dominant species, resulting in too simplified plant species. The light plays an important role on the growth of plants. In the absence of light, the aquatic plants cannot complete the process of photosynthesis, and the plant growth would be directly affected. Besides the temperature, the pH value and the light, the microorganisms also affect the function of aquatic plants. The absorption of nitrogen and phosphorus by plants is often associated with rhizospheric microorganisms. It is reported that the microorganisms play an important role in the nitrogen nitrification and the organic matter degradation[45].

1.3 *Removal mechanism*

The aquatic plant uptake, the microorganism metabolism and the adsorption, the filtration, and the precipitation of root substrates play important roles in removing nutrients from water, including physical, chemical and biological processes. The aquatic vegetations require nutrients for their growth and reproduction, and take up nutrients primarily through their root systems and stems. As an indispensable material, NH_4^+-N can be assimilated by plants to synthetise protein and organic nitrogen, and finally transform them into big biomass[49]. Inorganic phosphorus is the essential element for plant growth, and the absorbed phosphorus can be transformed into ATP, DNA, RNA and other organic components[50]. After harvesting these aquatic plants, the nutrients are removed from aquatic environments together with the plants.

The aquatic plant communities provide an adherent substrate and habitat for microorganisms. These microorganisms greatly accelerate the interception of organic colloidal matters surrounding the roots and the decomposition of suspended particles. Bacillus degrades the organic and insoluble phosphorus into the inorganic and soluble phosphate, which can be absorbed by vegetations directly[50]. In addition, the plant roots also secrete exudates, which promote the growth of phosphobacteria, thereby indirectly improve the purification rate. In the nitrogen removal process, despite the fact that the vegetations absorb nitrogen, the nitrification and the denitrification remain the major removal mechanisms. Based on the previous report[51], more than 45% of the total nitrogen removal rate is contributed by the bacterial nitrification and denitrification. Through the combined effects of aquatic plants and microorganisms, the nutrients can better be removed.

The sediment-plant seems to be a natural filter to filtrate pollutants from water. The substrate of rhizosphere and luxuriant foliage can filtrate and retain pollutants, especially, algal particles[45]. At the same time, the bacteria attached to the root systems agglutinate in the endogenous respiration process. Some part of zoogloea helps to settle down the suspended organic matter and the product of metabolism. Some kinds of aquatic plant roots would secrete allelopathic substances, which inhibit the algae growth and prevent the eutrophication of the water body.

2. Effects of vegetation on metal removal

2.1 *Removal effect*

The heavy metal contamination is one of the most serious problems in aquatic environments. Because of its high stability and nondegradation property,

Table 2 Metal removal efficiency (%) of vegetations in aquatic environments

Location[Ref.]	Vegetation	Removal efficiency (%)				
		Cd	Cr	Pb	Cu	Zn
Argentina[53]	*Typha domingensis*		65.00			
Canada[54]	*Myriophylhum*				73.10	99.90
	Ludwigina palustris				92.90	99.90
China[55]	*Reineckea carnea*	95.20	79.90	82.00	97.90	
	Acorus gramineus	95.20	91.80	91.00	98.50	
	Iris pseudacorus	96.10	95.80	93.40	99.10	
	Lythrum salicaria	92.20	81.30	87.00	98.70	
China[2]	*Potamogeton pectinatus*	96.00		79.00	74.00	66.00
	Potamogeton malaianus	88.00		78.00	65.00	67.00
India[56]	*Canna indica*				81.50	93.00
	Cyperus alternifolius		68.40		72.70	93.17
	Typha angustifolia		66.20		68.30	99.30
India[26]	*Pistia stratoites*	78.00	81.00		96.00	90.00
	Spirodela polyrrhiza	63.00	83.00		91.00	90.00
	Eichhornia crassipes	81.00	85.00		95.00	92.00
Iran[57]	*Azolla filiculoides*	57.00		61.00		74.00
Pakistan[58]	*Phragmites australis*	91.94	80.00	50.00	48.28	
Spain[59]	*Juncus effusus*		92.00	84.10	88.30	84.50
Taiwan Island[60]	*Typha latifolia*				83.00	92.00
		Hg	Ni	Fe	Mn	
Argentina[53]	*Typha domingensis*		52.00	73.00		
Canada[54]	*Myriophylhum*	34.40		42.60		
	Ludwigina palustris	34.70		30.90		
China[55]	*Reineckea carnea*			98.50	98.70	
	Acorus gramineus			99.70	99.30	
	Iris pseudacorus			99.60	99.60	
	Lythrum salicaria			99.10	99.60	
China[2]	*Potamogeton pectinatus*				89.00	
	Potamogeton malaianus				83.00	
India[56]	*Canna indica*					
	Cyperus alternifolius		83.60			
	Typha angustifolia		76.40			
India[26]	*Pistia stratoites*			87.00		
	Spirodela polyrrhiza			83.50		
	Eichhornia crassipes			85.70		
Iran[57]	*Azolla filiculoides*		68.00			
Pakistan[58]	*Phragmites australis*		40.94	74.07		
Spain[59]	*Juncus effusus*		50.20	70.50		
Taiwan Island[60]	*Typha latifolia*					

it is harmful to the health of human beings directly or indirectly through the accumulation in the food chain. Turning the metal ions from a soluble phase to a solid phase through macrophytes with the sorption is an important process for the removal of metals from water. Table 2 shows the percentages of different metals removed by using various vegetations. 19 typical aquatic plants, including emergent, floating and submerged plants, are selected to compare the removal efficiency for 9 metals. For emergent plants, the removal efficiency for the 9 metals is in the following order: Mn > Zn > Cd > Cu > Pb > Cr > Fe > Ni > Hg. From Table 2, it is seen that *Iris pseudacorus* and *Acorus gramineus* have high removal rates (> 90%) among the listed metals, indicating a good effect. For the floating plants, the order of removal rates is: Cu > Cd > Zn > Fe > Cr > Pb > Ni. *Eichhornia crassipes* is a typical plant with a strong ability of absorbing pollutants[26]. The whole parts of submerged plants in the water create a special physiological structure. The roots, the stems and the leaves of the submerged plants can all accumulate metals, and the roots have the strongest enrichment capacity. The removal rate of the submerged plants is in the following order: Mn > Cd > Cu > Pb > Zn. It is reported that the removal ability for metals is usually in the following order: submerged plants > floating plants > emergent plants[52]. However, it is also highly related to the plant species and surrounding environments.

2.2 *Influencing factors*

Many factors affect the removal efficiency of aquatic plants for heavy metals. Generally, the species and the biomass of the plants, the type and the initial concentration of the metals, the temperature and the pH value are the important factors that influence the removal rate. Different species of plants have different accumulation abilities for metals. Various types of plants behave differently in (1) the biomass production, (2) the root structure and depth, which affect the substrate oxygenation, (3) the production of root exudates, which implicates the level of soluble ions and molecules in the rhizosphere, (4) the provision of habitat for rhizosphere microbes and rhizosphere fungi, and (5) the ability of plants to absorb and accumulate contaminants[61]. The roots are the most important parts to absorb and fix metals, so the plants with a developed root system can remove metals better. The biomass of aquatic plants affects the removal of heavy metals directly, and the increase of biomass will improve the removal efficiency significantly. The available reports point out that for the aquatic plants, in order to purify the contaminative water, an appropriate amount of biomass is required[26,55]. When the growth density is too large, the reproduction ability is reduced due to the limited space. However, the small biomass also results in a poor removal effect. With the increase of the contact time, the metals accumulate too much in an individual plant, which inhibits the asexual reproduction of the plants.

The heavy metal has its own unique property, which leads to different accumulation abilities of the aquatic plants. For example, two submerged plants, *Potamogeton pectinatus* and *Potamogeton malaianus*, make different accumulations of five heavy metals as in the following order: Cd > Mn > Pb > Cu > Zn[2]. Kamal et al. [54] found that the removal capacity of *Myriophylhum* and *Ludwigina palustris* for different metals varied greatly, in the following order: Zn (99.83%) > Cu (76.57%) > Fe (39.74%) > Hg (33.90%). The initial concentration of heavy metals is an important factor of influencing the plant accumulation capacity. The accumulation capacity of plants is often stronger in a higher metal concentration (below the lethal threshold) water than that in a lower metal concentration water. In the process of accumulating Cr^{6+} (1-200 μmol/L) by *Nymphaea alba*, the metal contents in roots, stems and leaves of *Nymphaea alba* increase with the increase of the Cr^{6+} concentrations[62]. However, Mishra and Tripathi[26] suggested that the exorbitant metal concentrations in water are not conductive to the metal absorption by plants. Their studies of three floating plants, *Pistia stratoites*, *Spirodela polyrrhiza* and *Eichhornia crassipes*, show that the removal ability of plants are in an increase-decrease trend with the increase of the metal concentrations.

The temperature is an essential factor for the growth of vegetations, hence, it also affects the accumulation effect of heavy metals. When the temperature is high, the growth and the metabolism of aquatic plants are exuberant, leading to an enhancement of metal accumulation. For instance[63], the growth of *Eichhornia crassipes* stops at 5°C, and it does not resume until the temperature rises to 13°C. The most suitable growth temperature of *Eichhornia crassipes* is 30°C. Under this condition, the removal ability of this plant for metals is the best. The effect of temperature on the plant accumulation of heavy metals is also reflected in seasonal changes. In summer and autumn, many thermophilic plants grow fast, and consequently show high accumulation efficiencies. In the late autumn and winter, the thermophilic plants are gradually in the aging and death phase, they show a decline of their accumulation ability. For hardy plants, on the contrary, the lower temperature is beneficial to the removal of metals from water. Another important factor of controlling metal accumulation is the pH value. Metal ions bounding to H^+ and OH^- are affected by the pH values of the water body[61]. For example, agglutinating matters can be formed from Cu^{2+} under alkaline conditions, greatly affecting the metal ion absorption of aquatic plants. On the other hand, the pH values have a great influence on the plant growth.

Table 3 Removal efficiencies (%) of vegetations in aquatic environments for POPs

Location[Ref.]	Vegetation	Removal efficiency (%)				
		Total PAHs	Total PCBs	Phenanthrene	Pyrene	Organochlorines
Australia[70]	*Baumea juncea*			97	50	
	Juncus subsecundus			95	39	
Belgium[71]	*Salix viminalis* L.	23				
China[72]	*Vallisneria spiralis*			53.20-75.30		70
China[73]	*Robinia pseudoacacia*		39.70-58.1			85.6
	Cucurbita pepo		33.60-40.9			
USA[74]	*Vetiver zizanoides*	37				
	Hibiscus tiliaceus	58				
USA[75]	*Salix*			4.8		
	Scirpus			4		
USA[76]	*Zostera marina*	73	60			
		Chlorobenzene	Petrol hydrocarbons	Benzo[a]pyrene	2,4- dichlorophenol	
Belgium[71]	*Salix viminalis* L.		79			
China[77]	*Salix matsudana*				52.20-73.70	
France[78]	*Phragmites australis*					
France[79]	*Phragmites australis*					
USA[74]	*Vetiver zizanoides*			54		
	Hibiscus tiliaceus			73		
USA[75]	*Salix*	3.8				
	Scirpus	5.7				

2.3 *Removal mechanism*

The metal removal by vegetations in the aquatic environment mainly depends on adsorption, absorption and sedimentation. Adsorption includes physisorption, i.e., physical processes with weak bindings, and chemisorption, i.e., chemical processes with st- rong bindings. Vegetations play a role in maintaining oxidizing conditions by shoot-to-root oxygen transport. The amount and the form of Fe in the water body strongly affect the metal removal. Fe (II) is soluble and represents an important bioavailable fraction. It can be oxidized to Fe (III) in conjunction with H^+ consumption under aerobic conditions[64]. Fe (III) can be deposited onto root surfaces of aquatic plants, forming plaques with a large capacity to adsorb metals[65]. Adequate physico-chemical substrate conditions offer an efficient matrix for the metal removal. However, without any plants the substrate will become devoid of organic matter, thus the capacity of the substrates to maintain the sulphate reduction and the metal immobilization will be reduced[61]. In addition, it is a common way for metals to be adsorbed into particles by ion exchange, depending upon the factors such as the type of the metals and the presence of other elements compe-tting for adsorption sites[66].

Absorption occurs in the biochemical processes when a compound from the external media enters into a living organism. The absorption of metal ions by vegetations can take place in different tissues. The ions can be directly absorbed by the roots, or through the surface of the stems and the leaves. The chelation and the compartmentation are usually used by the plants to absorb heavy metals from the external environment, fixing the metals in a certain organ[67]. Some metals, such as Fe, Zn and Cu, are the essential elements for the plant growth. However, the excessive essential metal ions will be harmful to the plants. The plants also absorb some undesirable metals, which are accumulated in some tissues. Remediation of metals by plants is a process turning the metals from one profile to another. The plants with abundant accumulative metals should be harvested in time. The vicinity of the plant roots, the rhizosphere, is a preferred environme-nt for many sediment microorganisms. The root surfa-ce is covered with various microorganisms, and the growing roots may transport microorganisms through the sediments. These microorganisms can also help the absorption of heavy metals by plants.

Vegetations, such as *Phragmites australis*, promote the sedimentation of SPM and prevent the erosion by decreasing the surface wind and the water flow velocities. Water columns may be either static, with virtually no flow, or dynamic, with water passing through at a relatively high flow velocity[61] Under static conditions, the removal of heavy metals by vegetations is mainly accomplished by the adsorption and the absorption. Under dynamic conditions, the existence of vegetations decreases the flow velocity effectively, which is beneficial for the SPM sedimenttation. The SPM may adsorb many types of suspended materials, including metals, from water, and the contaminants with the SPM gradually settle down into the surface sediments. The hydraulic retention time increases with the increase of the vegetation density, thus improves sedimentation.

3. Effects of vegetation on organic pollutant removal

3.1 *Removal effect*

According to the toxicity and the degradability, the organic pollutants can be divided into two categories, the degradable organic pollutants and the persistent organic pollutants (POPs). The degradable organic pollutants include the carbohydrate, the fat, the protein, etc., and they can be mineralized to CO_2 and H_2O under the action of microorganisms. The POPs are permanent, semi volatile organic pollutants with bioaccumulation and toxicity. The typical POPs include the polycyclic aromatic hydrocarbons (PAHs), the polychlorinated biphenyls (PCBs), the polychlorinated dibenzo-p-dioxins, dibenzofurans (PCDD/Fs), the organic chlorine pesticides (OCPs), etc. Because of their low water solubility and hydrophobicity, they are densely distributed in the non-aqueous phase and are adsorbed by suspended particles[68]. The phytoremediation of the organic pollutants is not realized by using hyper-accumulation but there is a potential to completely mineralize or transform the pollutants into less- or non-toxic components[69]. Table 3 summarizes the removal efficiencies of 14 plants in aquatic environments for some kinds of POPs. From this table, it can be seen that different plants have different removal capacities for POPs under external environments. Because of different processing procedures, the same plant, such as *Phragmites australis*, has varied removal effects on the same pollutant. In general, the removal effects for POPs are not only related to the basic characteristics of the plants and the pollutants, but also related to the other external factors, such as the plant arrangement, the sediment characteristics, the hydraulic resistant time, etc..

3.2 *Influencing factors*

The temperature is one of the important parameters which affect the removal of POPs in aquatic environments[80,81]. Previous studies show that a high temperature has a significant positive impact on the removal of certain organic pollutants, including the diclofenac, the ibuprofen, the salicylic acid, and the methyl dihydrojasmonate, most possibly due to the increased rates of the biodegradation, the volatilization and the photodegradation[82-84]. Matamoros et al.[82] indicated that a low temperature badly affects the biodegradation kinetics and a low sun irradiation decreases the photodegradation rate. Furthermore, Reyes-Contreras et al.[84] concluded that certain pollutants (e.g., salicylic acid, methyl dihydrojasmonate) which were supposed to be removed by the microbial degradation or the plant-mediated process tended to be eliminated more rapidly in summer than in winter. In addition, Hussain et al.[85] also pointed out the significant correlation between the pollutant removal and the temperature.

The behavior of POPs can be influenced by the pH value which may be a determinant factor for microbiologically mediated processes[86,87]. The strong pH value dependency of the sorption of certain pollutants was reported in a previous study[88]. However, Hijosa-Valsero et al.[87] observed that the pH value did not seem very important in the removal of pharmaceuticals and no significant linear correlation was found between the pH value and the removal efficiencies of any compound. It was indicated that these results could be due to the narrow range of the pH values (6.48-8.34). Similarly, Hussain et al.[85] also concluded that the small range of the pH values (6.8-8.0) in their study made it difficult to verify an observed correlation between the pH value and the removal percentage of organic pollutants. Because the pH value variation has a significant effect on the activities of microorganisms, the removal of POPs by the degradation of microorganisms would be affected accordingly.

The redox potential is also a very important factor which influences the removal efficiency of organic pollutants. High redox potentials are related to aerobic conditions and would induce aerobic metabolic pathways for the degradation of certain pollutants[89]. Matamoros et al.[80] studied the removal effects of three pharmaceuticals (clofibric acid, ibuprofen and carbamazepine) by *Phragmites australis* in two contrasted wetlands with different water depths (0.3 m and 0.5 m). They found that the redox potential was higher in the water in the shallow beds compared to that in the deep beds, and the more oxidizing conditions in the shallow beds could promote more energetically favorable biochemical reactions, leading to a higher removal efficiency of micro-contaminants. Similarly, Hijosa-Valsero et al.[87] observed a positive linear correlation between the redox potential and the removal efficiencies of some organic pollutants.

3.3 *Removal mechanism*

Many kinds of pollutants can be removed from aquatic environments by phytoremediation. The phytoremediation of organic pollutants is a complex process with varied mechanisms. Generally speaking, for the plants, three kinds of mechanisms are involved to remove organic pollutants: (1) to absorb POPs directly, and to turn them into non-toxic metabolites accumulating in the plant tissues, (2) to release enzymes by the plant roots to promote the degradation of POPs, (3) combined effects of plant and rhizosphere microorganisms.

The plant absorption, extraction, transportation and enrichment of POPs are among the important means of the phytoremediation in aquatic environments. Plant roots can absorb POPs directly, which is related to the lipophilicity of the pollutants. After that the absorbed pollutants are transported and accumulated in the plant tissues waiting to be harvested. Cheema et al.[90] studied the absorption and accumulation effects of tall fescue on pyrene and phenanthrene, and demonstrated that the removal of pyrene and phenanthrene through the plant uptake only accounted for 0.18%-2.04% (pyrene) and 0.10%-1.42% (phenanthrene) in their total amounts. Thus we can see that the plant absorption is not the main process to remove POPs from sediments.

Generally speaking, the absorption ability of the plant roots for POPs is smaller than that for degradable organic pollutants and inorganic pollutants. The POP removal by plants mainly depends on the complexation and degradation by the root exudates or the degradation by secretions and enzymes directly[91]. Plants can secrete many materials including carbohydrates, amino acids, fatty acids, sterols, organic acid, auxin, nucleotide and other compounds in the growth processes[92]. These secretions change the physical and chemical conditions of sediments to promote the degradation of POPs. Enzymes secreted by the plant roots can degrade organic pollutants into harmless substance, or completely degrade them into small molecules of CO_2 and H_2O. In addition, some kinds of secretions can provide sufficient carbon and nitrogen sources for the growth of microorganisms and in favor of reproduction and metabolism of microorganisms. Some compounds can also be used as substrates for the microorganism growth, not only favoring the degradation of toxic chemicals, but also stimulating the rhizosphere microorganism activity[93].

The absorption and the degradation of organic pollutants by the plant roots are mainly under the combined effects of microorganisms and plants. The number and the activity of microorganisms in the sediments of the plant root systems are increased 5-10 times (sometimes up to 100 times) over those in the sediments without plants and they accelerate the organic pollutant degradation[94]. In the rhizosphere, the plant roots interact with the microorganisms there and may enhance their degradation activities by supplying them with nutrients from the root exudates[95,96]. In addition, the plant root metabolic activities provide an appropriate micro-environment for the growing microorganisms. The huge surface area of the plant root systems provides habitats for microorganisms, making the number of microorganisms in rhizosphere obviously larger than that in the surrounding areas[97].

4. Effects of vegetation on contaminant removal under hydrodynamic conditions

4.1 *Contaminant release under hydrodynamic conditions*

Contaminant release from the bottom sediments is one of the main problems when the water body is disturbed by an external force. Contaminants are released from the sediments into the overlying water under different hydrodynamic conditions through the pore-water, and the release mechanism can be divided into the convection diffusion, the molecular diffusion and the adsorption/desorption[11]. It is known that the transport process across the sediment-water interface in the static release is dominated by the direct diffusive process, such as the convective diffusion and the molecular diffusion, with a diffusive boundary layer in this process[98]. When the water body is disturbed greatly, the large shear stress near the interface can affect the thickness of the diffusive boundary layer, to influence the transport of contaminants.

Recently, laboratory experiments such as by oscillating grid, annular flume and open water channel were conducted to study the contaminant release from sediments under hydrodynamic conditions. Cheng et al.[11] conducted the flume experiment and found that phosphorus release rates were different at varying flow velocities. The experimental results from Denison et al.[99] show that the dissolved reactive phosphorus concentration decreases with the increase of the flow velocity within a certain velocity range. Nakamura[100] simulated the release of phosphorus from sediment and it is shown that the relationship between the phosphorus release rate and the flow velocity is linear at a low flow velocity. When the flow velocity increases, the liner relationship breaks down. Song et al.[101] investigated the metal release under a static condition and the tidal action condition. They found that the tidal action could accelerate the metal release from sediments significantly, and the average release rate increased 0.77-4.2 times.

4.2 *Vegetation growth under hydrodynamic conditions*

In the aquatic environment, there are strong interactions between the vegetation and the water flow. The existence of the vegetation influences the flow structure significantly, thus affecting the transfer behavior of pollutants. In turn, the changes of the flow structure will also affect the growth of aquatic plants. Then, the growth of plants directly affects the removal of pollutants. In general, the growth of aquatic plants is influenced by some direct factors, such as stretching, breakage, uprooting, as well as some indirect factors, such as the changes in gas exchange, the bed material distribution, the sediment resuspension under hydrodynamic conditions[102]. Both of them affect vegetation growth, development and reproduction in a complex way.

In order to adapt to different hydrodynamic conditions, the vegetation should change its shape to adjust to the increasing flow velocity through flattening close to the substrate, alignment of shoots in the flow direction and compaction of leaves[103]. The growth, development and reproduction of vegetation are all influenced by the water flow directly. For example, some morphological changes, including the reduced plant height, the reduced leaf size and the increased underground organs, frequently observed for plants growing under hydrodynamic conditions[104]. Compared with the direct effects, the plant growth is also affected by the water flow indirectly. Enough light and nutrients are two key factors for plant photosynthesis. Under hydrodynamic conditions, the water turbulence reduces the thickness of the boundary layer and leads to increased nutrients[105], however, the sediment resuspension induced by the water movement can potentially limit the light penetration in the water[106].

4.3 *Contaminant removal by vegetation under hydrodynamic conditions*

Aquatic vegetation is usually considered as a source of the hydraulic resistance in rivers or lakes. In fact, the vegetation also influences the transfer of materials in the aquatic environments. It not only directly affects the exchange of different kinds of materials between water and sediment, but also significantly affects the contaminant removal through changing the flow characteristics such as the flow velocity, the velocity distribution and the turbulence intensity[107]. Wang et al.[13] found that the impact of a submerged vegetation on NH_4-N release should be considered along with the flow intensity. When the flow Reynolds number is relatively small, the submerged vegetation is quite capable of reducing NH_4-N release, when the Reynolds number reaches a certain value, the presence of aquatic plants promotes the NH_4-N release. *Vallisneria spiraslis* L. was used to study the removal effect of nutrients under different hydrodynamic conditions, and it is found that an appropriate flow velocity may promote the removal of TN and NH_4-N from the overlying water[108].

Water turbulence can accelerate the movement of heavy metal ions and enhance the dispersion of solid particles, which is beneficial to the diffusion of heavy metal ions across the sediment-water interface. For the sediments polluted by metals, the water turbulence is beneficial to the metal desorption from sediments. The sediment resuspension often occurs under hydrodynamic conditions. Meanwhile, many kinds of metals are released from the sediment into the overlying water. The vegetation and the adnexed microorganisms can absorb metal ions and adsorb particulate metals. In addition, the vegetation can promote the settlement and flocculation of particulate metals. Ouyang[109] studied the Cu accumulation by *Vallisneria spiraslis* L. under different hydrodynamic conditions, and is is found that the leaves and roots of *Vallisneria spiraslis* L. could absorb more Cu at a larger flow velocity. This may be because the water turbulence damages the barriers of the plant surface, which promotes the absorption of metal ions.

In aquatic environments, the existence of vegetations can change the flow structures in different extents[110,111]. The differences of hydrodynamic conditions result in various removal effects of contaminants. The change of hydrodynamic conditions not only directly affects the contaminant removal by vegetation, but also influences the contaminant removal by changing aquatic environmental factors. For example, the changes of pH value, temperature, dissolved oxygen, suspended particulate matter concentration can affect the adsorption and desorption, flocculation and complexation, dissolution and precipitation processes of pollutants. It is a necessary method to use aquatic plants to remove contaminants from water environment under appropriate hydrodynamic condition. It is well known that the vegetation plays a key role in constructed wetlands. At present, a widely applied practice is to regulate the hydraulic conditions in constructed wetlands to achieve the best removal effects. Luederitz et al.[38] compared the removal effects of TP, TN and organic pollutants in two kinds of wetlands (horizontal flow wetlands and vertical flow wetlands). The constructed wetland systems were used by some researchers to remove heavy metals by means of regulating the hydraulic retention time[55,59].

4.4 *The deficiencies of existing researches and future researches*

At present, many studies focus on the contaminant removal by vegetation in aquatic environments. However, there are still a number of things to be improved in this research field. Firstly, the removal effect and the mechanism of pollutants under the synergistic reactions of plants, secondly, the removal efficiency of pollutants by plants under different hydrodynamic conditions, and thirdly the subsequent treatment of plants which have absorbed abundant pollutants. It is well known that the phytoremediation technology can well improve the water quality. The researches to be suggested in the future are as follows.

(1) The study of the purification abilities of a single aquatic plant, which is far more in consideration than that of the combinations of various plants. The purification abilities of the aquatic plant communities and the interactions between different kinds of plants should be made further study. Using the combinations of various plants to remove contaminants from the aquatic environments should be paid more attention.

(2) The study of the pollutant removal mechanisms of plants, especially, the plant root and microorganism coexistence system. Meanwhile, the knowledge of pedology, botany and molecular biology can be used to study the migration and transformation of elements in the phytoremediation process. Combined remediation technologies including the physical, chemical and biological remediations should be used together to improve the water quality.

(3) Strengthening the screening and cultivation of hyper-accumulation plants. For this purpose, the transgenic technology can be used to obtain plants with strong enrichment ability. In addition, after harvesting the plants absorbed a large amount of pollutants, it needs to be taken into consideration how to recycle or deal with these plants.

(4) Numerical simulations help us to understand the interactions of various factors involved in the phytoremediation process. Although some models were established, the accuracy of the predicted results still needs to be verified. More field and indoor experiments should be conducted to validate and optimize these models.

(5) In the natural rivers and lakes with vegetations, the hydrodynamic conditions usually vary significantly. We should study the removal effects and mechanisms under varying conditions. Then the results can be used for removing contaminants in aquatic environments.

5. Conclusion

This paper reviews the effects of vegetations on the removals of nutrients, metals and organic pollutants in aquatic environments. Three aspects including the removal effects, the influencing factors and the removal mechanisms for these contaminants are discussed. The influences of vegetations on contaminant concentrations in the water column come mainly through restraining contaminant release from the sediments and promoting contaminant removal from water. In addition, the contaminant removal by vegetation under hydrodynamic conditions is discussed. Although the existing researches are abundant, there are still some deficiencies. Aquatic plants play an important role in the water pollution control and remediation. Hence, some directions for future researches are pointed out.

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