Chapter 10
Constructed Wetlands: Role in Phytoremediation of Heavy Metals

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10.1 Constructed Wetlands: Importance and Types

Constructed wetlands (CWs) are engineered systems that are designed and constructed to utilize the natural processes, involving wetland vegetation, soils, and their associated microbial assemblages to assist in treating wastewater [1]. According to the Interstate Technology Regulatory Council Wetlands Team, USA (ITRC) [2], constructed wetlands (CWs) are "*engineered systems, designed and constructed to utilize the natural functions of wetland vegetation, soils and their microbial populations to treat contaminants in surface water, groundwater or waste streams.*" Synonymous terms for constructed wetlands include man-made, engineered, and artificial wetlands. The first full-scale constructed wetland (CW) for wastewater treatment was built at Petrov near Prague in May 1989. Constructed wetlands are a cost-effective and technically feasible approach to treating wastewater and runoff. The constructed wetland provides a natural environment of warm climate, high water table, and high organic matter for microbes to break down contaminants [3].

The use of constructed wetlands for wastewater treatment is becoming more and more popular in many parts of the world. Today, subsurface flow constructed wetlands are quite common in many developed countries, such as Germany, the UK, France, Denmark, Austria, Poland, and Italy [4]. Constructed wetlands are also appropriate for developing countries but due to lack of awareness their use is not widespread [5–7]. Constructed wetlands can be less expensive to build than other treatment options. Operation and maintenance expenses (energy and supplies) are low and require only periodic, rather than continuous monitoring. Constructed wetlands are primarily used to treat domestic municipal wastewaters, but their use for other types of wastewaters such as agricultural and industrial

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wastewaters, various runoff waters, and landfill leachate have become more frequent [8–10].

Mitsch [11] suggests the following guidelines for creating successful constructed wetlands:

1. Keep the design simple. Complex technological approaches often invite failure.
2. Design for minimal maintenance.
3. Design the system to use natural energies, such as gravity flow.
4. Design for the extremes of weather and climate.
5. Design the wetland with the landscape, not against it.
6. Integrate the design with the natural topography of the site.
7. Avoid over-engineering the design with rectangular basins, rigid structures and channels, and regular morphology. Mimic natural systems.

10.1.1 Types of Constructed Wetlands

The classification of constructed wetlands is based on various factors, such as the vegetation type, hydrology, and flow of direction (vertical or horizontal) [12]. There are mainly three types of constructed wetlands: surface flow wetlands, subsurface flow wetlands, and hybrid systems.

10.1.1.1 Surface Flow Wetlands

In case of surface flow wetlands, water level is above the ground surface; vegetation is rooted and emerges above the water surface: water flow is primarily above ground. The different macrophytes that are used in this type of constructed wetlands include *Phragmites australis, Typha ungustifolia, Sparganium erectum* etc.

10.1.1.2 Free Floating Macrophyte-Based Wetlands

In this type of constructed wetlands, floating macrophytes are used. The main floating macrophytes used in these systems are *Azolla cristata, Salvinia natans*, water hyacinth *Eichhornia crassipes and* duckweeds [13]. The different submerged species used in these constructed wetlands prevent entry of light into the system thereby inhibiting the growth of different algal groups. Hence the macrophytes need to be periodically removed from the wetland. The floating plant mat blocks out sunlight, thereby preventing photosynthesis and inhibiting algae growth hence the macrophytes need to be periodically removed from the system [14]. Duckweeds are extremely invasive and grow in most environments [15].

10.1.1.3 Submerged Macrophyte-Based Wetlands

In these constructed wetlands there are used different kinds of submerged macrophytes. The main submerged species used in these constructed wetlands include *Ceratophyllum demersum, Hydrilla* sp., *Potamogeton* sp. etc. They have been proposed as final polishing steps following primary and secondary treatment [16].

10.1.1.4 Emergent Macrophyte-Based Wetlands

In this type of constructed wetlands, emergent macrophytes are used. Emergent macrophyte-based wetlands are the most common type of constructed wetlands. The different emergents used in these constructed wetlands include *Juncus effusus, Phregmites australis, Typha ungustifolia, Sparganium erectum* etc. [17, 18, 19]. A slow flow rate is applied so that a shallow depth is maintained [20].

10.1.1.5 Subsurface Flow Wetlands

They are also called vegetated submerged beds, or plant-rock filter systems. They have below ground water level. The basin mainly consists of sand or gravel. The different macophytes used in this type of constructed wetlands include *Glyceria maxima, Iris pseudacorus, Phragmites australis, Typha ungustifolia, Sparganium erectum* etc.

10.1.1.6 Horizontal Flow Constructed Wetland (HF CWs)

This type of constructed wetland was developed in the 1950s in Germany by Käthe Seidel [12]. This type of constructed wetland consists of rock or gravel beds, impermeable layer and wetland vegetation. Waste water afer entering through the inlet passes through the horizontal path before it is discharged through the outlet. Hence the name horizontal flow constructed wetland.

10.1.1.7 Vertical Flow Constructed Wetlands (VF CWs)

In this type of constructed wetland water percolated down through sand medium. Among different kinds of constructed wetlands this type of constructed wetland has very high operational costs.

10.1.1.8 Free Water Surface Constructed Wetland (FWS CW)

This type of constructed wetland consists of a series of impermeable bains about 20–40 cms deep. In this type of constructed wetland the main macrophytes planted include emergents like *Phragmites australis, Typha ungustifolia, Sparganium erectum* etc.

10.1.1.9 Constructed Wetlands with Floating Leaved Macrophytes

Constructed wetlands with floating leaved macrophytes are very rare, and there are no guidelines to design, operate, and maintain these systems [1]. In these systems, the different plants used are *Nelumbo nucifera* [21, 22] and *Nuphur lutea* [23].

10.1.1.10 Hybrid Systems

Different types of constructed wetlands may be combined with each other in order to exploit the specific advantages of the different systems. In hybrid or multistage systems, different cells are designed for different types of reactions. During the 1990s, HF-VF and VF-HF hybrid systems were introduced [24]. Hybrid systems are used especially when removal of ammonia-N and total-N is required [1].

10.1.2 How Constructed Wetlands Work

Constructed wetlands are made up of a series of ponds each designed to perform a particular function. Solids are allowed to settle in the primary storage ponds. The water then enters another pond containing vegetation. Here physical, chemical, and biological reactions reduce contaminants. Nitrogen and phosphorus are used by aquatic vegetation. Heavy metals are also removed by different plants which show tolerance for these metals. Water then enters the tertiary cell. It serves as a habitat for wildlife.

10.1.3 Costs for Creating Constructed Wetlands

The main requirements for establishing constructed wetlands include land, design, vegetation, hydraulic control system and fencing. The total investment costs for establishing constructed wetlands vary from county to country and could be as low as 29 USD per m^2 in India [25] or 33 USD per m^2 in Costa Rica [26], or as high as 257 EUR per m^2 in Belgium [27].

For the development of constructed wetlands, the basic requirements are containers, plant species, sand, and gravel media in certain ratio. In different types of constructed wetlands microbes and other invertebrates develop naturally [28]. The three types of macrophytes that are used in constructed wetlands are floating macrophyte (i.e., *Azolla sp., Salvinia natans*, *Lemna* spp. or *Eichhornia crassipes*), submerged macrophyte (i.e., *Ceratophyllum demersum, Potamogeton* sp. *Elodea canadensis*) and rooted emergent macrophyte (i.e., *Phragmites australis, Typha* spp. *Sparganium erectum* [29]). Plants (free-floating, emergent or submergent vegetation) are the part of constructed ecosystem to remediate contaminants from municipal, industrial wastewater, metals, and acid mine drainage [30]. The different macrophytes that are used in subsurface flow CWs in warm climates are Papyrus sedge (*Cyperus papyrus*), Umbrella sedge (*Cyperus albostriatus* and *Cyperus alternifolius*), Dwarf papyrus (*Cyperus haspens*), Bamboo, smaller ornamental species, Broad-leaved cattail (*Typha latifolia),* Species of genus—*Heliconia:* lobster-claws, wild plantains—*Canna:* Canna lily—*Zantedeschia:* Calla lily Napier grass or Elephant grass (*Pennisetum purpureum*).

10.2 Heavy Metals: Sources and Impacts

Constructed wetlands are designed for the removal of different kinds of pollutants including heavy metals from the wastewater. Heavy metals released from different sources enter into the water bodies and pose serious threats to different trophic levels of the food chain including human beings. Heavy metals are metals having a density of 5 g/cm^3 [31]. Heavy metals include a category of 53 elements with specific weight higher than 5 g/cm^3 [32, 33]. Heavy metals are elements with metallic properties and an atomic number >20. Heavy metals mainly include the transition metals, some metalloids, lanthanides, and actinides. The most common heavy metal contaminants are As, Cd, Cr, Cu, Hg, Pb, and Zn.

Over population, industrialization, rapid urbanization, overuse of pesticides, detergent and agricultural chemicals, liquid and solid waste products, and discharge of municipal wastes resulted in heavy metal pollution of natural water resources [34]. Man-made activities such as mining and smelting of metal ores, industrial, commercial, and domestic applications of insecticides and fertilizers have all contributed to elevated levels of heavy metals in the environment [35, 36].

The primary sources of metal pollution are the burning of fossil fuels, mining and smelting of metalliferous ores, municipal wastes, sewage, pesticides, and fertilizers [37] oil, gasoline and coal combustion, smelting, and refuse incineration [38]. In uncontaminated soil, the average concentrations of heavy metals vary in orders of magnitudes, but on average the concentrations are, e.g., Zn: 80 ppm, Cd: 0.1–0.5 ppm and Pb: 15 ppm. However, in polluted soil dramatically higher concentrations are found, e.g., Zn: >20,000 ppm, Cd: >14,000 ppm and Pb: >7000 ppm (http://www.speclab.com/elements/). Heavy metals are ubiquitous environmental pollutants that arise from a variety of industrial, commercial, and domestic activities

[36]. Increasing industrial activities have led to an increase in environmental pollution and the degradation of several aquatic ecosystems with the accumulation of metals in biota and flora [39]. According to Phuong et al. [40], most heavy metal contaminants originate from anthropogenic sources such as long-term discharge of untreated domestic and industrial wastewater runoff, accidental spills, and direct soil waste dumping. In addition, heavy metals can enter the water bodies through atmospheric sources [41] and nearby rice fields [42]. Due to innovations in mining and metal-working techniques during ancient times, the close relationship between metals, metal pollution, and human history was formed [43]. Energy intensive and chlor-alkali industries for the manufacture of agrochemicals deteriorate the water quality of lakes and reservoirs due to the discharge of various pollutants, especially a range of heavy metals [44]. Coal mining [45] and its allied/dependent industries (thermal power plants) are major sources of heavy metals in the industrial belts of developing countries such as India [44, 46]. Metals are natural components in soil [47]. Lead is a common pollutant from road runoff. Zinc is a common metal present in variable amounts and if found in appreciable amounts can be an indicator of industrial pollution. While copper is also an indicator of industrial contamination of urban waters [48, 49]. The different macrophytes have a potential to sequester heavy metals from the soils contaminated with these metals. Colonization of macrophytes on the sediments polluted with heavy metals and the role of these plants in transportation of metals in shallow coastal areas are very important [50].

Contamination of aquatic environment by heavy metals is a serious environmental problem, which threatens aquatic ecosystems, agriculture, and human health [51]. Accumulation of metals and their toxic effects through the food chain can lead to serious ecological and health problems [52]. Heavy metals are the most dangerous contaminants since they are persistent and accumulate in water, sediments and in tissues of the living organisms, through two mechanisms, namely "bioconcentration" (uptake from the ambient environment) and "biomagnification" (uptake through the food chain) [53]. Trace elements such as Cu, Fe, Mn, Ni, and Zn are essential for normal growth and development of plants. They are required in numerous enzyme catalyzed or redox reactions, in electron transfer and have structural function in nucleic acid metabolism [54]. Metals like Cd, Pb, Hg, and As are not essential [55]. High levels of Cd, Cu, Pb, and Fe can act as ecological toxins in aquatic and terrestrial ecosystems [56, 57]. Excess metal levels in surface water may pose a health risk to humans and to the environment [50]. Since HM are not biodegradable and may enter the food chain, they are a long-term threat to both the environment and human health [58]. Some of these metals are micronutrients necessary for plant growth, such as Zn, Cu, Mn, Ni, and Co, while others have unknown biological function, such as Cd, Pb, and Hg [59]. Metal pollution has harmful effect on biological systems and does not undergo biodegradation. Toxic heavy metals such as Pb, Co, and Cd can be differentiated from other pollutants, since they cannot be biodegraded but can be accumulated in living organisms, thus causing various diseases and disorders even in relatively lower concentrations [60]. Heavy metals, with soil residence times of thousands of years, pose numerous health dangers to higher organisms. They are also known to have effect to plant growth, ground cover, and have a negative impact on soil microflora [61]. It is well known that heavy metals cannot be chemically degraded and need to be physically removed or be transformed into nontoxic compounds [59]. Table 10.1 shows the harmful effects of different heavy metals on living organisms.

10.3 Role of Constructed Wetlands in Phytoremediation

The use of wetlands for quality improvement of wastewater, referred to as rhizofiltration, is the best known and most researched application of constructed wetlands. Flooding of wetland sediments leads to rapid denitrification because of anoxic conditions; therefore, wetland soils contain low levels of nitrate [62]. CWs have proven successful for remediating a variety of water quality issues, with advantages over the natural wetland, Constructed wetland (CWs) thus designed to take advantage of natural wetland systems, but do so within a more controlled way. The plants most often used in CWs are persistent emergent plants, such as bulrushes (*Scirpus*), spikerush (*Eleocharis*), and other sedges (*Cyperus*), Rushes (*Juncus*), common reed (*Phragmites*), and cattails (*Typha*). Plants for CWs must be able to tolerate continuous flooding and exposure to waste streams containing relatively high and often variable concentrations of pollutants. The functions of wetland plants make them an important component of CWs. Plants contribute to contaminant removal by altering hydrology, sequestering particulates, and accumulating pollutants [63]. These processes can be utilized to design CWs with a number of treatment approaches, which are mainly phytoextraction, rhizofiltration, and phytostabilization.

Some other macrophytes that are used in wetlands for the removal of heavy metals include *Acorus calamus, Carex* spp. (sedges), *Cyperus* (sweet manna grass), *Juncus* sp. (Rushes)*, Phalaris arundinacea* (reed canary grass), *Phragmites australis* (common reed), *Sagittaria* (arrow heads), *Scirpus* sp. (Balrushes), *Sparganium* sp. (bur reeds), *Spartina* spp. (cordgrasses), *Typha* sp. (cattails), *Ziznia aquatic* (wild rice), *Ceratophyllum* sp. (coontails), *Eggeria densa* (Brazilian waterweed), *Hydrilla verticillata* (Hydrilla), *Isoetes* sp. (Quillworts), *Myriophyllum* spp. (water milfoils), *Najas* spp. (water nymphs), *Potamogeton* sp. (pond weeds), *Urticularia* spp. (bladderworts), *Lemna* spp. (duckweed), *Azolla* (aquatic fern) and *Hydrocharis* (frog bit). These macrophytes are highly beneficial to aquatic ecosystems because they provide food and shelter for fish and aquatic invertebrates, wildlife also produce oxygen, which helps in overall lake functioning [50]. Macrophytes are considered as important components of the aquatic ecosystems not only as food source for aquatic invertebrates, but they also act as an efficient accumulator of heavy metals [64, 65]. Aquatic plants sequester large quantities of metals [66–68]. Trace element removal by wetland vegetation can be greatly enhanced by the judicious selection of appropriate wetland plant species. Selection is based on the type of elements to be removed, the geographical location, environmental conditions, and the known accumulation capacities of the species.

Table 10.1 Harmful effect of different heavy metals on living organisms

Heavy metal	Harmful effects	References
As	It interferes with oxidative phosphorylation and ATP synthesis	Tripathi et al. [79]
Cd	Inhaling Cd leads to respiratory and renal problems. It also interferes with calcium regulation in biological systems; causes chronic anemia. It is also carcinogenic, mutagenic, and teratogenic; endocrine disruptor	Salem et al. [80] and Awofolu [81]
Cr	It can result in gastritis, nephrotoxicity, and hepatotoxicity. Chromium toxicity causes hair loss	Salem et al. [80] and Paustenbach et al. [82]
Cu	Excessive free copper impairs zinc homeostasis, and vice versa, which in turn impairs antioxidant enzyme function, increasing oxidative stress. It causes brain and kidney damage, liver cirrhosis and chronic anemia, stomach and intestinal irritation	Salem et al. [80], Wuana and Okieimen [83], and Sandstead [84]
Hg	Anxiety, autoimmune diseases, depression, difficulty with balance, drowsiness, fatigue, hair loss, insomnia, irritability, memory loss, recurrent infections, restlessness, vision disturbances, tremors, temper outbursts, ulcers and damage to brain, kidney, and lungs. Toxic effects include damage to the brain, kidneys, and lungs. Mercury poisoning can result in several diseases, including acrodynia (pink disease), Hunter-Russell syndrome, and Minamata disease	Neustadt and Pieczenik [85], Ainza et al. [86], and Gulati et al. [87], Clifton [88], Bjørklund [89], Tokuomi [90], and Davidson [91]
Pb	Exposure to lead produces deleterious effects on the hematopoietic, renal, reproductive, and central nervous system, mainly through increased oxidation. Its poisoning causes problems in children such as impaired development, reduced intelligence, loss of short-term memory, learning disabilities, and coordination problems; causes renal failure; increased risk for development of cardiovascular disease	Flora et al. [92], Salem et al. [80], Padmavathiamma and Li [93], Wuana and Okieimen [83] and Iqbal [94]
Zn	Long-term excessive zinc intakes (ranging from 150 mg/day to 1–2 g/day) have included sideroblastic anemia, hypochromic microcytic anemia, leukopenia, lymphadenopathy, neutropenia, hypocupremia, and hypoferremia. Over dosage can cause dizziness, nausea, vomiting, epigastric pain, lethargy, and fatigue	Hess and Schmid [95] and Fosmire [96]
Mn	Neurological effects in humans and animals and causes disabling syndrome called *manganism*. It also causes lethargy, increased muscle tonus, tremor, and mental disturbances	USEPA [97] and Kawamura [98]

Macrophytes are unchangeable biological filters and play an important role in the maintenance of the aquatic ecosystem. Aquatic macrophytes are taxonomically closely related to terrestrial plants, but are aquatic phanerogams, which live in a completely different environment. Their characteristics to accumulate metals make them an interesting research objects for testing and modeling ecological theories on evolution and plant succession, as well as on nutrient and metal cycling [69]. Many industrial and mining processes cause heavy metal pollution, which can contaminate natural water systems and become a hazard to human health. Therefore, colonization of macrophytes on the sediments polluted with heavy metals and the role of these plants in transportation of metals in shallow coastal areas are very important. [50]. Despite this, roots of wetland plants may accumulate heavy metals and transport them to aboveground portions of plants [70, 71].

The extent of metal accumulation within aquatic macrophytes is known to vary significantly between species. For example, the emergent aquatic plants usually accumulate lower amount of metals than submerged aquatic vegetation [72]. The emergent macrophytes growing in constructed wetlands designed for wastewater treatment have several properties in relation to the treatment processes that make them an essential component of the design. Several of the submerged, emergent, and free-floating aquatic macrophytes are known to accumulate and bioconcentrate heavy metals [73, 74]. Aquatic macrophytes take up metals from the water, producing an internal concentration several fold greater than their surroundings. Many of the aquatic macrophytes are found to be the potential scavengers of heavy metals from water and wetlands [75]. Yet research has focused mainly on the interaction between biological factors such as competition, coexistence, grazing, life cycles, adaptation, and environmental factors (salinity, depth, wave exposure) of importance for structuring brackish water macrophytes and algal communities [76].

10.4 Heavy Metal Pollution in Kashmir Himalayan Wetlands

Though a number of studies pertaining to the ecology of Kashmir Himalayan wetlands have been carried out, there are only a few attempts related to heavy metal analysis in these ecosystems. Of these studies, worth mentioning are the attempts by Ahmad et al. [77] in recent past. According to Ahmad et al. [77], the main source of heavy metals in the Kashmir Himalayan wetlands is use of pesticides in the rice fields and orchards of Kashmir and use of lead shots for hunting/poaching of birds.

In a series of studies, Ahmad et al. [77, 78] and other unpublished data heavy metal dynamics in different components of the wetland systems including water, sediments, and macrophytes have been worked out. In *Phragmites australis*, the accumulation of the different heavy metals was in order of Al > Mn > Ba > Zn > Cu > Pb > Mo > Co > Cr > Cd > Ni. Translocation factor, i.e., ratio of shoot to root metal concentration revealed that metals were largely retained in the roots of *P. australis*, thus reducing the supply of metals to avifauna and preventing their bioaccumulation. Moreover, the higher retention of heavy metals in the belowground parts of *P.*

australis reduces the supply of metals to avifauna, which mainly feed on aboveground parts of the plant, thereby preventing bioaccumulation of heavy metals in higher trophic levels. This further adds to the desirability of *P. Australis* as a phytoremediation species [77]. Ahmad et al. [78] also assessed the heavy metal accumulation capability of two dominant species (*Ceratophyllum demersum* and *Potamogeton natans*) in a Kashmir Himalayan Ramsar site. The accumulation of the different metals in *P. natans* was in the order of Al > Mn > Pb > Cu > Zn > Ni > Co > Cr > Cd, while in *C. demersum* it was Al > Mn > Zn > Co > Cu > Pb > Cr > Ni > Cd. In *C. demersum*, the highest bioconcentration factor (BCF) was obtained for Co (3616) and Mn (3589) while in *P. natans* the highest BCF corresponded to Cd (1027). Overall *Potamogeton–Ceratophyllum* combination provided a useful mix for Co, Mn, and Cd removal from contaminated sites. Beside *Phragmites australis* some other macrophytes that showed good phytoremediation potential were *Azolla cristata, Hydrocharis dubia, Myriophyllum spicatum, Nymphaea alba, Nymphoides peltata, Salvinia natans, Typha angustata, Sparganium erectum, and Trapa natans.* Ahmad et al. [77] reported that Hokersar an important Ramsar site of Kashmir Himalayas filters 73 % of Co, 88.24 % of Cu, 65.13 % of Pb, 51.98 % of Zn, 40.93 % of Mn, 58.36 % of Fe, 41.02 % of Cd, 75.07 % of Cr, and 86.59 % of Ni.

10.5 Knowledge Gaps and Future Directions

Kashmir Himalayas are gifted with a number of wetlands like Hokersar wetland, Haigam wetland, Malangpora wetland, Mirgund wetland, Narkura wetland, etc. These Kashmir Himalayan wetlands are presently subjected to various anthropogenic pressures like encroachment, rapid urbanization and industrialization, dumping of solid waste, sites of gunshots for hunting/poaching, etc. There have been scanty studies of heavy metals in Kashmir Himalayan wetlands except a few attempts in recent past by Ahmad et al. [77, 78]. Constructed wetlands are not common in Kashmir Himalayas. Realizing the important role played by the constructed wetlands, it is expected that constructed wetlands will also become popular in Kashmir Himalayas.

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