Chapter 10
Application of Macrophytes for Remediation of Wastewater in Constructed Wetlands

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10.1 Introduction

Wastewater is posing serious environmental problems in urban areas, particularly in underdeveloped countries (Ajibade et al. 2013; Bhat et al. 2017). The proper treatment of wastewater, both municipal and industrial, is a method of environmental management (Bhat et al. 2018a, b) that aims to avoid any sort of pollution to receiving waters by reducing the organic load and recovery of nutrients (Queiroz et al. 2019).

In small-scale industries, conventional methods of treating the effluents are rarely used due to operational, economical, and regulation issues. Operations like activated sludge process, membrane bioreactors, etc. are not viable for smaller industries when located in rural areas (Wu et al. 2015). Wastewater management and treatment technology, thus, needs to be suitable and sustainable (Ajibade et al. 2014). It also needs to consider cost-effectiveness, ease of operation and maintenance, and high efficiency in removing both organic matter and heavy metals. The removal of unwanted components in wastewater can be done by processes like sedimentation, precipitation, filtration, adsorption, microbial application, and

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phytoremediation (Hammer 1989), which is the most effective one among all the strategies in constructed wetland (CW) technologies.

10.2 Wastewater Treatment Technologies

The availability of water is a global concern due to increasing demand and increase in population, industrial expansion, unsustainable agricultural practices and climate change as well as inadequate water resources. For example, the Middle east, south and central Asia, Southern USA, South Europe, and North Africa (Almuktar et al. 2018). Due to this shortage of water throughout the globe, alternative non-conventional sources play an important role in meeting the requisite demands of water. Among these, wastewater has been a viable alternative for fulfilling the water demand (Bichai et al. 2012; Noori et al. 2014; Almuktar and Scholz 2015; Almuktar et al. 2015a, b; Almuktar and Scholz 2016a, b).

Discharge of wastewater directly into fresh water resources poses a threat to human health (Khurana and Pritpal 2012). Hence, to reduce its impact it needs to be treated. According to FAO, wastewater water treatment and recycling can potentially provide sufficient quantities of fresh water in coming decades (FAO 2003). To harness the wastewater, a suitable economical and rapid treatment technology needs to be developed against the conventional one (Kumar et al. 2012).

10.3 Conventional Technologies

These technologies involve mainly the usage of modern instrumentation for the removal of the chemicals from the wastewater. These treatment technologies include low to high end techniques for the wastewater treatment, with varying removal efficiencies. The sewage treatment plants (STPs) are one of the technologies that are being used for decades now. Reverse osmosis (RO) is one of such high end techniques used for the treatment of the wastewater. Although these technologies have high efficiencies in treating wastewater, these are not preferable at many places due to certain factors like high installation and operational costs, difficult operations, maintenance costs, trained personnel, etc., which become limiting factors while opting for such techniques in the treatment of wastewater.

10.4 Emerging Technologies Using Plants

The use of plants for the removal/uptake of chemical toxicants from the wastewater and from contaminated soils is called as phytoremediation (Bhat et al. 2018a, b). It is an emerging technology which involves the use of specialized plants for waste removal from natural ecosystems, like terrestrial ecosystems, aquatic ecosystems, wetlands, etc. These specialized plants are known as hyperaccumulators, as they can uptake such chemicals from the media, in which they grow, many times more than other plants. Nowadays, hybrid plant species are developed to increase the efficiency of the plants selected for the removal of wastes from wastewaters.

A constructed wetland (Fig. 10.1) is an artificially maintained wetland used to treat wastewaters from municipal or industrial sources, including gray-water or storm-water runoff. They are designed to remove water quality constituents like organic matter, suspended solids (SS), nutrients (e.g., nitrogen and phosphorus), heavy metals, etc. Phytoremediation strategy, using the constructed wetlands (CWs) technology, is the most effective technology used today. Various macrophytes have been used to treat wastewaters in the constructed wetlands, so as to reduce the waste concentration in the wastewater as per norms (Table 10.1), before the wastewater finally discharges into other water bodies.

Different macrophytes show varying waste removal efficiencies, which is a function of various parameters and is calculated as given by the following formula:

$$\text{Removal efficiency}\left(\%\right)=\frac{\left(\text{Influent concentration}-\text{Effluent concentration}\right)}{\text{Influent concentration}}\times 100$$

Based on previous studies, the variation in waste removal percentage may be related to differences in the selected macrophyte species and density, wastewater type, media, loading rates, retention times, temperature, other climatic conditions, design, and size of the experimental setups (Tanner et al. 2012). Based on previous studies, most of the plants used in effective constructed wetlands are either weeds or aquatic plants, possessing higher growth rates than others, which is an important criterion in effective phytoremediation.

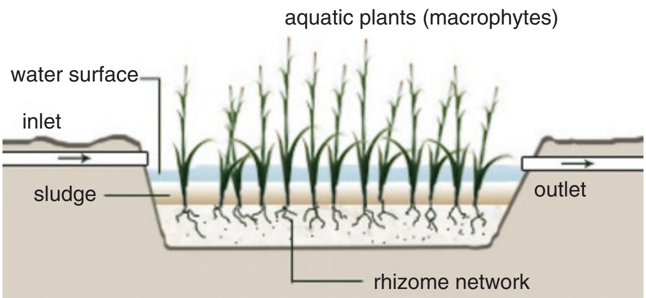

Fig. 10.1 A constructed wetland (free-water surface constructed wetland). (Onyango et al. 2009)

Table 10.1 Recommended standard for the safe disposal of treated wastewater (Adams 1989)

S. no.	Parameter	WHO standards	
		Desirable limits	Maximum permissible limits
1.	pH (at 20 °C)	7.0–8.9	6.5–9.5
2.	Turbidity (NTU)	5.0	5.0
3.	Nitrite (mg/L)	10	50
4.	Nitrate (mg/L)	0.2	3
5.	Sulfate (mg/L)	250	500
6.	Odor	Unobjectionable	Unobjectionable
7.	Taste	Unobjectionable	Unobjectionable

10.5 Classification of Constructed Wetlands (CWs)

The constructed wetlands are classified generally on three main factors: water level in the system (surface and sub-surface flow); macrophytes; and the direction of water movement (Kadlec and Knight 1996; Nikolić et al. 2009; Langergraber et al. 2009; Hoffmann et al. 2011; Vymazal 2014). In addition, CWs may also be categorized according to their objectives into habitat creation, wastewater purification, or flood control (Vymazal 2013, 2014; Stefanakis et al. 2014).

The two main flow types of constructed wetlands (CWs) are considered to be (a) free water surface flow with substantial macrophytes along with an exposed water surface and (b) subsurface flow with no clear water surface (Kadlec and Knight 1996; Kadlec et al. 2000; Langergraber et al. 2009; Knowles et al. 2011; Nivala et al. 2012; Vymazal 2013; and Wu et al. 2014). Constructed wetlands are classified into two categories depending upon the direction of flow viz., vertical-flow and horizontal-flow types (Fig. 10.2), which together can form a hybrid system to achieve high pollutant removal (Vymazal 2013, 2014; Wu et al. 2014).

10.6 Parameters of Efficient Macrophytic Phytoremediation in Constructed Wetlands

The prerequisite parameters for the effective phytoremediation process to occur are to be kept in consideration while planning. The important parameters include macrophyte species, pH, temperature, and salinity of the target waters.

10.6.1 Macrophyte Species

A number of macrophytes have been reported to have been used in the treatment of wastewater in constructed wetlands as well as natural aquatic ecosystems (Table 10.2). While determining the utilization of any macrophyte for

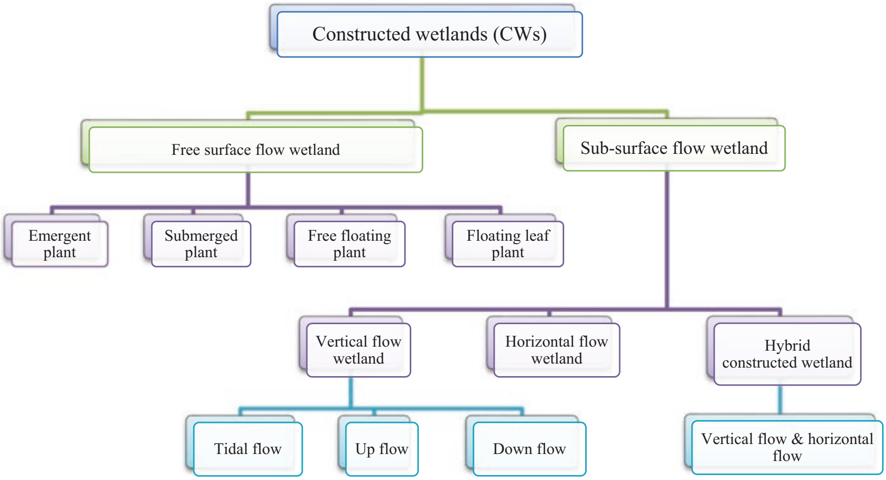

Fig. 10.2 Classification of constructed wetlands. (Almuktar 2018)

Table 10.2 List of some commonly used macrophytes for the treatment of wastewater in constructed wetlands

S. no.	Macrophyte species	Reference(s)
1.	*Phragmites australis*	Vymazal and Brezinova (2016), Ajibade and Adewumi (2017), and Vymazal (2013)
2.	*Eichhornia crassipes*	Ajibade and Adewumi (2017)
3.	*Commelina cyanea*	Ajibade and Adewumi (2017)
4.	*Ludwiga helminthorriza*	Nunez et al. (2011)
5.	*Polugonum punctatum*	Nunez et al. (2011)
6.	*Typha latifolia*	Vidayanti and Choesin (2017) and Vymazal (2013)
7.	*Colocasia esculenta*	Obi and Woke (2014)
8.	*Alocasia puber*	Thani et al. (2019)
9.	*Alocasia macrorrhiza*	Thani et al. (2019)
10.	*Pistia stratiotes*	Thani et al. (2019)
11.	*Lemna minor*	Basile et al. (2012) and Lemon et al. (2001)
12.	*Elodea canadensis*	Basile et al. (2012)
13.	*Leptodictyum riparium*	Basile et al. (2012)
14.	*Salvinia rotundifolia*	Reddy and Tucker (1985)
15.	*Wolffia borealis*	Lemon et al. (2001)
16.	*Trapa natans*	Tsuchiya and Iwakuma (1993)
17.	*Hydrocharis dubia*	Tsuchiya (1989)
18.	*Nymphaea tetragona*	Kunii and Aramaki (1992)
19.	*Spirodela polyrhiza*	Lemon et al. (2001)
20.	*Azolla micrphylla*	Mishra et al. (2016)

phytoremediation, the rate of uptake of wastewater constituents by plants and the assimilation of such chemicals (nutrients) into the macrophytic biomass are of utmost importance (Kinidi and Salleh 2017). The suitability of macrophyte for various types of wastewaters depends on the macrophytes tolerance with respect to exposure to different types of contaminants in the wastewaters. Besides, while choosing the macrophyte for a constructed wetland, it should be kept in mind that it should be locally available, tolerant to anoxic, waterlogged, and hyper-eutrophic conditions (Kadlec and Knight 1996).

10.6.2 pH of Wastewater

The pH value of wastewater does influence the efficiency of macrophytes in the remediation process. A pH value of 6–9 is reported to be the most favorable for the treatment of wastewater using macrophytes (Shah et al. 2014). El-Gendy et al. (2004), in their study, used *Lemna minor, Eichhornia crassipes*, and *Pistia stratiotes* for remediation of municipal wastewater and concluded that *Eichhornia crassipes* show maximum growth at pH 7. However, it can even withstand the pH values ranging from 4 to 10 (El-Gendy et al. 2004).

10.6.3 Temperature

Temperature variations significantly determine the efficiency of phytoremediation by macrophytes (Shah et al. 2014), because the phytoremediation potential depends upon mainly on the plant growth. It acts as one of the important environmental factors which affects the productivity of a particular macrophyte species in any natural aquatic ecosystem or any constructed wetland. Most of the macrophyte species grow between 20 and 30 °C and show retarded growth below 10 °C (Perdomo et al. 2008). However, some species do grow in cooler months, like *Centella asiatica,* which, thus, can be used to replace *Eichhornia crassipes*-based nitrogen wastewater treatment systems (Reddy and Debusk 1985).

10.6.4 Salinity

The salt stress affects the growth and reproduction of macrophytes, depending upon the difference in tolerance ranges exhibited by the macrophyte species. The tolerance of macrophytes towards salt stress affects their efficiency and performance in the treatment of wastewaters due to the reduction of total dry weight and transpiration rates at higher salinity levels and may even cause death of macrophyte species (Haller et al. 1974).

10.6.5 Availability of Oxygen

The availability of oxygen in the constructed wetlands depends mainly on the design and type of constructed wetland used. Thus, availability of oxygen will determine the fate of the reactions, whether they will be aerobic or anaerobic.

10.6.6 Design of the Constructed Wetlands (CWs)

The design of the constructed wetlands has a vital role in the treatment of wastewater. For example, the water depth in a constructed wetland has an impact of treatment efficiency of organic matter removal and has been shown that shallow water depth is better than the deep ones, mainly in terms of biochemical oxygen demand (BOD). However, for a CW meant for phytoremediation through use of macrophytes, the depth is determined by the maximum root depth of the macrophyte. Table 10.3 summarizes the specific design and operational recommendations for the treatment of wastewater in the constructed wetlands (Wu et al. 2015).

Table 10.3 Design and operational recommendations for treating wastewater using the constructed wetlands

S. no.	Parameter	Design criteria	
		FWSF CW	SSF CW
1.	Bed size (m^2)	As larger as possible	<2500
2.	Length-to-width ratio	3:1–5:1	<3:1
3.	Water depth (m)	0.3–0.5	0.4–1.6
4.	Hydraulic slope (%)	<0.5	0.5–1
5.	Hydraulic loading rate (m/day)	<0.1	<0.5
6.	Hydraulic retention time (days)	5–30	2–5
7.	Media	Natural media and industrial by-product preferred, porosity of 30–50%, particle size <20 mm, 50–200 mm for the inflow and outflow, respectively	
8.	Vegetation	Native species preferred, plant density 80% coverage	

Adapted from Wu et al. (2015)
Note: FWSF CW stands for "free water surface flow constructed wetland" and SSF CW for "subsurface flow constructed wetland"

10.6.7 Inflow Properties

The inflow qualities of the wastewater will definitely affect the use of a particular type of constructed wetland. For example, vertical flow CWs perform well in terms of nitrification of wastewater; that is why they are preferred in ammonia-nitrogen rich wastewaters and not preferred in denitrification cases. On the other hand, horizontal-flow constructed wetlands perform well in terms of denitrification and poor in nitrification. That is the reason of them being recommended for inflow wastewater with elevated nitrate-nitrogen values.

10.7 Advantages of Phytoremediation in CWs

Phytoremediation by macrophytes in constructed wetlands (CWs) are numerous, whether it is ease of operation, cost effectiveness, potential environmental risks, etc., and some of them are enlisted in Table 10.4.

Table 10.4 Advantages of phytoremediation over conventional wastewater treatment techniques

S. no.	Parameter	Conventional treatment technologies	Phytoremediation in constructed wetlands or other aquatic ecosystems
1.	Type of chemical used	Various chemicals are used (e.g., lime, chlorine gas, various electrolytes, etc.)	Notably no chemical is needed
2.	Generation of harmful by-products	Corrosive, explosive, and toxic by-products are commonly generated	No harmful by-products generated
3.	Consumption of energy	Demand large amounts of energy, based upon the treatment techniques used. Reverse osmosis is one of such techniques, which consumes large quantities of input energy	Harvest energy from sunlight
4.	Environmental risks (*if any)*	Although modern technologies are safe nowadays, still a scope of potential risks exists	No environmental risks
5.	Cost	Although quicker method of treating wastewater than phytoremediation in many cases	Comparatively cheaper and efficient technology than conventional treatment technologies
6.	Operational ease	They are not easy and require proper training and knowledge of the instruments for effective operation	They are comparatively easier to use
7.	Maintenance cost	Due to wear and tear, and other technical faults, require decent investment of money. Besides, human negligence in operation can increase such costs	Require little or minimum investment for operation as well as maintenance

10.8 Other Potential Benefits from Sustainable Waste Management Practices Like Phytoremediation Using Constructed Wetlands

Some of the potential benefits of using macrophytes in constructed wetlands by the process of phytoremediation are discussed below,

10.8.1 Biogas Production

The anaerobic digestion of organic waste (macrophytes) can be done to produce biogas, which is an environmentally clean fuel (Yadvika et al. 2004). Macrophytes, due to their high C/N ratio and high proportion of fermentable matter, can be used to generate biogas. Macrophytes such as *Trapa natans, Lemna minor, Eichhornia crassipes, Typha latifolia, Salvinia molesta*, *and Pistia stratiotes* can be decomposed easily and thus generate high biogas yield (Gunnerson and Stuckey 1986; Strom 2010; Sudhakar et al. 2013; Mathew et al. 2015; Pantawong et al. 2015).

10.8.2 Vermicomposting

Vermicompost is the nutrient-rich product of microbial degeneration of organic waste with the help of earthworms (Gajalakshmi et al. 2002). Vermicompost from the macrophyte *Eichhornia crassipes* can be used as an organic fertilizer (soil enhancer) because it is rich in nutrients (Bernal and Hernandez 2016). Vermicompost with phytoremediated aquatic macrophytes biomass is effective and environmentally friendly for sustainable agriculture (Mishra et al. 2016). Among the aquatic macrophytes used were *Azolla microphylla, Pistia stratiotes, Salvinia cucullata*, and *Salvinia molesta* (Mishra et al. 2016).

10.8.3 Biochar Production

Biochar basically comprises of carbon-rich material generated from organic waste (Kameyama et al. 2011) by means of pyrolysis technology. The pyrolysis product of *Lemna minor* can be converted into gasoline and diesel (Miranda et al. 2014).

10.8.4 Paper Making

Due to their high moisture content, many macrophytes are suitable with the aqueous characteristics of paper pulp (Asuncion 2003). Macrophytes like *Typha angustifolia, Scripus grossus*, and *Cyperus rotundus*, due to their fiber characteristics, physical properties, and chemical composition, can be used in the manufacture of paper (Bidin et al. 2015), and thus can be used to lessen the pressure of paper making from forests.

10.9 Guidelines to Consider During Decision-Making and Planning for Setting Up of Constructed Wetlands for Treatment and/or Reuse of Wastewater

Although constructed wetlands are generally efficient in treating wastewater from different sources, their effluent quality is primarily dependent on influent properties of the wastewater. As per the studies conducted so far, many guidelines/tips have been suggested for obtaining the better results and efficiencies while using any constructed wetland for the treatment of wastewater and/or its use thereof (Table 10.5).

Table 10.5 Guidelines for decision-making while using constructed wetlands for treatment of wastewater

S. no.	Particulars	Remarks
1.	Location	The location of the constructed wetland system will affect the type of wetland to be used. For instance, free water surface-flow wetlands are not recommended in cities, mainly due to the high chances of exposure of humans to pathogens
2.	Environmental conditions	Environmental conditions play an important role while constructing wetlands. For instance, at high temperatures, evapotranspiration rate will increase the salinity of the effluent. In such conditions, subsurface flow constructed wetlands (SSF CWs) are highly recommended. (However, it is noteworthy to mention that a slightly high temperature may positively affect the system behavior due to the higher activity of microorganisms resulting in higher wastewater treatment efficiencies)
3.	Longer hydraulic detention time	It helps in providing more contact time between the activated biomass and the chemicals or contaminants, leading to a better effluent quality
4.	Moderate resting time	Moderate resting time of wetlands provides the system with ample oxygen content, thus supporting the growth of microbes, and improving effluent quality
5.	Selection of suitable macrophyte	The selection of a proper macrophyte is a must, which depends upon the inflow properties and plants tolerance to the particular chemical (nutrient, heavy metals, salts, etc.) in the inflow wastewaters
6.	Inflow properties	It greatly affects the efficiency of any constructed wetland, as it is the primary factor that decides the constructed wetland type, macrophyte to be selected, hydraulic detention time to be given, etc.
7.	Depth	It depends on the selected plant root depth. However, shallow constructed wetlands are more efficient than deeper ones

10.10 Conclusion

The role of macrophytes in the phytoremediation in constructed wetlands is gaining importance day by day, as it has emerged as an eco-friendly technique. Besides, it has a lot advantages over the conventional wastewater treatment techniques. Nowadays, scientists are seeing this technique as a potential way of acquiring of metals, reclaiming of damaged wetlands, and as a viable option in water scarce areas for providing drinking water facilities during the lean months of the year in arid and semi-arid areas, areas with meager water resources.

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