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Application of constructed wetlands for wastewater treatment in tropical and subtropical regions (2000–2013)

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ABSTRACT

Constructed wetlands (CWs) have been successfully used for treating various wastewaters for decades and have been identified as a sustainable wastewater management option for developing countries. With the goal of promoting sustainable engineered systems that support human well-being but are also compatible with sustaining natural (environmental) systems, the application of CWs has become more relevant. Such application is especially significant for developing countries with tropical climates, which are very conducive to higher biological activity and productivity, resulting in higher treatment efficiencies compared to those in temperate climates. This paper therefore highlights the practice, applications, and research of treatment wetlands under tropical and subtropical conditions since 2000. In the present review, removal of biochemical oxygen demand (BOD) and total suspended solid (TSS) was shown to be very efficient and consistent across all types of treatment wetlands. Hybrid systems appeared more efficient in the removal of total suspended solid (TSS) (91.3%), chemical oxygen demand (COD) (84.3%), and nitrogen (*i.e.*, 80.7% for ammonium $(NH)_4$-N, 80.8% for nitrate $(NO)_3$-N, and 75.4% for total nitrogen (TN)) as compared to other wetland systems. Vertical subsurface flow (VSSF) CWs removed TSS (84.9%), BOD (87.6%), and nitrogen (*i.e.*, 66.2% for NH_4-N, 73.3% for NO_3-N, and 53.3% for TN) more efficiently than horizontal subsurface flow (HSSF) CWs, while HSSF CWs (69.8%) showed better total phosphorus (TP) removal compared to VSSF CWs (60.1%). Floating treatment wetlands (FTWs) showed comparable removal efficiencies for BOD (70.7%), NH_4-N (63.6%), and TP (44.8%) to free water surface (FWS) CW systems.

Introduction

Inadequate access to clean water has become one of the most pervasive problems affecting human health, and these problems are expected to worsen in coming decades (Shannon et al., 2008). According to a recent report by the World Health Organization (2012), more than one tenth of the global population (780 million) still relied on sub-standard drinking water sources in 2010. Moreover, many cities in developing countries have generally fallen behind in constructing and managing sewage treatment facilities, since treatment of wastewater is always considered one of the

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lowest priorities among the various infrastructure developments (Ye and Li, 2009; Konnerup et al., 2011). Consequently, discharging large volumes of untreated wastewater into surface waters is a common practice, so that as much as 80%–90% of all wastewater generated in developing countries is discharged directly into surface water bodies (UN Water, 2008). Unmanaged wastewater can be a source of pollution, a hazard to the health of human populations and the environment alike. The Millennium Ecosystem Assessment (MEA) (2005) reported that 60% of global ecosystem services are being degraded or used unsustainably, and highlighted the inextricable links between ecosystem integrity and human health and wellbeing.

Constructed wetlands (CWs) are engineered systems designed and constructed to utilize the natural functions of wetland vegetation, soil media, and their associated microbial associated assemblages for wastewater treatment within a more controlled environment (Kadlec and Knight, 1996). Based on the water flow regime and the type of macrophytic growth, CWs may be classified into three groups: free water surface flow CWs (FWS CWs), subsurface flow CWs (SSF CWs), and hybrid systems (Kadlec and Knight, 1996; Vymazal, 2007). Because of their high pollutant removal efficiency, easy operation and maintenance, low cost, good potential for water and nutrient reuse, tolerance to high variability, and function as significant wildlife habitat, CWs have been recognized as a sustainable wastewater management option for tropical developing countries (Kadlec and Wallace, 2008; Stottmeister et al., 2003).

Although CWs have been mostly utilized to treat domestic or municipal sewage in tropical countries (Greenway, 2005; Jinadasa et al., 2006), recently, the application of CWs has been increasingly extended to address other types of wastewaters including industrial wastewaters (Chen et al., 2006; Maine et al., 2007), agricultural wastewaters (Lin et al., 2002; Lee et al., 2004; He et al., 2006), lake waters (Martín et al., 2013), sludge treatment effluent (Kantawanichkul et al., 2003), stormwater runoff (Ko et al., 2010; Ávila et al., 2013), hospital wastewaters (Shrestha et al., 2001) and winery wastewaters (Serrano et al., 2011). Furthermore, the removal of conventional wastewater treatment parameters such as the biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), fecal indicator bacteria and pathogens, nutrients and heavy metals has been the subject of extensive research in both tropical and subtropical climates (Tanaka et al., 2013; Dan et al., 2011). In addition, the assessment of the removal performance of a wide range of micro-pollutants (*e.g.*, pharmaceutical and personal care products) in tropical regions has also been recently reported (Zhang et al., 2011, 2012).

In wastewater treatment wetlands, the pollutant removal efficiency varies considerably not only from system to system, but also within the same system (Stottmeister et al., 2003; Trang et al., 2010). Such variability can be traced back to the complex combination of physical, chemical and biological processes for contaminant removal brought about by the plants, microorganisms, and soil matrix, as well as their interactions with each other. The pollutant removal efficiency in constructed treatment wetlands depends on a number of variables including wastewater application rate, organic loading rate, hydrologic regime, hydraulic retention time (HRT), operational mode, and vegetation type (Kadlec and Wallace, 2008). Hydraulic and hydrologic conditions may strongly influence the biotic community composition, biogeochemical processes, and the fate of pollutants in these treatment wetlands (Mitsch and Gosselink, 2007). Therefore, pollutant removal is often accomplished by manipulating the system's hydraulic and hydrologic conditions and by selecting the type of dominant vegetation accordingly (Vymazal, 2007; Kadlec and Wallace, 2008). Nevertheless, adverse impact on treatment performance can be expected from low ambient temperatures (especially inhibition of N-removal), peak flows (washout of solids), and clogging of SSF systems.

The potential for application of treatment wetland technology in the tropical regions is enormous, since most of the developing countries have warm tropical and subtropical climates (Kivaisi, 2001; Diemont, 2006). It is generally accepted that CWs are more suitable for wastewater treatment in tropical regions than in temperate regions (Denny, 1997; Kivaisi, 2001). Tropical regions are characterized by a relatively steady solar energy flux, as well as high humidity and warm temperatures throughout the whole year. Differences inherent to tropical as opposed to temperate environments can have important effects on wetland functions and this will in turn have impact on the use of wetlands for wastewater treatment (Poh-Eng and Polprasert, 1998). As the rates of almost all biological processes are temperature dependent and increase with increasing temperature, a warm climate is conducive to year-round plant growth and heightened microbiological activity, which in general have a positive effect on treatment efficiency (Kaseva, 2004; Zhang et al., 2012). Therefore, the tropical environment should favor the biodegradation of organic matter and nitrification/denitrification, etc. Truu et al. (2009) indicated that tropical conditions can enhance the removal of contaminants, as microorganisms living in the CWs usually reach their optimal activity at warm temperatures (15–25°C). Vymazal (2005) reported that the optimum temperature for nitrification in pure cultures ranges from 25°C to 35°C and from 30°C to 40°C in soils. Temperature also has a strong effect on the removal efficiencies of total Kjeldahl nitrogen (TKN) and ammonium. Nitrogen removal rates at a water temperature greater than 15°C are significantly higher than those observed at lower temperatures (Caselles-Osorio and García, 2007). Ammonia volatilization increases 1.3–3.5 times with each 10°C rise in temperature from 0°C to 30°C, and denitrification rates almost double (1.5–2.0) with each 10°C increment (Ng and Gunaratne, 2011).

Although about half of the world's wetland area (~450 million ha) is found in the tropics, the rate of adoption of wetland technology for wastewater treatment in these regions has been slow (Kivaisi, 2001). Moreover, there are relatively few published reports on CW applications under tropical and subtropical conditions (Denny, 1997; Diemont, 2006). This study therefore seeks to highlight the CW practice, applications, and research under tropical and subtropical conditions since 2000. A comprehensive review of the effectiveness of contaminant removal in different wetland systems treating various wastewaters in tropical regions is also presented.

Table 1 – A summary of the wetland design/operation and treatment efficiency of free water surface (FWS) systems in tropical and sub-tropical regions.

	Type of waste-water (WW) & stage of treatment	Removal performance							Wetland design and operation				Reference
		TSS	BOD_5	COD	NH_4-N	NO_3-N	TN	TP	Dimension (m × m × m) (L × W × D)	Plant species	HLR (m^3/day)	HRT (day)	
Peradeniya, Sri Lanka													
Effluent value (mg/L)	Municipal WW & secondary	45.8	19.2	–	3.4	0.9	–	1.36	25.0 × 1.0 × 0.6	*Scirpus grossus*	13	18 hr	Jinadasa et al. (2006)
Removal efficiencies (%)		71.9	68.2	–	74.4	50.0	–	19.0		*Typha angustifolia*			
Pompia, Crete, Greece													Tsihrintzis et al. (2010)
Effluent value (mg/L)	Municipal WW & secondary	5.6	7.7	18.0	–	–	18.0	6.2	4300 m^2	*Phragmites australis*	144	–	
Removal efficiencies (%)		95.5	94.4	96.1	–	–	52.5	53.1	1200 m^2	*Arundo donax*			
Southern Spain													Ávila et al. (2013)
Effluent value (mg/L)	Municipal WW & stormwater	6	7	50	2.3	–	7.9	5.3	23.5 × 13.5 × 0.8	*Phragmites australis*	44 mm/day	–	
Removal efficiencies (%)		97.9	98.22	90.72	94.54	–	85.53	34.57	26 × 8.8 × 0.4	*Typha spp.*			
Hsin-Hai, Taiwan													Ko et al. (2010)
Effluent value (mg/L)	Domestic WW & stormwater	–	20	–	6.9	–	–	1.9	1.07 ha × 0.5 m	*Typha orientalis*	4000	7	
Removal efficiencies (%)		–	–	–	46	–	–	44		*Phragmites communis*			
Cairns, Australia													Greenway (2005)
Effluent value (mg/L)	Municipal WW & tertiary	–	–	–	0.2	0.1	1.5	7.0	–	–	500 m^3/(ha·day)	10	
Removal efficiencies (%)		–	–	–	33.3	99	75	12.5					
Blackall, Australia													Greenway (2005)
Effluent value (mg/L)	Municipal WW & tertiary	–	–	–	1	1	6	<0.05	–	–	–	20	
Removal efficiencies (%)		–	–	–	92.3	87.5	76	75					
Taiwan													Chen et al. (2006)
Effluent value (mg/L)	Industrial WW & tertiary	17	9	67	–	6	16	45	4.0 × 1.0 × 1.0	*Pistia stratiotes*	0.4	5	
Removal efficiencies (%)		81	89	61	–	85	46	35		*Phragmites communis*			

EI, Salvador													Katsenovich et al. (2009)
Effluent value (mg/L)	Municipal WW & secondary	–	20.08	72.80	0.54	–	6.08	1.86	48.9 × 15.0 × 0.6	*Typha angustifolia*	151.4	9.8	
Removal efficiencies (%)		–	80.78	65.18	95.75	–	58.59	66.5					
Taipei, Taiwan													Hsu et al. (2011)
Effluent value (mg/L)	Municipal WW & tertiary	19.6	10.89	28.24	0.533	–	8.40	0.47	–	*Phragmites australis*	–	–	
Removal efficiencies (%)		–	59.85	64.48	–	–	56.66	63.85	–	*Typha orientalis*			
Petchaburi, Tailand													Klomjek and Nitisoravut (2005)
Effluent value (mg/L)	Municipal WW & saline condition	40.4	12.7	–	5.18	0.35	–	2.2	4.0 × 1.0 × 1.5	*Typha angustifolia*	6–150 mm/day	2	
Removal efficiencies (%)		46.5	74.3	–	75.4	–	–	44.9					
Santo Tomé, Argentina													Maine et al. (2007)
Effluent value (mg/L)	Industrial WW & sewage	–	13	37	2.0	3.1	–	0.155	50 × 40 × 0.5	*Typha domingensis*	100	7–12	
Removal efficiencies (%)		–	64	68	28	72	–	43		*Eichhornia crassipes*			
Valencia, Spain													Martín et al. (2013)
Effluent value (mg/L)	Lake water	13.2	–	33.2	0.116	0.59	1.6	0.143	715–9791 m^3	*Cattails*	11232	–	
Removal efficiencies (%)		75	–	–	78.07	58	52	65		*Rushes*			
SACB, Florida, USA													Katsenovich et al. (2009)
Effluent value (mg L^{-1})	–	20.08	72.80	0.54	–	–	6.08	1.86	15 × 49 × 1.2	*Typha angustifolia*	151.4	9.8	
Removal efficiencies (%)	–	80.78	65.18	95.75	–	–	58.59	66.50		*Cyperus alternifolius*			
Nyanza, Kenya													Bojcevska and Tonderski (2007)
Effluent value (mg/L)	Sugar factory WW	11.0	–	–	2.9	–	–	4.1	3.0 × 20.0 × 0.4	*Cyperus papyrus*	75 mm/day	–	
Removal efficiencies (%)		76	–	–	36	–	–	29		*Echinochloa pyramidalis*			
Average effluent value (mg/L)	–	19.85	19.24	38.35	2.28	1.72	7.95	5.54	–	–	–	–	–
Average removal (%)	–	78.07	77.10	77.32	65.38	75.25	62.32	46.57	–	–	–	–	–

FWS: Free Water Surface; HSSF: Horizontal Subsurface Flow; VSSF: Vertical Subsurface Flow; TSS: Total Suspended Solid; BOD5: Biochemical Oxygen Demand; COD: Chemical Oxygen Demand; NH4-N: Ammonium; NO3-N: Nitrate; TN: Total Nitrogen; TP: Total Phosphorus; HLR: Hydraulic Loading Rate; HRT: Hydraulic Retention Time.

Table 2 – A summary of the wetland design/operation and treatment efficiency of horizontal subsurface flow (HSSF) systems in tropical and sub-tropical regions.

	Type of waste-water and stage of treatment	Removal performance							Wetland design and operation				Reference
		TSS	BOD_5	COD	NH_4-N	NO_3-N	TN	TP	Dimension (m × m × m) (L × W × D)	Plant species	HLR (m^3/day)	HRT (day)	
Egypt													Abdel-Shafy et al. (2009)
Effluent value (mg/L)	Greywater & secondary	8.9	29.1	58.0	–	–	4.6	1.7	1.1 × 1.0 × 0.4	*Phragmites australis*	–	5	
Removal efficiencies (%)		82.2	70.3	65.9	–	–	36.0	32.4					
Effluent value (mg/L)	Black water & secondary	9.0	25.0	67.0	–	–	39.6	9.3	1.1 × 1.0 × 0.4	*Phragmites australis*	–	10	
Removal efficiencies (%)		89.0	86.4	83.5	–	–	69.3	56.2					
Juja, Nairobi city, Kenya													Mburu et al. (2013)
Effluent value (mg/L) — CW1	Municipal WW & secondary	25.5	28.9	91.0	19.0	1.1	–	0.8	7.5 × 3.0 × 0.6	*Cyperus papyrus*	–	–	
Removal efficiencies (%) — CW1		75.27	60.73	42.76	26.36	–	–	42.86					
Effluent value (mg/L) — CW2	Municipal WW & secondary	27.9	34.6	89.5	18.8	0.9	–	0.6	7.5 × 3.0 × 0.6	*Cyperus papyrus*	–	–	
Removal efficiencies (%) — CW2		72.91	52.98	43.89	17.13	22	–	57.14					
Mother Dairy Pilot Plant, India													Ahmed et al. (2008)
Effluent value (mg/L)	Municipal sludge & tertiary	12.0	4.0	55.0	–	–	7.5	1.5	69 × 46 × 0.3	*Phragmites australis*	43.05 L/(m·day)	5.15	
Removal efficiencies (%)		81	90	72	–	–	67	75					
Singapore													
Effluent value (mg/L)	Municipal WW & secondary	–	–	12.4	1.3	0.2	–	6.7	1.2 × 0.6 × 0.6	*Thpha angustifolia*	5.6 cm/day	4	Zhang et al. (2012)
Removal efficiencies (%)		–	–	95.8	95.2	–	–	69.6					
Costa Rica, Central America													Dallas et al. (2004)
Effluent value (mg/L)	Greywater & secondary	–	–	1	–	–	11	–	14.0 × 1.2 × 0.6	*Cois lacryma-jobi*	2500 L/day	24	
Removal efficiencies (%)		–	–	99.4	–	–	31.25	–					
Futian, Shenzhen, China													
Effluent value (mg/L)	Municipal WW & secondary	–	8.37	25.31	6.28	–	8.27	0.65	33 × 3 × 0.5	*Kandelia candel* *Aegiceras corniculatum*	5	3	Yang et al. (2008)
Removal efficiencies (%)		–	90	70	50	–	46	60					

Pingtung, Taiwan													Lee et al. (2004)
Effluent value (mg/L)	Swine effluent &	21	39	190	1.44	1.7	156	21	9.5 × 2.6 × 0.7	*Eichhornia crassipes*	–	8.5	
Removal efficiencies (%)	secondary	96	91	84	22	54	24	47					
Dhaka, Bangladesh													Saeed et al. (2012)
Effluent value (mg/L)	Tannery WW &	12.1	0.08	0.2	15	33	–	3	1.3 × 1.0 × 0.8	*Phragmites australis*	6 cm/day	12.5	
Removal efficiencies (%)	secondary	55	98	98	86	50	–	87					
Peradeniya, Sri Lanka													Tanaka et al. (2006)
Effluent value (mg/L)	Municipal WW &	47.33	18.6	105.9	4.08	0.71	–	8.03	1 × 25 × 0.6	*Scirpus grossus*	–	18	
Removal efficiencies (%)	secondary	65.8	65.7	40.8	74.8	38.8	–	61.2		*Hydrilla verticillata*			
Shatian, Shenzhen, China													
Effluent value (mg/L)	Municipal WW &	7.92	7.68	33.90	–	–	9.11	0.56	80 × 30 × 1.5	*Canna indica*	–	11.5 h	Shi et al. (2004)
Removal efficiencies (%)	secondary	86.78	86.40	76.72	–	–	44.93	81.70	58 × 20 × 1.6	*Thalia dealbata*		8 h	
EI, Salvador													
Effluent value (mg L^{-1})	Municipal WW &	32.13	62.80	147.13	–	–	12.04	2.61	18.3 × 7.3 × 0.6	*Phragmites australis*	151.4	–	Katsenovich et al. (2009)
Removal efficiencies (%)	secondary	84.15	–	56.2	–	–	39.3	–					
Hong Kong													Wu et al. (2008)
Effluent value (mg L^{-1})	Municipal WW &	–	–	–	1.71	0.14	16.23	0.09	0.67 × 0.54 × 0.38	*Kandelia candel*	–	10	
Removal efficiencies (%)	secondary	–	–	–	91.83	47.5	69.63	91.83					
Can Tho University, Vietnam													Trang et al. (2010)
Removal efficiencies (%)	Municipal WW &	93	83	84	91	–	84	99	12 × 1.6 × 1.1	*Phragmites*	31 mm/day	–	
Removal efficiencies (%)	secondary	94	65	68	69	–	61	98		*vallatoria*	62 mm/day		
Removal efficiencies (%)		95	81	57	65	–	62	85			104 mm/day		
Removal efficiencies (%)		86	76	63	–	–	16	72			146 mm/day		
Average effluent value (mg/L)	–	20.38	23.47	67.41	26.27	5.39	29.37	4.35	–	–	–		–
Average removal (%)	–	82.58	78.32	70.64	62.57	42.46	50.03	69.75	–	–	–		–

1. Contaminant removal in free water surface (FWS) CWs

FWS treatment wetlands exhibit a broad spectrum of biological characteristics that are capable of removing various constituents for water quality improvement, and have been applied to treat wastewater at different stages and from different sources (Ghermandi et al., 2007; Kadlec and Wallace, 2008). In particular, FWS CWs provide a potentially effective buffer between tertiary wastewater treatment plants and natural waterways (Stottmeister et al., 2003; Vymazal, 2007). Therefore, FWS CWs may be a viable option for the ecological restoration of polluted rivers. FWS treatment wetlands typically contain water depths less than 0.4 m, and a typical hydraulic loading rate is between 0.7 and 5.0 cm/day, which corresponds to a wetland area of 2 to 14 ha per 1000 m^3/day of flow (Kadlec and Knight, 1996). FWS CWs can be classified according to the dominant vegetation community: free-floating aquatic vegetation, emergent aquatic vegetation, or submerged aquatic vegetation dominated systems (Vymazal, 2007).

In FWS CWs, removal efficiencies above 70% can be achieved for TSS, COD, BOD, and pathogens, primarily bacteria and viruses (Kadlec and Wallace, 2008). However, CWs often show limited capacity for nutrient (especially phosphorous) reduction (Vymazal, 2007). Removal efficiencies typically range from 40% to 50% (for nitrogen) and from 40% to 90% (for phosphorous) (Anderson et al. 2005; Vymazal, 2007). Ghermandi et al. (2007) assessed the performance of 38 tertiary treatment wetlands worldwide using FWS CWs and found that on average, these CWs removed approximately 50% of BOD, 23% of TSS, and 89% of fecal coliforms. A summary of the design/operational parameters and treatment efficiency for FWS systems in tropical and sub-tropical regions is shown in Table 1. FWS CWs can efficiently remove BOD (77.1%), TSS (78.1%) and COD (77.3%). The removal of NO_3-N (75.3%) and total nitrogen (TN) is also reliable (62.31%). The removal of NH_4-N (68.54%) and total phosphorous (TP) (47.92%) is rather variable, ranging from 28% to 96%, and 13% to 75%, respectively.

In FWS CWs, nitrification proceeds in the water column where oxygen is mostly supplied by photosynthesis of algae, cyanobacteria and submerged plants. Denitrification may take place in the bottom layer of decaying litter material. In addition, when photosynthetic activity of macrophytes and submerged plants is high, ammonia may volatilize at high pH values (Kadlec and Wallace, 2008). In FWS CWs, plant uptake is considered as the primary mechanism for reducing nitrogen (Vymazal, 2007). The vegetation is usually not harvested and the litter provides organic carbon necessary for denitrification, which may proceed in anaerobic zones within the litter layer. Phosphorus removal in FWS CWs is variable and is largely dependent on both hydraulic loading rate (HLR) and sizes of systems (Braskerud et al., 2005; Tonderski et al., 2005).

Three FWS CWs (9 ha) were built in the border of the highly eutrophic Lake L'Albufera de Valencia, which is located in a semi-tropical area in Spain (Martín et al., 2013). The function of the set of FWS CWs was to treat the eutrophic water from the lake with the objective of reducing the phytoplankton population and nutrients. The removal efficiencies were reported to be 75% for TSS, 65% for TP, 52% for TN, 61% dissolved inorganic nitrogen, and 58% for NO_3-N. The authors also indicated that at progressive hydraulic application rates ranging from 7 to 47 m/year, there were significant variations in the removal of selected contaminants. A significant correlation between input loading and output concentration was only shown for nitrogen species, and not for TSS or TP. In Sri Lanka, a case study was carried out using three FWS CWs (1 m × 25 m × 0.6 m) in treating domestic wastewater (Jinadasa et al., 2006). One unit was planted with *Scirpus grossus*, one was planted with *Typha angustifolia*, and the unplanted third was the control. The primary-treated wastewater supply was fed into the units by gravity flow and the inlet HRT was estimated to be 18 hr. The average BOD_5 removal efficiencies were 44%, 68%, and 54%, while TSS removal efficiencies were 64.7%, 71.9% and 76.0%. The average removal efficiencies were reported to be 59.9%, 33.3% and 14.1% for NH_4-N, NO_3-N and TP, respectively.

2. Contaminant removal in subsurface flow constructed wetlands (SSF CWs)

SSF CWs typically consist of a rectangular bed planted with the common reed (*Phragmites australis*) or other higher aquatic plants and lined with an impermeable membrane. Bed depth for SSF CWs is generally less than 0.6 m (Kadlec and Knight, 1996). Pre-treated wastewater is fed in at the inlet and passes slowly through the filtration medium under the surface of the bed in a more or less horizontal path until it reaches the outlet zone whereupon it is collected before discharge. Typical depths vary from 0.49 to 0.79 m (Cooper et al., 1996), and hydraulic application rates are between 2 and 20 cm/day, which correspond to a wetland area of 0.5 to 5 ha per 1000 m^3/day of flow (Kadlec and Knight, 1996). SSF CWs may be classified into two basic flow types: horizontal subsurface flow constructed wetlands (HSSF CWs) and vertical subsurface flow (VSSF CWs).

Tables 2 and 3 show summaries of the wetland design, operational treatment parameters and efficiencies for HSSF and VSSF CW systems in both tropical and sub-tropical regions. Both HSSF (82.58%) and VSSF (84.91%) CWs show very efficient removal performance for TSS. VSSF CWs (87.61%) show higher removal of BOD compared to HSSF CWs (78.32%), while COD removal was better in HSSF CWs (70.64%) than that in VSSF CWs (64.06%). Generally, wetlands are known to perform very well with respect to BOD and COD removal, as well as in reducing bacterial contaminants (Sundaravadivel and Vigneswaran, 2010). The high removal rate of BOD and COD may be attributable to filtration/sedimentation of suspended solids as well as degradation by microorganisms. In particular, VSSF CWs are expected to perform better than the HFCWs for the removal of BOD, since VSSF CWs, being intermittently loaded, have unsaturated flow, resulting in a higher transfer of oxygen to the filter medium as compared to HSSF CWs (Kadlec and Wallace, 2008).

Nitrogen removal in SSF CWs is affected by the HRT, temperature, vegetation type and properties of the soil medium (Akratos and Tsihrintziz, 2007). VSSF CWs have been reported to remove NH_4-N (66.02%) slightly ($p > 0.05$) more efficiently than do HSSF CWs (62.57%) (see Tables 2 and 3), mainly due to the fact that the intermittent feeding leads to increased transfer of oxygen in VSSF CWs, which promotes a more oxidizing environment for organic matter biodegradation. The results of this study clearly confirmed the important role of VSSF CWs for NH_4-N removal. Although HSSF CWs show a high potential for NO_3-N reduction due to the presence of anaerobic conditions, the present review shows surprisingly low removal efficiencies of NO_3-N in HSSF (42.46%), compared to VSSF CWs (73.33%). Removal efficiencies of TN in SSF CWs generally range from 40 to 55%, and the removal level depends on the type of SSF CW and the influent loading (Vymazal, 2007). In studies surveyed by the present review, removal efficiencies for TN in VSSF CWs were just slightly ($p > 0.05$) higher (53.32%) than those in HSSF CWs (50.03%).

In contrast, phosphorus is removed primarily by ligand exchange reactions, whereby phosphate displaces water or hydroxyls from the surface of Fe and Al hydrous oxides (Faulkner and Richardson, 1989). Furthermore, the vegetation species, types of substrate, influent styles or climate also plays a significant role in phosphorous removal, compared to the influence of pH, TSS and TP load (Shan et al., 2011). Phosphorus removal rates are rather low in most CW systems, and P removal remains close to 50% (Verhoeven and Meuleman, 1999). In SSF systems, phosphorous removal appears more variable than nitrogen removal and different authors have reported TP removal efficiencies ranging from 26%–70% (Rousseau et al., 2004). Vymazal (2005) reviewed phosphorus removal rates in HSSF CWs throughout the world and calculated an average mass-based efficiency of 32% with an average effluent concentration (mostly for secondary wastewater treatment) of 5.15 mg/L. In the present review, HSSF CWs exhibited better TP removal efficiencies (69.75%) as compared to those in VSSF CWs (60.08%) (Table 3). CWs with SSF flow have a major potential for phosphorus removal, and among those systems, HSSF CWs have an even higher potential as the substrate is constantly flooded and there is little fluctuation in redox potential in the bed (Vymazal, 2007).

Zurita et al. (2009) investigated the use of four commercially valuable ornamental species in two types of SSF wetlands for domestic wastewater treatment in a tropical area in Jalisco, Mexico. The results for most pollutant removal were significantly higher in the VSSF CWs than in the HSSF CWs; 81.9% for BOD, 80.3% for COD, 50.6% for Org-N, and 72.2% for NH_4^+ in the VSSF CWs, as compared to removal efficiencies of 77.9% for BOD, 76.3% for COD, 42.4% for Org-N, and 47.2% for NH_4^+ in the HSSF CWs. However, statistically significant differences were observed for only two pollutants, with NO_3-N (47.7%) and TSS (82%) showing significantly higher removal in the HSSF as compared to the VSSF CWs. In Istanbul (Turkey), the removal efficiencies of nitrogen and the effects of hydraulic loading rate (HLR) in both HSSF and VSSF CWs planted with *Iris australis* and *P. australis* in subtropical climate were investigated (Tunçsiper, 2009). The author reported that the volume-based first-order nitrification and denitrification removal constants (1 day^{-1}) were 0.388 and 0.785 for the HSSF bed, and 0.412 and 0.293 for the VSSF bed, respectively, implying that HSSF CWs can provide good conditions for denitrification and VSSF can successfully remove NH_3-N, but denitrification is not promoted in these VSSF systems. In a similar way, Konnerup et al. (2011) assessed the suitability of using CWs for the treatment of fishpond water in a recirculating aquaculture system in the Mekong Delta of Vietnam. The author also indicated that the outlet concentrations of NO_3^--N were significantly higher in VSSF CW as compared to the HSSF CW, mainly due to the substantial nitrification activity in the VFCWs.

3. Contaminant removal in hybrid constructed wetlands

Hybrid CWs are primarily used for enhanced removal of TN because the various types of wetland environments provide different redox conditions, which are suitable for nitrification and denitrification (Vymazal, 2011). Due to their inability to provide both aerobic and anaerobic conditions simultaneously, single-stage CWs cannot achieve high removal of total nitrogen (Vymazal, 2007). In general, HSSF CWs can provide good conditions for denitrification; the ability to nitrify ammonia is however very limited. In contrast, VSSF CWs can remove NH_3-N successfully, but denitrification hardly takes place in these systems. In this regard then, various types of CWs may be combined with one another in order to leverage the strength of each type of individual system. As many types of wastewaters are difficult to treat in a single stage system, hybrid systems that consist of various types of CWs arranged in series have been successfully introduced.

VSSF–HSSF combinations are probably the most frequently used hybrid systems among the many types of combinations and are gaining more attention in many European countries (Vymazal, 2007). In a pilot study at Chongqing University, which is located in a subtropical humid monsoon climate zone in southern China, a new type of hybrid CW consisting of both vertical-baffled flow wetland and a HSSF CW was built to naturally accelerate the removal of organic matter and nitrogen (Zhai et al., 2011). The authors reported that the results from the system were a good example of CW application in a semi-tropical region. All the beds were filled with graded gravel (3–20 mm) and operated at an overall HLR of 26.9 cm/day. The removal performance was reported as 97% for TSS, 84% for COD, 80% for NH_4-N and 85% for TP. The HSSF–VSSF system consisted of a large HSSF bed followed by a small VSSF bed as the second stage. In the HSSF–VSSF systems, nitrification takes place in the vertical flow stage at the end of the process sequence. If nitrate removal is needed, it is then necessary to re-circulate the effluent back to the front end of the system where denitrification can take place in the less aerobic HSSF bed. Similarly, Rivas et al. (2011) investigated a multi-stage municipal wastewater treatment system consisting of a HSSF CW followed by a VSSF CW in Santa Fe de la Laguna, Mexico. The authors reported relatively good removal efficiencies for BOD_5 (94%–98%), COD (91%–93%), TSS (93%–97%), and TN (56%–88%); however, significant TP removal was not well accomplished in this study (25%–52%).

To achieve higher TN removal or to treat more complex industrial and agricultural wastewaters, hybrid systems, besides incorporating HSSF–VSSF and VSSF–HSSF CWs, can include a FWS stage. Meutia (2001) investigated the treatment of laboratory wastewater in a tropical integrated system in

Table 3 – A summary of the wetland design/operation and treatment efficiency of vertical subsurface flow (VSSF) in tropical and sub-tropical regions.

	Type of waste-water	Removal performance							Wetland design and operation				Reference
		TSS	BOD_5	COD	NH_4-N	NO_3-N	TN	TP	Dimension (m × m × m) (L × W × D)	Plant species	HLR (m^3/day)	HRT (day)	
Gomati, Chalkidiki, Greece													Tsihrintzis et al. (2010)
Effluent value (mg/L)	Municipal WW &	9	39	62	–	–	14	5.6	640 m^2 × 1 m	*Phragmites australis*	180	–	
Removal efficiencies (%)	secondary	95	92	89	–	–	77	62	360 m^2 × 1 m				
Ocotlán, Jalisco Mexico													Zurita et al. (2009)
Effluent value (mg/L)	Municipal WW &	21.9	20.8	49.5	–	–	14.6	4.2	1.8 × 1.8 × 0.7	*Strelitzia reginae*	128 L/day	–	
Removal efficiencies (%)	secondary	61.56	81.94	80.32	–	–	49.38	50.14		*Anthurium andreanum*			
Kampala, Uganda													Kyambadde et al. (2004)
Effluent value (mg/L)	Municipal WW & tertiary	–	–	–	7.1	0.09	16.1	2.6	0.58 m^2 × 0.82 m	*Cyperus papyrus*	0.064	5	
Removal efficiencies (%)		–	–	–	75.43	60.87	72.48	83.23					
Wuxi, China													
Effluent value (mg/L)	Livestock WW &	96	61.8	–	32.9	41.3	–	–	2.0 × 2.0 × 1.0	*Phragmites communis*	0.4	–	He et al. (2006)
Removal efficiencies (%)	secondary	77.1	81.3	–	61.7	66.6	48.9	–		*Phragmites typhia*			
Chiang Mai, Thailand													Kantawanichkul et al. (2003)
Effluent value (mg/L)	UASB effluent &	4	15	92	51	–	97	0.6	2.0 × 2.0 × 1.4	*Scirpus grossus Linn.*	–	–	
Total removal (%)	secondary	98	96	91	84	–	76	97					
Wuhan, China													Wu et al. (2011)
Effluent value (mg/L)	Municipal WW &	–	–	115.5	22.59	0.34	25.6	1.418	1.0 × 1.0 × 1.0	*Typha orientalis*	250 mm/day	1.2	Chang et al. (2012)
Total removal (%)	secondary	–	–	59.9	–	79.52	15.0	52		*Arundo donax*			
Effluent value (mg/L)		–	–	130.1	22.56	0.37	26.4	1.51		*Canna indica*			
Total removal (%)		–	–	62.8	–	–	12.8	51.1		*Arundo donax*			
India													Ghosh and Gopal (2010)
Effluent value (mg/L)	Municipal WW & tertiary	–	10.09	15.11	0.41	0.14	3.41	2.46	2.1 × 0.8 × 0.6	*Typha angustifolia*	236 mm/day	4	
Total removal (%)		92.91	84.41	89.28	99.96	96.78	83.99	43.36					
Guangzhou, China													Chen et al. (2008)
Effluent value (mg/L)	Municipal WW & secondary	–	8.37	25.31	6.28	–	8.27	0.65	5.0 × 3.0 × 1.8	Cyperus alternifolius	0.45	18	
Total removal (%)		–	90	70	50	–	46	60					
Ankara, Turkey													
Effluent value (mg/L)	Landfill	–	–	–	–	–	–	–					Yalcuk and Ugurlu (2009)
Removal efficiencies (%)	Leachate	–	–	27.3	62.3	–	–	52.6	1.0 × 0.5 × 0.4	*Typha latifolia*	10 L/day	11	
Removal efficiencies (%)		–	–	30.6	48.9	–	–	57.9				8	
Taihu, China													
Effluent value (mg/L)	Lake water	–	–	4.25	0.89	0.5	2.37	0.05	20 × .1.5 × 1.0	*Typha angustifolia*	0.64 m/day	–	Li et al. (2008)
Total removal (%)		–	–	40.4	45.9	62.9	51.6	51.6					
Average effluent value (mg/L)	–	32.73	25.84	61.72	17.97	7.12	23.08	2.12	–	–	–	–	–
Average removal (%)	–	84.91	87.61	64.06	66.02	73.33	53.31	60.08	–	–	–	–	–

Jakarta, Indonesia consisting of a FWS CW planted with *Typha* sp. and a SSF CW planted with floating *Lemna* sp. The author reported removal efficiencies of 95% for COD and TP, and 82% for TN during the dry season. In the transition period from the dry season to the rainy season, COD removal efficiency decreased to 73%, TN increased to 89%, and TP was almost the same (95%) as for the dry season. These results showed that a hybrid system comprising both a SSF and a FWS CW was capable of treating the laboratory wastewaters to a rather high degree. Similarly, Lim et al. (2001) investigated nutrient removal from aquaculture wastewaters using an integrated system consisting of a FWS CW and a HSSF CW in Malaysia. The results showed that nitrogen removals were excellent, with efficiencies of 86% to 98% for NH_4-N and 95% to 98% for TN. A phosphate removal efficiency of 32% to 71% was observed, with the efficiencies being inversely related to hydraulic loading. A hybrid system consisting of three VSSF CWs (depth: 0.7 m), three HSSF CWs (depth: 0.6 m), three FWS CWs (depth: 0.6 m) and polishing ponds (area of 200 m^2; depth: 0.7 m) was built on the island of Koh Phi Phi west on the Thai-Malayan peninsula in Thailand (Brix et al., 2011). This system was built for the restoration of wastewater management after the Indian Ocean tsunami that hit the island in 2004, and received considerable notoriety because of its "flower and butterfly design". Results showed very high removal of pollutants, with removal efficiencies of 92% for BOD_5, 90% for TSS, and 90% for oil and grease. The removal of TKN (39%) and TP (46%) was only relatively modest, and the removal of fecal coliforms was only about one order of magnitude (92%).

A summary of the wetland design and operational parameters as well as treatment efficiencies of hybrid systems in tropical and sub-tropical regions is shown in Table 4. The most commonly used hybrid system is a VSSF–HSSF constructed wetland, which has been used for treatment of both sewage and industrial wastewaters. Out of 11 of the surveyed hybrid systems, 8 were designed to treat municipal sewage, while the other hybrid systems were designed to treat various wastewaters including agricultural wastewaters, laboratory wastewater, and winery wastewater. In sum, all types of hybrid systems were found to be more efficient in the removal of TSS (91.28%), COD (84.31%), NH_4-N (80.71%), NO_3-N (80.76%) and TN (75.41%) compared to other types of CWs.

4. Contaminant removal in floating treatment wetlands (FTWs)

FTWs are a novel treatment concept that employ rooted, emergent macrophytes growing on a floating mat (Tanner and Headley, 2011; Fonder and Headley, 2010). To date, FTWs have been used for water quality improvement, habitat enhancement, and aesthetic improvement at ornamental ponds and lakes (Tanner and Headley, 2011). One of the main advantages of FTWs over conventional sediment-rooted wetlands is their ability to cope with the highly variable nature of hydrologic and pollutant input that is typical for event-driven stormwater systems (Kerr-Upal et al., 2000). In this way, emergent macrophytes are able to colonize areas of deep water without investing in physiological adaptations to cope with deep flooding (Azza et al., 2006). This feature also enables the FTW system to be designed as an extended detention basin, so that large runoff events can be captured and released slowly over subsequent days.

A summary of the design and operational parameters and treatment efficiency of FTWs is shown in Table 5. Based on the present review, FTW systems showed comparable removal efficiencies for BOD_5 (70.73%), NH_4-N (63.58%), and TP (44.80%) as compared to FWS CW systems (65.34% for BOD_5, 65.38% for NH_4-N, and 45.57% for TP). It is conceivable that plant assimilation of nutrients may be even higher in a FTW system compared to a sediment-rooted wetland (Headley and Tanner, 2011), since in a FTW the plant roots are not in contact with the benthic sediments or soil and can only access nutrients contained within the floating mat and in the water column (Kadlec and Wallace, 2008). This is in contrast to a sediment-bound wetland, such as a FWS CW, where the plant roots acquire nutrition from the underlying soil. Beneath the floating mat, a network of roots, rhizomes, and the hanging root-biofilm network provides a biologically active surface area for the biochemical transformation of contaminants and physical processes such as filtering and entrapment of particulate matter (Kyambadde et al., 2004). However, in the present review, FTW systems actually showed lower removal efficiencies for TSS (46.6%), COD (55.2%), NO_3-N (54.1%) and TN (50.7%) compared to FWS CWs (78.1% for TSS, 77.3% for COD, 75.3% for NO_3-N and 62.3% for TN).

Boonsong and Chansiri (2008) examined the capacity of a FTW planted with *Vetiveria ziznnioides* in Bangkok, Thailand to treat domestic wastewater at three different HRTs of 3, 5, and 7 days. The TN and NH_4-N removal efficiencies were found to be 9.9%–62.5% and 13.4%–58.6%, while the TP and phosphate-P removal efficiencies ranged from 6.3% to 35.9% and from 7.4% to 23.5%. The results indicated that the 7-d HRT showed the best treatment performance for BOD, TN, and TP, with average removal efficiencies of 90.5%–91.5%, 61.0%–62.5%, and 17.8%–35.9%, respectively. In Southern China (Guangzhou), Sun et al. (2009) investigated nitrogen removal from polluted river waters (inlet concentration of 8.7 g/m^3) using FTW mesocosms at a HLR of 120 $L/(m^2 \cdot day)$. Some enhanced methods, including use of immobilized denitrifying bacteria and aeration, were used to improve the performance of nitrogen removal. Experimental results showed that the removal efficiencies with enhancement were 72.1% for TN, 100% for NH_4-N, 75.8% for NO_3-N, 95.9% for NO_2-N, and 94.6% for COD, while the *Canna* floating bed system removed only 50.4% of TN, 22.4% of NO_3-N, 5.3% of NO_2-N and 39.9% of COD, respectively, in 5 days without any enhancement. The wastewater treatment efficiencies of FTWs containing two types of macrophytes, *T. angustifolia* and *Canna iridiflora*, were investigated in a pilot scale study in the tropical climate of Sri Lanka (Jinadasa et al., 2006). In batch experiments, over 80% removal of BOD and NH_4-N was observed, while NO_3-N removal was over 40%. The authors indicated that *T. angustifolia* showed slightly higher removal efficiencies than *C. iridiflora*, and FTWs with *T. angustifolia* may be considered a possible solution for lake restoration where there are space and cost constraints.

Table 4 – A summary of the wetland design/operation and treatment efficiency of hybrid systems in tropical and sub-tropical regions.

	Type of waste-water and stage of treatment	Removal performance							Wetland design and operation				Reference
		TSS	BOD_5	COD	NH_4-N	NO_3-N	TN	TP	Dimension (m × m × m) (L × W × D)	Plant species	HLR (m^3/day)	HRT (day)	
Kathmandu Valley, Nepal													Shrestha et al.
Effluent value (mg/L)	Hospital WW & secondary	2.83	3.29	20.20	1.61	–	–	4.22	7 × 20	*Phargmites Karka*	20	–	(2001)
Total removal (%)		97.25	97.01	93.80	95.18	–	–	46.60	11 × 11				
Texcoco, Mexico													Belmont et al.
Effluent value (mg/L)	Municipal WW & secondary	56.6	–	223.3	22.9	5.2	44.6	–	8.8 × 1.8 × 0.6	*Phragmites communis*	2.88	2.3	(2004)
Total removal (%)		85.98	–	85.83	65.46	81.7	72.62	–	2.8 × 4.0				
Nepal													Singh et al. (2009)
Effluent value (mg/L)	Municipal WW & secondary	37.8	173.3	318.6	45	–	–	17.1	8.0 × 9.5 × 0.5	*Pharagmites Karka*	0.13 m/day	–	
Total removal (%)		97.49	89.12	89.07	68.30	–	–	29.91	10.0 × 7.5 × 0.6	*Canna latifolia*			
Turkey													Tunçsiper (2009)
Effluent value (mg/L)	Municipal WW & secondary	–	–	–	3.24	0.26	4.59	–	1.5 × 3.5 × 0.4	*Iris australis*	60 L/(m^2·day)	–	
Total removal (%)		–	–	–	91.20	88.79	91.33	–	1.5 × 3.5 × 0.32	*Phragmites australis*			
Bogotá Savannah, Columbia													Arias and Brown
Effluent value (mg/L)	Municipal WW & secondary	10	28	–	9	–	15	3	4354 m^2 × 0.6 m	–	40 cm/day	4.5	(2009)
Total removal (%)		96.90	92.26	–	62.5	–	63.41	40	17416 m^2 × 0.5 m		10 cm/day		
Jakarta, Indonesia													Meutia (2001)
Effluent value (mg/L)	Laboratory WW & secondary	–	–	1.23	0.06	0.65	3.04	0.6	3.0 m^2 × 0.4 m	*Typha sp.*	250 L/day	1	
Total removal (%)		–	–	97.72	97.21	85.96	65.66	37.33		*Lemna sp.*			
Santa Fe de la Laguna, Mexico													Rivas et al. (2011)
Effluent value (mg/L)	Municipal WW & secondary	20	33	100	–	–	31	15	1.5 × 1.5 × 0.6	*Typha latifolia*	–	0.5	
Total removal (%)		79	52	68	–	–	82	14		*Phragmites australis*	–		
Koh Phi Phi, Thailand													Brix et al. (2011)
Effluent value (mg/L)	Municipal WW & secondary	16	25	–	–	0.1	33	4.5	2300 m^2 × 0.7 m	*Canna, Heliconia*	400	–	
Total removal (%)		90	91.58	–	–	50	68.89	46.43	750 m^2 × 0.6 m	*Papyrus*			
Taiwan													Lin et al. (2002)
Effluent value (mg/L)	Agricultural WW & secondary	–	–	–	0.11	0.07	0.18	3.53	5.0 × 1.0 × 0.8	*Phragmites australis*	1.35 cm/day	–	
Total removal (%)		–	–	–	86.25	97.37	95.36	31.98					
Pontevedra, Spain													Serrano et al.
Effluent value (mg/L)	Winery WW & secondary	17	279	448	12.5	–	25.2	1.9	8.3 × 6.0 × 1.4	*Phragmites australis*	17.6	–	(2011)
Total removal (%)		87.02	67.52	71.66	–	–	64.04	57.59	10 × 10 × 0.35	*Juncus effusus*			
Chongqing, China													Zhai et al. (2011)
Effluent value (mg/L)	Municipal WW	3.2	–	21	2.2	–	–	0.45	433–3283 m^2	*Phragmites australis*	26.9	–	
Total removal (%)		96.6	–	84.1	79.6	–	–	84.5					
Average effluent value (mg/L)	–	20.43	90.27	161.76	10.73	1.26	19.57	5.59	–	–	–	–	–
Average removal (%)	–	91.28	81.58	84.31	80.71	80.76	75.41	43.15	–	–	–	–	–

Table 5 – A summary of the wetland design/operational parameters and treatment efficiency of floating treatment wetlands in tropical and sub-tropical regions.

	Type of waste-water and stage of treatment	Removal performance							Wetland design and operation				Reference
		TSS	BOD_5	COD	NH_4-N	NO_3-N	TN	TP	Dimension (m × m × m) (L × W × D)	Plant species	HLR (m^3/day)	HRT (day)	
Kandy, Sri Lanka													
Effluent concentration (mg/L)	Municipal WW	–	9.7	–	4.6	3.9	–	11.5	1.0 × 0.5 × 0.65	*Canna iridiflora*	–	14	Weragoda et al. (2012)
Total removal (%)		–	65.5	–	81.6	50.0	–	88.5		*Typha angustifolia*			
Taihu Lake, China													Yang et al. (2008)
Effluent concentration (mg/L)	Agricultural runoff	–	–	36.70	0.54	1.42	2.86	1.34	2.0 × 1.0 × 0.75	*Oenanthe javanica*	–	1	
Total removal (%)		–	–	47	60	71	64	13					
Effluent concentration (mg/L)		–	–	40.2	1.31	0.05	2.95	1.16					
Total removal (%)		–	–	24	–	97	35	15			–	2	
Kampala, Uganda													Kansiime et al. (2005)
Effluent concentration (mg/L)	Municipal WW & tertiary	–	–	–	7.7		8.5	5.4	–	*Cyperus papyrus*	–	–	
Total removal (%)		–	–	–	89.3		89.76	84.53	–		–	–	
Effluent concentration (mg/L)	Municipal WW & tertiary	–	–	–	23.4		28.4	12.5	–	*Colocasia esculenta*	–	–	
Total removal (%)		–	–	–	70.45		67.76	64.71	–		–	–	
Pear River, China													Sun et al. (2009)
Effluent concentration (mg/L)	River water	–	–	1.98	0	0.67	2.42	–	1.2 × 0.8 × 1.2	*Canna*	–	–	
Total removal (%)		–	–	94.6	100	75.8	72.1	–					
Jiaxing, Zhejiang, China													
Effluent concentration (mg/L)	River water	–	–	–	1.66	3.05	4.92	–	–	*Hydrocharis dealbata*	–	–	Zhao et al. (2012)
Total removal (%)		–	–	–	44.8	25.6	39.6	43.3		*Eichhirnia crasslpes*			
Kranji, Singapore													
Total removal (%)	Urban catchment	–	–	–	–	–	40.8	19.1		*Vetiver*	–	–	
Total removal (%)		–	–	–	–	–	67.5	39.2		*Typha angustifolia*	–	–	Chua et al. (2012)
Total removal (%)		–	–	–	–	–	7.8	46.0		*Polygonum barbatum*	–	–	
Orlando, Florida, USA													
Effluent concentration (mg/L)	Stormwater	–	–	–	0.103	0.022	0.349	0.0338	7.4 m^2	*Pontederia cordata*	–	–	Chang et al. (2013)
Total removal (%)		–	–	–	51.1	20.6	15.7	47.7		*Juncus effusus*			
Madhya Pradesh, India													
Effluent concentration (mg/L)	River water	–	–	–	–	–	–	–					Billore et al. (2009)
Total removal (%)		46.6	45	–	50	39	–	–	200 m^2	*Phragmites karka*	–	–	
Bangkok, Thailand													Boonsong and
Effluent concentration (mg/L)	Municipal WW & secondary	–	7.5	–	15	–	19.9	4.3		*Polystyrene sheet*	–	7	Chansiri (2008)
Total removal (%)		–	91.89	–	50	–	57.57	31.75	–				
Effluent concentration (mg/L)		–	18	–	18.5	–	23	–		*Polystyrene sheet*	–	5	
Total removal (%)		–	80.54	–	38.54	–	50.96	–					
Average concentration (mg/L)	–	–	11.73	26.29	7.28	1.51	10.37	5.18	–	–	–	–	–
Average removal (%)		46.6	70.73	55.2	63.58	54.14	50.71	44.80					

5. Overall evaluation

This review shows the great potential CWs have to treat a broad range of wastewaters, especially in developing countries in tropical regions. Fig. 1 shows a comparison of the treatment performance of the different types of CWs. In the present review, removal of BOD and TSS was very efficient and consistent across all types of treatment wetlands. All modes of hybrid systems appeared more efficient in the removal of TSS (91.3%), COD (84.3%), NH_4-N (80.7%), NO_3-N (80.8%) and TN (75.4%), as compared to other types of CWs. VSSF CWs removed TSS (84.9%), BOD (87.6%), and nitrogen (*i.e.*, 66.2% for NH_4-N, 73.3% for NO_3-N, and 53.3% for TN) more efficiently than HSSF CWs, while HSSF CWs (69.8%) showed better TP removal as compared to VSSF CWs (60.1%). Compared to other types of CWs, both HSSF (69.8%) and VSSF (60.1%) CWs showed superior TP removal. VSSF systems showed the best BOD removal (87.6%) among all the CW types. FTWs showed comparable removal efficiencies for BOD (70.7%), NH_4-N (63.6%), and TP (44.8%) to FWS CW systems.

Haberl et al. (1995) reported on the pollutant removal efficiencies of 268 operational treatment wetlands in Europe. Using CW performance in tropical and semi-tropical regions (see Tables 1–5), a comparison of removal efficiencies of FWS CWs, HSSF CWs, VSSF CWs, hybrid systems, and FTWs can be made between tropical countries and the treatment wetlands in Europe. Mean removal efficiencies of BOD_5 for tropical regions were 77.1%, 78.3%, 87.6%, 81.6%, and 70.7% for FWS CWs, HSSF CWs, VSSF CWs, hybrid systems, and FTWs, respectively. In comparison, the value for treatment wetlands in Europe was 79.1% (Haberl et al., 1995). Apparently, except for FTWs, all the types of treatment wetlands in tropical regions appear to show BOD removal efficiencies within the same general range as those in Europe. Furthermore, compared to the mean COD removal efficiency in Europe (69.5%), the performance of all the CW systems (except for FTW) in tropical countries was satisfactory, with removal efficiencies of 77.3%, 70.6%, 64.1% and 84.3% for FWS CWs, HSSF CWs, VSSF CWs and hybrid systems. With regard to NH_4-N removal in tropical countries, efficiencies of 65.4%, 62.6%, 66.0%, 80.7%, and 63.6% for HSSF CWs, VSSF CWs, hybrid systems, and FTWs, were all significantly higher than that in Europe (30.30%) (Haberl et al., 1995). Additionally, the mean TN removal efficiencies of 62.3%, 50.0%, 53.3%, 75.4%, and 50.7% for FWS CWs, HSSF CWs, VSSF CWs, hybrid systems, and FTWs in tropical regions were significantly higher than the mean TN removal rate of 39.6% for European treatment wetlands (Haberl et al., 1995). On the other hand, except for SSF CWs, the mean removal efficiencies for TP of 46.6%, 43.2%, and 44.8% for FWS CWs, hybrid systems, and FTWs in tropical regions were generally lower than the value reported for European systems of 47.1% (Haberl et al., 1995).

For wastewater treatment using CWs, cost is always an important factor for consideration. However, there have been very few studies on the cost for construction and operation and maintenance (O&M) for CW systems in tropical and subtropical countries. Even if case studies were available, due to the inconsistent units used for cost calculations (*e.g.*, per capita *versus* per m^3), it remains difficult to make an overall and comprehensive comparison among different types of

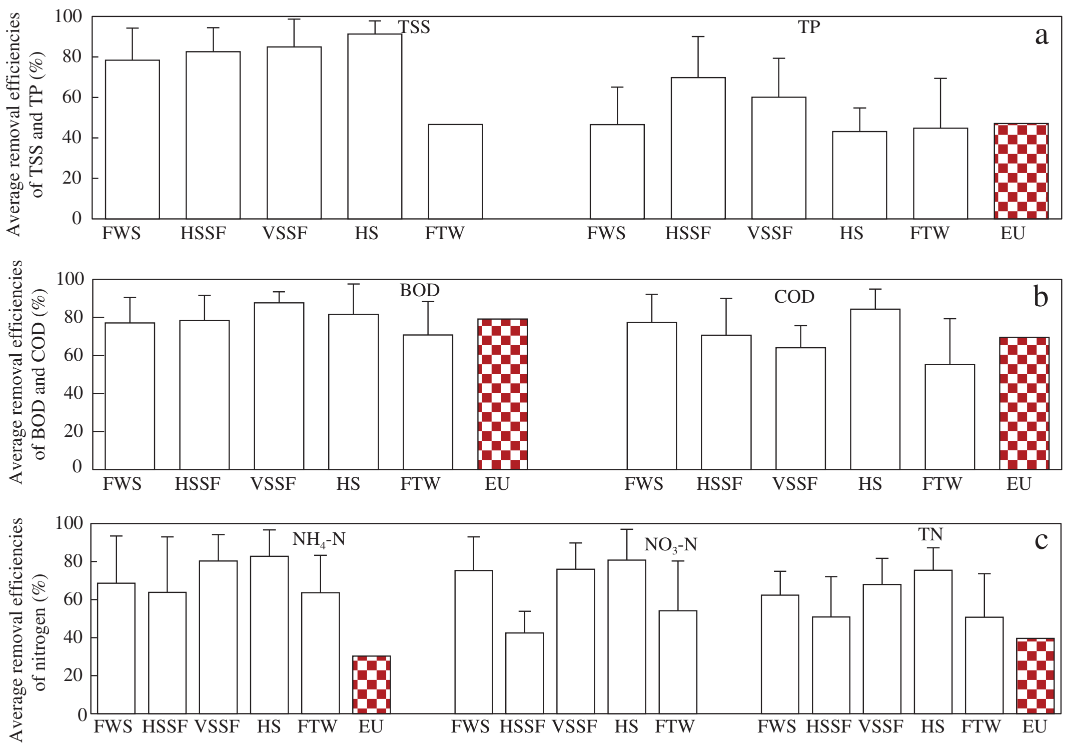

Fig. 1 – Average removal efficiencies of contaminants in various CW systems: a) TSS and TP removal; b) BOD and COD removal; and c) nutrient removal. Note: 1) HS: hybrid system; 2) EU: countries of European Union; and 3) Error bar: standard deviation.

Table 6 – Comparison of cost requirements between CWs and WWTPs.

	Types of CWs	Design capacity (m^3/day)	Total capital cost (US$)	Construction cost (US$/$m^3$)	O/M cost US$ (m^3/year)	Energy cost (US$/$m^3$)	Reference
Conventional WWTP							
China					0.1151–0.2465		Liu et al. (2008)
Worldwide				0.7717	0.6362	0.1036	Hernández-Sancho and Sala-Garrido (2009)
Bogota Savannah, Colombia				0.293	0.360		Arias and Brown (2009)
CWs in China					0.0082–0.039		Liu et al. (2008)
CWs in the present study							
Bogota Savannah, Colombia		65	14,672	0.246	0.0134		Arias and Brown (2009)
Crete, Greece	FWS CWs	144	387,350	364 per capita	0.0381		Tsihrintzis et al. (2010)
	VSSF CWs	180	521,779	521 per capita	0.1397		

CWs. A comparison of cost for WWTPs and CWs is shown in Table 6. In general, CWs have been considered as the best sustainable alternatives to conventional WWTPs due to being low-cost and low-maintenance. For example, in China, the cost of CW construction (US$ 164–460 m^{-3}) amounts to only one-third to one-half of that for building a WWTP (US$ 246–657 m^{-3}), and CW systems usually have extremely low O&M cost (US$ 0.0082–0.039 m^{-3}) compared to that for a conventional WWTP (US$ 0.1151–0.2465 m^{-3}) (Liu et al., 2008). Arias and Brown (2009) compared the monetary and resource investment between a model CW system and a WWTP in Bogotá Savannah, Colombia. Their analysis indicated quite similar final construction costs for the two systems: 0.246 US$/$m^3$ (CW) *versus* 0.293 US$/$m^3$ (WWTP). However, their analysis also indicated a superior advantage of the CW in O&M cost: 0.0134 US$/$m^3$ (CW) *versus* 0.0360 US$/$m^3$ (WWTP). Nevertheless, the cost for the construction and maintenance of different types of CWs can differ quite significantly. Tsihrintzis et al. (2010) compared the performance and costs of FWS and VSF CW systems treating domestic wastewater in Crete, Greece. The author reported that the total construction cost of the FWS CW system was 364 US$/capita, while the construction cost of the VSSF CW system amounted to 521 US$/capita. The total O&M cost of the FWS CW system was 0.0381 US$/$m^3$, while the value for the VSSF CW system was 0.1397 US$/$m^3$.

6. Conclusions

Given the pressing need for clean water and the tropical location of many developing nations, CWs have been successfully implemented as an appropriate technology to solve water and wastewater problems in many tropical and subtropical regions. However, there are relatively few published reports on CW applications under tropical and subtropical conditions. The emphasis of this review is placed on the treatment performance of various types of wetlands including FWS CWs, SSF CWs, hybrid constructed wetlands, and FTWs. This review demonstrates that CWs have great potential to treat a broad range of wastewaters, especially in developing countries in tropical regions.

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