Chapter 11
Efficiency of Constructed Wetland Microcosms (CWMs) for the Treatment of Domestic Wastewater Using Aquatic Macrophytes

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Contents

Abstract Constructed wetland microcosms (CWMs) are engineered wastewater treatment systems that are designed to treat wastewater from small communities, involving aquatic plants, a variety of substrate materials, soils and their associated microbial fauna. CWMs are considered as promising ecological technology that requires low or no energy input, low operational cost and provides more benefits and better alternative to conventional wastewater treatment systems. In CWMs dissolved oxygen (DO), pH and temperature are controlled to achieve the desirable treatment efficiency. Several other components such as plant, substrate, water depth, hydraulic loading rates (HLRs) and hydraulic retention time (HRT) are also critical to establishing viable CWMs for the better performance. The literature on CWMs suggests excellent nutrient removal performances which are achieved with low and

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R. C. Sobti et al. (eds.), *Environmental Biotechnology: For Sustainable Future*,
https://doi.org/10.1007/978-981-10-7284-0_11

stable effluent concentrations. Further, the choice of appropriate macrophyte species having high uptake of pollutants and high pollutant tolerance and choice of substrate materials are critical for treatment performance. CWMs can be differentiated based on existing native vegetation type (such as floating leaved macrophytes, free-floating macrophytes, emergent macrophytes and submerged macrophytes, in which emergent macrophytes are common) and, hydrology (surface flow constructed wetlands (SFCWs), subsurface flow constructed wetlands (SSFCWs) and hybrid systems). The focus of this paper is to review the state of the art in improving the overall efficiency of CWMs for wastewater treatment. The paper documents both the design and operation of CWMs which are critically dependent on environmental, operational and hydraulic factors. It further outlines key challenges and future prospects for their wider replication.

Keywords Constructed wetland microcosms · Hydraulic loading rates · Hydraulic retention time · Macrophytes · Treatment efficiency

Introduction

Rapid urbanization due to enormous population growth and changing living standards, intensification of agricultural activities and over-exploitation of freshwater ecosystems have caused both global and regional water scarcities (Wang et al. 2017). There has been an emergent need of moving towards new and alternative technologies for improving the quality of water in both developed and developing countries. The treatment of wastewater containing high proportion of nutrients and organic matter (OM) or refuse water from communities has been a great challenge and sometimes hard to achieve in conventional treatment processes (Wojciechowska et al. 2017). Therefore, wastewater treatment technologies such as constructed wetlands (CWs) have emerged as an innovative, economical and sustainable way of protecting and rehabilitating freshwater ecosystems in developing countries (Vymazal 2011). Designer CWs have emerged as novel engineered systems that have primarily been developed and implemented in Europe and the USA. These systems are now routinely used in subtropical and tropical regions in countries like India and Brazil (Machado et al. 2017). CWs with better control systems have been also widely implemented in Central and Eastern Europe having higher proportion of inhabitants living in small rural settlements (Istenic et al. 2015). In China, CWs have been used for ecological engineering since more than 20 years (Zhang et al. 2012). In India, CWs are used as decentralized wastewater systems for smaller communities as well as for small drains outfalling in large rivers (Rai et al. 2013). The use of this technology has grown more progressively in recent decades because of their low and easy operational and maintenance cost, reliable efficiency and environmental friendliness, relying fully on natural and continuous ongoing processes compared with other conventional treatment technologies (Zhang et al. 2014). Natural wetlands provide us a wide range of ecosystem services, such as CO_2 uptake

Table 11.1 Treatment of different types of wastewater in CWs using emergent macrophytes

S. no.	Type of wastewater	Vegetation	References
1	Domestic wastewater	*H. psittacorum*, *P. australis* ,*P. karka*, *T. latifolia*, *T. angustifolia*, *A. halimus*, *J. acutus*, *S. perennis*	Bohórquez et al. (2017), Butterworth et al. (2016), Fountoulakis et al. (2017)
1	Industrial wastewater	*T. latifolia*, *T. domingensis*, *S. cyperinus*, *P. australis*, *J. articulates*	Khan et al. (2009)
2	Sewage	*T. latifolia*, *S. acutus*, *S. validus*, *P. australis*, *P. karka*	Ladu et al. (2012), Mulling et al. (2013)
3	Agriculture runoff	*P. karka*, *T. angustifolia*, *S. mucronatus*	Sim et al. (2011)
4	Runoff + sewage	*P. australis*, *T. orientalis*, *C. malaccensis*	Wang et al. (2011)
5	Pesticides in runoff	*P. australis*, *T. latifolia*	Elsaesser et al. (2011)
6	Eutrophic water	*T. angustifolia*	Li et al. (2008)

and release as a regulating service (Yamochi et al. 2017), while CWs are promising technology for the treatment of various types of wastewater such as domestic sewage, industrial drainage, storm water runoff, animal wastewaters, agricultural runoff, leachates and polluted river water (Wu et al. 2015a; Maine et al. 2017; Li et al. 2017) (Table 11.1). In a CW, community composition and species richness both represent a diverse effect on nutrient removal. Higher plant species richness habitually results in increased primary production (Naylor et al. 2003) that reduces effluent nutrient concentration due to increased plant uptake (Wang et al. 2013; Han et al. 2016; Zhao et al. 2016a, b).

Constructed Wetland Microcosms (CWMs)

CWs are engineered systems that are used to forecast the behaviour of natural wetlands under more controlled conditions (Zhang et al. 2014). A CWM unit has different kind of filter material (substrates), planted with different macrophytes (Fig. 11.1). Wastewater passes through the basin and flows over the surface to meet with substrate and is discharged out from the CWM unit through a discharge point (Sudarsan et al. 2015).

A CWM unit has the following main components (Sudarsan et al. 2015):

a. Basin
b. Substrate
c. Vegetation
d. Inlet system
e. Outlet system

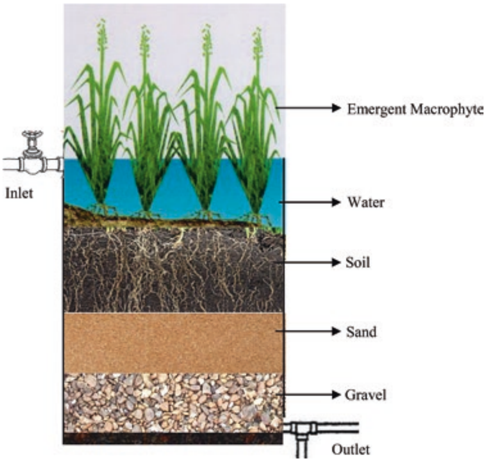

Fig. 11.1 CWM unit planted with emergent macrophyte. (Shao et al. 2014)

On the basis of hydrology, CWs are characterized mainly into surface flow constructed wetlands (SFCWs) or free water surface (FWS), subsurface flow constructed wetlands (SSFCWs) and hybrid systems (or mixed systems) (Wu et al. 2015a). SSFCWs may further be categorized into horizontal flow constructed wetlands (HFCWs) and vertical flow constructed wetlands (VFCWs) on the basis of effluent flow. According to the macrophytic growth, they are further categorized into emergent, free floating, submerged and floating leaved. Most widely used CWs are subsurface flow, and nowadays hybrid system has gained great attention in comparison with others because of their high treatment efficiency. They are designed to acquire benefit of the natural wetlands under controlled environment. Gaining a better knowledge of the mechanisms linked with CWs, various designs and operational mode are available to achieve greater efficiency of domestic sewage treatment, e.g. single-stage modification (Kumari and Tripathi 2014), multistaged in series (Melián et al. 2010) and/or combination with other treatment technologies (Singh et al. 2009). Accordingly, a number of researchers have published review articles related to the use of CWs for wastewater treatment (Haynes 2015; Liu et al. 2015; Vymazal and Březinová 2015; Wu et al. 2015a). Nevertheless, there are relatively few studies on the present knowledge aimed at on-site treatment of wastewater. Still, there is an uncertainty about the selection of the suitable type of CWs which is more appropriate for domestic wastewater treatment in decentralized system. Most of the research on the use of macrophytes in CWs has been done in temperate regions; while there are much more untested macrophytes in tropical regions. Tropical conditions can lead to considerable uptake of wastewater nutrients by macrophytes (Zhang et al. 2014). The roots of the macrophytes provide substrate for microbial growth and transfer oxygen and dissolved organic matter from leaves and aerial parts to the rhizosphere (Meng et al. 2014).

More recent research on CWs has primarily focused on water purification (Ávila et al. 2014), selection of appropriate plant and configuration (Wang and Sample 2013), choice of substrates (Ge et al. 2015), hydraulic loading rates (HLR) (Mexicano et al. 2013) and hydraulic retention time (HRT) (Dzakpasu et al. 2015). Some studies have also found how physical properties of the substrates, such as substrate depth and size, influence pollutant removal.

Mechanism Involved in CWs for the Domestic Wastewater Treatment

Components Involved

The main components involved in CWs are wetland vegetation, media material (which are either natural, industrial by-product or artificially prepared material) and microbial communities. Together, these systems utilize a combination of biological, chemical and physical processes to remove most of the contaminants from wastewater.

Wetland Vegetation

In CWs, a number of wetland plants have been employed having several properties required for the treatment process. Most often used macrophytes in CWs systems are broadly categorized into free-floating plants, submerged plants, floating-leaved plants and emergent plants, typically grown in water or soil media. Even though more than 150 macrophytic plant species have been reported that are used in CWs globally, only a few of these are very frequently used (Saeed and Sun 2012; Vymazal 2013a). Highly dense macrophytes provide more substrates to the biofilms for microbial action to enhance treatment (Badhe et al. 2014; Zheng et al. 2015, 2016; Wang et al. 2016; Wu et al. 2016).

Floating-Leaved Macrophytes

These are rooted in submerged sediments with the water depth of 0.5–3.0 m and have slightly aerial or floating leaves; examples include *Nymphaea odorata* and *Nuphar lutea.*

Free-Floating Macrophytes

They freely float on surface water. These plants are able to remove nitrogen (N) and phosphorus (P) by means of increased plant biomass and by denitrification, and they also remove suspended solids; main examples are *Eichhornia crassipes* (Pontederiaceae), *Nymphaea tetragona* (Nymphaeaceae), *Trapa bispinosa* (Lythraceae), *Marsilea quadrifolia* (Marsileaceae), *Salvinia natans* (Salviniaceae), *Azolla* spp. (Salviniaceae) and *Lemna minor* (Arecaceae).

Emergent Macrophytes

Emergent plants are generally observed on water-saturated or submerged soil and are able to grow in water depth of 0.5 m or more. Commonly used emergent macrophytes are *Phragmites* spp. (Poaceae), *Typha* spp. (Typhaceae), *Canna indica* (Cannaceae), *Scirpus* spp. (Cyperaceae), *Iris* spp. (Iridaceae), *Juncus* spp. (Juncaceae) and *Acorus calamus* (Acoraceae). They transfer oxygen from roots to rhizosphere, which gives rise to degradation of pollutants aerobically.

Use of emergent macrophytes in CWs greatly reduces surface speed, enhances sedimentation and makes the available substrate for periphyton breeding to support pollutant degradation. The most often used macrophyte species are *Typha*, *Scirpus*, *Phragmites* and *Juncus* (Vymazal 2013b).

Submerged Macrophytes

These have their tissues submerged in water, grow healthy in oxygenated water and are principally used for polishing wastewater after secondary treatment. Examples include *Hydrilla verticillata* (Hydrocharitaceae), *Ceratophyllum demersum* (Ceratophyllaceae), *Vallisneria natans* (Hydrocharitaceae), *Potamogeton crispus* (Potamogetonaceae) and *Myriophyllum spicatum* (Haloragaceae).

From the above-mentioned macrophytes, emergent macrophytes are the key species in CWs for wastewater treatments because of their high treatment efficiency (Vymazal 2013b); amongst them *Phragmites australis* is the most frequent species in Asia and Europe (Vymazal 2011).

Media material (Substrates)

Substrates are selected on the basis of hydraulic permeability and the ability to absorb pollutants. Poor hydraulic conductivity may cause clogging of systems, decrease the efficiency of the system, lower the adsorption and also affect the performance of CWs for long-term applications (Wang et al. 2010). Previous studies

Table 11.2 Common media substrates used in CWs systems

S. no.	Substrate type	Source
1	Artificial material	
	Compost	Saeed and Sun (2012)
	Activated carbon	Ren et al. (2007)
	Lightweight aggregates	Saeed and Sun (2012)
	Calcium silicate hydrate Basic oxygen furnace slag (BOFS)	Li et al. (2011) Barca et al. (2014)
2	Industrial by-products	
	Fly ash	Xu et al. (2006)
	Coal cinder	Ren et al. (2007)
	Slag	Cui et al. (2010)
	Alum sludge	Babatunde et al. (2010)
	Oil palm shell	Chong et al. (2013)
	Hollow brick crumbs	Ren et al. (2007)
3	Natural material	
	Sand	Saeed and Sun (2013)
	Gravel	Calheiros et al. (2008)
	Clay	Calheiros et al. (2008)
	Calcite	Ann et al. (1999)
	Limestone	Tao and Wang (2009)
	Zeolite	Bruch et al. (2011)

Wu et al. (2015a)

for the choice of wetland substrate media especially for phosphorus removal from wastewater explain that the substrates mainly include natural materials, artificial media and industrial by-products (Table 11.2) (Yan and Xu 2014). From these studies it is proved that most of the natural substrates are less efficient for long-term phosphorus removal; in contrast, industrial and artificial products with high hydraulic conductivity have high phosphorus sorption capacity. Several other studies also provided some knowledge on substrate choice in order to maximize the removal efficiency of nitrogen and organics. Substrates such as alum sludge, compost, peat, rice husk and marble are the best choices (Babatunde et al. 2010).

Microorganisms

The well-known microbial population in CWs is present in the form of the biofilms associated with plant's roots or attached with the surface of the filter media (Faulwetter et al. 2009). The structure of microbial community in various layers of planted soil in wetlands system for the treatment of domestic wastewater was given by Truu et al. (2005). They observed that the depth is a crucial factor affecting the microbial community composition and microbial activity (Truu et al. 2009) in

CWMs (Iasur-Kruh et al. 2010). Various studies have experimented microbial populations in full-scale CWs and laboratory-scale units under controlled conditions (Zhang et al. 2010; Dong and Reddy 2010). However, there is a short of information on the changes of the microbial communities and diversity in long-term operations for the domestic wastewater treatment (Adrados et al. 2014). It is represented by several studies that the below- and above-ground parts of the macrophytic plants increase the diversity of microorganisms which make available large surface area for the growth of well-defined biofilms, responsible for nearly all of the microbial processes taking place in the wetlands (Chen et al. 2014; Button et al. 2015). Excessive nutrients such as N and P (eutrophication) (Giaramida et al. 2013) and the presence of other toxic substances affect biofilms and their structure (Calheiros et al. 2009) in the wetland system. In CWs different wetland plants, rhizospheric zones are able to provide unique add-on sites for certain microbial populations and mediate the environment by the release of oxygen and root exudates which can control the function and development of certain microbial communities (Lv et al. 2017; Zhang et al. 2016).

Treatment Efficiency of CWMs

Recent research in CWs for domestic wastewater treatment using halophytes shows that they have great potential to build up salts in their tissues (Fountoulakis et al. 2017). The design parameters and operational phase must be chosen according to the environmental conditions of the site and the effluent quality needed after treatment (Bohórquez et al. 2017). HLR and HRT both are significant design parameters for determining the treatment efficiency of a CW; removal efficiencies decreased with increasing HLR and decreasing HRT (Abou-Elela et al. 2017).To date nearly all of the developing countries have warm tropical and subtropical climates throughout the year, and it is commonly known that CWs are more feasible in tropical regions compared to temperate regions (Zhang et al. 2015). In tropical regions, wetlands are exposed to higher temperatures and direct sunlight throughout the year and show higher year-round plant productivity and a simultaneous decrease in the time needed for microbial biodegradation. A warm climate is favourable for plant growth and microbiological activity, which have positive effects on treatment performances (Zhang et al. 2014). In CWs, the core mechanisms associated with contaminant removal are microbial activities. However macrophytes also play a central role in contaminant removal from wastewater. They utilize nutrients and add them into plant tissue and consequently increase plant biomass (Zhang et al. 2007; Mthembu et al. 2013).

Different types of wastewater such as industrial, agricultural, landfill leachate and storm water runoff are hard to be treated in a single-stage system. Recently hybrid systems of different configurations were built together for the treatment of combined sewer overflow (Ávila et al. 2013) or refinery effluent (Vymazal 2005; Wallace and Kadlec 2005; Elfanssi et al. 2017). It is reported that CWs with different designs and planted with different macrophytes obtain high percentage reduction of organic load, total phosphorus and ammonium ions, at short detention times in small communities (Kadlec and Wallace 2008).

Removal of Organics

In CWs organic matter degradation involves both aerobic and anaerobic microbes (Table 11.3). Removal efficiency of organic pollutants which are present in wastewater used in CWs is dependent on influent strength (Saeed and Sun 2012; Wu et al. 2015b). The aerobic heterotrophic bacteria have comparatively faster metabolic rate than autotrophs to oxidize organics that make use of oxygen as the final electron acceptor and release carbon dioxide, ammonia and other stable chemical compounds (Garcia et al. 2010). The intensity of organic matter biodegradation in CWs is also dependent on the biodegradability of the organic matters; such characteristics are best represented by the biological oxygen demand (BOD) and chemical oxygen demand (COD) ratio of the wastewater. Usually, the ratio of BOD and COD for untreated domestic wastewater ranges from 0.3 to 0.8. A BOD and COD ratio of 0.5

Table 11.3 Mechanisms of wastewater treatment by using CWs

S. no.	Wastewater components	Removal mechanisms
1	Suspended solids	Sedimentation
		Filtration
2	Soluble organics	Aerobic microbial degradation (biotransformation)
		Anaerobic microbial degradation
3	Nitrogen	Ammonification and microbial nitrification
		Denitrification (conversion of NO_3 to N_2)
		Plant uptake (accumulation into plants parts)
		Matrix sorption (sorption through the substrates)
		Ammonia volatilization (vaporization)
4	Phosphorus	Matrix sorption
		Plant uptake
5	Metals	Adsorption and cation exchange
		Complexation (formation of coordination compounds)
		Plant uptake
		Precipitation (formation of insoluble compound)
		Microbial oxidation/reduction
6	Pathogens	Sedimentation
		Filtration
		Natural die-off
		Predation
		UV irradiation
		Excretion of antibiotics from macrophytes

Cooper et al. (1997), Mthembu et al. (2013)

or more indicates that the organics are simply degraded, while the ratio below 0.3 shows that the available organics which are present are difficult to degrade by the microorganism (Saeed and Sun 2012). Organic matter degradation is enhanced with sufficient and efficient oxygen supply (Vymazal and Kröpfelová 2009; Ong et al. 2010). Therefore, by increasing the airflow rate, COD removal efficiencies were progressively enhanced because of additional oxygen supply and the highest efficiency to be found at the aeration rate of 2.0 L $min^{-(1)}$ (Saeed and Sun 2012).

Earlier researches pointed out that intermittent aeration strategy greatly enhances the removal efficiency in CWs (Jiang et al. 2017). Removal efficiencies in intermittently aerated CWs with biochar or without biochar were better than non-aerated CWs with or without biochar that means a significant improvement was achieved in organic matter removal through artificial aeration (Headley et al. 2013), while removal efficiency of COD was greater than other CW treatments such as bioaugmentation (Zhao et al. 2016a, b), polyvinyl alcohol immobilized nitrifier, (Wang et al. 2016) and earthworm eco-filters (Zhao et al. 2014).

Removal of Nitrogen

Discharge of nitrogen in excessive is able to cause serious environmental consequences, like eutrophication, which deteriorates water quality and downgrades the aquatic ecosystems (Li et al. 2014; Fan et al. 2016). Nitrogen in wastewater is present mainly in two forms, organic and inorganic (Stefanakis et al. 2014), and removal mechanisms include ammonification (conversion of organic nitrogen to ammonia), nitrification (conversion of ammonia to nitrite and then nitrite to nitrate), denitrification (conversion of nitrate to N_2 gas), nitrate usually used as electron sink and to end with dinitrogen gas (Drizo et al. 1997; Elfanssi et al. 2017), plant uptake (nitrogen taken by plants as nutrients in the form of mainly nitrates and ammonia) and adsorption (mostly ammonia adsorbed on the media material) (Table 11.4) (Tsihrintzis 2017).

In CWs, both nitrification and denitrification are extensively accepted pathways for biological nitrogen removal (Fig. 11.2). The process requires both aerobic and anaerobic environments, while nitrification can convert nitrogen into various forms but cannot achieve its removal from the wastewater (Fan et al. 2013). A continuous aeration strategy has been developed and adopted to attain complete nitrification (Ong et al. 2010; Wu et al. 2015b). However intermittent aeration mode is known to be a more cost-effective strategy because it has more nitrifying and other viable bacteria in comparison with non-aerated CWs (Foladori et al. 2013; Fan et al. 2013). They greatly increased total nitrogen (TN) removal efficiency by creating favourable conditions (alternate aerobic and anaerobic conditions). It is reported that the removal efficiency of TN in CWs can be altered by using different designing models, by controlling environmental conditions (e.g., temperature, pH and dissolved oxygen, etc.) and by different operational factors (e.g., C/N ratio, HLRs, HRT, etc.) (Saeed and Sun 2012). Recently, a lot of investigations were carried out by the

Table 11.4 Significance of novel and classical routes for the removal of nitrogen in wastewater

Mode	Route	Significance
Microbiological	Partial Nitrification–denitrification	NO_2 removal over NO_3, reducing TN content of wastewater
Microbiological	Anammox	Anaerobic NH_4^+ oxidation into N_2
Microbiological	Canon	Completely autotrophic NO_2 removal over NO_3
Microbiological	Ammonification	Transforms N_2 in wastewater, e.g. from organic nitrogen to NH_4–N
Microbiological	Nitrification	Changes NH_4–N to NO_2–N and NO_3–N. Net quantity of TN remains constant
Microbiological	Denitrification	Reduces NO_3–N to N_2 gas. The process also reduces TN when combined with nitrification
Microbiological	Dissimilatory nitrate reduction	Reduces NO_2–N and NO_3–N to NH_4–N. As such, the quantity of TN remains constant
Microbiological	Biomass assimilation	Adsorbs NH_4–N, thereby reducing nitrogen content of wastewater
Biological	Plant uptake	Remove nitrogen from wastewater by accumulation into plants parts
Physico-chemical	Volatilization	Converts NH_4^+ to NH_3 gas, followed by gaseous strip, and then eliminates N_2 from wastewater
Physico-chemical	Adsorption	Adsorbs NH_4–N from wastewater, reducing TN content. However, aerobic environment can nitrify the adsorbed NH_4–N, followed by desorption

Saeed and Sun (2012)

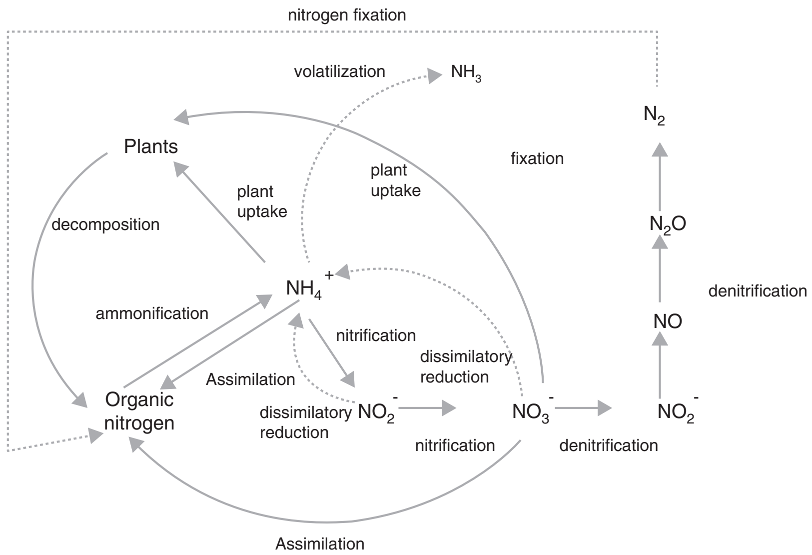

Fig. 11.2 Classical nitrogen removal routes in CWs. (Source: Saeed and Sun 2012)

researchers to study the role of C/N ratio on nitrogen removal in treatment of wastewater (Zhao et al. 2010). From the study done previously, it is stated that the TN removal efficiency was found to be higher at C/N ratio of 2.5–5. In addition, another study (Fan et al. 2013) shows that the high removal rate of TN (82%) was found in aerated SSFCWs with C/N ratio of 10. Later (Zhu et al. 2014) it was reported that the highest removal efficiency of TN was at a C/N ratio of 5, and the removal efficiency rose with an increase of C/N ratio. Nevertheless, the best possible C/N ratios to attain maximum nitrogen removal in SFCWs still remain uncertain especially for purifying the effluent of sewage treatment plant. Actually, the higher removal efficiencies for TN are always coupled with higher C/N ratios. In CWs, degradation of organic matter consumes more DO which threatens the activity of nitrifying microorganisms (Zhu et al. 2014).

Removal of Total Phosphates (TP)

Anthropogenic activities such as agricultural practices and rapid urbanization have altered the biogeochemical cycling of phosphorus (Bouwman et al. 2013; Penuelas et al. 2013; Geng et al. 2017). In wastewater, phosphorus can be found in organic or inorganic forms; orthophosphates ($PO4^{3-}$) is the common form. In CWs phosphate removal is done primarily by adsorption, precipitation and immobilization by microbes (Seo et al. 2005) and high removal efficiency is achieved when there is more oxygen exposure to the rhizosphere through the vascular bundle transformation (Wu et al. 2015c). Dissolved phosphorus is taken by macrophytes or adsorbed onto the substrate media and precipitated, predominantly when Al, Fe, Ca or Mg cations are present at high proportion. Some specialized media materials such as zeolite, bauxite, dolomite, limestone, etc. are probably used to enhance phosphorus adsorption (Stefanakis and Tsihrintzis 2012; Stefanakis et al. 2014). However, high water depth, subsequent to a low flow velocity, is complimentary to increase the rate of this removal process (Guo et al. 2017). TP removal rates varied according to the seasons, linked to the rising of plant biomass and microbial activity from cold to warm one. A positive correlation was found in between total phosphorus removal and seasonal variation (Zhao et al. 2011). Precipitation and adsorption can easily saturate the adsorption sites during pollutant treatment, thus decreasing the treatment efficiency. Consequently, the selection of filter media with high adsorption capacity is necessary to achieve higher treatment efficiency and for the longevity of a CW. Therefore, ongoing study to develop new filter media with enhanced phosphate adsorption capacity has become a main concern for researchers in the last two decades (Park et al. 2017).

Recently a number of substrate materials have been used in CWs to improve phosphate treatment capacity among which basic oxygen furnace slag (BOFS) (Barca et al. 2014) and electric arc furnace (EAF) slag (Okochi and McMartin 2011) are promising substrates.

Sustainability of CWs

The physical functions and chemical composition of wetlands affect all natural biological processes. The DO, pH and temperature are the most significant factors affecting the performance of CWs (Kadlec and Wallace 2008). The criteria for suitable CW design and sustainable operation include site, substrate selection, wastewater type, plant selection, (based on their role in treatment process as a whole plant or by their tissues) (Table 11.5), HLR, HRT and water depth (Akratos et al. 2009; Kadlec 2009; Wu et al. 2014). Particularly, the factors such as plant, substrate, water depth, HLR, HRT and feeding mood are vital for development of sustainable CW system to achieve maximum treatment performance (Fig. 11.3). Brundtland Commission on Sustainable Development (formally known as the World Commission on Environment and Development (WCED)) defined cost–benefit analysis for the sustainability of any project that aims at improving the quality of the environment. In CWs criteria such as land acquisition, energy consumption, ecological benefits, investment and operation costs must be considered during construction and operation phase. A number of earlier studies point out that CWs have an evident advantage of construction and operation cost savings in comparison with other conventional wastewater treatment plants (WWTPs) (Zhang et al. 2012; Wu et al. 2014).

Table 11.5 Parts of macrophytes and their role in treatment process

S. no.	Plant parts	Role in treatment process
1	Aerial plant tissue	Reduced growth of phytoplanktons by light attenuation Reduced wind velocity and risk of resuspension Influence of microclimate–insulation during winter Store nutrients and add aesthetic values
2	Plant tissue in water	Filtering effect – filter out bulky debris Amplified rate of sedimentation, reduced current velocity and risk of resuspension Enhanced aerobic degradation Nutrient uptake Acts as a filter medium, provides oxygen
3	Roots and rhizomes in the sediment	Stabilizing the sediment surface – less erosion Offers surface for bacterial growth Prevents clogging of the medium Increases degradation by release of oxygen Release of antibiotics Promotes biodegradation

Vymazal (2011)

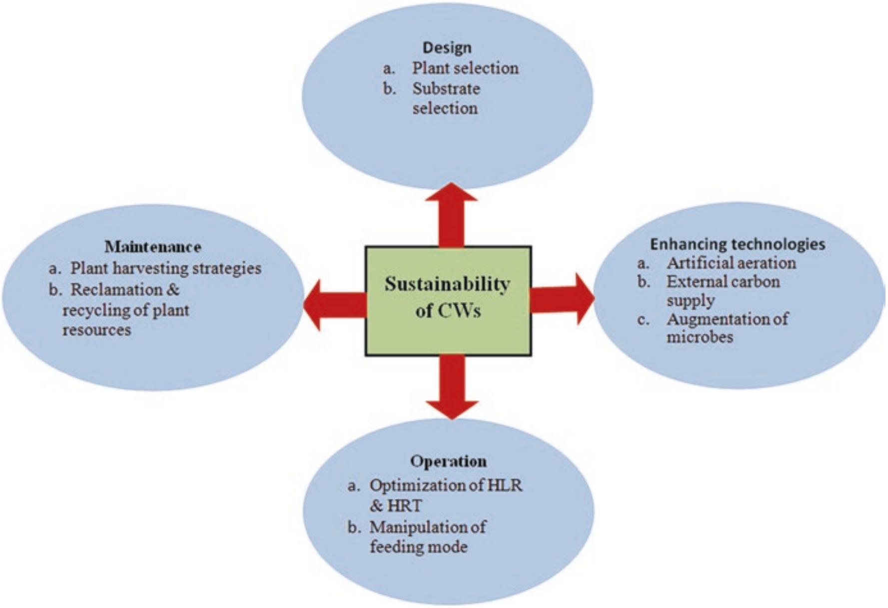

Fig. 11.3 Recent developments and future considerations for improving the sustainability of the CWs. (Wu et al. 2015a)

Future Prospects

The performance of CWs has improved considerably by innovation in the design and mode of operation in recent years. The exceptional treatment efficiency and performance of CWs for treating high strength wastewater containing nutrients can be achieved by appropriate selection of plants and substrates, proper management of the hydraulic loads, mode of operation and pollutant loading rate. These factors can be effectively controlled through innovations in design criteria. Therefore, optimization of these conditions requires extensive research in the future. The challenge is to develop appropriate plant harvest strategies as well as recycling of plant resources because when they die and decay, they could release nutrients and other pollutants into receiving water which may decrease the overall removal performance. There is an emergent need for more research and improvement for traditional CWs to develop new technologies for the enhancement in treatment efficiencies, which are required for sustainable water quality improvement, especially in developing countries. Future research should be devoted to develop artificial aeration, various filter media (non-conventional media materials such as industrial by-products, agricultural wastes, etc.), additional carbon addition, tidal operation, step feeding, microbial augmentation, baffled flow and hybrid CWs.

Conclusion

CWs are considered as an environmental-friendly wastewater treatment technology. CWs have emerged as an alternate, cost-effective solution for treatment of different types of wastewater especially in remote locations of developing countries. The focus of this review has been on the efficiency of CWMs for domestic wastewater treatment. Both the design and operation of a CW are crucial to achieve the sustainable treatment performance which is critically dependent on environmental, operational and hydraulic conditions. There will also be a significant change in removal efficiencies with HLR and HRT, as pollutant removal efficiencies decreased when the HLR is increased and HRT is decreased and removal efficiency increased when HLR is decreased and HRT is increased. However, the removal of plant nutrients (N and P) is highly variable. Still, the choice of appropriate macrophyte species (i.e. supply more oxygen, high uptake of pollutants, and tolerate high pollutant loadings) and substrates are critical for the sustainable wastewater treatment performance.

Acknowledgement The authors are grateful to the Department of Environmental Science, Babasaheb Bhimrao Ambedkar University (a Central University), Lucknow, India, for their continuous support throughout this study. Junior Research Fellowship (JRF) from University Grants Commission, New Delhi to the first author is greatly acknowledged.

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