Article

Hybrid constructed wetlands for wastewater treatment: A worldwide review

M.H. Sayadi[1], R. Kargar[2], M.R. Doosti[2], H. Salehi[3]

[1] Environmental Sciences Department, University of Birjand, Birjand, Iran

[2] Civil and Environmental engineering Department, University of Birjand, Birjand, Iran

[3] General Director of the Environment Department South Khorasan, Head Office Iran

E-mail: Mh_sayadi@yahoo.com

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Abstract

The utilization of environmentally friendly and eco-safe wastewater treatment plan is nowadays widespread. This study aimed to assess the potentiality of hybrid constructed wetlands for treating of landfill leachate, river polluted water, domestic, industrial, hospital, runoff and agricultural wastewaters in lab-scale, pilot-scale and full-scale with various configurations. The results revealed that the hybrid constructed wetlands are effective to remove organic matter (BOD_5, COD) and suspended solid, while in terms of nutrient removal such as N and P components, the removal efficiencies were depending to system properties and operational condition. Additionally it is very useful system to remove the heavy metals and pharmaceuticals pollutants from different wastewaters. Combination of constructed wetlands enhances pollutants removal efficiency as hybrid constructed wetlands could cover the limitation of each single constructed wetlands. It could be concluded that the hybrid constructed wetlands ensure a more stable removal rate of pollutants from various wastewaters in comparison with other wastewaters treatment plans.

Keywords hybrid constructed wetlands; wastewater treatment; macrophytes; organic and inorganic pollutants.

1 Introduction

Treatment of wastewater plays a vital role on human health; furthermore the limitation of water resources and sustainable use of alternative water sources have leaded to demand for the development (Kaseva, 2003; Kyambadde 2005; Doosti et al., 2012). There are the different conventional methods for wastewaters treatment such as active sludge process (ASP), rotating biological contactor (RBC), stabilization ponds, oxidation ditch, trickling filter (TF), sequence batch reactors (SBR), lagoons and up flow anaerobic sludge blanket (UASB), Micro-algae techniques etc.. These methods having the limitations like energy, economic, need for large land, complex construction and operation, sensitive to temperature and excessive sludge (Simi and Mitchell, 1999; Tanner and Sukias, 2003; Sayadi et al., 2011). Currently, the global interest for simple, safe, cost-effective and green technology has been developed. Constructed wetland as a natural process, environmentally friendly, eco-friendly with simple construction and low maintenance is one of the interested technique (Vymazal, 2002; Rousseau et al., 2008; Kadlec et al., 2009).

Constructed wetlands (CWs) as human made basin according to engineering design that create ecological condition same to natural wetlands for treating wastewater in different physical, chemical and biological conditions (Wallace and Knight, 2006). All types of CWs are attached growth bioreactor (Kadlec, 1989) while media material and roots, stems, leaves, and litter of wetland vegetation provide the surface for microbial attachment (USEPA 1993; Sinclair, 2000). CWs have been used as secondary treatment plan for domestic wastewater, industrial and agricultural wastewater, tertiary treatment, polishing wastewater, urban runoff and contaminated groundwater (Cristina et al., 2007; Khan et al., 2009; Braeckevelt et al., 2011; O'Neill et al., 2011). CWs could categorize depending on type of macrophytes and flow regime (Brix and Schierup, 1989; Vymazal and Kröpfelová, 2008). CWs on the type of macrophytes are classified into 4 groups that called, Free-floating Macrophytes, Floating-leaved Macrophytes, Submerged Macrophytes, Emergent Macrophytes and CWs depending on wastewater flow regime could be named as Free Water Surface (FWS), Subsurface Flow (SSF). Also subsurface flow constructed wetland (SSFCW) subdivided to two types according to direction and pattern of wastewater flow that pass trough media matrix of CW as horizontal and vertical subsurface flow (Imfeld et al., 2009).

Classification of different types of CWs depending on macrophytes and wastewater level in relation to the surface and direction of flow is shown in Fig.1.

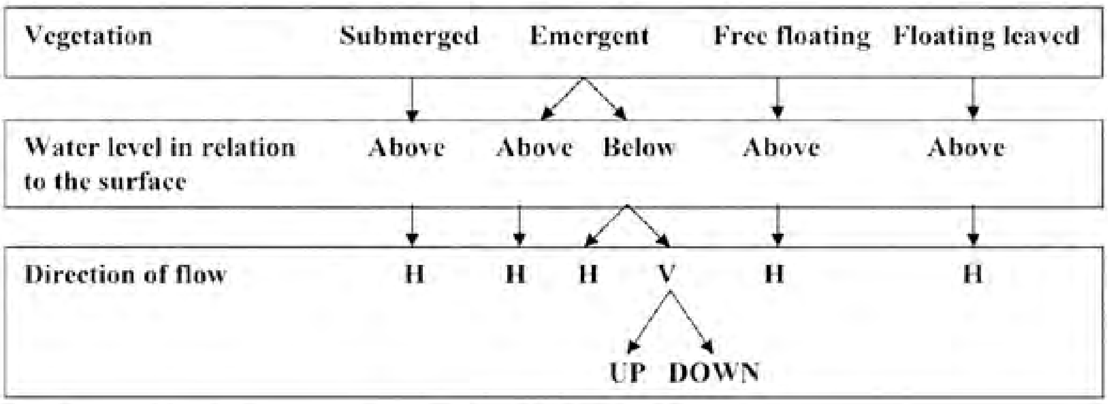

Fig. 1 Various types of CWs depending on macrophytes, water level and direction of flow (Vymazal, 2010).

1.1 Free water surface constructed wetland (FWSCW)

FWSCW is consist of shallow basins that filled by various materials, commonly soil, sand and gravel that supports the root of plans and wastewater flow direction are normally arranged horizontally (Kadlec and Knight, 1996).

1.2 Subsurface flow constructed wetland (SSFCW)

In SSFCW, wastewater surface is usually below of the surface of media matrix. Wastewater could flow horizontally or vertically in media matrix. In this system, media material is an important factor because it could avoid clogging to ensure a sufficient hydraulic conductivity (Kaseva, 2003).

The different types of CWs could be combined together on various configurations to formation combined-system, which called "hybrid constructed wetlands". Hybrid CWs are used to achieve higher efficiency wastewater treatment rather than single CW, particularly in removal of nutrients components. Initial experiment of hybrid CW was performed by *Seidel* in Germany at 1980. Many configurations would be design for hybrid CWs, such as series FWS and SSF, Vertical SSF (VSSF) and Horizontal SSF (HSSF). Further researches were performed to evaluation of hybrid CWs application for different wastewaters treatment. In hybrid systems, the advantages of various systems can be combined and improve the wastewater treatment plan efficiency. For example, the total nitrogen (TN) removal (nitrification/denitrification) needs an aerobic/anaerobic condition which would be provided by combination of FWS, VSSF (aerobic condition) and HSSF (anaerobic condition) (Vymazal, 2005).

2 Methodology

Potential of hybrid CWs for treating various type of wastewaters have evaluated in some studies in lab-scale, pilot-scale and full-scale. In this study, application of hybrid CWs with various configurations for different wastewaters is reviewed as following:

a) Domestic wastewater
b) Industrial wastewater
c) Landfill leachate
d) Other wastewaters

2.1 Application of hybrid CW for domestic wastewater treatment

Domestic wastewater is recognized as the major source of TDS, TSS, salts, color, metals, nutrients, BOD_5, COD, indicator organisms like *E. coli* and organic contaminants. Household wastewater comes from toilets, sinks, bathing and laundry. CWs are applied successfully for domestic wastewater treatment particularly in small communities, rural areas and villages.

A innovate three stage Towery hybrid CW was designed for enhance nitrogen removal from domestic wastewater (Fenxia and Li, 2009). At the first and third stage, a rectangular HSSFCW and at second stage used three circular cells of FWSCW with various diameters. Fig. 2 shows the schematic layout of this hybrid CW.

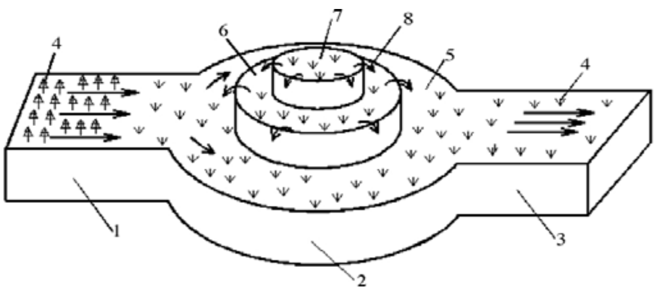

Fig. 2 Schematic layout of Towery hybrid constructed wetland: 1, first stage; 2, second towery stage; 3, third stage (discharge); 4, wetland plants; 5, bottom circular cell; 6, middle circular cell; 7, upper circular cell; 8, cascade (Fenxia and Li, 2009).

Average removal efficiency for total suspended solid (TSS), chemical oxygen demand (COD), ammonia nitrogen (NH_4), total nitrogen (TN) and total phosphorus (TP) was 89%, 85%, 83%, 83% and 64% respectively. High TN removal may be result of passive aeration of a tower type cascade overflow from the upper layer into the lower layer in the second stage of hybrid CW (Fenxia and Li, 2009). In other study, removal efficiencies were reported 86% for BOD_7, 84% for TSS, 89% for TP, 53% for TN and 73% for NH_4^+ by application of VSSF-HSSF hybrid CW (Mander et al., 2007).

Effective of different plan, different hydraulic retention time (HRT) and seasonal change on treatment efficiency of a pilot scale hybrid CW consists of HSSF-VSSF for wastewater driven from septic tank were evaluated in China (Cui et al., 2006). Three parallel systems were built that two systems were planted (S1, S2) and other system (S3) was unplanted. HSSF and VSSF were planted by *cyperus alternifolius* and *hedychium coronarium* in S1 and by *schoenoplectus lacustris* and *canna indica. L.* in S2 respectively. Average removal efficiencies of COD, BOD_5, TP and TN under different HRT are shown in Fig. 3. Results were demonstrated that S1 system and 3 day HRT is the best operational system.

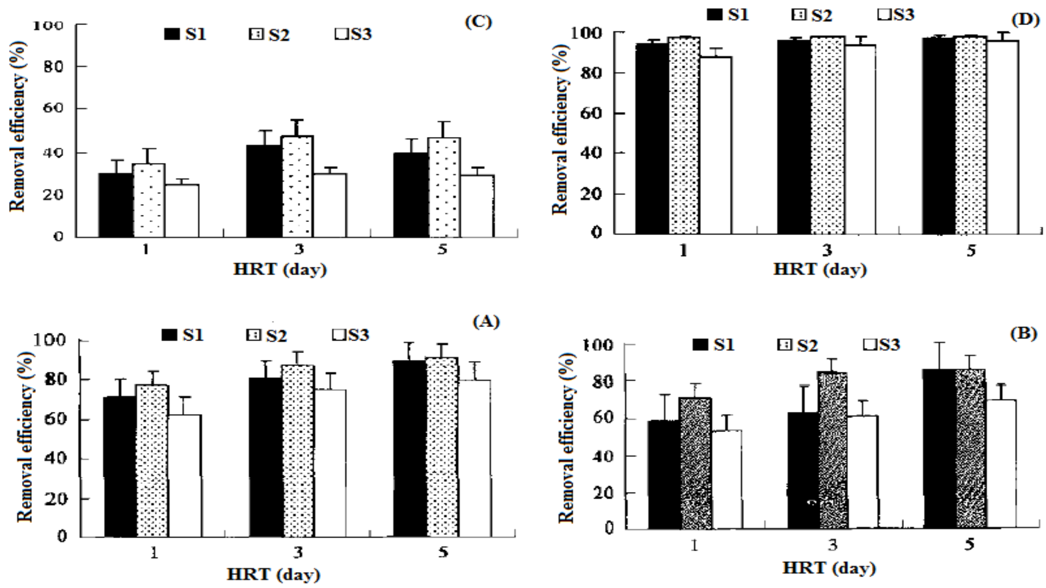

Fig. 3 Mean removal efficiency of COD (A), BOD_5 (B), TN (C) and TP (D) at different HRT in hybrid CW systems (S1, S2, S3) (Cui et al., 2006)

Zhao and et al., (2011) were studied on the effective of different carbon/nitrogen ration (C/N) on treatment efficiency in two-mode hybrid CW (Zhao et al., 2011). Two hybrids CW consist of two series of VSSF that in one line up-up or down-down flow and in other line up-down or down-up flow were carried out. Average influent concentrations and removal efficiency for COD, TN, TP and TOC in each hybrid CW are shown in Table 1. It is clearly revealed that hybrid CW consist of vertical down flow (VDF) and vertical up flow (VUF) at C/N=10 for all pollutant are shown highest removal efficiency. Two hybrid CW systems, VUF-VUF and VDF-VDF have lowest TN removal efficiency due to inability of the systems to create aerobic/anaerobic for nitrification/denitrification process. Zhao et al. (2010) confirmed the highest removal efficiency in single VSSF at C/N=10 (Zhao et al., 2010).

Table 1 Average concentrations in the influent and pollutant removal efficiencies in four hybrid CWs (Zhao et al., 2011)

C/N ratio	CW configuration	Influent concentration (mg/l)				Removal efficiency (%)			
		COD	TN	TP	TOC	COD	TN	TP	TOC
C/N = 2.5	VUF[a]- VUF	104.88	40.19	5.24	46.87	73.68	46.03	74.98	48.95
	VDF[b]- VDF					74.71	71.52	77.74	44.05
	VUF-VDF					86.62	78.27	83.69	51.27
	VDF-VUF					88.19	81.27	81.51	60.57
C/N = 5	VUF- VUF	202.34	41.82	5.09	94.32	77.65	70.82	86.08	42.74
	VDF- VDF					82.33	77.15	86.51	40.12
	VUF-VDF					87.67	80.72	88.71	59.82
	VDF-VUF					91.12	86.76	89.95	64.49
C/N = 10	VUF- VUF	402.95	41.36	5.17	184.45	79.16	62.49	82.64	43.44
	VDF- VDF					84.13	75.34	83.57	41.05
	VUF-VDF					87.89	79.59	84.39	61.23
	VDF-VUF					93.48	84.05	86.95	66.41

a: Vertical Up Flow (VUF); b: Vertical Down Flow (VDF)

Melián and et al. (2010) were studied on the Effect of two hydraulic load rate (HLR) at pollutant removal in a hybrid CW consist of VSSF follow by HSSF (Melian et al., 2010). At first period of application, HLR was

37 mm/d and at second period, HLR was 79 mm/d. Average removal efficiency of hybrid CW by the two HLR is illustrated in Table 2. According to the result, removal efficiency for all pollutants mainly for NH_4^+ was high. COD removal was higher in high HLR mode, but other pollutant removal was approximately same in high and low HLR mode. A pilot scale hybrid CW consists of VSSF and HSSF was used to investigate effect of HLR and recirculation rate of removal efficiency (Zaytsev et al., 2007). Experiments were shown that by decreasing HLR from 52 to 14 mm/d and increasing recirculation rate from 34 to 300%, removal efficiency were increased from 58 to 99% for BOD_5 and from 11 to 82% for TN, while no significant different for TP removal efficiency was not detected (Zaytsev et al., 2007).

Table 2 Average pollutant removal in low and high HLR mode for hybrid CW (Melian et al., 2010).

Pollutant	Low HLR = 37 mm/d			High HLR = 79 mm/d		
	Influent (mg/l)	Loading rate ($l/m^2.d$)	Removal (%)	Influent (mg/l)	Loading rate ($l/m^2.d$)	Removal (%)
BOD_5	162 ± 15	6±0.6	85	310±50	23±4	87
COD	274±23	10±0.8	74	462±73	35±6	83
SS	72±14	2.6±0.6	95	80±14	5.9±1	95
NH_4^+	122±13	6±0.6	91	124±9	12±0.9	85

Tuncsiper. (2009) studied on long term effect of HLR, nitrogen loading rate (NLR) and effluent recirculation rate on nitrogen removal from a hybrid CW. Vertical flow-gravel filtration (v-GF) bed without plant, HSSF and VSSF were applied in three stages (Tuncsiper, 2009). Average removal percentages in hybrid system were 91.3%, 91.1% and 88% for TKN, NH_4^+ and NO_3^- respectively. Average nitrogen components removal in three recycling ratio and four HLR in two stage of hybrid CW is presented in Table 3. It shows that by increasing recycling ration and decreasing HLR, removal efficiency have increased. Highest removal efficiency was obtained by 100% recycling and HLR=30 $L/m^2.d$. In other hybrid CW consist of vertical vegetated bed combined with horizontal flow sand bed, NO_3^- removal was 60% at recycle ratio, 50% and HLR, 56 $L/m^2.d$ (Kantawanichkul et al., 2000)

Table 3 Average nitrogen components removal in different recycling and the HLR in two stages of hybrid CW (Tuncsiper, 2009).

		HLR= 100L/m^2.d		HLR= 80L/m^2.d		HLR= 60L/m^2.d		HLR= 30L/m^2.d	
Recycling ratio	N components	HSSF	VSSF	HSSF	VSSF	HSSF	VSSF	HSSF	VSSF
0%	TKN	35%	60%	45%	65%	50%	51%	62%	86%
	NH_4^+	38%	60%	45%	66%	49%	51%	61%	86%
	NO_3^-	38%	28%	55%	34%	69%	27%	81%	39%
50%	TKN	40%	61%	50%	66%	55%	52%	72%	96%
	NH_4^+	38%	61%	49%	68%	53%	52%	74%	96%
	NO_3^-	46%	35%	65%	40%	69%	19%	91%	43%
100%	TKN	53%	63%	53%	52%	62%	61%	77%	98%
	NH_4^+	49%	64%	52%	51%	60%	62%	80%	97%
	NO_3^-	56%	28%	70%	19%	70%	25%	97%	48%

The studies were developed in the field scale on application of hybrid CWs. In Taiwan, a hybrid system including oxidation pond, FWS and HSSF in series was used to treat secondary treated dormitory sewage (Yeh and Wu, 2009). In this hybrid system, average removal efficiency for BOD_5, COD and TSS was 86.5%, 57.8% and 86.7% respectively.

In addition, removal efficiency for two heavy metals such as Copper and Zinc was reached to 72.9 and 68.3%, respectively. In aerobic condition 'oxidation pond and FWS' the nitrification was occurred and nitrate nitrogen increased from 1.91 to 3.85 mg/L, while in next stage of hybrid CW by anaerobic environment in HSSF, nitrate nitrogen decrease from 3.85 to 1.43 mg/L. In this system, TN is decreased from 7.61 to 3.61 mg/L, by removal efficiency around 52.6%. According to results, effluent from this system is reached to groundwater discharge standard.

A hybrid pilot plant consisting of an upflow anaerobic sludge blanket (UASB) reactor followed by two sequentially connected FWS and HSSF was applied to survey removal efficiency of 16 pharmaceuticals and personal care products (PPCPs) from domestic wastewater (Contreras et al., 2011). According to Fig. 4 the removal efficiency in summer was higher than winter. The treatment efficiency for PPCPs in FWS CW was more in summer period than other stages of hybrid system.

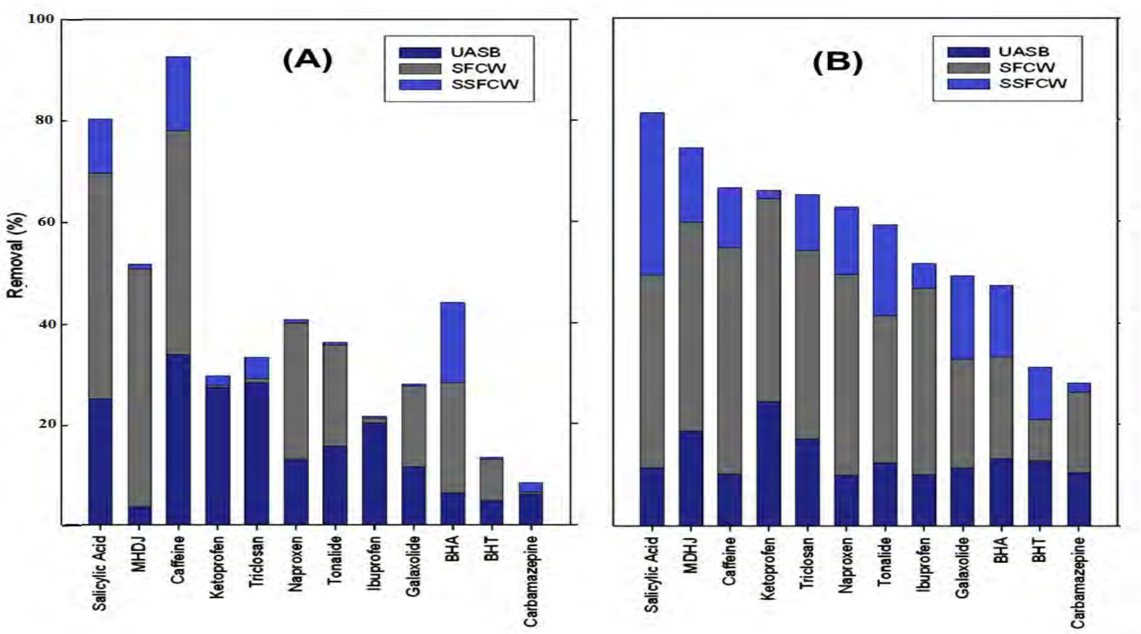

Fig. 4 Relative mass removal of dissolved PPCPs according with treatment stage, UASB, FWS, HSSF (A) winter (February 2008) (B) summer (June–July2009). Compound identification as following; MHDJ: methyl dihydrojasmonate, BHA: butylated hydroxylanisole, and BHT: butylated hydroxytoluene (Contreras et al., 2011)

The removal efficiencies of different type of organic substances were assessed in three hybrid CWs as HSSF-VSSF-HSSF (CW1), HSSF-VSSF-VSSF-HSSF (CW2) and VSSF-HSSF (CW3) (Tuszynska et al., 2008). In this study, different fraction of COD such as mineral suspended solids (COD-X_I), hard-to-decompose organic suspended solids (COD-X_S) and soluble substances; organic easy-to-decompose (COD-S_S) and inert (COD-S_I) were analyzed in each hybrid CW and results are shown in Fig. 5. As shown the highest fraction of COD in influent of CW1 and CW2 were COD-X_S and in CW3 was COD-S_S, and the highest COD fraction of effluent of three systems was COD-S_I. Therefore, significant fraction of COD removal in these hybrid CWs were attributed to COD-X_S and COD-S_S.

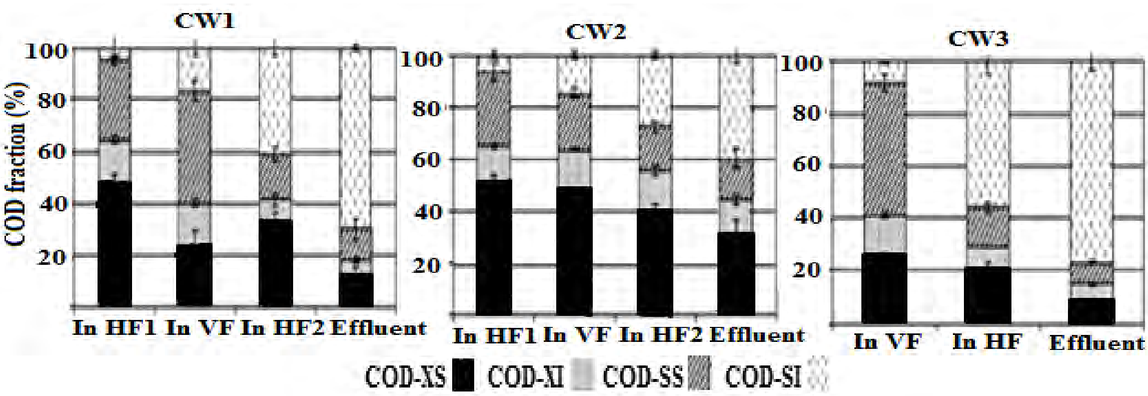

Fig. 5 COD fraction in different sampling point of three hybrid CWs (1, 2, 3) (Tuszynska et al., 2008).

Performance of hybrid CWs with different configurations to treating domestic wastewater are summarized in Table 4. It is clearly demonstrated that the organic matter (BOD_5, COD) and TSS removal efficiency were high in all hybrid CWs configuration.

Table 4 Application of various hybrid CWs for domestic wastewater treatment

Configuration	BOD_5	COD	TSS	N	TP	References
HSSF-VSSF	83%	77%	81%	NH_4^+ : 74%	-	Abidi et al.,2009
VSSF-HSSF	81%	78%	80%	NH_4^+ : 76%	-	Abidi et al.,2009
VSSF-HSSF	94%	94%	-	TN: 93%	-	Song et al., 2010
Anaerobic baffled reactor(ABR)-HSSF-VSSF	90.1%	90%	95.9%	NH3 :69.5	26.1%	Singh et al., 2009
UASB-FWS-SSF	90.3%	85%	95%	-	-	El-Khateeb et al., 2009
VSSF-HSSF	-	88-94%	-	TN: 75-78%	-	Foladori et al., 2012
VSSF-VSSF-HSSF-HSSF	97%	-	-	NH_4^+ : 78%	-	Cooper, 2001
VSSF-VSSF-HSSF	90%	-	-	NH_4^+ : 67%	-	O'Hogain, 2003
VSSF-HSSF-HSSF	86%	-	-	NH_4^+ : 72%	-	Mæhlum et al., 1999
VSSF-HSSF	90%	-	-	NH_4^+ : 78%	-	Mæhlum et al., 1999
HSSF-VSSF	97%	-		NH_4^+ : 99%	-	Laber et al., 2003
HSSF-VSSF	90%	-	-	NH_4^+ : 83%	-	Brix et al., 2003
HSSF-VSSF-HSSF	92.5%	-	-	NH_4^+ : 91%	-	Obarska et al., 2003
vertical-baffled flow CW (VBF) - HSSF	-	83.6%	95%	NH_4^+ : 71.7 TN: 64.5%	68.1%	Zhai et al., 2011
HSSF-VSSF	86.4%	76.72%	86.7%	TN: 44.9%	81.7%	(Shi et al., 2004)
HSSF-VSSF	95%	94%	84%	NH_4^+ :86% TN: 60%	94%	Masi and Martinuzzi, 2007
HSSF-FWS	97%	86%	66%	TKN: 68%	95%	Laouali et al., 1996
Stabilization pond-HSSF-VSSF	-	84%	85%	TN: 71.7% NO_3^-: 81.7% NH_4^+:53.9%	-	Belmont et al., 2004

2.2 Application of hybrid CW for industrial wastewater treatment

Industrial wastewaters depending on type of industry have wide range quality and quantity. Different types of single CWs have been used for various wastewater treatments. For instance, CWs have applied for treat petrochemical, Pulp and paper, Textile, Mining, food processing and abattoir wastewater (Lavigne et al., 2000; Abira et al., 2005; Gerth et al., 2005; Khalil et al., 2005; Yang and Hu, 2005; Bulc et al., 2006). Pollutants removal efficiencies of some applications of single CWs for industrial wastewater are presented in Table 5.

Table 5 Performance of single CW in treatment of various industrial wastewaters

Type of CW	Type of industry	Removal efficiency (%)					References
		COD	BOD_5	TSS	N	P	
HSSF	food-processing	92	89	-	NH_4^+: 86	PO_4^{3-}: 92	Gorra et al., 2007
HSSF	cheese-processing	96	98	94	TKN: 62	TP: 45	Mantovi et al., 2007
HSSF	distillery	64	84	-	TKN: 59	TP: 79	Billore et al., 2001
anaerobic lagoon- HSSF	abattoir	90	91	85	-	-	Varaldo et al., 2001)

A three stage hybrid CW consist of HSSF first stage, two parallel VSSF second stage and a HSSF third stage was used for treat mix wastewater of wine, apple vinegar, chemical department of packing of detergents and soaps industries (Justin et al., 2009). The results of the study show the average removal of COD (67%), BOD_5 (66%), TOC (64%), TN (83%), nitrate-N (83%), phosphate (62%) and anionic tensides (67%). The study reveals that for the improving efficiency, the separation of wastewater increase the efficiency due to anionic tensides that need more degradation time. Welz et al. (2011) for degradation of ethanol from winery wastewater used a unplanted HSSF-VSSF hybrid CW and two influent COD concentrations introduced to system and resulted higher removal efficiency in higher concentration (Welz et al., 2011). As in the high COD concentration (15800 mg/l), maximum COD concentration effluent was 180 mg/l, while in the low COD concentration (7587 mg/l), maximum COD concentration effluent was 1400 mg/l. Masi et al. (2002) studied on two full scale hybrid systems (HSSF-FWS and VSSF-HSSF-FWS) that were designed for winery wastewater treatment in Italy (Masi et al., 2002). Performance monitoring of systems was detected that effluents of the two systems were meet to Italian outlet standard. Average removal efficiency of hybrid CWs has been presented in Table 6.

Table 6 Average influent and effluent concentration of hybrid CWs (Masi et al., 2002)

Pollutants	HSSF-FWS			VSSF-HSSF-FWS		
	In (mg/l)	Out (mg/l)	Removal (%)	In (mg/l)	Out (mg/l)	Removal (%)
BOD_5	1792.7	29.4	98	424.9	28.6	93
COD	4044.9	90.6	97	1003.2	78.6	92
TSS	221.8	24.3	89	102.7	25.3	75
TN	14.7	2.6	82	26.6	2.65	90
TP	4.9	1.3	73	1.92	0.12	93

Shepherd et al. (2001) reported that COD concentration of winery wastewater was decreased from 4720 mg/l to 51 mg/l in the full scale HSSF (Shepherd et al., 2001). The full scale hybrid CW consist of hydrolytic upflow sludge bed (HUSB) digester, VSSF and three parallel HSSF was designed for treat mixed effluent come from a winery and tourist establishment in Spain (Serrano et al., 2011). Average pollutants concentrations for different stage of hybrid CW are shown in the Table 7. The study revealed that surface load rate (SLR) and temperature play key role in the system performance for VSSF. The influent concentration and SLR were control parameter for HSSF system. In VSSF system, SLR was 43-466 g COD/m^2.d and 22-296 g BOD_5/m^2.d with removal efficiency 29-70% and 36- 68% for COD and BOD_5 respectively. SLR having 3.6-55 g COD/m^2.d and 1.5-32 g BOD_5/ m^2.d, while COD and BOD_5 removal efficiency 23 – 79% and 13 – 85% respectively.

Table 7 Average pollutant concentration ± SD at different sampling points of hybrid CW (Serrano et al., 2011)

Sampling point	Pollutants concentration					
	COD (mg/l)	BOD_5 (mg/l)	TSS (mg/l)	TKN (mg/l)	NH_3 (mg/l)	PO_4^3(mg/l)
Influent	1558±1023	942±682	129±88	52.9±33.0	28.0±40.0	2.3±2.1
VSSF effluent	711±769	418±482	65±38	26.0±15.7	19.4±25.7	2.4±1.8
HSSF effluent	448±541	279±430	17±15	25.2±12.7	12.5±14.7	1.9±1.8

Domingos et al. (2007) assessed the efficiency of two hybrid CWs for removal N components from industrial wastewater driven from fertilizer and chemical manufacturing (Domingos et al., 2007). Performance of the hybrid CWs for nitrogen components removal is summarized in the Table 8. Negative removal of NO_3^- in VSSF-HSSF is due to further ammonia removal in HSSF but it is unable to remove the nitrate generated by the VSSF stage.

Table 8 Performance of hybrid CWs for N components removal (Domingos et al., 2007)

Hybrid CW	Average influent concentration (mg/l)			Average removal efficiency (%)		
	NH_4^+	NO_3^-	TN	NH_4^+	NO_3^-	TN
FWS-VSSF	36.0	13.1	49.0	79.4	78.4	79.1
VSSF-HSSF	35.9	14.6	50.6	96.9	-10.2	65.9

Performance of treating milking parlor wastewater by a three stage full scale hybrid CW including VSSF-VSSF-HSSF under cold climate condition was evaluated in Japan (Sharma et al., 2010). Temperature was ranged from -22.8 ^oC to 30.6 ^oC and annual average 6.4 ^oC. Average influent concentration of COD, BOD_5, TSS, TN, NH_4^+ and TP was 4425, 1574, 770, 183, 77 and 29 mg/l, while removal efficiency was achieved 88%, 89%, 98%, 76%, 66% and 76% respectively. The results showed that this hybrid CW was less sensitive to low temperature conditions.

The hybrid CW, consists of two and parallel VSSF, first stage and a HSSF, second stage were applied for treating cheese factory wastewater in cold climate. The results of pollutants removal in four monitoring periods are shown in Fig. 6 (Comino et al., 2011). It is clearly demonstrated that cold climate with low temperature having less affect on system performance for pollutants removal.

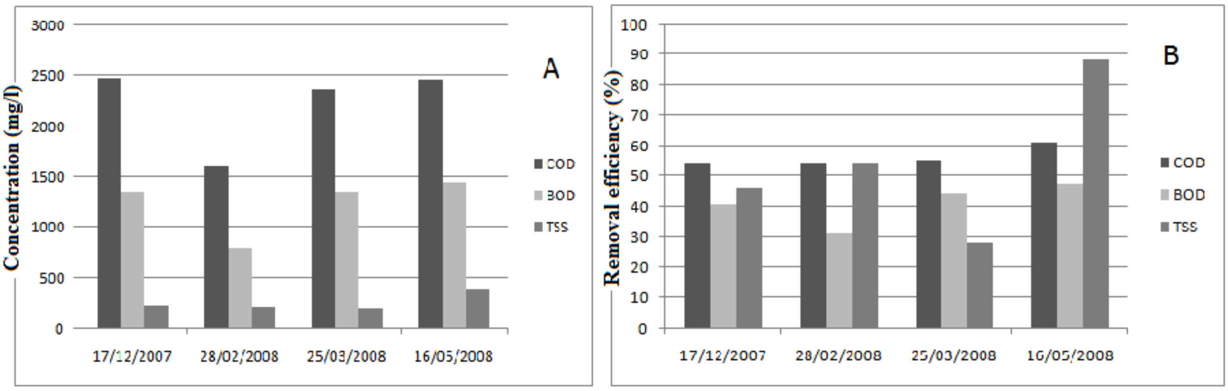

Fig. 6 average pollutants influent concentration (A) and average removal efficiency (B) at different period of system operation (Comino et al., 2011)

Heavy metals are common parameters in industrial wastewaters, such as textile and chemistry industries, tanneries and mining activities that can cause serious human health effect (Sayyed and Sayadi., 2011; Prajapati et al., 2012). Byekwaso et al. (2002) studied on potential of heavy metals removal by hybrid CWs (FWS-HSSF) from a cobalt processing mining plan (Byekwaso et al., 2002). The results shown (Table 9) that hybrid CW was effectively removed Pb, Co, Ni, Cu, Cd and Fe, but concentration of Mn was increased and concentration of Zn was not changed.

Table 9 Performance of hybrid CW in heavy metals removal (Byekwaso et al., 2002)

Metals	Influent (kg/day)	Effluent (kg/day)	Removal efficiency (%)
Mn	0.05	0.31	-520
Pb	0.016	0.01	37.5
Co	0.039	0.02	48.7
Ni	0.02	0.007	65
Cu	0.009	0.001	88.9
Cd	0.002	0.0011	50
Fe	0.019	0.014	26.3
Zn	0.004	0.004	0

2.3 Application of hybrid CW for landfill leachate treatment

Landfill leachate is results of infiltration and precipitation of water trough municipal solid waste that disposal in landfills. Its quality differ depending on disposal site, climate, amount of infiltration water and operational life of landfill, but is mainly contain heavy metals, organics with different biodegradation and inorganic matters such as ammonia, sulfate and cationic metals (Kulikowska and Klimiuk, 2008). Landfill leachate could create some dangerous environmental problems such as groundwater pollution. Therefore, collection and treatment is necessary. Traditional methods such as chemical precipitation, activated carbon adsorption, ion exchange, membrane filtration, reverse osmosis, anaerobic biological treatment and aerobic biological treatment usually undesirable due to cost effectiveness ratio, large land demand and generation by-products (Higgins, 2000; Kappelmeyer, 2005). CWs as a cost-effective and environmental friendly technique are used for landfill leachate treatment. Average treatment efficiency of seventeen HSSF for landfill leachate treatment was 32.8%,24.9%, 54.5%, 33.1%, 38.7% and 66.1% for BOD_5, COD, TSS, TN, NH_4^+ and TP respectively (Vymazal and Kröpfelová, 2008). Pollutants removal efficiency of landfill treatment plan in the single types of CW has been tabulated in the Table 10.

Table 10 Pollutants removal efficiencies of landfill leachate by application of CWs

Type of CW	Pollutants removal efficiencies (%)	References
HSSF	COD: 50, BOD_5: 59, TP: 53, Fe: 84	(Bulc, 2006)
FWS	BOD_5: 83, PO_4: 57, NO_3: 99	(Nordin, 2006)
FWS	NO_3: 64.5, Mn: 53.13	(Thien, 2005)
HSSF	COD: 70, BOD_5: 70, NH_4^-: 80, TP:80	(Kadir, 2004)

Bulc (2006) were surveyed the long term performance of a pilot scale hybrid CW consists of two parallel HSSF and one VSSF for landfill leachate treatment (Bulc, 2006). Average influent concentration and removal efficiency of pollutants in this hybrid CW collected in the Table 11.

Table 11 Average influent concentration and removal efficiency of pollutants in hybrid CW

Influent concentration (mg/l)							Removal efficiency (%)						
COD	BOD_5	TSS	NH_4^+	CL_2	Fe	TP	COD	BOD_5	TSS	NH_4^+	CL_2	Fe	TP
485	76	38.3	496	1369	3.9	2.3	50	59	33	51	35	84	53

Two series of lab-scale planted and unplanted hybrid CW including a HSSF at the first and a FWS at the second stage were applied to treating landfill leachate by a recirculation line under influence of magnetic field (Saat and Kamariah, 2006). Average influent concentrations of NH_3, PO_4^{3-}, Fe, Mn and TSS in landfill leachate were 73.4, 49.5, 18.3, 0.49 and 150 mg/l respectively. The results of pollutants removal after 21 days operation of the two hybrids CW are illustrated in Fig. 7. It is clearly shows that planted hybrid CW having higher removal efficiency but with a little different from unplanted system. Eckhardt et al. in 1998 have studied on landfill leachate treatment by a FWS-HSSF hybrid CW which showed removal efficiency about 98% for Fe and 99% for TP (Eckhardt, 1998).

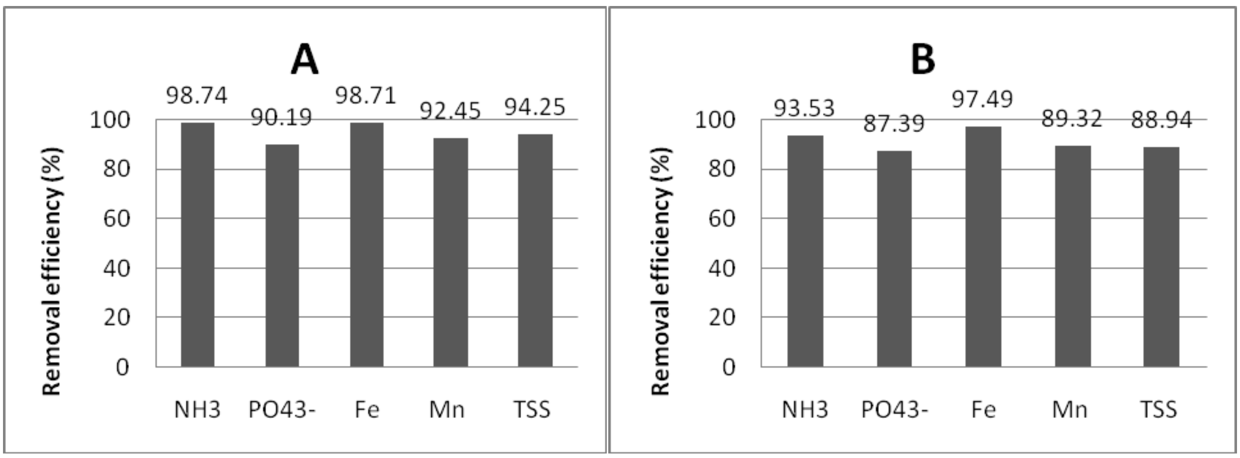

Fig. 7 average pollutants removal efficiency at planted (A) and unplanted (B) hybrid CW (Saat and Kamariah, 2006).

A pilot scale multistage treatment system consists of trickling filter at first stage that follow by a HSSF second stage and a FWS latest stage were designed to landfill leachate treatment (Kinsley et al., 2007). The system was operated at different HLR, while highest removal efficiency was 93%, 90% and 97% for BOD_5, TKN and NH4-N respectively. Application of hybrid CWs for landfill leachate were evaluated in others studies such as investigation on HSSF-FWS in Norway and VSSF-HSSF in Portugal which shown the higher efficiency to removal of pollutants (Mahlum et al., 1999; Dias et al., 2006]

2.4 Application of hybrid CW for other wastewater treatment

In addition of domestic, industrial and landfill leachate wastewater, there are various sources of wastewater such as runoff, agricultural and hospital wastewater. Some types of single and hybrid CWs were used to treating these types of wastewaters. Greenhouse wastewater as the agricultural wastewater is treated by hybrid CWs. For instance, Seo et al. (2008) applied a pilot-scale hybrid CWs to reaching optimum design for treating greenhouse wastewater in South Korea (Seo et al., 2008). The pilot-scale hybrid CW was built in six parallel lines with different CW configurations. Means of pollutants removal efficiency of hybrid CWs are presented in the Table 12. It is indicating that HSSF-VSSF-HSSF hybrid CW was introduced as highest removal efficiency than other configurations. Also shown, pollutants removal velocity for VSSF was greater than HSSF in HSSF-VSSF-HSSF system.

Table 12 Mean± SD pollutants removal efficiency in hybrid CWs (Seo et al., 2008)

Hybrid CW configuration	Mean pollutant removal efficiency (%)		
	COD	TN	TP
VSSF-VSSF	90.5±2.3	35.3±5.9	68.3±3.5
VSSF-HSSF	85.3±1.9	42.6±7.4	83.6±3.9
HSSF-HSSF	78.3±5.4	39.7±4.9	90.5±4.7
HSSF-VSSF	90.2±2.5	45.1±4.3	85.4±2.3
HSSF-VSSF-VSSF	95.1	47.7	91.2
HSSF-VSSF-HSSF	96.5	68.4	94.3

Seo et al. (2010) examined treatment of hydroponic wastewater from greenhouse by hybrid CWs and Thiobacillus denitrificans (Seo et al., 2010). The hybrid CWs were including HSSF-HSSF, HSSF-VSSF, VSSF-HSSF and VSSF-VSSF. The results detected that best configuration of CWs is HSSF-HSSF. This system with *Thiobacillus denitrificans* was achieved to 53%, 91%, 91%, 69%and 71% removal efficiency for COD, TSS, TP, TN and NO_3, while the results without *Thiobacillus denitrificans* were 55%, 93%, 93%, 51% and 47%, respectively.

Hybrid CWs also were used to treating dairy farm wastewater in USA (Lee, 2009). Four hybrid CWs were designed with HSSF-HSSF and VSSF-HSSF configurations. In two systems, HSSF was filled with electric arc furnace (EAF) steel slag in order to enhance phosphorous removal. Average influent concentrations were 2500, 46, 740 and 260 mg/l for BOD_5, dissolved reactive phosphor (DRP), TSS and NH_4^+, respectively. The result showed hybrid CW including HSSF that filled with EAF steel slag is very effective for phosphorous removal (Table 13).

Table 13 Performance of four hybrid CWs in dairy wastewater (Lee, 2009)

Hybrid CW	Average removal efficiency (%)			
	BOD_5	TSS	DRP	NH_4^+
HSSF-HSSF	86	95	75	64
VSSF-HSSF	89	94	68	61
HSSF-Slag HSSF	83	93	99	62
VSSF-Slag HSSF	90	93	99	68

Soroko (2007) evaluated the VSSF-VSSF-HSSF hybrid CW to removal of TN from wastewater that comes from slaughterhouse (Soroko, 2007). Influent concentration of TN was 560 mg/l that this system was removed 78.2% of TN, while by usage of recirculation ranged from 100 to 200%, TN removal efficiency was reached to 85.7 – 96.6%.

Lin et al. (2003) were used a pilot scale FWS-HSSF hybrid CW to treating shrimp culture wastewater in Taiwan (Lin et al., 2003). Average removal efficiency under low HLR (HLR=0.3 m/day)for BOD_5, TSS, NH_4^+, NO_3 and NO_2 were 24%, 74%, 57%, 68% and 90% respectively. Other study on shrimp culture wastewater treatment plan was performed by FWS-HSSF under higher HLR (HLR=1.5 m/day) that this system was achieved to reduction 54%, 55%, 64% and 83% of BOD_5, TSS, NH_4^+ and NO_2 respectively (Lin et al., 2005). Potential of nutrients removal from wastewater driven from a fishpond by application of a pilot scale FWS-HSSF hybrid CW were surveyed (Lin et al., 2002). The system was operated in five periods by different HLR. A summary of system performance at different HLR presents in the Table 14. It is clearly showed that phosphorus removal efficiency was reduced by decreasing HRT due to increasing HLR.

Table 14 Mean influent concentration and removal efficiency of nutrients in hybrid CW (Lin et al., 2002).

Nutrient	HLR= 1.8 cm/day		HLR= 2.3 cm/day		HLR= 3.4 cm/day		HLR= 6.8 cm/day		HLR= 13.5 cm/day	
	I[a] (mg/l)	RE[b] (%)	I (mg/l)	RE (%)	I (mg/l)	RE (%)	I (mg/l)	RE (%)	I (mg/l)	RE (%)
NH_4^+	0.16	-250	3.31	97	1.3	93	1.46	95	0.80	86
NO_2	0.03	83	0.432	99	0.647	99	0.474	99	0.423	99
NO_3	0.26	27	0.74	82	0.94	99	2.26	99	2.66	97
TIN[c]	0.45	-33	4.48	95	2.88	96	4.19	98	3.88	95
PO_4^{3-}	2.39	69	7.44	71	10.45	45	8.57	38	5.19	32

a) I: Influent concentration (mg/l); b) RE: Removal Efficiency (%); c) TIN: Total Inorganic Nitrogen

A hybrid system consists of septic tank-HSSF-VSSF was used to treating hospital wastewater in Nepal (Laber et al., 2003). Surface areas of HSSF and VSSF were $140m^2$ and $120m^2$ respectively. Performances of every stage of this system are showing in the Table 15. Result was shown that this system could be an effective on-site hospital wastewater treatment plant.

Table 15 Average influent and effluent concentration and removal efficiency in three stages hybrid CW (Laber et al., 2003)

Pollutants	Septic tank			HSSF			VSSF		
	In (mg/l)	Out (mg/l)	R (%)	In (mg/l)	Out (mg/l)	R (%)	In mg/l)	Out (mg/l)	R (%)
BOD_5	118	67	43	67	25	63	25	2	92
COD	261	162	38	162	45	72	45	10	78
TSS	159	57	64	57	19	67	19	1.5	92
NH_4^+	32	32	0	32	27	16	27	0.1	96
TP	4.6	4.4	4	4.4	2.6	41	2.6	1.4	46

CWs also have been used for treating of polluted river water. A hybrid CW consist of two parallel FWS that followed by a SSF applied to remove TSS from high polluted river in Taiwan (Jing et al., 2001). Monitoring of the system detected that the hybrid CW was effectively removed TSS, but in sometimes an increasing of TSS was occurred due to uncontrolled algae growth especially in FWS.

3 Conclusion

In this study, the application of hybrid CWs for various wastewaters was surveyed. It demonstrated that combination of CWs together and formation hybrid system could enhance to increase pollutants removal efficiency. Hybrid CWs could cover the limitation of each single CW. For instance, by combination of HSSF to VSSF, desirable condition for nitrification-denitrification process would create due to aerobic-anaerobic environment. Some design and operational parameter such as HLR, bed material, system configuration (number of beds, layout of system), influent concentrations of pollutants and recirculation of effluent could be affected by hybrid CWs performance. It is interesting to note that with only a few exceptions the hybrid CWs were effective to remove organic matter (BOD_5, COD) and suspended solid, while in terms of nutrient removal such as N and P components, the removal efficiencies were depending to system properties and operational condition.

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