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REVIEW ARTICLE

Constructed wetland microcosms as sustainable technology for domestic wastewater treatment: an overview

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Abstract

Constructed wetland microcosms (CWMs) are artificially designed ecosystem which utilizes both complex and ordinary interactions between supporting media, macrophytes, and microorganisms to treat almost all types of wastewater. CWMs are considered as green and sustainable techniques which require lower energy input, less operational and maintenance cost and provide critical ecological benefits such as wildlife habitat, aquaculture, groundwater recharge, flood control, recreational uses, and add aesthetic value. They are good alternatives to conventional treatment systems particularly for smaller communities as well as distant and decentralized locations. The pH, dissolved oxygen (DO), and temperature are the key controlling factors while several other parameters such as hydraulic loading rates (HLR), hydraulic retention time (HRT), diversity of macrophytes, supporting media, and water depth are critical to achieving better performance. From the literature survey, it is evaluated that the removal performance of CWMs can be improved significantly through recirculation of effluent and artificial aeration (intermittent). This review paper presents an assessment of CWMs as a sustainable option for treatment of wastewater nutrients, organics, and heavy metals from domestic wastewater. Initially, a concise note on the CWMs and their components are presented, followed by a description of treatment mechanisms, major constituents involved in the treatment process, and overall efficiency. Finally, the effects of ecological factors and challenges for their long-term operations are highlighted.

Keywords Constructed wetland microcosms · Domestic wastewater · Nutrients · Heavy metals · Macrophytes · Sustainability

Introduction

Lack of appropriate wastewater management practices are contributing to both scarcity and decline of fresh water quality worldwide (Almuktar et al. 2018). The situation is posing serious threat to ecosystems especially in developing countries (Wu et al. 2017). Discharge of majority of raw wastewater directly into rivers has become a common practice due to lack of suitable and effective technologies, operational failures of larger treatment plants, and higher cost involved in setting new treatment units (Kumwimba et al. 2017). The constructed wetlands (CWs) are engineered systems that have evolved as an inventive approach to tackle wastewater from domestic sources mainly because of their reliable efficiency, ecological benefits, easy operation, and less maintenance cost (He et al. 2018: Kumar and Dutta 2019). They use natural functions of macrophytes, soil, and microorganisms to treat different water streams (Ilyas and Masih 2017). The use of this technique has grown-up over recent decades with various successful examples (Zhang et al. 2014). CWs are being used to treat almost all types of wastewater such as domestic sewage, stormwater runoff, agricultural runoff, industrial drainage, and polluted rivers water (Li et al. 2017). There are many co-benefits of CWs together with wastewater treatment and recycling as they also provide important ecological services such as valuable wildlife habitat, aquaculture, groundwater recharge, carbon sequestration, fisheries, flood control, silt capture, recreational uses, and add aesthetic values to the surroundings.

Classification of constructed wetlands CWs are characterized generally into three categories, namely, subsurface flow constructed wetlands (SSFCWs), surface flow constructed wetlands (SFCWs), and hybrid system. Further, on the basis of the flow path, SSFCWs are differentiated into vertical flow

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constructed wetlands (VFCWs) and horizontal flow constructed wetlands (HFCWs) (Wang et al. 2018). According to the macrophytic growth, they are categorized into emergent, free-floating, submerged, and floating-leaved macrophytes (Vymazal 2010).

Constructed wetland microcosms (CWMs) A working model of a CWM (Fig. 1) possesses various types of supporting media and aquatic macrophytes depending upon target pollutants. In general, wastewater reaches the treatment chamber, runs all the way through the supporting media, and is released out of the chamber from an outlet system. A CWM unit has following five major components: basin (or chamber), substrate/media materials, vegetation (mostly macrophytes), and inlet and outlet system (Sudarsan et al. 2015).

A number of researchers across the world have published their review articles on the use of CWs for wastewater treatment (Liu et al. 2015; Haynes 2015; Almuktar et al. 2018). However, there are somewhat few studies detailing the treatment dynamics, rather the information is meant to provide onsite domestic wastewater treatment that are site specific. Recent investigation on CWs has principally provided information on wastewater decontamination (Avila et al. 2014), suitable working models and appropriate choice of macrophytes (Wang and Sample 2013), retention time (HRT), hydraulic loads (HLR) (Dzakpasu et al. 2015), and variety of supporting media (Ge et al. 2015) (Fig. 2).

Treatment mechanisms involved in CWMs

Treatment mechanisms involved in CWMs are biogeochemical transformations and solid/liquid separations. Transformation possesses reduction, oxidation, acid/base reactions, biochemical reactions, flocculation, and precipitation. Separation includes adsorption, absorption, gravity separation, stripping, leaching, filtration, and ion exchange (Choudhary et al. 2011).

Major constituents involved in treatment mechanisms

Wetland vegetation (macrophytes)

In CWMs, macrophytes are primary vegetation. They are essentially grouped in four categories, namely, emergent, submerged, floating-leaved, and free-floating macrophytes (Kumar and Dutta 2019). Growth characteristics and nutrient uptake capacity of some frequently used macrophytes are presented in Table 1. The macrophytes relocate oxygen and provide dissolved organic matter and supporting media for microbial attachment (Meng et al. 2014). They are also contributing to enhance porosity and permeability of the substrate, act as a catalyst, and promote a number of biological and chemical reactions (Yahiaoui et al. 2018). More than 150 species of macrophytes have been reported that are used in CWMs worldwide; however, only a few of them are commonly used. It is observed that emergent aquatic macrophytes are preferred choice because they have high contaminant removal efficiency (Vymazal 2013). The choice of macrophytes must be indigenous which can grow naturally in wetlands. They should be also capable to withstand with short dry periods as well as shocks generated by wastewater loads. Macrophytes which have well developed root and rhizome systems inside the supportive material are most preferable.

Supporting media

Currently, available and frequently used supportive media are the industrial by-products, natural and artificial or synthetic materials (Yan and Xu 2014). Some frequently used supporting media in CWMs are presented in Table 2. They must be chosen according to their capacity to absorb/adhere wastewater contaminants and their permeability. It is generally observed that reduced hydraulic conductivity greatly influenced adsorption ability (Wang et al. 2010). Ultimately, the long-lasting applications of the treatment system are highly affected by the chosen media materials (Wang et al. 2010).

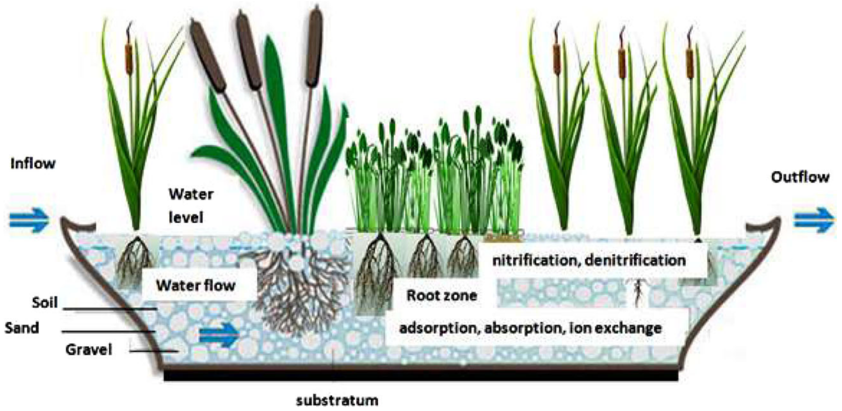


Fig. 1 CWM unit planted with emergent macrophytes

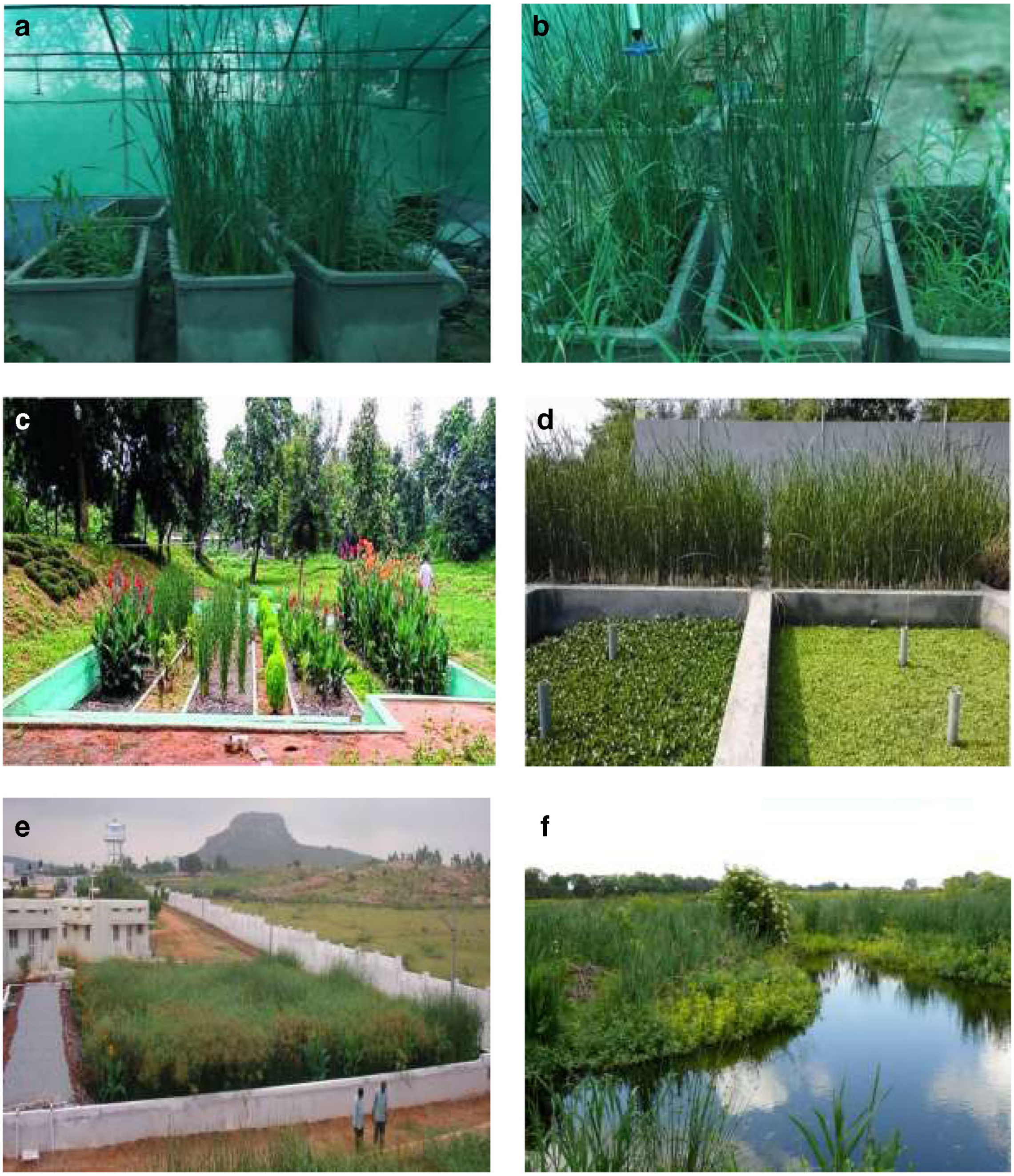


Fig. 2 **a**, **b** CWM units designed under net house of Department of Environmental Science, Babasaheb Bhimrao Ambedkar University, Lucknow, India. **c** CSIR- Institute of Minerals and Materials Technology, Bhubaneswar, Odisha. **d** International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Telangana, India. **e** Constructed wetland for wastewater treatment for a colony in Andhra Pradesh, India. **f** CWs working successfully in Georgia treating runoff from a plant nursery

Microorganisms

The principal microorganisms concerned with wetlands system are bacteria, yeasts, protozoa, fungi, and algae. Collectively, all these microorganisms participate in the degradation of nearly all of the wastewater contaminants into insoluble or harmless substances. The well-established microbial communities are attached to the supporting media, plant roots, and/or in leaves in the form of biofilms (Faulwetter et al. 2009). The complex microbial communities in the form of biofilms formed by interactions with wastewater are primarily responsible for the breakdown of the wastewater pollutants and increase the overall treatment performance of the CWMs (Sleytr et al. 2009). Several previous studies have identified and characterized microbial communities in full-scale constructed wetlands and laboratory scale units under

Table 1 Growth characteristics of some frequently used aquatic macrophytes in CWMs treating municipal wastewater

Type	Macrophytes	Optimal temperature (°C)	Optimal pH	Root penetration (cm)	Maximum water depth (in.)	Growth	Drought resistance	Nutrient uptake capabilities (kg ha^{-1} yr^{-1})	
								Nitrogen	Phosphorous
Emergent	*Phragmites* sp. (common reed)	12–23	3.7–8	60	3	Very rapid	High	2500	120
Emergent	*Typha* sp. (cattail)	10–30	4–10	75	12–18	Rapid	Possible	1000	180
Emergent	*Scirpus* sp. (bulrush)	16–27	4–9	75	12	Moderate to rapid	Moderate	–	–
Emergent	*Juncus* sp. (rush)	16–26	5–7.5	25	3	Rapid	Moderate	–	–
Free-floating	*Lemna* sp. (duckweed)	6–33	6.5–7.5	2	19	Very rapid	No	–	–
Free-floating	*Pistia stratiotes* (water lettuce)	15–35	6–6.8	80	–	Very rapid	No	900	40
Free-floating	*Eichhornia crassipes* (water hyacinth)	12–35	6.5–7.5	100	–	Very rapid	No	2400	350

*Compiled from various sources

specific environments (Calheiros et al. 2009; Krasnits et al. 2009; Sleytr et al. 2009; Dong and Reddy 2010; Zhang et al. 2010). However, in case of domestic wastewater, there is lack of information about how the microbial communities and diversity change during long-term operations (Adrados et al. 2014). Comprehensive information about the structure of these communities must be attained by suitable design improvisation in order to understand the biological developments that are taking place inside them (Dong and Reddy 2010). It is observed that the rhizosphere region of the CWMs is capable of providing unique add-on sites for microbial connection and release root exudates and oxygen which helps in estimating the role of the microbial cosmos (Zhang et al. 2016; Lv et al. 2017). Different design and operational parameters undertaken to treat various wastewater in several countries are presented in Table 3.

Removal of organics

Biodegradation of organics takes place by both aerobic as well as anaerobic microorganisms depending upon the availability of oxygen. For aerobic degradation, oxygen can be added from convection, atmospheric dispersal and through root organization of macrophytes (Cooper et al. 1996), while pores of supporting media are sites responsible for anaerobic biodegradation. Settleable organics are removed rapidly under gravitational forces by filtration and sedimentation whereas soluble organics are removed by attached or suspended microbial growth. Degradation of organics by aerobic processes mainly proceeds by aerobic chemoheterotrophs because they have a faster metabolic rate as compared to chemoautotrophs. These chemoheterotrophic bacteria oxidize organic compounds using oxygen and release carbon dioxide (CO_2), ammonia (NH_3), and other stable compounds (Garcia et al. 2010). Sufficient supply of oxygen greatly enhances degradation of organic matter by increasing biochemical oxidation (Vymazal and Kropfelova 2009). Anaerobic degradation of organic matter by anaerobic heterotrophic bacteria involves two processes namely methanogenesis and fermentation. In methanogenesis, methanogens (methane-producing bacteria) convert organic compounds into methane (CH_4) and CO_2 and produce new bacterial cells whereas fermentation utilizes acid-forming bacteria to convert organic matter into organic acids and alcohols. These two processes continue in anaerobic zone of wetland system (Kadlec and Knight 1996).

Removal of nitrogen

The contribution of macrophytes in terms of nitrogen removal varies among several species such as *Typha latifolia* contributing 1.73 to 8.81%, *Canna indica* 0.98 to 17.95%, and for

Table 2 Frequently used supportive media in CWMs (Revised from Wu et al. 2015)

S. no.	Supporting media type	Type of wastewater*	Reference
1	Industrial by-products		
	Fly ash	Municipal	Xu et al. 2006
	Coal cinder	Domestic	Ren et al. 2007
	Slag	Domestic	Zuo et al. 2018
	Alum sludge	Synthetic	Babatunde et al. 2010
	Oil palm shell	Synthetic	Chong et al. 2013
	Hollow brick crumbs	Domestic	Ren et al. 2007
2	Natural material		
	Sand	Textile	Saeed and Sun 2013
	Gravel	Tannery	Lima et al. 2018
	Clay	Tannery	Calheiros et al. 2008
	Limestone	Synthetic	Tao and Wang 2009
	Zeolite	Municipal	Bruch et al. 2011
	Maerl	Synthetic	Saeed and Sun 2012
	Shale	Synthetic	Saeed and Sun 2012
	Peat	Domestic	Saeed and Sun 2012
	Organic wood mulch	Synthetic	Saeed and Sun 2012
3	Artificial material		
	Compost	Refinery	Saeed and Sun 2012
	Activated carbon	Domestic	Ren et al. 2007
	Lightweight aggregates	Synthetic	Lima et al. 2018
	Basic oxygen furnace slag (BOFS)	Synthetic	Barca et al. 2014
	Rice straw	Hypereutrophic water‡	Cao and Zhang 2014
	Light ceramsite	Hypereutrophic water	Cao and Zhang 2014
	Electro-oxidation	Hypereutrophic water	Cao and Zhang 2014

*Domestic wastewater has been used here to include wastewater originating from household activities from a community whereas municipal wastewater is generated in towns and urban areas from any combination of domestic, commercial, or agricultural activities including wastewater from public facilities, surface runoff, stormwater, and any sewer inflow or sewer infiltration. Industrial wastewater is a by-product of industrial or commercial activities. Synthetic or artificial wastewater differs from domestic wastewater or municipal wastewater as it is synthetically made according to the treatment technologies to be tested

‡Hypereutrophic water is sourced from a lake or other water body characterized by excessive nutrient concentrations (nitrogen and phosphorous) and high productivity

Phragmites australis, it ranges from 7.15 to 17.04% (Jesus et al. 2018). In CWMs, the different macrophytes offer oxygen and surface which is necessary for the development of microbes in the root zone, consequently enhancing nitrification. In addition, there is supply of carbon from root system (5–25%, fixed photosynthetically) and optimization of denitrification process (Wang et al. 2012). Wastewater stream has typically inorganic and/or organic form of nitrogen (Stefanakis et al. 2014). Major nitrogen elimination pathways which are engaged with CWMs are classified into two broad categories—novel (new) and classical (traditional) nitrogen removal pathways (Saeed and Sun 2012). Traditional nitrogen removal pathways in CWMs include ammonification, ammonia volatilization, nitrification, denitrification, and adsorption. In the CWM system, ammonification is more in the upper aerobic facultative zone as compared to the bottom obligate anaerobic zone. Both ammonification and ammonia volatilization are pH-dependent process. The suggested pH value to get good results from ammonification ranges from 6.5–8.5 (Saeed and Sun 2012), while a notable rise in pH (> 9.3) converts ammonium ions into ammonia gas (Bialowiec et al. 2011). Adsorption takes place mostly in the form of ammonia into the supporting media (Tsihrintzis 2017) which is used to encourage cation exchange capacity. Supporting media with greater cation exchange capacity has been employed due to their enhanced nitrogen removal efficiency (Saeed and Sun 2012). Biochar is a potential material which supports the denitrification process and removal of NO_3^- by providing organic carbon source. A short description of novel nitrogen removal pathways is provided below:

Table 3 Wetland design and operational parameters considered for different wastewater in several countries

Type of wastewater (WW)	Total surface area m^2	Plant species	Plant density plants m^2	HLR m^3/m^2/day	HRT days	Flow rate m^3/ d	Study area/country	Reference
Municipal	185.5	*C. papyrus*	NA	0.18, 0.10, and 0.07	1.8, 3.2, and 4.7	8	Giza, Egypt	Abou-Elela et al. 2017
Municipal	1.5	*P. australis*	NA	0.37	1.75	0.75	Barcelona, Spain	Avila et al. 2017
Domestic	1.09	*H. psittacorum*	NA	0.15	NA	0.150	Pereira, Colombia	Bohórquez et al. 2016
Domestic	200	*P. australis* *T. latifolia*	4	0.46 0.1	0.7 1.2	65 76	Bedfordshire, UK	Butterworth et al. 2016
Secondary*	0.66	*C. articulatus*	33	0.46	3	0.028	Atlántico, Colombia	Caselles-Osorio et al. 2017
Domestic	0.6	*C. ligularis* *E. colona*	38	0.06	2.3	0.042	Barranquilla, Colombia	Casierra-Martínez et al. 2017
Domestic	130	*P. australis*	4	0.5 and 0.75	NA	NA	Marrakech, Morocco	Elfanssi et al. 2017
Domestic	45.36	*T. parviflora*, *J. acutus*, *S. perrenis*, *L. monopetalum*	1	0.053	3.48	2.4	Heraklion, Greece	Fountoulakis et al. 2017a
Domestic	1.08	*A. halimus*, *J. acutus* and *S. perennis*	9	0.095	NA	0.6	Heraklion, Greece	Fountoulakis et al. 2017b
Synthetic	0.137	*R. japonicas*, *O. hookeri*, *P. arundinacea* and *R. carnea*	12	NA	10	NA	Beijing, China	Geng et al. 2017
Domestic	180	*C. generalis*	4–5	1728	0.25	NA	Udupi District, India	Ojoawo et al. 2015
Urban	51.87	*T. latifolia, P. australis*, and *C. esculenta*	NA	NA	2–3	NA	Haridwar, India	Rai et al. 2015
Municipal	0.0004	*L. perenne*	0.1	0.0375	6	0.15	Xian, China	Ren et al. 2016
Domestic	404	*T. latifolia* L and *S. tabernaemontani*	NA	0.022	NA	NA	Ontario, Canada	Rozema et al. 2016
Synthetic	0.2	*E. crassipes*	NA	NA	2	0.012	Parana, Brazil	Lima et al. 2018
Domestic	30	*P. stratiotes*, *T. latifolia*, *C. indica*, and *A. conyzoides*	NA	0.10	5	3	Telangana, India	Tilak et al. 2017
Domestic	0.13	*P. australis*	8	NA	6	0.21	Shaanxi, China	Wu et al. 2016
Secondary	8,660,000	*P. australis*, *T. orientalis*, *Z. latifolia*, *N. nucifera*, *N. tetragona*, *P. crispus*, *L. minor* and *E. crassipes*	NA	0.035	7	380,000	Shaanxi, China	Wu et al. 2017
Synthetic	0.72	*T. angustifolia*	14–15	0.056	4	0.02	Singapore	Zhang et al. 2012
Synthetic	0.19	*R. japonica*, *O. javanica. P. arundinacea* L. and *J. effusus* L	12	NA	NA	NA	Hangzhou, China	Zhao et al. 2016

*Secondary wastewater is primary-treated wastewater

Novel nitrogen removal pathways

Recently, some new and more efficient nitrogen exclusion routes are pointed out which comprises of partial nitrification-denitrification, anaerobic ammonium oxidation (Anammox), and completely autotrophic nitrite removal (Canon). The main operating factors of partial nitrification processes (i.e., Anammox and Canon) include temperature, pH, free ammonia, free nitrous acid, HRT, dissolved oxygen, salt, organic compounds, and hydroxylamine (Wang and Yang 2004; Lee et al. 2009). They are described briefly in the following section.

Partial nitrification-denitrification This process involves translation of NH_4–N to NO_2–N which is called nitrification (Eq. 1) after that the denitrification of NO_2–N to N_2 gas (Eq. 2) takes place.

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+ \quad (1)$$

$$NO_2^- + 1/2CH_3OH + H^+ \rightarrow 1/2N_2 + 1/2CO_2 + 1.5H_2O \quad (2)$$

Jianlong and Ning (2004) reported that this process needs approximately 40% and 25% lower organics and oxygen respectively, as compared to other available nitrogen removal methods.

Anammox Oxidation of ammonium anaerobically (anammox) is a recently revealed nitrogen removal pathway in which ammonium changes into nitrogen gas with the assistance of *Planctomycetes* bacterial group under anaerobic environment. The anammox process is more advantageous than another treatment system as it requires external carbon in negligible amount. Further, oxygen and energy requirements are also very low and nitrogen is removed at greater speed (Saeed and Sun 2012).

Canon Removal of nitrite over nitrate in the complete autotrophic way involves the anammox process and partial nitrification simultaneously; together, these processes remove all available total nitrogen (TN) in a particular region. There is a mutual co-existence between anammox bacteria and ammonium oxidizing bacteria. Sun and Austin (2007) reported that the canon process in a vertical flow constructed wetlands (VFCWs) removed a significant amount of nitrogen (approximately 52%).

Removal of Total phosphate (TP)

A mixture of inert and natural phosphate is available in the wastewater stream, out of which, the most common is orthophosphates ($PO4^{3-}$). The performance of CWMs is reduced due to low phosphorus removal efficiency. The treatment efficiency of CWMs towards phosphate depends on the prevailing ecological situations, type and the number of macrophytes, available form of phosphate, and the loading rates (USEPA 2000). The contribution of macrophytes in removal of phosphate ranges from 4.8 to 74.87% (Jesus et al. 2018). Various macrophytes possess different plant uptake capacity such as *Typha latifolia* contributing 0.06 up to 74.87%, for *Canna indica*, 0.43 to 4.17%, and for *Phragmites australis*, it ranges from 0.56 to 36.7% (Jesus et al. 2018). It is pointed out that the higher water depth with reduced flow velocity advances the removal rate (Guo et al. 2017). Phosphate removal is regulated by immobilization by microorganisms, the adherence capability of a range of filter media used in different seasons, temperature, and growth periods. Dissolved state of phosphorus is taken up by macrophytes or adhered to the substrates when the cations such as Fe, Al, Mg, and Ca are present in excess. The process starts by ligand exchange reactions. Phosphate allocates H_2O and OH^- ions on the face of iron oxides and aluminum. However, the rate of deletion typically decreases unless an appropriate adsorbent matter is incorporated in the system (Vymazal 2010). Removal of phosphorus through various supporting media is ranging between 40 and 60%. Currently, a number of specialized media materials are used in CWMs to attain enhanced removal performance such as slag (Okochi and McMartin 2011), basic oxygen furnace slag (BOFS), sandstone, zeolite, dolomite bauxite (Stefanakis et al. 2014), and electric arc furnace (EAF) (Barca et al. 2014). It is reported that biochar has huge potential to enhance phosphorus removal by providing maximum adherence sites. Inorganic, organic, dissolved, and insoluble phosphate is not as such taken up by macrophytes until they are transformed into a simple soluble form (Choudhary et al. 2011). It has been observed that magnesium (Mg)-containing materials such as magnesia and magnesite, in the supporting media improves TP removal performance (Lan et al. 2018). In terms of plant uptake, macrophytes have lower phosphorus uptake capacity compared to nitrogen because

a. Under aerobic setting, unsolvable phosphate is precipitated with Fe, Ca, and Al ions.
b. Organic peat, clay, and Fe and Al hydroxides and oxides have participated in phosphate adsorption.
c. Phosphorus is bound up in organic matter through assimilation by bacteria, algae, and macrophytes.

A number of man-made substrates such as zirconium oxide nanoparticle (ZON), magnetic iron oxide nanoparticle (MION), and iron oxide coated granular activated carbon

(Fe-GAC) have been identified with improved adsorption capability. Because of high-cost involvement, discharge of secondary contaminants, and complications in manufacturing processes, the use of these materials is limited in full-scale treatment systems (Park et al. 2017). As a result, the selection of right filter media with better adsorption ability is crucial for better performance.

Removal of heavy metals

Wastewater which is contaminated with trace metals has the great impact on biosphere; therefore, the remediation of these trace metals is essential. The presences of such metals greatly affect the flora and fauna of an aquatic system (Parnian et al. 2016). Remediation of wastewater polluted with heavy metals implies various technologies in which adsorption, reverse-osmosis, electrodialysis, and ion exchange are more common. Almost all of such technologies are expensive, energy-intensive, and generally metals-specific. However, macrophytes in the CWMs are known to have the huge potential towards trace metals buildup in their tissues (Mishra and Tripathi 2008). Removal of metals from domestic wastewater through CWMs involves mainly filtration, sedimentation, adsorption, cation exchange, precipitation, complexation, macrophyte uptake, and microbial oxidation/reduction processes. Several biotic, abiotic, and environmental factors like pH and temperature in the CWMs have direct consequences on bioaccumulation of trace metals (Xing et al. 2013). Removal of heavy metals in CWs using aquatic macrophytes by different studies has been shown in Table 4.

Sustainability of CWMs

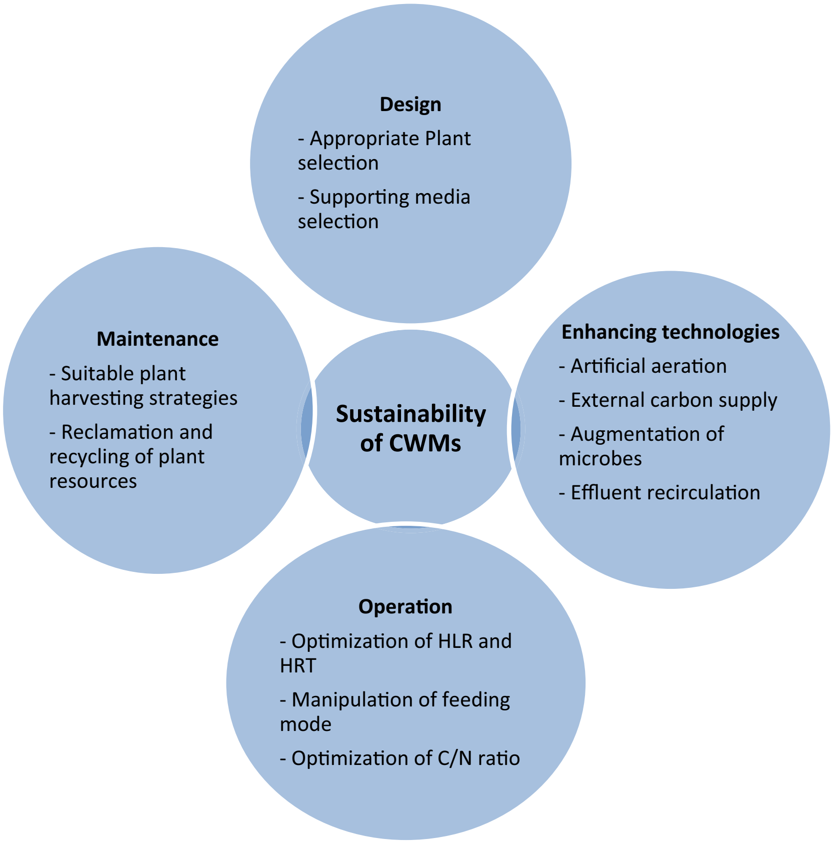
A sustainable design of CWMs for domestic wastewater treatment includes the suitable design of CWMs at proper site with efficient macrophytes and supporting media. Design in a way that it acquires the natural features of the surroundings and to diminish its disturbance. The working model is set by the prevailing landscape, geology, and availability of land. Supply of additional oxygen is via artificial aeration, water

Table 4 Removal of heavy metals in CWs using aquatic macrophytes

CWs type	Wastewater type	Plants used	Target metals	Removal efficiencies (%)		Study area/country	References
				Winter	Summer		
HFCW	Urban	*T. latifolia*	Pb, Cu	78.5, 72.5	86, 84.0	Haridwar, India	Rai et al. 2015
			Zn, Co	68.4, 65.1	83.4, 76.8		
			Cr, As	64.5, 63.2	81.6, 82.2		
			Mn, Ni	53.3, 51.4	62.2, 68.1		
NA	Municipal	*E. crassipes*	Hg,	Up to 95		Irbid, Jordan	Qasaimeh et al. 2015
HFCW	Municipal	*P. phalaris*	Cu, Pd	84, 78		Brehov, Czech Republic	Kropfelova et al. 2009
			Ni, Zn	46, 86			
			Hg	39			
HFCW	Domestic	*P. phalaris*	Cu, Pd	84, 88		Leon, Spain	Pedescoll et al. 2015
			Ni, Zn	12, 87			
HFCW	Domestic	*P. australis*	Cu, Pd	88, 67		Zemst, Belgium	Lesage et al. 2007
			Ni, Zn	36, 86			
HFCW	Municipal	*P. phalaris*	Cu, Pd	73.8, 84.2		Morina, Czech Republic	Kropfelova et al. 2009
			Ni, Zn	49.1, 90.5			
			Hg	29.4			
VFCW	Synthetic	*C. indica*	Cr	98.3		Bhubaneswar, India	Yadav et al. 2010
			Ni	96.2			
FWS	Rainfall	*P. australis*, *T. latifolia*	Cu, Pd	60, 31		Dublin, Ireland	Gill et al. 2017
			Zn, Cd	86, 05			
NA	Synthetic	*P. stratiotes*	Pd	13.0–84.3		Parana, Brazil	Lima et al. 2013
			Cr	92.0–95.0			
NA	Synthetic	*S. grossus*	Pd	99		Selangor, Malaysia	Tangahu et al. 2013
NA	Municipal	*P. australis* and *T. latifolia*	Cu, Cd	78, 60		Varanasi, India	Kumari and Tripathi 2014
			Cr, Ni	68, 73.8			
			Fe, Pb, Zn	80.1, 61, 61			

NA, not available

Fig. 3 Sustainability of CWMs—key criteria (modified from Wu et al. 2015)



depth, optimization of HLR and HRT, bioaugmentation of specific microorganisms, proper plant harvesting; reuse/recycling methods, and the addition of extra organic matters (Fig. 3) (Kadlec and Wallace 2009). Recently, the recirculation of effluent within the CWM system attains huge potential towards enhancement of removal performance through sufficient settling time. The removal performance of CWMs declines considerably when the environmental parameters such as water temperature, pH, and DO are not properly managed (Kadlec and Wallace 2008).

Future concerns and challenges

Firstly, optimization of hydraulics, selection of appropriate macrophytic species and supportive media, mode of operation, and pollutant loading rate are important factors to gain higher removal efficiencies. Suitable plant harvest techniques are vital because when they die and decay, leave nutrients and several other contaminants into the water body. In future research, there is a need to develop techniques to improve treatment efficiencies which could be achieved by microbial augmentation, artificial aeration, a range of supporting media, and supply of additional carbon, tidal action, step feeding, baffled flow, and mixed systems (Wu et al. 2015). CWMs are land intensive, requiring large land area and prone to seasonal weather conditions. Therefore, suitable design improvisation could be done to reduce the overall land requirements. This is also reported by various researchers that the CWMs are by nature prime mosquito habitat. This challenge could be tackled by conserving natural enemies (invertebrates) such as dragonflies, damselflies, beetles, predatory flatworms, true bugs, and crustaceans such as copepods, tadpole shrimp. Fishes, amphibians, spiders, bats, and microbial larvicide *Bacillus thuringensis* var. *israelensis (Bti)* are also used to control mosquitoes' larvae (Mazzacano and Black 2013).

Conclusion

CWMs can be designed as biofilters to imitate the features of natural wetlands for removing nutrients, and other contaminants from the wastewater streams. The focus of this review paper has been on evaluation of treatment performance of CWMs treating domestic wastewater. Both ecological factors such as temperature, pH, DO, and working parameters such as availability of carbon, HLR, HRT, pollutant loads, recirculation, C/N ratios, plant harvesting techniques, addition of extra organic matter, and bioaugmentation of specific microorganisms are vital to achieving sustainable contaminant removal efficiency. Supply of additional oxygen via artificial aeration (mainly intermittent) and effluent recirculation greatly enhances the removal efficiency for organics and nutrients. Novel nitrogen removal pathways have greatly enhanced the nitrogen removal. The removal efficiency increased at influent C/N ratio between 1 and 3 and decreased significantly at the increasing C/N ratios between 3 and 15. The contribution of macrophytes in terms of nitrogen removal varies from 0.98 to 93% and for phosphate ranges from 4.8 to 74.87% depending upon area of the root surface and root oxidizing capacity. Removal of phosphate mostly occurs by adsorption and its efficiency is usually low until a suitable supporting media is not incorporated. Biochar has great potential to support denitrification rate and NO_3–N removal by providing carbon source and also enhance phosphorus removal. Typically, the removal of phosphorus from a variety of supportive media ranged from 40 to 60%. Removal of heavy metals from wastewater implies various technologies such as ion exchange, electrodialysis, adsorption, and reverse-osmosis. Almost all these technologies are expensive metals-specific and energy-intensive. However, macrophytes are known to have huge potential towards trace metals buildup in their tissues.

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