Phytoremediation Applications for Waste Water and Improved Water Quality

Klaudia Borowiak and Jolanta Kanclerz

Summary Macrophytes play an important role in natural and constructed wetlands (CWs). Their most important function is removal of excessive levels of some substances, such as nutrients, total suspended solids, trace elements, etc. CWs are widely used all around the world to treat many types of wastewater, with relatively high removal efficiency (5-day biochemical oxygen demand [BOD_5]—around 80 %, total nutrients—approx. 40 % in the case of domestic sewage). Considering the purpose of CWs application, a few types were created with several variants in certain environmental conditions and for many effluent types with various loads of many substances. Two main types of flow through CWs are considered—surface and subsurface flow. The latter is further divided into horizontal and vertical flow. The most popular use of CWs is for domestic and municipal wastewater as secondary and tertiary treatment stages. Among macrophytes applied for phytoremediation, great diversity of plant species has been observed, especially native species and a wide range of ubiquitous species, such as *Phragmites australis* and *Typha* spp. Most macrophyte species also play an important role in natural ecosystems in improvement of surface water quality. Many species are utilized as indicators of water quality, even when low pollutant levels occur, while others are important for phytoextraction or phytostabilization.

Keywords Macrophyte • Constructed wetland • Natural water ecosystems • Nutrient and heavy metals removal

1 Constructed Wetlands

Water plants can contribute to removal/absorption of many substances and significantly improve water quality, both in constructed wetlands (CWs) and natural water ecosystems (NWEs). The list of substances removed from the ecosystem is quite

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long, and includes excess concentrations of nutrients (such nitrogen and phosphorus), organic compounds, suspended solids, various elements (including heavy and noble metals), and pathogens [1]. CWs have been becoming more and more common due to their high removal efficiency and relatively low costs of construction and maintenance [2, 3]. Therefore, in rural areas CWs can be used as an alternative to treat wastewater. Moreover, the growing interest in using CWs can be related to growing recognition of the natural treatment functions performed by wetlands and organisms living in these ecosystems, as well as to increasing costs of conventional treatment systems and to some additional benefits provided by CWs [4]. It has also been reported that CWs are still not widely used in tropical climates due to a lack of knowledge and design criteria that are inappropriate for the local weather conditions. These authors also noted that the climate and local conditions strongly affect the removal efficiencies in constructed wetlands [5]. Hence, there is a great necessity to investigate possibilities of wider use of CWs.

Constructed wetlands initially were mostly used for domestic or municipal sewage from separate and combined sewerage [6]. Presently, they are widely used as small wastewater treatment plants, for purification of storm water runoff [7] or municipal wastewater [2, 8]. Many investigations have been performed for many other types of wastewater, such as cadmium-polluted water [9], pulp and paper industry wastewater [10], highway runoff treatment [11], different land structure conditions such as mountainous areas [4], petrochemical industries wastewater [12], an airport-runoff treatment system [13], dairy effluent [14], pig farm effluent [15], fish-farm effluent [16, 17], horticultural plant nursery runoff [18], agricultural runoff [19], textile industry [20], chemical industry [21], tannery industry [22], landfill leachate [23], and laundry wastewater [24].

Another application of constructed wetlands concerns salt-enriched soils and water. It is a global level problem due to the assessment that 20 % of agricultural land and 50 % of cropland in the world are salt-stressed. Around 1 % of all plant species are halophytes that can complete their life cycle in relatively high saline environments, as much as 200 mM NaCl or more [25]. For the purpose of water phyto-desalination, salt includers are more suitable if they are able to accumulate sodium in their tissues and reduce the media's sodium content and overall salinity [26]. Shelef et al. [27] found that *Bassia indica* can accumulate sodium in the amount up to 10 % of its dry weight, significantly improving water quality.

In the literature there is a discussion on the proper nomenclature for constructed wetlands. Their other proposed name is "treatment wetlands" [28], a term that is also used in scientific papers. Founder and Headley [29] proposed to use the term treatment wetlands (TWs) for wetland systems constructed specifically for water quality improvement for the first time. Moreover, these authors pointed out those also natural or restored wetlands can provide treatment functions. However, they proposed in this case to use the name "natural treatment wetlands" to avoid misunderstanding. The definition of CWs or TWs can be formulated as a human-made system to increase natural water system possibilities to improve or balance physical and/or biochemical processes for further removal of unwanted substances from polluted water [29]. Additionally, Zhang et al. [30] also proposed the term "engineered wetlands" (EWs), which can be used for semi-CWs in which operating conditions are more actively monitored, manipulated and controlled, which allows optimization of operating conditions. All EWs are CWs, but not all CWs can be EWs.

2 Types of Constructed Wetlands

There are several types of CWs designed to work in different conditions using various plant species. The main classification of CWs is related to hydrology and vegetation characteristics. Furthermore, such features as water position, flow direction, media saturation, surface flooding, vegetation traits, vegetative growth form, and emergent vegetation variants can also be taken into account. Considering hydraulic regimes and the life-form of dominating macrophytes, the following types of constructed wetlands can be distinguished:

1. Surface flow wetlands with an exposed free water surface: free-floating macrophyte-based systems; submerged macrophyte-based systems, and rooted emergent macrophyte-based systems.
2. Subsurface flow emergent macrophyte-based systems: with horizontal subsurface flow; with vertical subsurface flow (percolation)—up or down flow direction; fill and drain CWs with mixed flow directions.
3. Complex multi-stage systems—a combination of the above-mentioned and other types of low-technology systems [29, 31].

Based on the literature it is possible to identify many CWs variants (Table 1) depending on hydrology, vegetation, and flow direction. It should be emphasized that the majority of plant species applied in CWs can grow under water-logged (saturation) conditions, whereas some others (e.g., *Salix sp.*) can grow under unsaturated conditions, in which oxygen diffusion from the atmosphere plays an important role in the purification processes.

2.1 Surface Flow Systems

This system is quite similar to natural wetlands due to the occurrence of an open water surface, floating vegetation, and emergent plants. It is also the most common CWs type. There is a horizontal flow direction. Quite high efficiency of removed substances has been demonstrated. It was reported that for total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and pathogens, primarily bacteria and viruses, removal efficiency reaches the level of 70 % [32], while for N and P the level is 40–50 % and 40–90 %, respectively [33]. The real removal efficiency is of course dependent on many factors such as pollutant loading, hydrologic conditions, and vegetation type [32]. The removal of organic compounds is connected with microbiological properties and processes.

Table 1 Scheme of constructed wetland types [29]

Constructed wetlands				
Hydraulics		Vegetation		CWs types
Water position	Flow direction	Sessility	Growth form	
Surface flow		Sessile	Emergent	Surface flow
			Submerged	Surface flow
			Floating leaved	Surface flow
		Floating	Free-floating	Free-floating macrophytes
			Emergent	Floating emergent macrophyte
Subsurface flow	Horizontal			Horizontal flow
	Vertical mixed			Fill and drain
	Vertical Down flow			Down flow
				Stormwater retention
				Evapotranspirative down flow
				Saturated down flow
				Anaerobic down flow
	Vertical Up flow			Up flow
				Non-flooded up flow

Nitrogen removal is connected with anaerobic water conditions through de-nitrification. The phosphorus removal mechanism is peat accumulation by which phosphorus is stored in organic matter and buried through sedimentation [34, 35]. However, chemical precipitation and adsorption of this element to binding sites of sediments plays an important function in removal of P from wastewater [2]. Constructed wetlands also play an important role in elimination of trace elements from effluents. However, the process of heavy metal removal is affected by many environmental factors, such as redox potential, pH, and the availability of several anions (e.g., sulfide and carboxyl groups of organic matter) in wetlands [36, 37]. These factors influence how heavy metals transform and interact with other elements in the environment.

Plants play an important role in nutrient removal, as well as in heavy metal absorption. During the growing season, high accumulation of nutrients is noted in above-ground plant organs. At the senescence stage, most of them are translocated to the below-ground parts. However, these parts are characterized by lower tissue decomposition than shoots, and their nutrients can be stored through burial by litter in a low oxygen environment, where the decomposition rate is relatively slow [38]. Surface flow CWs for phosphorus elimination from wastewater are mainly constructed to be kept flooded for a whole year, and anaerobic conditions result in higher possibility of P storage in sediments. To ensure high efficiency of nitrogen removal, it is necessary to maintain 50 % plant coverage in CWs [39]. There is a huge application variability of surface flow CWs in the world. It has also been emphasized that this type of CWs for municipal wastewater should follow a primary or secondary pre-treatment [2, 40].

Moreover, the post-treatment for disinfection may also be needed for pathogen removal. The primary applications of surface flow CWs are municipal and domestic wastewater, animal wastewater, agricultural, and urban runoff [32, 41]. However, several applications have been investigated for this type of CWs, such as dairy wastewater, pharmaceutical (including antibiotics) and personal care removals, improvement of surface water quality, highly polluted rivers, etc. (Table 2). The important role of surface flow CWs as a polishing step in municipal wastewater reclamation and its reuse is also emphasized. Investigations revealed that tertiary free-water CWs have a potential for efficient removal of fecal coliforms. However, as the authors indicated, the efficiency varied between systems, and further analyses are required to definitely indicate the possibilities of surface flow CWs in this process. Anyway, in some cases the water was suitable to reuse after the treatment in the wetland [2, 59].

The main role of surface flow CWs is removal of excessive amounts of some compounds and substances. There are however some additional applications, such as biodiversity conservation in the ecosystem for this wetland as well as for surrounding areas. Esthetic values and biotic regulation are very important aspects of landscape and nature conservation [60]. Moreover, an occupied area for CWs can be an important avian area for many important and endangered bird species [61]. Additionally, the removed above-ground biomass with high nitrogen nutrient load may also be used for composting or energy generation [62], and can be used as biogas production through fermentation [63].

Several macrophyte species are used in surface flow CWs. The most popular in many countries is common reed (*Phragmites australis* Trix. ex Steudel), which is characterized by very intensive biomass production, absorption of compounds and substances, as well as by the environmental range of occurrence in natural ecosystems. The usefulness in surface flow CWs of this species was found for such types of wastewater as municipal, domestic, industrial, pharmaceutical and personal care product removal, improvement of surface water quality, and highly polluted river. The second most common plant is the cattail group (*Typha* spp.), including *T. latifolia*, *T. orientalis*, and *T. angustifolia*, which were successfully used in wetlands for removal of excess substances from municipal and domestic wastewater, pharmaceutical and personal care products, urban sewage, agricultural runoff, polluted river, and storm water. Also very common is *Lemna* spp., used for various types of effluents. Finally, many geographically specific and native macrophyte species are utilized in surface flow CWs in various countries with high possibilities for removal of unwanted substances and relatively high biomass production (Table 2).

2.2 Subsurface Constructed Wetlands

Subsurface CWs are also widely used in the world. Most of the flow occurs through the porous media, and most treatment processes take place in this part. In some systems ephemeral or permanent flooding of the surface of the media can also occur.

Table 2 Plant species used in surface flow constructed wetlands in various countries and types of wastewater

Plant species	Type of wastewater	Country	Author/s
Alisma lanceolatum, Carex cuprina, Epilobium hirsutum, Iris pseudacorus, Juncus inflexus	Industrial effluents and road runoffs constitute	France, Marignane	Guittonny-Philippe et al. [42]
Phragmites australis	Highly polluted river water	Xi'an, northwestern China	Zheng et al. [43]
Typha latifolia	Stormwater	Canada, Ontario	Goulet and Pick [44]
Lemna minor	Dairy wastewater	East Lansing, USA	Adhikari et al. [45]
Phragmites australis, Typha spp.	Improvement of water quality	Bahr El Baqar, Egypt	El-Sheikh et al. [46]
Brachiaria mutica, Ludwigia taiwanensis, Eichhornia crassipes, Lemna aequinoctialis, Typha orientalis, Phragmites australis, Cyperus imbricatus	Municipal wastewater	New Taipei City, Taiwan	Hsueh et al. [47]
Cyperus flabelliformis, Hymenocallis littoralis, Phragmites australis, Vetiveria zizanioides	Domestic wastewater	Guangzhou, China	Kong et al. [48]
Phragmites australis	Improvement of water quality	Castelnovo Bariano, Italy	Bragato et al. [49]
Phragmites australis, Bolboschoenus maritimus	Improvement of water quality	Venice, Italy	Bragato et al. [50]
Ipomoea aquatic, Typha latifolia Scirpus fluviatilis, Zizania caduciflora, Najas marina, Hydrilla verticillata, Myriophyllum spicatum, Elodea canadensis, Potamogeton crispus, Nelumbo nucifera, Canna indica	Polluted river	Jialu River, China	Wang et al. [51]
Typha sp., *Scirpus* sp.	**Agricultural runoff**	Washington, USA	Beutel et al. [52]
Zizania latifolia	**Secondary effluent from a dormitory**	Mito, Japan	Abe et al. [53]
Phalaris arundinacea, Typha latifolia	**Antibiotic removal**	Quebec, Canada	Hussain et al. [54]
Typha sp., *Phragmites australis*	**Industrial and domestic sewage**	Granollers, Spain	Regueiro et al. [55]
Typha sp., *Phragmites australis*	**Pharmaceutical and personal care removals**	León, Spain	Hijosa-Valsero et al. [56]
Typha latifolia	**Urban sewage**	India	Badhe et al. [57]
Typha latifolia	**Domestic wastewater**	Garip village, Turkey	Gunes et al. [58]

This type of CWs is subdivided into horizontal and vertical concerning the flow direction [64]. Horizontal flow subsurface CWs are the most widely used type in European countries [6] and are characterized by an inlet and outlet which are horizontally opposed. The trench or bed contains a medium which supports growth of emergent vegetation. There are several media used in this type of CWs, such as different soils, sand, gravel, and crushed rocks, alone or in combinations. There are also some investigations concerning the usefulness of other media, such as light-expanded clay aggregates (LECA), zeolite, shale, and industrial wastes, and the investigators found them to be efficient filter materials [65–67]. The wastewater comes through the rhizosphere part of plants, and these systems are usually small, less than 0.5 ha, and characterized by higher hydraulic loading rates than surface flow CWs. The anaerobic conditions mostly occur low in the media, but the subsurface zone is saturated through the root system supporting aerobic micro sites adjacent to roots and rhizomes [29, 31].

The primary pretreated wastewater slowly passes through the media and when it reaches the outlet is collected before discharge via level control management at the outlet. A common horizontal flow subsurface CWs is planned with a filtration depth of 0.6–0.8 m to give an opportunity for plants to grow roots inside the media and properly penetrate the whole bed and ensure oxygenation through oxygen release from roots. The amount of oxygen should be sufficient to achieve aerobic degradation of oxygen-consuming substances in the wastewater, and for nitrification of the ammonium. However, many studies have shown that this type of CWs has quite a low possibility for nutrient removal due to the system's inability to oxidize ammonium, the predominant form of nitrogen in domestic and municipal wastewater, as well as the low sorption capacity of the filtration medium for phosphorus. Also harvesting of aboveground plant organs is optional; hence there is quite a small amount of nitrogen sequestered [68]. However, this type of CWs is sufficient for removal of organics and suspended solids and fulfils the criteria for small sources of pollution. The efficiency of horizontal flow subsurface CWs is approximately at the level of 40 % for nutrients, and around 80 % for total suspended substances, as well as BOD_5 and COD [41]. There is a very important role of soil microbes in removing many substances. As well as soil, enzymatic activity is responsive to the intensity and direction of biological activities in CWs. The mineralization of organic matter is mainly carried out by microbes both under aerobic and anaerobic conditions. Microbes play an important role in nitrogen and phosphorus removal. Hence, their role and activities have been more and more thoroughly investigated in CWs [69].

The most common species for this type of constructed wetland is *P. australis*. However, it is also found that quite often species from the genera *Schoenoplectus*, *Cyperus*, *Typha*, *Baumea*, and *Juncus* are used [29]. *P. australis* is used very often in combination with *Typha* spp. or *Phalaris arundinacea*. The range of wastewater types embraces mainly municipal and domestic sewage. There are however some other uses of these species in horizontal flow subsurface CWs, such as purification of heavy metal rich wastewater, sulfate rich groundwater, or highway runoff. Moreover, some other species were also investigated in this type of CWs for possible removal of excessive substances in pharmaceutical wastewater, urban runoff, dairy effluent, etc. There are several species used in horizontal flow CWs whose range of occurrence is small; hence they are typical only in some countries (Table 3). It has also been reported that mixed vegetation is more effective in pollutant removal as compared to stands of single species [84, 85]. However, this subject is still being discussed and investigated.

Table 3 Plant species used in subsurface flow constructed wetlands in various countries, types of wastewater, and type of flow direction

Plant species	Type of wastewater	Country	Author/s	Flow direction
Cyperus alternifolius, Cynodon dactylon	Refining and petro-chemical company effluent	Kaduna, Nigeria	Mustapha et al. [70]	Vertical
Phragmites australis, Typha spps., *Canna indica*	Municipal	Turkey, Edirne Province	Çakir et al. [71]	Horizontal
Phalaris arundinacea, Phragmites australis	Mechanically pre-treated municipal sewage	Czech Republic, Morina and Cicenice	Brezinová and Vymazal [72]	Horizontal
Typha latifolia, Phragmites australis, Colocasia esculenta	Urban wastewater	Haridwar, India	Rai et al. [73]	Horizontal
Phragmites australis, Typha angustifolia, E. arundinaceus	Pulp and paper industry	India, Karur	Arivoli et al. [10]	Vertical
Acorus calamus	Domestic wastewater	China	Chen et al. [1]	Vertical
Phragmites spp.	Highway runoff treatment	Nanjing city, China	Singh et al. [11]	Vertical
Cyperus alternifolius Typha latifolia	Urban wastewater	Sicily, Italy	Leto et al. [74]	Horizontal
Phragmites australis	Sulfate-rich groundwater	Germany	Chen et al. [59]	Horizontal
Phragmites australis	Domestic wastewater	France	Silveira et al. [75]	Vertical
Typha angustifolia	Pharmaceutical compounds	Singapore	Zhang et al. [76]	Horizontal
Schoenoplectus, Tabernaemontani, Bidens comosa	Dairy wastewater	East Lansing, USA	Adhikari et al. [45]	Horizontal
Phragmites australis	Domestic wastewater	Ain, France	Morvannou et al. [77]	Vertical
Phragmites australis	Heavy metal-rich wastewaters	Belgium	Lesage et al. [78]	Vertical, horizontal
Phalaris arundinacea, Phragmites australis	Municipal sewage	Morina, Czech Republic	Vymazal et al. [8]	Horizontal
Bassia indica	Salt phytoremediation	Midreshet Ben Gurion, Israel	Shelef et al. [26]	Vertical
Arundo donax, Acorus calamus	Micro-polluted river water	Chongqing, China	Huang et al. [69]	Horizontal
Panicum maximum	Domestic wastewater	Côte d'Ivoire	Pétémanagnan Ouattara et al. [79]	Vertical
Typha domingensis	Mercury enriched wastewater	Trȩs Marias, Brasil	Teles Gomes et al. [80]	
Phragmites australis, Typha latifolia	Municipal wastewater	Greece	Akratos et al. [81]	Horizontal
Phalaris arundinacea Phragmites australis	Municipal wastewater	Ceske Bud˘ejovice, Czech Republic	Vymazal et al. [82]	Horizontal
Typha orientalis, Arundo donax, Canna Indica, Pontederia cordata	Domestic wastewater	Wuhan City, China	Chang et al. [83]	Vertical

Vertical flow subsurface constructed wetlands were first designed as pre-treatment units before wastewater treatment in horizontal flow beds [82]. There are several types of vertical flow subsurface CWs, which are categorized according to downward flow, upward flow, and combinations of these, which are called mixed flow. The vegetation is always emergent [29]. The system consists of vertical flow through several beds and discharge via a drain [31]. The structure of vertical flow CWs usually comprises a flat bed of graded gravel topped with sand planted with macrophytes. The size fraction decreases to the top of the bed (from ca. 30–60 mm to ca. 6 mm) to facilitate the uniform distribution of applied sewage [29]. Vertical flow constructed wetlands (VFCWs) are popular when the nitrogen forms contained in wastewater have to be nitrified.

In the down flow the system remains unsaturated for most of the time. Pipes distribute the flow across the surface of the bed. Surface flooding should be avoided. The bottom layers with coarse media usually consist of a network of perorated drainage pipes, which promote ventilation for passive aeration of the substrate. The second type of vertical CWs is up flow with a constantly saturated medium which is permanently flooded over the surface. Wastewater is distributed from the bottom of the bed through the series of pipes and afterward is moved slowly to the surface of bed. The last type of vertical flow CWs is fill and drain, which is a mixture of upward and downward flow directions. The flow can sometimes be close to a diagonal direction. The sequences of filling and draining are the reason for the occurrence of saturation and instauration periods of the bed. The upper surface is usually not flooded. The system is a very good solution to complete nitrogen removal in one reactor, through ammonia adsorption on the medium during the filling stage, nitrification in aerobic conditions during the draining phase, and de-nitrification with anaerobic condition in the next filling stage [86].

Concerning possibilities of application, vertical flow CWs are mostly applied for municipal and domestic wastewater treatment. There are, however, many other applications, such as salt phytoremediation, highway runoff, pulp and paper industry, refinery, and petrochemical company effluent (Table 3). Several applications of vertical flow subsurface CWs can be observed, which are especially common in the USA, Australia, and New Zealand with down flow direction. This system in European countries is especially useful for achieving the secondary treatment of pre-treated sewage. This system is also more common for removal of higher concentrations of ammonium, due to higher oxygen transfer rates. The up flow vertical CWs are applied to provide anaerobic conditions. They can be sufficient for removal of total suspended solids and organic compounds. Hence, their applications include mining and industrial wastewater. The fill and drain systems can be applied for wastewater with high oxygen demands or high nitrogen removal. Moreover, due to lower loss of evapotranspiration they are more suitable in arid regions [29].

The vertical flow CWs can provide complete nitrification and promote the mineralization of organic matter [87], but do not provide de-nitrification. It would be sufficient to use a combined vertical and horizontal CWs system [88]. However, it requires space and can be costly. There is variation of macrophyte species used for vertical flow CWs, beginning with *P. australis* and *Typha* spp. and including various native wetland species, as well as those whose range of countries is wide (Table 3).

3 Macrophyte Function in Surface Water Quality Improvement

Natural water ecosystems are a type of sink for surrounding areas; hence elevated amounts of some elements and substances can be noted. Almost three-quarters of water in rivers, lakes, and wetlands are threatened by excessive levels of organic pollutants and trace elements, which furthermore are also a threat to macrophytes and phytoplankton [89]. The wetland systems may play a role of natural filters for the abatement of heavy metals [49]. There is a well-known role of macrophytes in removal of excess levels of nutrients [90–92]. Plants can also survive some concentrations of heavy metals. Some mechanisms have already been described. It is known that plant rhizospheric secretion of various organic acids, aided by plant-producing chelating agents, pH changes, and redox reactions, are able to solubilize and accumulate trace elements at low levels, even from nearly insoluble precipitates [93]. It is also known that plants tolerant of metal contamination are able to segregate toxic elements in the root cortical tissue outside the endodermis, thereby preventing or reducing translocation to other parts of the plants [94]. Using vegetation to remove, detoxify, or re-stabilize polluted sites has been a widely accepted tool in developed countries for cleaning such polluted water as it regenerates the original water permanently [95].

Heavy metal accumulation varies between plant species and even among morphologically similar species growing in the same area [96]. Most of them have a toxic effect on the plant life cycle and biochemical processes. There is however a group of trace elements which are necessary for proper plant functioning. The dual role elements include zinc, copper, and nowadays nickel, which are necessary for many metabolic/biochemical processes, including enzyme activity. Hence, some amount in the environment is necessary, while an excess can result in a negative plant response, including faster senescence and lower growth. Other heavy metals, such as cadmium, chromium and lead, are non-essential and extremely toxic to plants even at low concentrations. Moreover, there has also been observed a synergistic effect of several trace elements on plants, such as Cd and Pb [97]. It is important to recognize macrophyte species with higher efficiency to tolerate or even resistant to elevated concentrations of heavy metals in the water and sediment. A plant which accumulates higher levels of the contaminant in its harvestable sections (leaves and stems) is considered as a good candidate for phytoextraction, while a species which restricts the accumulation to its roots will be useful for stabilization of the contaminated environment, reducing human health and environmental hazards by a different and protective strategy, which is called phytostabilization [98].

Several investigations have proved that many species of macrophytes revealed features of phytostabilization in their natural habitat, which is very important from a practical point of view, due to possibilities of their usefulness while avoiding depletion of a specific plant population [99]. Moreover, phytoextraction can be very worthwhile, because some species have been proved to remove and translocate to above-ground plant parts some precious metals, such as gold, under certain circumstances [99]. Knowledge about the accumulation properties of wetland plant species is useful in choosing appropriate plants for wetland phytoremediation systems. There have also been conducted investigations confirming the water cleaning abilities shown by littoral plants, which can keep heavy metals away from bank zones and can protect water against human pressure on the bank zone. Littoral plants can be used as heavy metal bioindicators and/or as buffers against the spread of heavy metals over large areas in a freshwater environment. Besides the important role of macrophytes as accumulators and cleaning functions in the case of high trace element concentrations, they can also indicate the level of water contamination even when low concentrations occur [100, 101].

Investigations concerning possibilities for use of macrophytes in removal of trace elements from the environment are widely conducted, using plants naturally grown in water ecosystems as well in constructed wetlands. There are however many doubts concerning translocation of elements in plant bodies. Studying the range of macrophyte species revealed the high possibilities of accumulation and wide range of trace element translocation among plant species. Some investigators also suggest that mobility of elements in a plant is closely related to concentration ratios between certain trace elements (Table 4). Regarding uptake and translocation issues of trace elements, it is also important to remember that this depends on physicochemical processes, such as metal solubility, water temperature, and pH. Temperature and pH may change in both a spatial and a temporal manner. Seasonal changes increase the pH and decrease the metal solubility [116].

Table 4 Plant species and their accumulation potential in plant organs for trace elements in various countries and types of wetlands

Plant species	Country	Trace elements	Organs with higher accumulation, translocation or elements mobility	Type of ecosystem	Author/s
Typha angustata L.	India	Mn, Cu, Zn, Cr, Ni, Pb	Roots	Constructed wetland	Bose et al. [102]
Phragmites australis	Belgium	Al, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn	Belowground parts, except Mn	Constructed wetlands	Lesage et al. [78]
Spartina alterniflora, *Phragmites australis*	USA	Hg, Cu, Zn, Cr, Pb	Hg, Cr higher in leaves of *S. alterniflora* Cu, ZN higher in leaves of *P. australis*	Contaminated low marsh	Windham et al. [103]
Rubus ulmifolius, *Phragmites australis*	Portugal	Zn	Roots, poor translocation	Contaminated soil	Marques et al. [98]
Schoenoplectus lacustris, *Phragmites australis*	Turkey	Pb, Cr, Cu, Mn, Ni, Zn, Cd	Root accumulation except Cr	Lake Sapanca	Duman et al. [96]
Phragmites australis	Italy	Cu, Zn, Ni, Cr	Similar or higher accumulation in leaves	Constructed wetland	Bragato et al. [49]
Phragmites australis	Italy	Cr, Cu, Fe, Mn, Ni, Pb, Zn	Except Zn, higher levels in roots	Volcanic lake	Baldantoni et al. [104]
Potamogeton pectinatus, *Myriophyllum verticllatum*	Poland	Cd, Pb, Zn	Transport to leaves	River Przemsza	Lewander et al. [105]
Phragmites australis, *Phalaris arundinacea*	Czech Republic	Cu, Cr,	Roots as a filter for trace elements	Natural and constructed wetlands	Vymazal et al. [8]
Typha latifolia, *Phragmites australis*	China	Pb, Zn	Translocation from roots to shoots	Six wetlands	Deng et al. [106]
Phragmites australis, *Potamogeton natans*, *Iris pseudoacorus*, *Phalaris arundinacea*, *Carex remota*, *Calamagrostis epigeios*	Poland	Al, Ba, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sr, Zn	Only leaves were measured. Elevated level of Cd, Co, Cr, Cu, Mn	Anthropopgenic lakes	Samecka-Cymerman and Kempers [107]
Phragmites australis	USA	Cu, Zn, Pb, Cd, Fe	Transport of Pb and Zn to aboveground parts	Constructed wetland for landfill leachate treatment	Peverly et al. [108]
Salix spp., *Carex rostrata*, *Eriophorum* sp., *Phragmites australis*	Sweden	Cd, Cu, Zn, Pb, As	Most plants keep elements in roots, except *Salix sp.*	Submerged tailings impoundment	Stoltz and Greger [109]
Typha angustifolia, *Potamogeton pectinatus*	Turkey	Cd, Pb, Cr, Ni, Zn, Cu	High translocation of all elements, however *P. pectinatus* transported much higher Zn to leaves	Natural wetland	Demirezen and Aksoy [110]
Najas marina, *Potamogeton lucens*, *Nuphar lutea*, *Potamogeton nodosus*	Slovenia	As, Ni, Pb, Cr	Pb stays in roots, Ni relatively high mobility to upper parts of N. lutea	Artificial lake	Mazej and Germ [111]
Phragmites australis	Czech Republic	Al, Fe, Mn, Ba, Zn, Cd, Hg	Small mobility of Cd, while very high mobility of Zn	Constructed wetlands for treatment of municipal wastewater	Vymazal et al. [112]
Typha latifolia	Turkey	Zn, Mn, Cr	High Zn mobility to above parts of plants	Steam carrying secondary effluent	Sasmaz et al. [113]
Phragmites australis	Italy	Cd, Cr, Cu, Hg, Mn, Ni, Pb, Zn	High accumulation in all plant organs	Mouth area of the river	Bonanno and L Giudice [114]
Phragmites australis, *Typha angustifolia*	Poland	Cd, Pb, Zn, Cu	*T. angustifolia* revealed higher Cd translocation potential than *P. australis*, Pb and Cd stayed in rhizomes, Zn mobility	Natural and artificial lakes	Drzewiecka et al. [100], Drzewiecka et al. [101], Borowiak et al. [115]

An important issue in using macrophytes in CWs is to remember about the period of acclimation to certain loads of treated wastewater, such as a feeding day with a new type of wastewater prior to starting a real dose. Low strength wastewater was provided [117]. It is important to use native plants of the contaminated site for phytoremediation because these plants adapt better in terms of survival, growth, and reproduction under environmental stresses than those introduced from another environment. There has been continuing interest in searching for native plants that are tolerant of heavy metals. *P. australis* is the most widely distributed wetland plant species throughout the world. Moreover, it is known that this species grows very well in unpolluted ecosystems, as well as in polluted ones, e.g., by heavy metals. As mentioned before, this species is widely used as a main species for constructed wetlands. Moreover, several investigations have revealed the capacity of this species for removal of many trace elements from natural water ecosystems. *P. australis* is not a hyperaccumulator; however, due its high growth ratio and high biomass production, deep root system and tolerance to higher trace element concentrations in the environment, it can be treated as a plant for reduction of metal concentration in soils, sediments, and waters in natural and constructed wetlands [49].

Several investigations confirm its role as a great accumulator and bioindicator and its removal potential for both natural water ecosystems and constructed wetlands all around the world. However, various results were obtained concerning mobility/translocation of heavy metals from below- to above-ground plant organs. This discussion concerns especially the mobility potential of Cd and Pb, while in the case of zinc most investigations indicated a high translocation possibility. Possibly this is also connected with the dual role of this element and association with the concentration of other elements in the environment, such as Cu (Table 4). Other common species in natural water ecosystems are *Typha angustifolia* and *Typha latifolia*. Both species are already also well known as successful plants used in constructed wetlands as removal plants for heavy metals, such as Pb/Zn mine tailings. These species are resistant to stress factors in the polluted environment and have the capability to accumulate heavy metals in their tissue from contaminated wastewater [118]. *Typha angustifolia* is a perennial macrophyte that has an ability to produce large amounts of biomass and can grow rapidly [119]. The investigations in natural ecosystems revealed that *Typha* spp. has the ability to extract Pb, Cd, Cr, Mn, and Fe from their water surroundings [120]. Recent investigations based on calculation of the accumulation factor and translocation factor led to the conclusion that this species would be most appropriate for use in phytostabilization [121].

The above-mentioned macrophyte species are the most widely used and investigated. However, several other species are widely used, and their capacity for removal of excessive levels of many compounds and substances is also highly evaluated. Hence, it is extremely important to keep natural water ecosystems in a good condition in order to maintain the state of our environment and health, as well as for their esthetic values.

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