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Review

Constructed wetlands for treatment of industrial wastewaters: A review

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Constructed wetlands have been used for wastewater treatment for more than fifty years. Most applications have been designed to treat municipal or domestic wastewater but at present, constructed wetlands are successfully applied to many types of wastewater. The early constructed wetlands applied to industrial wastewaters included those for wastewaters from petrochemical, abattoir, meat processing, dairy and pulp and paper industries. During the 1990s constructed wetlands were also used to treat effluents from textile and wine industries or water from recirculating fish and shrimp aquacultures. The most recent applications include those for brewery or tannery wastewaters as well as olive mills effluents. The survey revealed that both subsurface and surface flow constructed wetlands have been used for treatment of industrial wastewaters. Within subsurface flow constructed wetlands both horizontal and vertical flow systems have been designed. Also, the use of various hybrid constructed wetlands for industrial effluent treatment has been reported in the literature recently. The survey also revealed that industrial wastewaters are treated in constructed wetlands in all continents and this paper includes the information from 138 constructed wetlands in 33 countries worldwide.

1. Introduction

Constructed wetlands are engineered systems that have been designed and constructed to utilize the natural processes involving wetland vegetation, soils, and their associated microbial assemblages to assist in treating wastewater. They are designed to take the advantage of many of the same processes that occur in natural wetlands, but do so within a more controlled environment. Some of these systems have been designed and operated with the sole purpose of treating wastewater, while others have been implemented with multiple-use objectives in mind, such as using treated wastewater effluent as a water source for the creation and restoration of wetland habitat for wildlife use, for reuse in agriculture or environmental enhancement. Synonymous terms to "constructed" include man-made, engineered, and artificial wetlands.

The first experiments with the use of wetland plants for wastewater treatment were carried out in Germany in the 1950s (e.g., Seidel, 1961) but the full scale systems were built only during the late 1960s (De Jong, 1976). Constructed wetlands have traditionally been used to treat municipal wastewaters but during last two decades the application of constructed wetlands also included industrial and agricultural wastewaters, landfill leachate and stormwater runoff (Vymazal, 2011). The purpose of this paper is to review the use of constructed wetlands for various types of industrial wastewaters. In the review, constructed wetlands for treatment of landfill leachate and acid mine drainage are not included as these two types of waters are very specific and in my opinion, they are not industrial wastewaters *sensu stricto*. Also, the review summarizes only results from field or pilot-scale studies and it does not include laboratory experiments and experiments with artificial wastewaters. The use of constructed wetlands for industrial wastewaters has been described by Vymazal and Kröpfelová (2008) and Kadlec and Wallace (2009), however, the present papers tries to be more comprehensive and summarizes 138 various constructed wetland installations in 33 countries treating a total of 26 various types of industrial wastewaters.

Abbreviations: AOX, adsorbable organic halide; AO7, acid orange 7; BTEX, benzene, toluene, ethylbenzene, xylenes; DRO, diesel range organics with 10–40 carbon atoms; FWS CW, constructed wetlands with free water surface (surface flow CW); GRO, gasoline range organics with 6–9 carbon atoms; HF CW, constructed wetlands with horizontal sub-surface flow; HLR, hydraulic loading rate (cm d^{-1}); HRT, hydraulic retention time (d); LAS, linear alkylbenzene sulfonates; OG, oils and grease; MTBE, methyl *tert*-butyl ether; TPH, total petroleum hydrocarbons; UASB, upflow anaerobic sludge blanket; VFA, volatile fatty acids; VF CW, constructed wetlands with vertical flow.

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2. Types of constructed treatment wetlands

Constructed wetlands may be categorized according to the various design parameters but three most important criteria are hydrology (open water-surface flow and sub-surface flow), type of macrophytic growth (emergent, submerged, free-floating, and floating-leaved) and flow path in sub-surface wetlands (horizontal and vertical). Different types of constructed wetlands may be combined with each other (i.e., hybrid or combined systems) to utilize the specific advantages of the different systems (Vymazal, 2005, 2008).

2.1. Constructed wetlands with free water surface

Constructed wetlands with surface flow (free water surface constructed wetlands, FWS CW) consist of basins or channels, with soil or another suitable medium to support the rooted vegetation (if present) and water at a relatively shallow depth flowing through the unit. The shallow water depth, low flow velocity, and presence of the plant stalks and litter regulate water flow and, especially in long, narrow channels, ensure plug-flow conditions (Reed et al., 1988).

Free water surface constructed wetlands with emergent macrophytes function as land-intensive biological treatment systems. The major removal mechanisms for suspended solids are sedimentation, filtration, aggregation and surface adhesion. The largest and heaviest particles will predominantly settle out in the inlet open water zone while smaller and lighter particles may only settle out after flowing into wetland vegetation. Wetland vegetation promotes this enhanced sedimentation by reducing water column mixing and re-suspension of particles from the sediment surface. FWS treatment wetlands typically have aerated zones, especially near the water surface because of atmospheric diffusion, and anoxic and anaerobic zones in and near the sediments. In heavily loaded FWS wetlands, the anoxic zone can move quite close to the water surface. Biomass decay provides a carbon source for denitrification, but the same decay competes with nitrification for oxygen supply. Low winter temperatures enhance oxygen solubility in water, but slow microbial activity (Kadlec and Knight, 1996).

Settleable organics are rapidly removed in FWS systems under quiescent conditions by deposition and filtration. Attached and suspended microbial growth is responsible for the removal of soluble organic compounds which are degraded aerobically in the water column as well as anaerobically in the litter layer near the bottom. The decomposition pathway by which wetland carbon loads are processed is determined by a balance between the carbon load and the supply of oxygen. Oxygen is supplied to the wetland water column by diffusion through the air–water interface and via the photosynthetic activity of plants in the water column, namely periphyton and algae (Kadlec et al., 2000). In FWS CWs with floating macrophytes, the plants cover completely the water surface thus prevent light penetration into the water column. As a result, the growth of algae is very limited and anoxic/anaerobic conditions may prevail due to lack of algal photosynthesis.

Nitrogen is most effectively removed in FWS constructed wetlands by nitrification/denitrification. Ammonia is oxidized by nitrifying bacteria in aerobic zones, and nitrate is converted to free nitrogen or nitrous oxide in the anoxic zones by denitrifying bacteria. Volatilization is likely in FWS CWs with emergent and submerged vegetation, as both plankton and periphyton algae grow in FWS CWs and higher pH values during the day may be favorable for ammonia loss. FWS CWs provide sustainable removal of phosphorus, but at relatively slow rates. Phosphorus removal in FWS systems occurs from adsorption, absorption, complexation and precipitation. However, precipitation with Al, Fe and Ca ions – is limited by little contact between water column and the soil.

2.2. Constructed wetlands with horizontal sub-surface flow

In constructed wetlands with horizontal sub-surface flow (HF CW), the wastewater is fed in at the inlet and flows slowly through the porous medium under the surface of the bed in a more or less horizontal path until it reaches the outlet zone where it is collected before leaving via level control arrangement at the outlet. During this passage the wastewater will come into contact with a network of aerobic, anoxic and anaerobic zones. The aerobic zones occur around roots and rhizomes that leak oxygen into the substrate (Brix, 1987; Cooper et al., 1996).

Organic matter is decomposed in HF CWs by both aerobic and anaerobic microbial processes as well as by sedimentation and filtration of particulate organic matter. Because of heavy loading and continuous saturation of the filtration bed anoxic/anaerobic processes prevail while aerobic processes are restricted to small zones adjacent to roots and rhizomes (radial oxygen loss) and to thin surface layer where oxygen diffusion from the atmosphere may occur. In lightly-loaded systems dissolved oxygen may be also carried out by inflowing wastewater (Vymazal and Kröpfelová, 2008). One of the primary removal/retention mechanisms for suspended solids in HF CWs is the flocculation and settling of colloidal and supracolloidal particulates. Other effective removal mechanisms in HF systems are gravity sedimentation, straining and physical capture and adsorption on biomass film attached to gravel and root systems.

Nitrogen is removed in HF CWS primarily by nitrification/denitrification. However, nitrification is limited by the absence of oxygen in the filtration bed due to continuous submergence of the filtration bed and, therefore, HF CWs are not effective in removal of ammonia. On the other hand, anoxic/anaerobic conditions are suitable for denitrification. Phosphorus is removed by sorption and precipitation. However, commonly used filtration materials such as gravel or crushed rock do not provide high sorption capacity. In order to enhance phosphorus removal it is necessary to select materials with high P adsorption capacity which depends on chemical and physical properties. Such materials may include minerals with reactive Fe or Al hydroxide or oxide groups on their surfaces, or calcareous materials which can promote precipitation of Ca-phosphate. Recently, industrial by- and waste-products including blast and electric arc furnaces steel slags, fly ash, crushed concrete, iron ochre and treated wood chips have been used (Vymazal and Kröpfelová, 2008).

2.3. Constructed wetlands with vertical sub-surface flow

Vertical flow (VF) constructed wetlands comprise a flat bed of graded gravel topped with sand planted with macrophytes. VF CWs are fed intermittently with a large batch thus flooding the surface. Wastewater then gradually percolates down through the bed and is collected by a drainage network at the base. The bed drains completely free and it allows air to refill the bed. This kind of dosing leads to good oxygen transfer and hence the ability to nitrify (Cooper et al., 1996). The oxygen diffusion from the air contributes much more to the filtration bed oxygenation as compared to oxygen transfer through plants aerenchyma system. The major role of macrophytes in VF CWs is to help maintain the hydraulic conductivity of the bed. Many of the vertical-flow systems are staged systems with parallel and series beds. There are sometimes parallel first-stage beds which are fed in rotation for 1–2 days and then rested for periods of 3–6 days (Cooper, 1999). Recently, VF systems with only one bed have been used. These systems are called 2nd generation VF constructed wetlands or compact vertical flow beds (Arias and Brix, 2005).

2.4. Hybrid constructed wetlands

Many of these systems are derived from original hybrid systems developed by Seidel at the Max Planck Institute in Krefeld, Germany. The process is known as the Seidel system, the Krefeld system or the Max Planck Institute Process (MPIP) (Seidel, 1965; Seidel, 1978). The design consists of two stages of several parallel VF beds ("filtration beds") followed by two or three HF beds ("elimination beds") in series. The VF stages were usually planted with *Phragmites australis*, whereas the HF stages contained a number of other emergent macrophytes, including *Iris*, *Schoenoplectus* (*Scirpus*), *Sparganium*, *Carex*, *Typha* and *Acorus*.

Various types of constructed wetlands may be combined in order to achieve higher treatment effect, especially for nitrogen. There has been a growing demand in achieving fully-nitrified effluents but secondary treatment HF systems cannot do this because of their limited oxygen transfer capacity. VF systems have a much greater oxygen transport capacity and, therefore, provide much better conditions for nitrification. However, very limited or no denitrification occurs in VF systems (Vymazal, 2007). Therefore, there has been a growing interest in hybrid systems (also sometimes called combined systems). Hybrid systems used to comprise most frequently VF and HF systems arranged in a staged manner, however, all types of constructed wetlands could be combined. In hybrid systems, the advantages of various systems can be combined to complement each other (Cooper, 1999). Various combinations of hybrid constructed wetlands have been reviewed by Vymazal (2005) or Vymazal and Kröpfelová (2008).

3. Industrial wastewaters

There are many industrial wastewaters which differ substantially in composition from municipal sewage and also among themselves (Table 1). In many industrial wastewaters the concentrations of organics, suspended solids, ammonia or some other pollutants are very high (Table 1) and therefore, the use of constructed wetlands nearly always requires some kind of pretreatment. The BOD/COD ratio is a parameter which tentatively indicates the biological degradability. If this ratio is greater than 0.5, the wastewater is easily biodegradable, such as wastewaters from dairies, breweries, food industry, abattoirs or starch and yeast production. The BOD/COD ratio for these wastewaters usually ranges between 0.6 and 0.7 but could be as high as 0.8. On the other hand, wastewaters with low BOD/COD ratio and thus low level of biodegradability are represented, for example, by pulp and paper wastewaters.

Tentative comparison of the industrial wastewater strength with municipal sewage could be done through population equivalent (PE = 60 g BOD_5 per person per day). Examples of these estimations are shown in Table 2. However, this approximation is only tentative and for the design of individual treatment systems it

Table 1
Examples of concentrations of major pollutants in various industrial wastewaters reported in the literature.

Wastewater type	BOD_5	COD	TSS	NH_4-N	TKN	TP	Phenols	References
Coke plant effluent	50–5300	525–10,000	20–4500	50–562	200–550	<1	81–1200	Ghose (2002); Marañón et al. (2008); Zhao et al. (2009)
Refinery effluents	10–1000	50–4000	10–300					Kadlec and Knight (1996)
Pulp and paper	100–13,300	500–40,000	100–23,300		11–600*	0.02–36		Pokhrel and Viraraghavan (2004)
Tannery effluents	800–4000	2000–23,000	1500–42,500	100–400		8–40		Espinoza-Quiñones et al. (2009); Mannucci et al. (2010); Pitter (2009)
Pharmaceuticals	1300–6400	5000–12,000	2500					Pitter (2009)
Laundry	200–1000	500–20,000	90–300		30			Ciabatti et al. (2009); Šostar-Turk et al. (2005); Pitter (2009)
Organic chemistry	400–20,000	800–50,000	100–300					Pitter (2009)
Textile	75–6300	220–31,300	25–24,500					Sharma et al. (2007); Dos Santos et al. (2007); Kadlec and Knight (1996)
Distillery	6000–65,000	4000–212,000	1000–17,000		7000	740–2500	35–10,000	Billore et al. (2001); Mancini et al. (1994); Strong and Burgess (2008); Mohana et al. (2009); Chandra et al. (2008)
Winery	500–40,000	500–45,000	1000–7300	0.001–2		5–77	13–247	Serrano et al. (2010); Anastasiou et al. (2009); Petruccioli et al. (2002); Arienzo et al. (2009)
Brewery	500–64,000	750–80,000	100–3000	1–8	67–216	17–216	7–124	Mancini et al. (1994); Bloor et al. (1995); Herrmann and Janke (2001); Parawira et al. (2005); Xiangwen et al. (2008)
Soft drink	770	1400–33,000	140–5000		54	2.5		Mancini et al. (1994); Oktay et al. (2007)
Sugar mill	4,000–7000	3500–10,000	350		53	4.8		Mancini et al. (1994); Güven et al. (2009)
Vegetable and food processing	270–8000	500–10,000	20–2500					Mancini et al. (1994)
Meat processing	600–4600	400–11,200	200–9300	65–740	530–810	15–50		Mancini et al. (1994); De Sena et al. (2008); Gannoun et al. (2009); Sayed and de Zeeuw (1988)
Fish processing	40–78,000	325–90,000	15–10,000	1–860	77–3000	10–390		Chowdhury et al. (2010); Guerrero et al. (1997)
Starch processing	1500–12,000	4000–18,000	250–2,000					Mancini et al. (1994)
Yeast processing	3000–21,000	10,000–30,000	50–2400					Mancini et al. (1994)
Dairy/cheese factory	1400–50,000	2000–95,000	20–22,000	20–150	14–5600*	8–540		Mancini et al. (1994); Perdomo et al. (2000); Demirel et al. (2005); Gonzáles Siso (1996); Farizoglu et al. (2004); Kalyuzhnyi et al. (1997)
Olive oil mill	10,000–150,000	37,000–318,000	6000–83,700 Brozzoli et al. (2009)		1540	410–840	3500–9200	Coskun et al. (2010); Dhouib et al. (2006); Herold et al. (2000); Jail et al. (2010)

* Total nitrogen.

Table 2
Examples of industrial wastewaters expressed in terms of PE according to BOD_5 (Pitter, 2009; Chudoba et al., 1991).

Type of wastewater	Unit	PE
Sugar mill	Sugar beet (1 t)	45–70
Dairy	Milk (1 m^3)	40–230
Paper mill	Paper (1 t)	200–900
Brewery	Beer (1 m^3)	150–350
Laundry	Laundry (1 t)	350–900
Tannery	Leather (1 t)	1000–5000
Cellulose (sulfite)	Cellulose (1 t)	3000–5000
Yeast factory	Yeast (1 t)	5000–7000

is necessary to take into consideration measured parameters for particular wastewater.

4. Petrochemical industry

Petroleum refineries convert raw oil and other hydrocarbon-bearing petroleum sources (such as natural gas and oil sands) into a variety of end products and intermediate materials. Wastewater is generated by the topping, cracking, and lube oil manufacturing processes; cooling tower blow-down; water and sludge drainage from tanks; and stormwater drainage and runoff (Kadlec and Knight, 1996). Typical wastewater pollutants at petroleum refineries include organics, oil and grease, suspended solids, ammonia, phenolics, H_2S and heavy metals (Kadlec and Knight, 1996). Trace organics include several hydrocarbon classes such as BTEX (benzene, toluene, ethylbenzene, xylenes), GRO (gasoline range organics with 6–9 carbon atoms) and DRO (diesel range organics with 10–40 carbon atoms). Total petroleum hydrocarbons (TPH) is a measure of the sum of paraffinic and aromatic constituents (Chapple et al., 2002; Kadlec and Wallace, 2009).

A FWS CW has been used to treat petroleum hydrocarbon-contaminated wastewaters from Amoco's Mandan, North Dakota facility since 1975 (Litchfield, 1993). The wastewater flowed into a constructed wetland from a conventional oil separator and a 6-ha lagoon. The constructed wetland consisted of 11 ponds with a total area of 16.6 ha. The lagoon-constructed wetland treatment system achieved very good results in terms of removal of BOD (98%), COD (93%), ammonia (84%), sulfides (100%), phenols (99%), oils and grease (99%) at the hydraulic loading rate of 1.2 cm d^{-1}.

In 1979, FWS constructed wetland was built to treat wastewaters from a Tizsa Petrochemical Plant in Hungary. The wetland consisted of series of shallow basins with algae and emergent macrophytes (*Typha* sp. and *P. australis*). The system occupied a total area of 18 ha and the daily flow varied between 2500 and 3000 m^3 d^{-1} (Lakatos, 1998). Wood and Hensman (1989) reported the use of 2000 m^2 HF CW filled with waste and coarse ash and planted with *Typha* at the inlet and *Phragmites* at the outlet for the treatment of petrochemical effluents.

A 20 ha FWS CW was built in Beijing Yanshan Petrochemical Company in 1992 to treat secondary treated petrochemical wastewaters (Xianfa and Chuncai, 1994). The removal efciiencies of 44% for TSS, 19% fot TN, 68% for TP and 50% for BOD_5 were very much affected by very high HLR of 47 cm d^{-1}. However, the wetland system was supplemented with a series of five ponds which made the effluent quality good enough to meet local discharge criteria for agricultural irrigation.

Hawkins et al. (1997) reported the use of FWS CW at the Shell Norco refinery in St. Charles Parish, Louisiana, USA. Two parallel wetland cells (30.5 m × 6.1 m) with an alluvial floodplain sediment planted with *Scirpus californicus* (Giant bulrush) were used. During a 4.5-month monitoring period the average inflow and outflow concentrations (Table 3) indicated good removal for heavy metals, TSS and organics at 46-h hydraulic retention time.

Table 3
Treatment efficiency of a FWS CW at the Shell Norco refinery in St. Charles Parish, Louisiana, USA. For the inflow, secondary wastewater was used. Data from Hawkins et al. (1997).

Parameter	Inflow (mg L^{-1})	Outflow (mg L^{-1})
Aluminum	738	102
Copper	22.4	15
Iron	2.5	0.3
Lead	10.5	2.2
Manganese	1208	98
Zinc	566	86
TPH[a]	18.9	1.5
Ammonia	0.7	0.3
BOD_5	38.6	8.1
Oil and grease	19.6	5.0
TSS	82.8	4.5

[a] TPH – total petroleum hydrocarbons.

Gillepsie et al. (2000) evaluated in the same system the elimination of zinc from the effluent. An average of 38% of the total recoverable and 65% of the soluble zinc was removed from the water with 24-h hydraulic retention time and water depth of 0.3 m. The results indicated that with deeper water column less total recoverable Zn (18%) was removed but soluble Zn removal remained unchanged. Only about 3% of the zinc removed was found in and on *S. californicus* roots and shoots. Zinc in sediments was unevenly distributed in the sediment but in general, higher Zn concentrations were found at the inflow zone.

Huddleston et al. (2000) reported the use of mesocosm FWS CW planted with *Typha latifolia* for tertiary treatment of petroleum refinery effluent in Mississippi, USA. During a 15-week study the average inflow BOD_5 concentration of 14 mg L^{-1} decreased to 2 mg L^{-1} in the outflow. The respective NH_4-N concentrations were 4.2 mg L^{-1} and 0.25 mg L^{-1}.

During 1997–1998, the HF CW was built at the Gulf Strachan Gas Plant, approximately 200 km northwest of Calgary, Alberta Canada to treat condensate-contaminated groundwater (Moore et al., 2000). The wetland was a gravel-filled cell with surface dimensions of 50 m × 17 m and planted with *P. australis* and *T. latifolia*. The inflow concentrations of 15–20 mg L^{-1} of C_5–C_{12} hydrocarbons including 50% BTEX compounds. When the wetland was aerated to prevent freeze-up during winter, hydrocarbon removal efficiency was 100% while without aeration during the period May–November the removal varied between 30 and 100%.

Wallace (2002a) reported on the use of HF CW for treatment of petroleum contact waste in a Williams Pipeline Company terminal facility in Watertown, South Dakota, USA. Petroleum contact waste is characterized as storm water runoff, hydrostatic test water, or other water sources that have come in direct contact with petroleum products. In July 1998, a 1486 m^2 HF CW with forced aeration was installed on site to process 1.5 m^3 d^{-1} on a seasonal basis (May–October). The system was initially planted with *P. australis* and over-seeded with *Phalaris arundinacea*. BOD_5 and ammonia removal amounted to 99% and 98%, respectively, with non-detect levels found at 80% of the bed length. However, the treatment effect was found to be strongly season-dependent. In most cases, BTEX was removed in the first 40% of the bed length due to enhanced volatilization as a result of the aeration system.

Chapple et al. (2002) reported on the use of HF constructed wetlands for reducing the dissolved hydrocarbons in the runoff from a decommissioned oil refinery. Two out of four pilot wetlands (300 m^2 each) were filled with soil and two were filled with gravel. All beds were planted with *P. australis*. The study focused on DRO, typically reported as C_{10}–C_{40}. Both types of beds were successful in removing hydrocarbons (up to 99.9% with the mean inflow DRO concentration of 410 mg L^{-1}) but soil-based beds suffered substantially from surface flow. The authors pointed out, however, that because of the much higher cost of gravel it is likely that any future full scale system will contain a mixture of soil and gravel beds.

Kadlec (in Haberl et al., 2003) reported on the efficiency of a pilot-scale vertical flow constructed wetlands for removal of hydrocarbon-contaminated groundwater at former Amoco Refinery Site in Casper, Wyoming, USA, where the continuous operation took place between 1912 and 1991. The pilot system was operated from July 2001 to January 2002 and four cells (7 m × 1.7 m each) were operated in an upward vertical flow mode. The cells were filled with layers of sand and gravel and planted with willows (*Salix* spp.), bulrush (*Scirpus* spp.), soft rush (*Juncus* spp.) and common reed (*P. australis*). The removal of benzene, BTEX, TPH and MTBE amounted to 65%, 66%, 93% and 18%, respectively. The removal was substantially enhanced by addition of air for benzene (87%) and BTEX (90%). The application of air affected only slightly the removal of TPH (97%) and MTBE (29%).

At the same locality, a full scale constructed wetland was commissioned in 2008. It consisted of two cells with free water surface (total area of 0.6 ha) followed by two circular HF cells with a total area of 1.3 ha. Due to the cold winter temperatures (−35 °C), the HF CW were covered by 15 cm of mulch insulation. The results indicated that the inflow concentrations of benzene (170 $\mu g\,L^{-1}$), BTEX (470 $\mu g\,L^{-1}$) and GRO (gasoline-range organics, 2020 $\mu g\,L^{-1}$) were reduced to non-detectable concentrations at the outflow (Wallace and Kadlec, 2005; Wallace et al., 2011).

Yang and Hu (2005) studied HF and FWS mesocosms for tertiary treatment of oil-refinery wastewaters in Taiwan. The mesocosms were filled with gravel and planted with *P. australis*. The authors concluded that constructed wetlands showed an obvious polishing effect and that HF wetland system performed better than FWS system.

A vertical flow constructed wetlands filled with gravel and organic compost and planted with *Phragmites karka* was used to treat wastewater from the Attock Refinery Ltd., Rawalpindi, Pakistan (Aslam et al., 2007). Both wetlands were intermittently fed with hydraulic loading rate (HLR) of 10 $cm\,d^{-1}$. The results revealed that the treatment performance during one year period was slightly better for compost wetland as compared to gravel wetland. The respective removal efficiencies were 51 and 49% for COD, 55 and 47% for BOD_5 and 51 and 42% for TSS. The compost-based wetland was also more efficient than the gravel-based wetland for heavy metals removal. The respective efficiencies were 48 and 37% for Fe, 56 and 41% for Cu and 61 and 45% for Zn.

Ji et al. (2007) used two FWS CWs (75 m × 7.5 m each) to treat heavy oil-produced waters from Chinas Liaohe Oilfield, northeastern China, pretreated in waste stabilization pond. The wetlands 1 and 2 operated under hydraulic retention time (HRT) of 7.5 and 15 days and organic loading rates of 26.7 and 13.3 $g\,COD\,m^{-2}\,d^{-1}$. The wetlands were quite effective under both hydraulic loading rates (Fig. 1).

At the same location, Ji et al. (2004) used constructed wetland planted with reeds to treat drill cuttings. Drill cutting are produced during the drilling operations in the petroleum industry and are composed of crude oils mixed with various amount of polymers and surface active agents. According to Ji et al. (2004), in the Laiohe oilfield, there is approximately 213,000 t of drill cuttings disposed into the environment each year, resulting in 250,000 m^2 of sol pollution. The constructed reed beds were supplied with 5–40 $kg\,m^{-2}$ of drill cuttings, corresponding to 150–1200 $g\,m^{-2}$ of extra heavy oil hydrocarbons. After two years, only 4.2% of the initial hydrocarbons residual were retained in the surface soil.

In 2008, a constructed wetland system was built to treat metals and organic compounds from the groundwater in Wellville, New York, USA, where the oil refinery operated from about

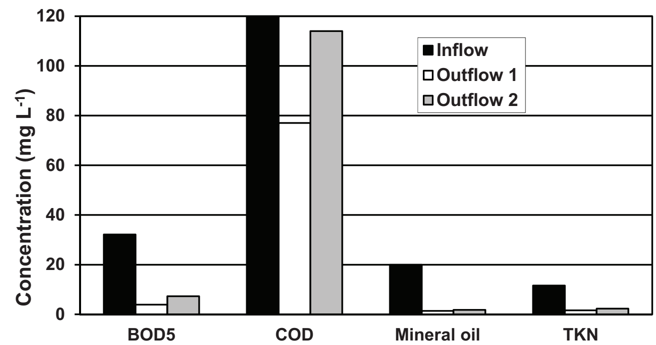

Fig. 1. Removal of organics, mineral oil and TKN from heavy oil-produced waters from Laiohe oilfield (data from Ji et al., 2007) in FWS constructed wetland. COD inflow concentration = 390 $mg\,L^{-1}$. For details see text.

1901 through 1958 (Wallace et al., 2011). The system consisted of (a) cascade aerator for iron oxidation, (b) sedimentation pond for Fe-precipitates sedimentation, (c) three parallel FWS CWs (with a combined area of 0.7 ha) for further removal of iron and removal of organics, namely aniline and nitrobenzene, and (d) five parallel VF CWs (with combined area of 700 m^2) with limestone to add alkalinity. The system was designed for 840 $m^3\,d^{-1}$ but the actual flow was 20% higher. The treatment efficiency during the period December 2008–April 2011 amounted to 87% for benzene, 87% for ethylbenzene, 77% for toluene, 89% for xylene, 94% for aniline, 93% for nitrobenezene, 98% for As and 98% for Fe. Removal of other contaminants such as acenaphtene, naphthalene, phenantrene and manganese varied between 63% and 80%. The system operated also at low winter temperatures below −20% °C (Wallace et al., 2011).

In Nyírbogdány, in the north-eastern part of Hungary, a 15,500 m^2 FWS CW was built to treat petrochemical wastewater at Bogdány Petrol Ltd. (Czudar et al., 2011). The system consisted of three cells dominated by *P. australis*, *Typha angustifolia* and *T. latifolia* and HLR ranged between 1.3 and 1.6 $cm\,d^{-1}$. The average annual removal of COD, BOD_5, TN and TP from mechanically and chemically pretreated wastewater amounted to 54%, 59%, 22% and 43%, respectively. The BOD_5 and COD removal was most effective during the summer while TP removal was the highest during the fall.

5. Pulp and paper industry

Pulp and paper industry produces large amounts of wastewater. Nemerow and Dasgupta (1991) reported the water usage between 75 and 225 $m^3\,t^{-1}$ of product. Thompson et al. (2001) pointed out that the pulp and paper making industry ranks third in the world, after the primary metals and the chemical industries, in terms of freshwater withdrawal. The composition of wastewater from pulp and paper industry depends on the type of process, type of wood material, process technology applied, management practices, internal recirculation of the effluent for recovery, and the amount of water used in the particular process (Pokhrel and Viraraghavan, 2004). Concentrations of organics (BOD_5 and COD) and suspended solids are usually high (Table 1) with many volatile organic compounds (e.g., terpens, phenols, chloroform, and methanol), fatty acids, lignin and its derivatives, AOX or resins being commonly present (Ali and Sreekrishnan, 2001; Pokhrel and Viraraghavan, 2004). While some of these pollutants are naturally occurring wood extractives (tannins, resin acids, stillbenes, and lignin), others are xenobiotic compounds that are formed during the process of pulping and paper making (chlorinated lignins, resin acids and phenols, dioxins, and furans) (Ali and Sreekrishnan, 2001).

At the end of the 1980s and beginning of the 1990s, several experiments with the use of constructed wetlands to treat wastewaters from pulp and paper production were carried out in the United States. Thut (1990a) reported the use of eight HF mesocosms for tertiary treatment of pulp mill effluent. It has been found that the increase in retention time from 6 to 24 h positively improved the removal of ammonia (from 31% to 88%), TSS (from 55% to 68%) and phosphorus (from 14% to 31%) while the removal of BOD_5 was not affected. There was no removal of color from the wastewater. The influence of plant species was also observed. Removal of ammonia decreased in the order *P. australis* (82%), *Spartina cynosuroides* (63%), *T. latifolia* (53%), unplanted unit (16%). For phosphorus, the unplanted unit achieved only 2% removal, while *Spartina*, *Typha* and *Phragmites* units achieved 16%, 23% and 26%, respectively. Removal of BOD_5 and TSS was better in *Typha* unit but the differences among other planted and unplanted unites were only negligible. Thut (1990b, 1993),) studied a 3750 m^2 HF CW planted with *P. australis* and *S. californicus* to treat pulp mill effluent. The system was very effective in removing BOD with removal being consistently between 80 and 90%. Because the secondary-treated effluent delivered to the wetland was of a high quality with an average of about 10 mg L^{-1}, this resulted in the 1–2 mg L^{-1} range in the wetland effluent throughout much of the study period. Removal of TSS and ammonia was variable but in general, quite high. However, the wetland had no beneficial effect on color or AOX. In addition, the HF system suffered from hydraulic problems and therefore a full-scale system (27 ha) was built with a free water surface where eight flow paths with a total of 33 cells were used to treat 60,000 m^3 d^{-1} of secondary wastewater. Over a two-year period the average BOD_5 and TSS concentrations of 69 mg L^{-1} and 27 mg L^{-1} were reduced to respective outflow concentrations of 16 mg L^{-1} and 14 mg L^{-1} (Kadlec and Wallace, 2009).

Tettleton et al. (1993) studied three parallel FWS CWs (surface area of 1300 m^2 each) planted with Torpedo grass (*Panicum hemitomon*) in Mississippi, USA, for tertiary treatment of bleach kraft pulp mill effluent. The removal efficiency was moderate for NO_3-N (80% in 1989, 64% in 1990), variable for TSS (81% and 33%) and TP (53% and −32%), low for NH_4-N (25 and 18%) and very low for BOD_5 (7 and 6%). In 1990, a FWS CW was built at Halsey, Oregon, USA to receive secondary treated pulp mill wastewater (Hatano et al., 1994; Moore et al., 1994). The system consisted of ten cells (1430 m^2 each) planted with either *Scirpus acutus* (Hardstem bulrush) or *T. latifolia* (Broadleaf cattail). Removal of BOD_5 amounted to only 17.8% at 2-d HRT and improved to 32.5% at 10-d HRT. However, the average inflow BOD_5 concentration was quite low – only 24.4 mg L^{-1} and, therefore, it is not easy to achieve high percentual removal. The average removal efficiency for TSS was 51% with the average outflow concentration of 6.8 mg L^{-1}. In the following study, Kuehn and Moore (1995) studied in this system the effect of vegetation type on the treatment performance. For removal of BOD_5, no difference was found in removal by vegetation type but for TSS, cattail ponds produced consistently better TSS effluent concentrations than bulrush.

Hammer et al. (1993) reported on the use of HF constructed wetlands for color removal from pulp mill wastewaters. The early color removal results were encouraging despite the concomitant export of BOD_5. The authors suggested that a treatment system for tannins and lignins should be designed to optimize environmental conditions and retention times to enhance fungal decomposition of complex organics, and incorporate similar components for further decomposition by bacterial populations. Since fungal populations require an attachment substrate, a vegetated sand or porous soil substrate is likely to simulate natural soil conditions and provide aerobic environment and hydraulic conductivity needed to enhance fungal growth. Boyd et al. (1993) used a HF CW for treatment of lightly pretreated raw paper mill wastewaters in Hodge, Louisiana, USA. The inflow BOD_5 concentrations varied between 955 and 1620 mg L^{-1} and treatment efficiency varied between 67% and 84%.

Knight et al. (1994) reported on the use of FWS constructed wetland consisting of six cells receiving secondary-treated effluent at Pensacola, Florida, USA, bleached kraft mill facility. The results indicated that the cells with the longest length:width ratio (10.1) performed better than cells with lower aspect ratio (5:1 and 2.5:1).

In China, FWS CW was built in Beijing, Qinghe District to treat wastewaters from a paper making facility (Xianfa and Chuncai, 1994). The wastewater was pretreated through a pond and overland flow and the wetland operated at the HLR and HRT of 1.5 cm d^{-1} and 5.6 days, respectively. The removal efficiency amounted to 38% for BOD_5, 84% for TSS, 29% for TN and 54% for TP.

Removal of phenol from pulp and paper mill wastewaters was studied by Abira et al. (2005) in Webuye, Kenya. The HF constructed wetland with an area of 30.7 m^2 was filled with gravel to a depth of 0.3 m and planted with *Cyperus immensus*, *Cyperus papyrus, Phragmites mauritianus* and *Typha domingensis*. The inflow phenol concentration varied between 0.43 and 1.7 mg L^{-1} while the outflow phenol concentrations ranged from 0.18 to 0.23 mg L^{-1} and from 0.1 to 0.13 mg L^{-1} for the HRT (hydraulic retention time) of 5 and 3 days, respectively. In India, Choudhary et al. (2010) used a HF CW to remove chlorinated resin and fatty acids (RFAs) from a paper mill effluent. The experimental wetlands with a total area of 5.25 m^2 was filled with gravel (particle size 0–10 mm) and planted with *Canna indica*. At a HRT of 5.9 days, the removal efficiency varied between 92% for 9,10,12,13-tetrachlorostearic acid and 96% for 9,10-dichlorostearic acid. The authors concluded that the most probable mechanisms for the removal of chlorinated RFAs were adsorption/absorption and microbial degradation in the root zone of the plants.

6. Tannery industry

The leather industry is well known as a high consumer of water. The average consumption of water from tanneries is between 25 and 80 m^3 t^{-1} of raw material processed. Tanning processes are classified according to the type of tanning reagent (tannins or chromium) used to bind the collagen fibers (Mannucci et al., 2010). The tannery wastewaters usually contain high concentrations of organics, dissolved and suspended solids, ammonia, organic nitrogen and chromium (Song et al., 2004). Chromium concentration may amount up to 50 mg L^{-1} (Espinoza-Quiñones et al., 2009). In the wastewaters from vegetable tanning processes chromium is absent but there is a significant concentration of recalcitrant COD due to the presence of tannins up to 3000 mg L^{-1} (Vijayaraghavan and Murthy, 1997). Also, tannery wastewaters may contain high concentrations of salts resulting in the *n* NaCl concentrations up to 80 g L^{-1} (Lefebre and Moletta, 2006).

For vegetable tannery wastewater mostly anaerobic treatment systems are used, namely anaerobic filters and upflow anaerobic sludge blanket (UASB) reactors (Mannucci et al., 2010). Other treatment processes include electrocoagulation (Espinoza-Quiñones et al., 2009), chemical coagulation (Song et al., 2004) or membrane bioreactors (Munz et al., 2008).

Kucuk et al. (2003) used FWS CW with a surface area of 378 m^2 planted with *P. australis* for ammonia and COD removal from tannery wastewater in Turkey. At the optimum HRT of 8 days, the removal of NH_4-N and COD amounted to 95% and 30%, respectively. Removal of chromium varied between 45% and 55% and the removal efficiency improved with the increasing HRT between 5 and 11 days.

Calheiros et al. (2007) reported on the use of HF CWs mesocosms for treatment of tannery wastewater in Portugal.

During the first experiments it was found that only *P. australis* and *T. latifolia* where the only species out of five species tested that were able to establish successfully. However, there was no significant difference among treatment efficiency between planted units and unplanted controls. There was also no significant difference in treatment efficiency at HLR of 3 and 6 cm d^{-1}. With the average inflow concentrations of 887 mg L^{-1} for BOD_5, 2030 mg L^{-1} for COD, 77 mg L^{-1} for TSS and 135 mg L^{-1} for TKN the respective average removal efficiencies were 48%, 59%, 72% and 25%. In the follow up experiments (Calheiros et al., 2009), only *P. australis* and *T. latifolia* were used and HLR of 6, 8 and 18 cm d^{-1} were evaluated. The results revealed that with the inflow BOD_5 concentration between 420 and 1000 mg L^{-1} the average removal efficiency amounted up to 88%. For COD inflow concentrations between 808 and 2449 mg L^{-1} the treatment efficiency amounted to 92%. There was no statistical difference in treatment effect between units planted with *P. australis* and *T. latifolia*. Overall mass removals of up to 1294 kg COD ha^{-1} d^{-1} and 529 kg BOD_5 ha^{-1} d^{-1} were achieved for respective loading rates up 1925 kg COD ha^{-1} d^{-1} and 900 kg BOD_5 ha^{-1} d^{-1}. For organics (COD, BOD_5) the highest removal was found at HLR of 6 cm d^{-1} (7 days HRT) while for TKN, NH_3-N and TP, the HLR of 8 cm d^{-1} (5 days HRT) was the most effective.

In the recent study, Calheiros et al. (2012) tested horizontal subsurface flow CWs for polishing of high salinity tannery wastewaters (2.2–6.6 g Cl^- L^{-1}) in a leather company in Portugal. The authors used two wetlands (each with surface area of 72 m^2 and depth of 0.35 m) planted with *Arundo donax* and *Sarcocornia fructicosa*. At the hydraulic loading rate of 6 cm d^{-1} both wetlands performed equally for COD (65% removal), BOD_5 (73%), TSS (65%), NH_4-N (73%) and TKN (75%) while removal of TP was slightly higher in *Arundo* wetland (83%) as compared to *Sarcocornia* wetland (79%). The system was able to fulfill the discharge standards.

Kaseva and Mbuligwe (2010) used a pilot-scale HF CW to remove chromium and turbidity from a tannery wastewater in Tanzania. The HF wetland was filled with crushed pumice and limestone with particle size 4–30 mm and planted with *P. mauritianus*. The average HLR was 10 cm d^{-1} and the average HRT was 1.6 days. The inflow Cr concentration of 372 mg L^{-1} was reduced by 99.8% in a planted wetland while a control unplanted cell exhibited slightly lower removal of 92.5%. The reduction of turbidity amounted to 71% and 66% in planted and unplanted cell, respectively.

In Bangladesh, a hybrid VF-HF-VF constructed wetland pilot-scale system was evaluated for tannery wastewater by Saeed et al. (2012). The wetland units were filled with locally available materials: organic coco-peat (1st VF), cupola slag, a by-product of cast iron melting process (HF) and pea gravel (2nd VF) and all units were planted with *P. australis*. The inflow concentrations were very high: COD 11,500 mg L^{-1}, BOD_5: 4200 mg L^{-1}, TSS 27,600 mg L^{-1}, PO_4: 30 mg L^{-1}, NO_3: 66 mg L^{-1} and NH_4: 111 mg L^{-1}. The overall treatment efficiency amounted to 98%, 98%, 55%, 87%, 50% and 86%, respectively, despite very high loadings (690 g COD m^{-2} d^{-1}). The pollutants were gradually removed through the system in all units with the exception of ammonia which was primarily removed in VF units.

7. Textile industry

The most common textile-processing set-up consists of sizing, desizing, scouring, bleaching, mercerizing, dyeing, rinsing and finishing (Dos Santos et al., 2007). Dyeing and finishing processes are two important steps in textile manufacturing process (Lin and Peng, 1994). Colored textile effluents represent severe environmental problems as they contain mixtures of colorants (dyes and pigments) of different classes with elevated organic parameters such as BOD_5, COD, TOC, AOX (adsorbable organic halogens), inorganic parameters such as metals, chloride, sulphate, sulphide and nitrogen (Sharma et al., 2007; Bulc and Ojstršek, 2008). Also, the textile wastewaters may have broad range of pH varying from 2 to 12 (Can et al., 2006). Robinson et al. (2001) pointed out that there are more than 10,000 commercially available dyes and due to their chemical complex structure and synthetic origin, dyes are resistant to fading on exposure to light, water, and many chemicals. Also, reduction of azo dyes results in production of aromatic amines which are generally considered as hazardous substances in the environment with many of them being toxic and/or carcinogenic (Pinheiro et al., 2004). Decolorization of textile dye effluent does not occur when treated aerobically by municipal treatment systems (Robinson et al., 2001) whereas anaerobic processes show a great removal of color (Tunay et al., 1996; Vandevivere et al., 1998). Pitter (2009) up to 100 mg L^{-1} MBAS.

Robinson et al. (2001) reviewed the current technologies for remediation of dyes in textile wastewaters. These technologies include wide variety of chemical (e.g., oxidation, ozonation or electrochemical destruction), physical (e.g., adsorption, membrane filtration, ion exchange, electrocoagulation or irradiation and biological (microbial and fungal cultures, and anaerobic cultures)) processes (Lin and Peng, 1994; Robinson et al., 2001; Kobya et al., 2003; Can et al., 2006; Dos Santos et al., 2007; Prigione et al., 2008).

Davies and Cottingham (1992) used HF constructed wetlands planted with *P. australis* for the treatment of complex wastewaters from a group of textile processing and dyeing facilities with a dark blue–blue coloration caused by dye residues. The experiments were carried out in Melbourne, Australia, in 150 m^2 wetlands which had been used for domestic wastewaters for three years before experiments with textile wastewaters started. The constructed wetland worked at hydraulic loading rate of 9.6 cm d^{-1}. The visible colorization of the textile wastewater was reduced very quickly as it passed through the bed and disappeared after only 6 m of travel. Also, the suspended solids inflow concentration of 80 mg L^{-1} quickly decreased to less than 10 mg L^{-1} after about 15 m of travel and then remained more or less unchanged.

Vertical flow pilot scale constructed wetlands were used to remove two textile azo dyes–Acid Blue 113 and Reactive Blue 171 from a synthetic wastewater simulating textile wastewater (Pervez et al., 2000). The wetlands were filled with layers of gravel of various size and planted with *P. australis*. For both dyes removal of 98% was achieved. The authors observed that the majority of dye (57%) was removed in the initial 12 h by adsorption onto charged surfaces in the substratum. The efficiency was substantially enhanced by addition of peat or other suitable organic substratum.

Davies et al. (2005) used a vertical-flow pilot-scale constructed wetland planted with *P. australis* to remove an azo dye acid orange (AO7). At the organic loading rates between 21 and 105 g COD m^{-2} d^{-1} the VF CW was able to remove 11–67 g COD m^{-2} d^{-1} and the removal of COD, TOC and AO7 amounted to 64%, 71% and 74%, respectively. The authors also found out that *Phragmites* had an active role in AO7 degradation. *Phragmites* not only degraded AO7 but also aromatic amines released during AO7 degradation.

Bulc et al. (2006) and Bulc and Ojstršek (2008) described the use of pilot VF-HF constructed wetland for treatment of real textile wastewater in Slovenia. The system consisted of two parallel VF beds (20 m^2 each) followed by a single HF bed (40 m^2). For vertical beds, a mixture of sands with fractions 0–4 and 4–8 mm was used while for HF bed a mixture of sands with fractions 0–4 and 8–16 mm was used. All beds were planted with Common reed (*P. australis*). At the flow of 1 m^3 d^{-1} (HLR = 1.25 cm d^{-1} for the whole system) the average treatment efficiency (Table 4) amounted to 84% for COD, 66% for BOD_5, 93% for TSS, 52% for TN, 87% for organic N, 88% for sulfate, 80% for anionic surfactants and 90% for color

Table 4
Performance of a pilot VF-HF constructed wetland treating textile wastewaters in Slovenia. Data from Bulc and Ojstršek (2008).

Parameter	BOD_5	COD	TOC	TN	Norg	NH_4-N	SO_4^{2-}	AS	TSS
Inflow ($mg\,L^{-1}$)	198	771	261	29	26	2.4	1165	5.2	129
Outflow VF ($mg\,L^{-1}$)	110	235	73	21	10	11	284	2.7	25.2
Outflow HF ($mg\,L^{-1}$)	66	122	27	14	3.4	10	137	1.0	9
Efficiency (%)	66	84	90	52	87	-331	88	80	93
Inflow VF load ($g\,m^{-2}\,d^{-1}$)	40	140	52	7.4	6.6	0.6	235	0.7	26
Inflow HF load ($g\,m^{-2}\,d^{-1}$)	24	58	19	4.9	2.7	2.3	74	0.4	5.1

AS = anionic surfactants.

with the majority of color removed in the first VF bed. The system exported ammonia-N (−331%) as a result of organic-N ammonification (−331%). Also, the alkaline pH of the wastewater (8.7) was lowered to neutral value of 7.2.

The same effect was observed by Mbuligwe (2005) during the experiments with HF constructed wetland filled with sand and planted with *Typha* sp. and *Colocasia esculanta* (Cocoyam) treating dye-rich wastewater from "tie-and-die" (batik) technology in Dar es Salaam, Tanzania. The initial pH of 10.7 was reduced to 7.8 and 7.9 in *Typha* and *Colocasia* beds, respectively. At a very high HLR of 45 cm d^{-1} the respective removal efficiencies in *Typha*, *Colocasia* and unplanted units amounted to 72%, 77% and 15% for color, 53%, 59% and 25% for sulfate and 68%, 72% and 51% for COD. The results revealed slightly better performance of *Colocasia* unit over the *Typha* unit and much better removal of vegetated units as compared to unvegetated unit. Bulc and Ojstršek (2008) pointed out that low BOD_5/COD ratio of textile wastewaters (often less than 0.2) indicates biologically hardly-degradable nature of textile wastewater and therefore, high BOD_5 removal cannot be expected.

Ong et al. (2009) studied in Japan the use of up-flow vertical constructed wetlands mesocosms 0.6 m deep for treatment of azo dye-containing wastewater. Acid Orange 7 (AO7) was used as a model less biodegradable organic contaminant in industrial wastewaters. Azo dyes are the most widely used dyes in textile industry and their degradation is difficult due to their complex structure and synthetic nature. Azo dyes are hence one of the most problematic contaminants in textile industry. The mesocosms were filled with 5.7 mm gravel and planted with *P. australis* and *Zizania aquatica* (Manchurian wild rice). Also, supplementary aeration was installed 30 cm below the bed surface in *Phragmites* and unplanted units. For COD, total-N and NH_4-N, the planted non-aerated units produced slightly better performance than unplanted unit. Additional aeration enhanced the treatment efficiency differently – for Total-N, COD and NH_4-N, supplementary aeration enhanced the removal efficiency by 6%, 5% and 53%. Removal of AO7 dye amounted to 96% in both planted and unplanted non-aerated units and the additional aeration increased the removal to 98%. This means that most of AO7 was removed in the anaerobic lower part of the wetland.

A 180 m^2 HF CW was built in 2003 at Prato, Italy, for post-treatment of textile wastewater for water reuse (Fibbi et al., 2011). The constructed wetland was filled with gravel (10–20 mm) and planted with *P. australis*. At a HLR of 13.3 cm d^{-1} the results from the period 2006–2010 revealed that removal of total and hexavalent chromium varied from 40 to 50% and 67 to 71%, respectively. The authors concluded that based on the data from a demonstration CW it could be estimated that a full-scale system of about 3.5 ha would be capable of meeting the criteria for recycled water in the Prato textile industrial complex.

8. Fish and shrimp recirculating aquaculture industry

Intensive aquaculture in recirculating systems has recently been rapidly developing, and with it the need for reliable treatment arises. To enable reuse of water in these systems, biological treatment is considered the most economically feasible approach (Van Rijn, 1996). The farm effluents are characterized by low waste concentrations at high volumes which are difficult to treat (Cripps and Kelly, 1995). Effluents from trout farms are typically 20–25 times more diluted than medium strength municipal wastewaters and even below municipal secondary treatment criteria with BOD_5, COD, ammonia and TP concentrations of about 15, 12, 1.3 and 0.3 mg L^{-1}, respectively (MENV, 1999). With respect to receiving water quality objectives, the most constraining element to remove from freshwater fish farm effluents is phosphorus (Comeau et al., 2001).

Zachritz and Jacquez (1993) reported the use of HF constructed wetland for a treatment of recycled water from a geothermal aquaculture-high density finfish culture in New Mexico. The system was filled with 5–8 cm rock and planted by *S. californicus*. Unfortunately, the authors did not provide any specific results on the treatment efficiency.

Schwartz and Boyd (1995) reported on the use of FWS CW with an area of 2352 m^2 to treat the effluent from a 6.9 ha channel catfish (*Ictalurus punctatus*) production pond in Alabama, USA. The wetland was planted with *S. californicus* (California bulrush), *Zizaniopsis miliacea* (Giant cutgrass) and *P. hemitomon* (Maidencane) and the treatment performance was tested at HRTs of 1–4 days with HLRs between 77 and 91 L m^{-2} d^{-1}. The overall performance was best when operated with a 4-d HRT in the vegetative season but good removal was achieved also for shorter HRTs and when vegetation was dormant. At the 4-d HRT the inflow concentrations of BOD_5 12.9 mg L^{-1}, SS 45 mg L^{-1}, TP 0.21 mg L^{-1}, NO_3-N 0,50 mg L^{-1} and total ammonia-N 1.29 mg L^{-1} were reduced to 4.45 mg L^{-1}, 5.1 mg L^{-1}, 0.03 mg L^{-1}, 0.13 mg L^{-1} and 0.68 mg L^{-1}, respectively.

Constructed wetlands have been used to treat sludge from the recirculating trout-production aquaculture system in West Virginia (Summerfelt et al., 1999). The sludge was applied at the rate of about 30 kg m^{-2} yr^{-1} in a six equal 60 L d^{-1} batches resulting in a HLR of 1.35 cm d^{-1}. The constructed wetlands – two HF and two VF (surface area of 4.44 m^2) were planted with Vetiver grass (*Vetiveria zizanioides*). Both types of constructed wetlands achieved very high removal (Table 5) and for all monitored parameters VF wetland removal was superior to horizontal one with the exception of nitrate. Nitrate occurred in VF CW outflow in much higher concentration due to lack of denitirification as a consequence of oxic conditions in the VF CW.

VF constructed wetland was used to treat wastewater from a tilapia (*Oreochromis niloticus*) recirculation aquaculture (Behrends et al., 2000a). The system consisted of an intermittent sand filter

Table 5
Treatment performance of VF and HF constructed wetlands treating sludge from trout-producing recirculating aquaculture. Data from Summerfelt et al. (1999).

	TSS	COD	NO_3-N	TKN	PO_4-P	TP
Inflow ($mg\,L^{-1}$)	7860	6855	0.057	234	106	238
Outflow VF ($mg\,L^{-1}$)	156	539	45.4	26.9	7.1	30.9
Outflow HF ($mg\,L^{-1}$)	229	1761	0.38	32.5	9.0	42.2
Removal VF (%)	98	92		89	93	87
Removal HF (%)	97	74		86	92	82

and two-stage reciprocating VF constructed wetlands with a total surface area of 9.5 m^2. At HRT of 5.5 days and organic loading of 460 kg BOD_5 ha^{-1} d^{-1} the treatment system achieved very high removal. The inflow concentrations of BOD_5, COD, TN, ammonium and TP of 771 mg L^{-1}, 3609 mg L^{-1}, 67.4 mg L^{-1}, 0.22 mg L^{-1} and 40.5 mg L^{-1} were reduced to respective values of 4 mg L^{-1}, 32 mg L^{-1}, 3.0 mg L^{-1}, 0.03 mg L^{-1} and 6.3 mg L^{-1}. Treatment efficiencies amounted to 99.5% for BOD_5, 99.1% for COD, 95.5% for TN, 85.9% for ammonia and 84.4% for TP.

Comeau et al. (2001) used two HF constructed wetlands in series to treat trout farm effluents at the Pisciculture du Lac William near St-Ferdinand, southeast of Québec City, Canada. Two beds (20 m × 8.5 m each) were filled with crushed limestone (0–2.5 mm in one bed and 2.5–5 mm in the other) and planted with *P. australis*. The experiments were primarily aimed at the removal of TP and TSS. The results indicated that the removal of TSS and TP were greater than 95% and 80%, respectively. The authors concluded that the potential of HF constructed wetlands as an ecologically attractive and economical method for treating fish farm effluents to reduce solids and phosphorus discharge appears promising.

Lin et al. (2002) used a pilot hybrid FWS-HF constructed wetland to treat aquaculture wastewater. The hybrid constructed wetland was built adjacent to pond for production of milkfish (*Chanos chanos*) in Tainan County, Taiwan. The hybrid systems consisted of FWS and HF constructed wetlands in series with both wetlands having the surface area of 5 m^2. The HF wetland was filled with river gravel (10–20 mm) and planted with *P. australis.* In FWS wetland local soil was used as rooting medium and the wetland was planted with water spinach (*Ipomea aquatica*) in the front half and Water finger-grass (*Paspalum vaginatum*) in the second half. The results revealed high removal of nitrogen – removal efficiency varied between 86% and 98% for NH_4-N and between 95% and 98% for total inorganic nitrogen. Removal of nitrogen was not affected by HLR which varied between 1.8 and 13.5 cm d^{-1}. Contrary, removal of phosphate varied between 32% and 71% and was inversely related to HLR. The authors pointed out that the outflow concentrations of NH_4-N and NO_2-N were low enough (<0.3 mg L^{-1} and 0.1 mg L^{-1}, respectively) to recycle the water back to the aquaculture without harming the fish.

Lin et al. (2003) used the same system to treat wastewater from recirculating aquaculture system for culturing of Pacific white shrimp (*Litopenaeus vannemei*). In this case, both wetlands were planted with *P. australis*. During an 80-days culture period, the wetland unit operated at a mean HLR of 0.3 m d^{-1} and the removal efficiency amounted to 24% for BOD_5, 71% for TSS, 88% for chlorophyll-*a*, 57% for total ammonium, 68% for nitrate. However, the phosphate removal was very low (54%). In addition, the results revealed that the shrimp growth and survival was better in recirculating wetland system as compared to conventional system without water recirculation.

Naylor et al. (2003) reported on the use of experimental HF constructed wetlands to treat diluted sludge from a freshwater fish farm anaerobic digester. Pollutant removal was generally very good with planted wetlands (*P. australis* and *T. latifolia*) clearly outperforming unplanted units in term of BOD_5, COD, TKN, NH_4-N. The removal of TSS, NO_3-N PO_4-P and TP were comparable.

Michael (2003) used three-cell FWS constructed wetland (90 m^2 each cell) planted with *S. acutus* (Hardstem bulrush), *Eleocharis palustris* (Spike rush) and *Sparganium emersum* (Single-stem bur reed) for the treatment of wastewater from salmonid hatcheries in Washington, USA. The treatment wetlands exhibited very good removal efficiency for organics, suspended solids, ammonia and phosphorus (Table 6).

Lymbery et al. (2006) studied the performance of constructed wetlands for treatment of wastewater from inland saline aquaculture in Australia. The experiments were carried out in 2003 in a series of sixteen 1 m^2 HF CWs filled with basalt gravel and planted with *Juncus kraussii* (Jointed rush) to simulate treatment of wastewater from Rainbow trout (*Oncorhynchus mykiss*) aquacultures. The inflow concentration of NaCl varied between 7.5 and 24 g L^{-1}. After 38 days, the wetland plots removed up to 69% of the TN load and 88.5% of the TP load, with active uptake by the soil-plant ecosystem being greatest at high nutrient levels. TN removal increased markedly over time, whereas TP removal remained relatively constant. Salinity did not affect TN removal, but did reduce TP removal. Although up to 54.8% of NaCl load was removed by the wetland plots, this appeared to be a passive consequence of water uptake.

Table 6
Treatment performance of constructed wetland system designed to treat salmon hatchery wastewater. Data from Michael (2003).

	Inflow ($mg\,L^{-1}$)	Outflow ($mg\,L^{-1}$)	Removal (%)
BOD_5	18.9	3.5	82
TP	0.76	0.13	82
NH_4^+-N	0.43	0.11	75
TSS	58	5.0	91

Chazarenc et al. (2007) used a combination of a HF constructed wetland (28 m^2) followed by static columns filled with electric arc furnace slag to treat effluent from anaerobic digester-sludge storage tank at the flow-through trout fish farm. The TSS, COD, TKN and TP concentrations of 120, 710, 29 and 25 mg L^{-1} in the storage tank effluent were reduced to respective values of 23, 43, 5.9 and 11 mg L^{-1} in the HF wetland effluent. Slag columns reduced the TP concentrations down to 2.3 mg L^{-1}.

Li et al. (2007) applied VF constructed wetlands for treatment of aquaculture ponds in China. The VF wetlands (80 m^2 each) were filled with gravel (1–16 mm) and planted with *C. indica* (Canna), *T. latifolia* (Broadleaf cattail), *Acorus calamus* (Sweet flag) and *Agrave sisalana* (Sisal hemp). The HRT during four experimental periods varies between 0.58 and 1.44 days and HLR varied between 15.7 and 39.1 cm d^{-1}. The wetlands proved to be very effective and the reduction amounted to 70.5% for BOD_5, 81.9% for TSS, 91.9% for chlorophyll-*a*, 61.5% for NH_4-N and 68% for NO_3-N. Only the removal of phosphorus (20%) was lower.

Zachritz et al. (2008) reported on the use a HF constructed wetland for treatment of tilapia production wastewaters in a recirculating two-step aquaculture system combining a simple clarifier and a constructed wetland in La Cruces, New Mexico, USA. The constructed wetland (area 53.8 m^2, W × L × D = 6.4 m × 8.4 m × 0.9 m) was filled with 380 mm lava rock media and planted with a mixture of Canna lilies (*Canna* sp.) and Bulrush (*Scirpus* sp.). The HLR was high (3.03 m d^{-1}) and resulting HRT was only 2.9 h. The system successfully supported a commercial scale level of production (>35 kg m^{-3}) for over three years of operation. The TSS, NO_2-N and NO_3-N removal amounted to 90%, 91% and 76%. The removal of COD (12.5%) and NH_3-N (7.5%) were lower and TP concentrations remained unchanged. The results indicated that the wetlands appeared to be oxygen limited at high total ammonia nitrogen loadings above 6 g m^{-2} d^{-1}).

Sindilariu et al. (2008) used HF constructed wetlands to treat effluent from an intensive trout farm in Germany. The authors used very high hydraulic loading rates (3.3–14.1 m d^{-1}) resulting in a very high loading rates, up to 61.7 g N m^{-2} d^{-1}, 48.7 g NO_3-N m^{-2} d^{-1}, 69.4 g BOD_5 m^{-2} d^{-1}, 143 g COD m^{-2} d^{-1} and 72.2 g TSS m^{-2} d^{-1}. The authors pointed out that the system was the most effective at HLR of 6.5 m d^{-1} and the removal efficiencies at this HLR amounted to 61% for total ammonia nitrogen, 43% for total phosphorus, 72% for BOD_5, 55% for COD and 85% for TSS. Removal of total nitrogen was low (5.5%) due to increase in nitrate-N concentration (+8.4%) in the outflow. However, dissolved PO_4-P concentration substantially increased by 150%. The authors suggested that PO_4-P is either leached out from the trapped particulate phosphorus in the wetland or from the fecal trout matter as evidenced by Steward et al. (2006). The increase in PO_4-P concentrations under high HLR was also reported by Schulz et al. (2003) or Lin et al. (2005).

Zhang et al. (2010) used a combination of parallel VF-downflow and VF-upflow constructed wetlands to improve recirculation water for Channel catfish (*I. punctatus*) aquaculture in China. The total area of the wetlands was 320 m^2. The downflow units were planted with *C. indica* while the upflow units were planted with *T. latifolia*, *A. calamus* with addition of sisal. The system operated under the HLR of 22.5–33.8 cm d^{-1} and HRT of 0.9–1.3 days. The removal efficiency was moderate with and amounted to 56% for BOD_5, 26% for COD, 58% for TSS, 17% for TP, 48% for TN and 34% for NH_4-N. However, the cyanobacterial blooms which occurred heavily in the control were suppressed effectively in the recirculating ponds where the water was treated by CWs.

Shi et al. (2011) reported on the use of a combination of vertical and horizontal flow constructed wetlands for treatment of recirculating and superintensive shrimp aquaculture in China. The constructed wetland consisted of one VF bed (21.3 m^2 filled with corallite, depth 0.68 m) and a series of five HF beds (40 m^2 each, filled with layers of 0.25 m of stones 8–10 cm, 0.20 m of coarse gravel 3–5 cm and 0.1 m of fine gravel 1–2 cm from bottom to top). The feed water was of mesohaline conditions (8.25‰) and therefore local salt-tolerant plant species were used: *P. australis* (wetlands 3 and 5) *Spartina alterniflora* (2 and 4) and *Scirpus mariquer* (1 and 6). The system exhibited good removal of TN (67%), TAN (71%), TSS (66%) but the removal of COD (27%), TP (24%) and nitrate (59%) was lower. The ratio between the surface areas culture tanks and constructed wetland was 1.15.

Konnerup et al. (2011) reported on the use of VF and HF constructed wetlands for the treatment of fishpond water in a recirculating aquaculture system in the Mekong Delta of Vietnam. The fish population in the pond was a polyculture of Nile tilapia (*O. niloticus* – 85% of fish biomass) and common carp (*Cyprinus carpio* – 15% of fish biomass). Two HF CW_S (surface area of 3.15 m^2 each) were filled with coarse gravel (30–50 mm) while two VF CW (surface area of 1.2 m^2 each) were filled with layers (from the bottom) of stones (50–100 mm), coarse gravel (30–50 mm) and fine gravel (10–20 mm). All wetlands were planted with *Canna* × *generalis*. The wetlands were studied under free different HLR (75, 150 and 300 cm d^{-1}) with inflow concentrations of BOD_5 16–27 mg L^{-1}, COD 116–132 mg L^{-1}, TN 6.2–9.7 mg L^{-1}, TAN 0.31–0.85 mg L^{-1} and TP 1.0–2.5 mg L^{-1}. There was a good removal of organic matter measured as oxygen demand with up to 50% removal of BOD and COD in both types of CWs despite the high loading rates and low concentration levels. However, the vertical flow CWs performed better than the horizontal flow CWs as they had higher nitrification rates and higher DO concentrations in the outlets.

The results given in Table 7 revealed that constructed wetlands for treatment of recirculating aquaculture wastewaters are operated under a wide range of hydraulic loading rate (1.8 cm d^{-1}–28.9 m d^{-1}) and consequently with wide range of hydraulic retention times (0.014 d–4.2 d).

Constructed wetlands have also been used to treat wastewaters from the flow-through aquacultures. Snow et al. (2010) reported on the use of a HF CW to treat wastewaters from a raceway-based salmonid hatchery located in Haliburton County, Ontario, Canada. Daily vacuuming of sediments from the raceway resulted in a production of concentrated wastewater. The treatment system consisted of a septic tank, two parallel HF cells planted with *Typha* spp. and *Carex* spp. and a single blast furnace slag filter. For the purpose of this paper, only HF wetland will be evaluated. The average inflow concentrations (average from two 6-months sampling campaigns during the period 2008–2010) to the HF wetland of TSS: 38 mg L^{-1}, BOD_5: 106 mg L^{-1}, COD: 133 mg L^{-1} and TP: 2.97 mg L^{-1} were reduced to 22 mg L^{-1}, 50 mg L^{-1}, 58 mg L^{-1} and 1.25 mg L^{-1}. However, the concentration of NH_4-N was higher at the outflow from the HF CW (6.7 mg L^{-1}) as compared to inflow (4.7 mg L^{-1}) as a result of ammonification of the organic nitrogen in the wetlands.

9. Alcohol fermentation industry

The alcohol fermentation industry is divided into three main categories: brewing, distilling and wine manufacture. Each of these categories produces wastewaters with common characteristics such as low pH values and high concentrations of organics (Strong and Burgess, 2008).

9.1. Winery

The wine industry generates large volumes of wastewaters originating from various steps during the crushing and pressing of grapes and also from rinsing of fermentation tanks, barrels and

Table 7
Comparison of constructed wetlands used to treat wastewaters from various recirculating aquaculture systems.

Type of aquaculture	Location	CW type	HLR	HRT	References
Milkfish (*C. chanos*)	Taiwan	FWS-HF	1.8–13.5 cm d^{-1}		Lin et al. (2002)
Not specified	Canada	HF	3 cm d^{-1}	4 d	Naylor et al. (2003)
Channel catfish (*I. punctatus*)	USA	FWS	7.7–9.1 cm d^{-1}	1–4 d	Schwartz and Boyd (1995)
Chinook salmon (*Oncorhynchus tsawytscha*)	USA	FWS	7.9 cm d^{-1}	4.2 d	Michael (2003)
Coho salmon (*Oncorhynchus kisutch*)					
Channel catfish (*I. punctatus*)	China	VF	22.5–33.8 cm d^{-1}	0.9–1.3 d	Zhang et al. (2010)
Channel catfish (*I. punctatus*)	China	VF	14.7–39.1 cm d^{-1}	0.58–1.44 d	Li et al. (2007)
Bluntsnout bream (*Megalobrama amblycephala*)					
Trout	Canada	HF	21.2 cm d^{-1}	1.3 d	Comeau et al. (2001)
Pacific white shrimp (*Litopenaeus vannamei*)	Taiwan	FWS-HF	30 cm d^{-1}	0.76 d	Lin et al. (2003)
Pacific white shrimp (*L. vannamei*)	China	VF-HF	86 cm d^{-1}	0.76 d	Shi et al. (2011)
Nile tilapia (*O. niloticus*)	Vietnam	VF, HF	75–300 cm d^{-1}		Konnerup et al. (2011)
Common carp (*C. carpio*)					
Red tilapia (*Oreochromis massambicus* × *O. aureus*)	USA	HF	3.03 m d^{-1}	0.12 d	Zachritz et al. (2007)
Rainbow trout (*O. mykiss*)	Germany	HF	1–5 m d^{-1}	1.5–7.5 d	Schulz et al. (2003)
Rainbow trout (*O. mykiss*)	Germany	HF	3.3–14.1 m d^{-1}		Sindilariu et al. (2008)
Rainbow trout (*O. mykiss*)	Germany	HF	10.6–28.9 m d^{-1}	0.014	Sindilariu et al. (2007)
Brown trout (*Salvelinus fontinalis*)					
Brook trout (*Salmo trutta*)					

Table 8
Treatment performance of three constructed wetlands treating winery wastewaters in Italy. All values in mg L^{-1}. Data based on Masi et al. (2002) and Italian CW database (Masi, pers. comm.).

Location	Cecchi			Ornellaia				La Croche	
	Inflow	HF_{out}	FWS_{out}	Inflow	VF_{out}	HF_{out}	FWS_{out}	Inflow	HF_{out}
BOD_5	1833	49	24.5	425	337	286	28.6	354	29.7
COD	3906	131	84	1003	690	431	79	722	90
TSS	213	13.3	23.4	103	41.8	23.9	25.3		
TN	18.9	4.8	3.5	26.6			2.65	65.2	27.5
NH_4-N				26.6	8.7	4.7	2.7	46.7	21.4
TP	4.7	1.5	1.3	1.9			0.12		

other equipment and winery rooms (Fumi et al., 1995; Anastasiou et al., 2009).

Winery wastewaters contain high concentrations of readily biodegradable soluble organic matter such as sugars (glucose and fructose), alcohols (ethanol and glycerol), acids (tartaric, lactic, and acetic) (Dombeck, 2005; Agustina et al., 2008) and recalcitrant high molecular weight compounds such as polyphenols, tannins and lignins (Dombeck, 2005) (Table 1). These are not easily removed by physical or chemical treatment alone and tannins in particular can inhibit microbial digestion (Sarni-Manchado et al., 1999). Alcohols usually represent more than 90% of the organic content of winery wastewaters. However, the composition and amount of wastewater is variable due to winemaking technologies involved (red, white, sparkling, special) and the working period with the peak wastewater generation during the period when grapes are processed into juice for fermentation (Fumi et al., 1995; Anastasiou et al., 2009). The period of crushing and fermentation takes usually 6–20 week period and it is called vintage (Agustina et al., 2008).

For treatment of winery wastewaters various technologies have been used including activated sludge (Fumi et al., 1995; Petruccioli et al., 2002), photocatalytic (photo-Fenton) oxidation (Mosteo et al., 2006; Anastasiou et al., 2009), land filtration (Christen et al., 2010).

Shepherd et al. (2001) used a pilot scale HF CW for treatment of winery wastewater from a moderate-sized winery in California. A 14.9 m^2 unit was filled with pea gravel with an average porosity of 36% and planted with *T. domingensis, S. acutus* and *Sagittaria latifolia*. During the test period between August 1996 and November 1997, the organic loading varied between 345 and 1640 kg COD ha^{-1} d^{-1} and the removal efficiency amounted to 98.4%, 96.7%, 98.5%, 78.2%, 63.3%, 100% and 77.9% for COD, TSS, S^{2-}, TKN, ortho-P, phenols and tannins/lignins, respectively.

At the end of the 1990s, attempts were made to use constructed wetlands to treat winery wastewaters in France (Rochard et al., 2002) and Germany (Müller et al., 2002). In Bordeaux winery, France, two constructed wetlands were used for finish the treatment of winery wastewater instead of commonly used sand filters. Intensive aeration of a storage lowered the inflow COD concentration of about 2000 mg L^{-1} and constructed wetlands further decreased COD concentration <300 mg L^{-1}. In other localities, treatment of combined domestic and winery wastewaters were applied. After a winery wastewater pretreatment through straw screening, the winery wastewater was mixed with domestic wastewater and treated in three constructed wetlands in series with a total area of 35.6 m^2 planted with a mixture of 18 wetland plants (Rochard et al., 2002). The results revealed that the inflow COD concentrations of about 7000 mg L^{-1} were reduced to required outflow COD concentrations only with a recycling regime. In Germany, constructed wetlands were applied in a full scale demonstration plant in Eschbach (Müller et al., 2002). The system consisted of a two-stage anaerobic digestor and a VF CW with a surface area of 120 m^2.

Masi et al. (2002) described three constructed wetland systems in Tuscany, Italy designed to treat winery wastewaters. The system La Croche consists of Imhoff tank and a single HF bed (215 m^2) filled with gravel 5–10 mm and operates at the HLR of 3.7 cm d^{-1}. The system Azienda Vitivinicola Ornellaia is a hybrid constructed wetland consisting of Imhoff tank, two 90 m^2 VF beds, 102 m^2 HF bed (filled with 8–12 mm gravel), 148 m^2 FWS wetland and 338 m^2 pond. The system operates at HLR of 2.3 mg L^{-1}. Hybrid CW Casa Vinicola Luigi Cecchi & Sons consists of 480 m^2 HF bed filled with 5–10 mm gravel and 850 m^2 FWS wetland. It operates at the HLR of 2.6 cm d^{-1}. All HF beds are planted with *P. australis*. The treatment efficiency of all systems is shown in Table 8. The results indicate very high efficiency for all monitored parameters. In hybrid CWs where FWS CW is the last part of the system, the concentration of TSS usually increases after passage through the pond due to phytoplankton growth and subsequent release of algae into discharge water.

The hybrid system Casa Vincicola Luigi Cecchi, which has been in operation since 2001, was upgraded in 2009 because the designed flow of 35 m^3 d^{-1} has risen due to increased production up to about 70 m^3 d^{-1} (Zanieri et al., 2010). The existing system was upgraded by addition of three VF CWs (total surface area of 1200 m^2) as the first stage, a new HF CW (480 m^2) parallel to the already exiting cell and a sand filter after the FWS CW. The total HRT of the new system is 7.3 d. The inflowing wastewater is very strong and each VF CW is loaded with the organic load of 486 g COD m^{-2} d^{-1}. The first results from the period September

Table 9
Treatment efficiency of constructed wetland at Hopland, California, treating winery wastewaters during crush and non-crush periods. Data from Grismer et al. (2003).

	Non-crush period			Crush period		
	Inflow (mg L^{-1})	Outflow (mg L^{-1})	Removal (%)	Inflow (mg L^{-1})	Outflow (mg L^{-1})	Removal (%)
TSS	1042	110	85	1428	808	30
COD	1721	362	79	7406	3748	49
Tannin	55	12.1	78	55.2	30	46
Nitrate	1.8	0.5	73	13.1	10.9	17
Ammonium	118	45	62	37	26	29
TKN	159	54	66	43	32	25
Sulfate	35	2	95	83	62	25
Sulfide	0.56	0.12	78	0.88	0.7	20

2009–July 2010 were very optimistic with reduction of the inflow COD concentration of 3418 mg L^{-1} to only 58 mg L^{-1} at the outflow. Also reduction of sulfides from 2.75 mg L^{-1} to 0.25 mg L^{-1} and TP from 10.9 mg l^{-1} to 4.4 mg L^{-1} were promising.

Grismer et al. (2003) reported on the use of full-scale constructed wetlands (304 m^2 and 4400 m^2) designed to treat winery wastewaters in moderate-production wineries in California, USA. The filtration beds were composed of pea gravel and rock and planted with cattails and bulrush vegetation. The larger system (Hopland) achieved, despite severe short-circuiting and solids overloading, significant treatment – the wetland system removed up to 1200 kg COD ha^{-1} d^{-1} even with hydraulic loading time of just 1 h. However, the treatment effect was much higher during the non-crush period as compared to crush period (Table 9). The smaller system performed much better due to lower flow and lack of short-circuiting. The average inflow COD and TSS concentrations of 290 mg L^{-1} and 145 mg L^{-1} were reduced in the constructed wetland to the average concentrations of 7 mg L^{-1} and 2 mg L^{-1}, respectively.

Sheridan et al. (2006) described the HF constructed wetland for treatment of winery effluent in South Africa. The wetland has surface area of 160 m^2, was filled with dolomitic gravel and was planted with *P. australis*. The influent COD concentrations reached the level of 7000 mg L^{-1}. However, the authors focused only on the COD removal modeling and did not provide any results of the treatment efficiency.

Mulidzi (2007) reported on the use of HF constructed wetland for treatment of winery and distillery wastewaters at Goudini, South Africa. The 180 m^2 gravel-based system was planted with *P. australis*, *Typha* sp. and *Scirpus* sp. and operated at HLR of 2.5 cm d^{-1} and HRT 14 days. The average COD inflow concentration of 14,000 mg L^{-1} was reduced by 83% during the winter and 80% during the summer. At the same system, Mulidzi (2010) reported 60% removal of COD at HRT of seven days and HLR of 4.5 cm d^{-1}.

In 2007, a HF CW was built to treat winery wastewater in Piedmont, Italy (Rochard et al., 2010). The treatment system consisted of equalization tank, solid separator grid, Imhoff tank and a 24 m^2 HF CW filled with zeolite and planted with *P. australis*. At the HLR of 48 cm d^{-1} and an average organic loading of 56 g COD m^{-2} d^{-1} the removal of COD quickly stabilized below the level of 20 mg L^{-1} (Fig. 2).

Serrano et al. (2011) used a VF-HF hybrid constructed wetland for treatment of winery wastewater in Spain. The treatment system consisted of pretreatment in hydrolytic upflow sludge bed digester followed by 50 m^2 VF wetland planted with *P. australis* and filled with 3–6 mm granite gravel and three 100 m^2 HF wetlands planted with *Juncus effusus* and filled with 6–12 mm washed gravel. The average loading of the system was very high – up to 466 g COD m^{-2} d^{-1} and 296 g BOD m^{-2} d^{-1} for VF unit and 55 g COD m^{-2} d^{-1} and 32 g BOD_5 m^{-2} d^{-1} for HF units. The treatment efficiency of the hybrid constructed wetlands is summarized in Table 10.

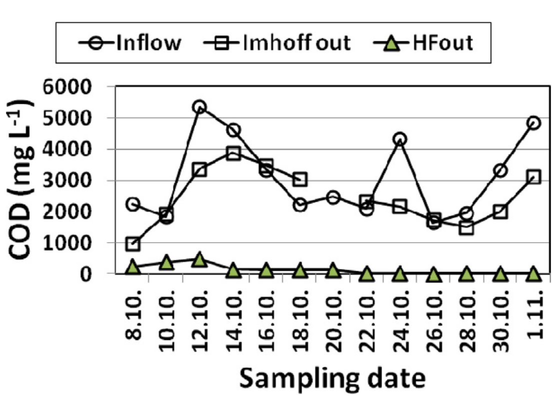

Fig. 2. Removal of COD from winery wastewaters. Data from Rochard et al. (2010).

Table 10
Treatment efficiency of a HF-VF hybrid constructed wetland for treatment of winery wastewater in Spain. Data from Serrano et al. (2011).

Parameter	TSS	COD	BOD_5	TKN	N-NH_3	PO_4^{3-}
Inflow (mg L^{-1})	129	1,558	942	52.9	28	2.3
VFout (mg L^{-1})	65	711	418	26.0	19.4	2.4
HFout (mg L^{-1})	17	448	279	25.2	12.5	1.9
Efficiency (%)	87	71	70	52	55	17

Grismer and Shepherd (2011) described the use of two HF CWs to treat winery wastewaters in California. The systems with surface area of 58 m^2 and 71 m^2 were planted with *T. domingensis, S. acutus* and *S. latifolia.* At the HRT of 6 and 18 days the systems achieved 97% and 99% removal of COD, respectively. In the first system the average inflow COD concentration of 72,965 mg L^{-1} was reduced to 2321 mg L^{-1} while in the second CW, the inflow COD concentration of 5080 mg L^{-1} was reduced to 31 mg L^{-1}. The removal of TSS amounted to 76% and 91%. In both constructed wetlands the systems with plants outperformed unplanted systems.

9.2. Distillery

Distillery wastewaters are characterized by high concentrations of BOD_5, COD, phenolic compounds and low pH (Table 1). Distillery spent wash (also called stillage) is the residual liquid waste generated during alcohol production and represents a serious threat to water bodies due to high organic load, dark brown color and unpleasant odor (Olguín et al., 2008; Archarya et al., 2010). The stillage yield with respect to the volume of ethanol produced from sugarcane is in the range of 10–15 L of stillage per liter of ethanol produced (Olguín et al., 1995; Saha et al., 2005). Anaerobic treatment is a widely accepted practice and various high rate anaerobic reactor designs have been used as well (Pant and Adholeya, 2007; Archarya et al., 2008; Mohana et al., 2009). However, aerobic biological systems (Pant and Adholeya, 2007) and physicochemical treatments such as adsorption, coagulation-flocculation and oxidation processes have also been used (Mohana et al., 2009).

A variety of wastewaters may be produced from distilleries using wine-related feedstocks. Red wine may be distilled to increase the concentration of ethanol and volatile organic compounds to produce brandy, resulting in a wastewater commonly known as rebate (Strong and Burgess, 2008).

Billore et al. (2001) reported on the use of HF constructed wetland to treat the secondary treated distillery effluent from a private distillery, Associated Alcohols and Breweries, Ltd., at Khodigram village in the outskirts of Baraha town in Central India. The treatment system consisted of pretreatment chamber and four cell-HF constructed wetland with total area of 364 m^2 planted with *T. latifolia* and *P. karka* in cells 3 and 4, respectively. The BOD_5 and COD concentrations in the distillery effluent even after the conventional secondary treatment amounted to 2540 mg L^{-1} and 13,866 mg L^{-1}, respectively, and therefore, additional treatment was necessary. The system achieved COD, BOD_5 TKN and TP reductions of 64%, 84%, 59% and 79%. The study indicated that constructed wetlands may be a suitable tertiary treatment option for distillery wastewaters.

Olguín et al. (2008) reported on the use of experimental HF CW for treatment of diluted (1:15 with tap water) sugarcane molasses stillage in Veracruz, México. The experimental units were filled with volcanic gravel and planted with *Pontederia sagittata*. Despite dilution, the inflow concentrations of organics were high and reached the average values of 1181 mg L^{-1} and 534 mg L^{-1} for COD and BOD_5, respectively. At the HRT of 2.5 and 5 days, the respective inflow COD loadings amounted to 473 and 946 kg COD ha^{-1} d^{-1}. There was not much difference in treatment efficiency between the studied HRTs, with the exception of BOD_5 and NH_4-N for which the removal efficiency at HRT of 5 days was superior to HRT of 2.5 days. The experimental units were able to remove COD in the range of 80.2–80.6%, BOD 82.2–87.1%, TKN 73.4–76.1%, NO_3-N 56–58.7%, NH_4-N 2–10% and SO_4^{2-} 68.6–69.5% depending on the HRT. The authors pointed out that phosphorus and potassium were not removed but this fact may not matter as the effluent can be used for sugarcane fields irrigation.

Murphy et al. (2009) reported on the use of 800 m^2 HF CW planted with *T. latifolia* to remove copper from a distillery effluent at a malt whisky distillery Dufftown in Banffshire, UK. The wastewater was pretreated in a series of tanks and a high rate trickling filter. The system was operated as FWS system in 2007 and during this period the removal of copper load amounted to 85% while during the operation in the HF mode, the removal amounted to only 53% in 2008.

9.3. Brewery

The brewery effluents contain high concentrations of organics arising from dissolved carbohydrates, the alcohol from beers wastes, and high concentrations of suspended solids such as spent maize, malt, and yeast (Bloor et al., 1995; Cronin and Lo, 1998; Xiangwen et al., 2008). Brewery effluents have usually very low pH, between 3 and 4 (Bloor et al., 1995; Xiangwen et al., 2008).

A pilot-scale HF CW was built at the South African breweries Millers plant, Ibhayi Brewery in Port Elisabeth, South Africa (Crous and Britz, 2010). The existing anaerobic digestor and integrated algal pond system were not able to meet the South African discharge limits and therefore constructed wetland was added to the system for final polishing of brewery wastewater. A 56 m^2 (14 m × 4 m), four channeled HF CW was planted with *Typha capensis* and *P. australis* in sequential blocks. The preliminary results indicated that the HF CW was efficient enough to reduce concentrations of monitored pollutant below the discharge limits for COD (75 mg L^{-1}), ammonia (3 mg L^{-1}), nitrate (15 mg L^{-1}), and phosphate (10 mg L^{-1}).

Kadlec and Wallace (2009) reported that The Coors Brewery in Golden, Colorado, USA, operate a FWS constructed wetland for unspecified purposes.

10. Food processing industry

10.1. Abattoir and meat processing industry

Slaughterhouses (abattoirs) produce large volumes of wastewater which usually contains high concentrations of biodegradable organics in soluble fraction as well as in insoluble fraction in the form of colloidal and suspended matter such as fats, proteins and cellulose (Gannoun et al., 2009). It contains high concentrations of oil and grease up to 1000 mg L^{-1} (de Sena et al., 2008; Gannoun et al., 2009). In addition, abattoir wastewaters carry high levels of pathogenic microorganisms that may constitute a risk for humans and animals (Gannoun et al., 2009).

Common treatment technologies include both aerobic and anaerobic systems (Johns, 1995; Tritt, 1992). Anaerobic treatment systems include covered anaerobic ponds (Safley and Westerman, 1992), high-rate systems such as anaerobic contact, upflow anaerobic sludge blanket and anaerobic filter processes (Toldra et al., 1987; Sayed and de Zeeuw, 1988; Johns, 1995; Caixeta et al., 2002) or anaerobic digestion (Gannoun et al., 2009). Aerobic processes include high rate algal ponds (Shelef and Azov, 1987), facultative ponds (Kawai et al., 1987; Orth et al., 1987), activated sludge (Hopwood, 1977; Heddle, 1979), trickling filters (Hopwood, 1977), rotating biological contactors (Bull et al., 1982), sequencing batch reactors with aerobic granular sludge (Cassidy and Belia, 2005).

In 1981, Finlayson and Chick (1983) tested a HF CW at Trewins Poultry, Griffith, NSW, Australia, to treat poultry abattoir effluent. Three trenches were 1.8 m wide, two of them were 20 m long and one was 15 m long. Beds were filled with 20 mm red gravel and planted with *T. domingensis* + *Typha orientalis*, *P. australis*, and *Scirpus validus* were used in individual wetlands. HRT varied between 2.7 and 3.6 days. The removal efficiency was high for TSS (83–89%) and moderate for turbidity (58–67%), total N (14–56%) and total P (37–61%). If a correction for water loss by evapotranspiration is taken into account, the three constructed wetlands reduced TN by 42–75% and TP by 68–79%. Of the three wetlands, that containing *Scirpus* was superior. In 1983, a larger HF CW was built in another poultry abattoir in Australia (Finlayson et al., 1990). Two trenches 50 m long and 2 m wide were built and one was planted with three species – the front third contained *Eleocharis sphacelata*, the center third *T. orientalis* and the last third contained *S. validus*. The second trench was left unplanted. During the period autumn 1983–summer 1995, removal of TKN and TP in constructed wetland varied from 51 to 72% and from 37 to 69%, respectively. On the other hand, the removals in unplanted trench were only 30–44% for TN and 22–33% for TP.

In New Zealand, pilot-scale HF and FWS constructed wetlands were built in 1987 and 1988, respectively, to treat partially pretreated meat processing effluents containing high concentrations of ammonium nitrogen (Van Oostrom and Cooper, 1990). Three HF CWs (18 m^2 each) were filled with gravel and planted with *Schoenoplectus validus* and *Glyceria maxima*, additional trench was left unplanted. Three FWS CWs (250 m^2 each) were planted in alternate strips of *G. maxima*, *Schoenoplectus lacustris*, *Iris pseudacorus* and *T. orientalis*. In the HF CW, the mean inflow concentrations of 125 mg L^{-1} for NH_3-N and 131 mg L^{-1} for TN, were reduced only by 20% and 18% in *Schoenoplectus* and *Glyceria* beds, respectively. The planted beds outperformed slightly unplanted trench where only 12.5% removal was achieved. At the same time, removal of COD and TSS amounted to 65% and 90%, respectively. There was no difference between *Glyceria* and *Schoenoplectus* beds for TSS and COD removal. However, the planted beds exhibited slightly higher removal than the unplanted trench for COD (61%) while unplanted trench removed the same amount of TSS as planted trenches. The greatest difference in removal occurred for TP where *Schoenoplectus*, *Glyceria* and unplanted beds removed 27%, 19% and 13%, respectively. In the FWS CWs, removal of TN varied between 18 and 20% depending on the pretreatment system at the HLR of 6 cm d^{-1} and HRT of seven days. Removal of COD, BOD and TSS varied between 30 and 78%, 72–84% and 80–95%, respectively. Subsequently, the authors evaluated nitrate removal from a nitrified meat processing effluent in a pilot FWS CW with floating mats of *G. maxima* in Horotiu, New Zealand (Van Oostrom and Cooper, 1994). At the HLR of 4.6 cm d^{-1} and the loading rate of 3.9 g NO_x-N m^{-2} d^{-1} the wetland achieved 37% removal of oxidized nitrogen. At the same time removal of COD, TN and TSS amounted to 42%, 30% and 94%, respectively. Further work with floating *Glyceria* improved removal of oxidized nitrogen to 46% at the HLR of 5.7 cm d^{-1} (Van Oostrom, 1995).

HF constructed wetland was built in 1994 in Pacucha, State of Hidalgo, Mexico, to treat anaerobically digested abattoir effluent (Rivera et al., 1996; Poggi-Varaldo et al., 2002). The constructed wetland (1144 m^2) was filled with gravel and planted with *P. australis* and *T. latifolia* in alternate strips. In Table 11, treatment performance of the HF part is presented. Reduction of fecal and total coliforms amounted to 5.5 and 5.0 log units, respectively.

Table 11
Removal efficiency of the abattoir wastewater treatment system in México. Data from Poggi-Varaldo et al. (2002). Concentrations in mg L^{-1}.

Parameter	Inflow	Inflow CW	Outflow CW	Removal[a]
COD	3633	1440	375	90 (74)
BOD_5	1593	585	137	91 (77)
TSS	1531	421	236	75 (44)
Org-N	26.6	10.1	5.3	80 (48)

[a] Removal efficiency (in %) of HF CW in parentheses.

Organic load was very high with the average values of 82 g COD m^{-2} d^{-1} and 33 g BOD_5 m^{-2} d^{-1}.

In 1999, a HF CW was put in operation in Shushufindi, Ecuador, to treat wastewater from a slaughterhouse (Lavigne and Jankiewicz, 2000). The system consists of a settling tank and two beds in series with a total surface area of 1200 m^2, planted with local plants *Echinochloa polystachia* (Caribgrass) and *Panicum maxium* (Saboya). The treatment performance of the system for the period June 1999–January 2000 was excellent (Table 12).

A FWS CW planted with *Typha* sp. was used to treat wastewaters from the abattoir at Pouliot near Québec, Canada (Goulet and Sérodes, 2000). The treatment system consisted of a 750 m^3 storage tank and two parallel cells with a total surface area of 1420 m^2. At a HLR of 1.4 cm d^{-1} the removal efficiencies for TSS, BOD_5, TKN, NH_4-N and TP amounted to 95%, 85%, 66%, 54% and 74%, respectively. The results of the treatment performance are shown in Fig. 3.

Gasiunas and Strusevičius (2003) and Gasiunas et al. (2005) presented the results from a 1880 m^2 HF constructed wetland designed to treat meat-processing wastewaters in Lithuania. The wetland is filled with sand and planted with *P. australis*. The pretreatment unit consists of a 500 m^3 septic tank. The average inflow concentrations of 826 mg L^{-1} BOD_5, 598 mg L^{-1} TSS, 41 mg L^{-1} TP and 107 mg L^{-1} TN were reduced to respective concentrations of 29.2 mg L^{-1}, 43 mg L^{-1}, 8.8 mg L^{-1} and 37.6 mg L^{-1}.

Soroko (2005) reported on the use of experimental VF-VF-HF system to treat slaughter wastewater in Poland. The individual beds surface areas were 10 m^2, 5 m^2 and 10 m^2, respectively. All beds were planted with *P. australis*. At the HLR of 0.6 cm d^{-1} for the whole system, the removal effect was very high (Table 4), namely for organics, suspended solids and ammonia. The denitrification of nitrate was very limited in the HF wetland most probably due to lack of organic matter which was removed in VF wetlands (Table 13).

In San Jacinto, Uruguay, a 1.5 ha HF constructed wetland was built to treat wastewaters from beef and lamb meat production in 2006. The system consisted of anaerobic and facultative anaerobic lagoons and four parallel HF beds planted with *T. domingensis*. The average flow of 3000 m^3 d^{-1} resulted in a HLR of 20 cm^{-1} (pers. observation).

10.2. Milk and cheese industry

The dairy industry generates strong wastewaters characterized by high concentrations of organics (BOD_5, COD), mainly carbohydrates, proteins and fats originating from the milk (Demirel et al., 2005). The dairy wastewaters are also characterized by wide range of pH values between 3.5 and 11 caused by the use of alkaline and acid cleaners and sanitizers (Demirel et al., 2005). The wastewater production is frequently seasonal and since the dairy industry produces various products (milk, butter, yoghurt, ice cream, and cheese) the composition of the effluent varies according to the type of product and technology used (Table 1).

Cheese whey is the liquid remaining following the precipitation and removal of milk casein during cheese-making. This by-product represents about 85–95% of the milk volume and retains substances like lactose, soluble proteins, lipids, mineral salts, lactic and citric acids, non-protein nitrogen compounds such as urea and uric acid. Because of its low concentration of milk constituents (about 6–7% dry matter), whey has commonly been considered a waste product (Gonzáles Siso, 1996). Wastewaters from the milk and cheese industry are commonly treated in upflow sludge blanket reactors (e.g., Yan et al., 1989; Ergüder et al., 2001).

One of the first installations for dairy wastewater was built in 1984 at Ingstrup, Denmark (Schierup et al., 1990). A 100 m^2 soil-based HF CW treated sewage and wastewater from a dairy farm. At the HLR of 2.6 cm d^{-1} the removal efficiency amounted to 91% for BOD_5, 91% for TSS, 74% for NH_4-N, >99% for NO_3-N, 80% for TN and 81% for TP. More detailed results are shown in Fig. 4.

Tanner (1992) used four HF and two up-flow constructed wetlands for treatment of dairy parlor wastewaters on the Ruakura Research Farm near Hamilton, New Zealand. The HF beds (9.5 m × 2 m each) and up-flow beds (1.5 m diameter) filled to 1 m depth with pre-washed alluvial rhyolitic gravel (10–30 mm diameter, 35–37% porosity) were fed at various hydraulic loading rates for 20 months. All wetlands were planted with *S. validus*. Reduction of BOD_5 (70–90%) and SS (40–90%) in relation to loading rate were similar in both flow formats. The HF wetlands showed 40–90% reduction of TN and 30–80% reduction of TP. The up-flow wetlands showed reduced levels of TN and TP removal, particularly when the loading rates were increased.

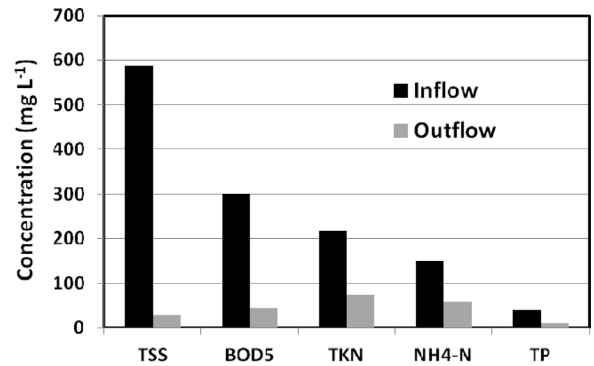

Fig. 3. Treatment performance of a FWS CW for treatment of abattoir wastewater at Pouliot, Québec, Canada. Data from Goulet and Sérodes (2000).

Table 12
Treatment effect of HF constructed wetland at Shushufindi, Ecuador, treating wastewaters from a slaughterhouse. Data calculated from Lavigne and Jankiewicz (2000).

Parameter	HF CW inflow (mg L^{-1})	HF CW outflow (mg L^{-1})	Removal (%)
BOD_5	237	4	98
COD	349	8	98
TSS	106	1.5	99
NH_4-N	22.5	4	82
PO_4-P	1.6	0.1	94

Table 13
Treatment efficiency of a VF-VF-HF constructed wetland treating slaughterhouse wastewater. Data from Soroko (2005).

	Inflow[a]	Outflow 1st VF	Outflow 2nd VF	Outflow HF[b]
BOD_5	2452	6	4	84
COD	3188	150	108	100
TSS	561	49	34	34
NH_4-N	391	16	5	4
NO_3-N	15	151	128	111
TN	494	184	145	129

[a] Settled wastewater.
[b] Final outflow.

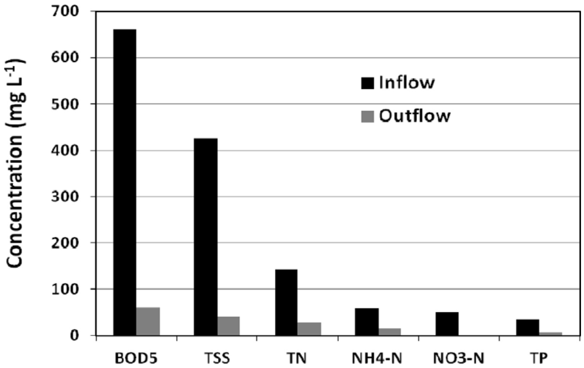

Fig. 4. Treatment performance of HF CW Ingstrup treating sewage and dairy wastewaters. Data from Schierup et al. (1990).

Wallace (2002b) reported on the use of 189 m^2 HF constructed wetland to treat cheese-processing wastewaters in Eichten cheese, a small dairy in Minnesota. The system was designed for an inflow BOD_5 concentration 174 mg L^{-1} but the initial sampling of the influent water indicated over 16 times greater concentration than the original design. The inflow BOD_5 and TN concentrations of 2076 mg L^{-1} and 91.2 mg L^{-1} were reduced only to 1369 mg L^{-1} and 51 mg L^{-1}, respectively. In order to enhance the treatment performance, artificial aeration was implemented. The aeration substantially improved removal efficiency, especially for BOD_5: the inflow concentration of 3140 mg L^{-1} was reduced to only 99 mg L^{-1}. The outflow TN concentration remained at the same level (49 mg L^{-1}) but during this period, the inflow TN concentration increased to 186 mg L^{-1}.

The experimental HF wetland for threatment of dairy farm wastewater was used in Potsdam, Germany (Kern and Brettar, 2002). The wetland with a surface area of 10 m^2 was filled with gravel (2–8 mm), compost and sand (0.5–2 mm) in the upper layer and planted with *Spartina pectinata*, *P. australis* and *Carex acutiformis*. The authors concluded that although environmental conditions for nitrifiers and denitrifiers were not suitable in winter, the results demonstrate a high efficiency of the wetland for treatment of dairy farm wastewater. Despite high inflow N concentrations (264 mg l^{-1}) a treatment efficiency of 85–90% could be maintained during the winter. The overall removal was 91.6% for NH_4 and 80.6 for N_{org}.

Mantovi et al. (2003) used the HF constructed wetland for treatment of dairy parlor wastewater in the province of Reggio Emilia in northern Italy. The treatment system consisted of the Imhoff tank and two HF beds (72 m^2 each) which operated in series. The first bed was filled with washed gravel 8–12 mm and the second bed was filled with washed fine gravel 3–6 mm. Both beds were planted with Common reed (*P. australis*). The wastewater was a mixture of domestic wastewater (1.9 m^3 d^{-1}) and wastewaters from milking parlor (1.6 m^3 d^{-1}) and washing operations (2.8 m^3 d^{-1}). The system performed at the hydraulic loading rate of 4.4 cm d^{-1} and met all the requirements of the legislation. The treatment efficiency is presented in Table 14.

Table 14
Treatment performance of HF CW at "Santa Lucia" farm in Casina, Italy Vymazal and Kröpfelová (2008). Data from Mantovi et al. (2003).

Parameter	Inflow (mg L^{-1})	Outflow (mg L^{-1})	Remova l(%)
TSS	690	60	90.8
COD	1,219	98	91.9
BOD_5	451	28	93.7
Total N	64.7	33.3	48.5
NH_4^+-N	22.4	24.5	
Organic N	42.3	8.8	79.1
Total P	12.8	5.0	60.6

Table 15
Treatment performance of the HF constructed wetland A. Visockas, Lithuania for dairy farm wastewater. All values in mg L^{-1}. Data from Strusevičius and Strusevičiene (2003).

Parameter	Inflow (mg L^{-1})	Outflow (mg L^{-1})	Removal (%)
BOD_5	920	28.7	97
COD	2,266	109	95
TSS	480	18.3	96
TP	30	12.6	58
TN	135	39.2	71
NH_4-N	96.5	28.7	70

HF constructed wetland was also used by Khalil et al. (2005) to treat cheese dairy farm effluent in southern France. The 200 m^2 bed was filled with the local brown loamy soil amended with calcareous gravel (4–8 mm), compost and iron oxides. The authors reported only on the early stages of operation so it is not possible to evaluate the treatment performance in a long-term run. The average treatment efficiencies over the first 8 months of operation amounted to 40%, 50%, 70% and 62% for TKN, BOD_5, TOC and TSS, respectively.

A hybrid constructed wetland was used to treat cheese production wastewaters including milk serum (whey) at the goat farm in France (Reeb and Werckmann, 2005). The systems consisted of VF stage (4 beds, 12 m^2 each, planted with *P. australis*), another VF stage (4 beds, 6 m^2 each, planted with *J. effusus*, *Carex acuta*, *I. pseudacorus* and *Scirpus lacustris*) and one HF bed (24 m^2, planted with *Mentha aquatica*, *A. calamus*, *Sparganium erectum*, *P. arundinacea*, *Polygonum hydropiper* and *Alisma plantago aquatica*). The authors presented only preliminary results but the reduction of COD was quite high.

Gasiunas et al. (2005) presented results from a HF constructed wetland treating domestic wastewater and wastewaters from a dairy farm in Lithuania (Table 15). The surface area is 100 m^2, the bed is filled with semi-coarse sand and planted with *P. australis*. Pretreatment consisted of a 3-chamber septic tank and the flow varied between 1.5 and 2.4 m^3 d^{-1}.

Gorra et al. (2007) reported on the use of HF constructed wetland for the treatment of wastewater from a medium size cheese-making plant in Aosta Valley, north-west Italy in mountain region at the altitude of 540 m. The wetland was formed by a long (ca. 100 m) narrow ditch 1 m deep and about 2 m wide and the slope followed a natural terrain configuration. The wetland was divided into five sections filled with gravel, ground ceramic wastes, magnetite, zeolite and local soil supplemented with compost and marble sand. The average influent BOD_5, N_{org} and NH_4-N concentrations of 839 mg L^{-1}, 176 mg L^{-1} and 22.7 mg L^{-1} were reduced to 130 mg L^{-1}, 133 mg L^{-1} and 16.6 mg L^{-1}, respectively, during the period summer 2003–spring 2005 (Gorra, pers. comm.).

Mantovi et al. (2007) described the use of HF constructed wetlands to treat wastewaters from the production of Italian cheese "Parmigiano-Reggiano" (400 m^2, 10.5 m^3 d^{-1}, HLR 2.6 cm d^{-1}) and "Grana Padano" (2700 m^2, 70 m^3 d^{-1}, 2.6 cm d^{-1}). The treatment efficiency in both systems was very high with the exception of ammonia (Table 16). In fact, the concentration of ammonia-N increase in the outflow due to limited nitrification in HF CWs. In addition, reduction of organic nitrogen (measured in terms of TKN) which proceeds both under aerobic and anaerobic conditions, yields ammonia-N to the system. Also, the reduction of vegetable fats and oils was very high – the inflow concentrations of 59 mg L^{-1} (Parmigiano) and 167 mg L^{-1} (Grana Padano) were reduced to 1 and 2 mg L^{-1}, respectively.

Table 16
Treatment performance of a HF constructed wetland treating cheese production wastewater in Italy. Data from Mantovi et al. (2007).

Parameter	Parmigiano-Reggiano			Grana Padano		
	Inflow ($mg L^{-1}$)	Outflow ($mg L^{-1}$)	Removal (%)	Inflow ($mg L^{-1}$)	Outflow ($mg L^{-1}$)	Removal (%)
TSS	253	14	94	321	19	94
COD	938	23	98	1062	49	95
BOD_5	595	5	99	700	19	97
TKN	33.7	12.5	63	34.2	13.6	60
NH_4-N	6	9	-50	6.4	11.3	-77
TP	7.7	2.1	73	13.3	11.1	16

Kato et al. (2010) reported on the use of three hybrid constructed wetlands for the treatment of dairy farm wastewaters in Japan. The systems configuration, surface areas and overall HLRs were as follows:

1. VF-VF-HF-VF; 256 m^2, 256 m^2, 512 m^2, 150 m^2, total area 1174 m^2; HLR 2 cm d^{-1},
2. VF-VF-HF; 160 m^2, 160 m^2, 336 m^2, total area 656 m^2; HLR 0.7 cm d^{-1},
3. VF-VF-HF-VF; 645 m^2, 484 m^2, 484 m^2, 176 m^2; total area 1789 m^2; HLR 0.9 cm d^{-1}.

The length of monitoring for individual systems was 4.6, 3.6 and 2 years, respectively. The inflow concentrations varied between 2385 and 5002 mg L^{-1} for COD, 101–198 mg L^{-1} for TN, 35 and 76 mg L^{-1} for NH_4-N and between 21.7 and 37.6 mg L^{-1} for TP. The treatment performance was very high for COD (93–96%). Removal of TN varied among systems but in general, was quite high as well (63–89%). Also removal of NH_4-N was very satisfactorily (62–82%). Removal of total phosphorus amounted to 70–88%. The treatment performance proved that this treatment technology was able to perform very efficiently even in cold climate where annual air temperature was between 5 and 8 °C.

Comino et al. (2011) reported on the use of VF-HF hybrid constructed wetland to treat mountain cheese factory wastewaters in northern Italy. The system consisted of two parallel VF beds (180 m^2 each) followed by HF CW (180 m^2). All wetlands were planted with *P. australis*. Despite overloading of the system the treatment efficiency amounted to 60% for TSS, 55% for BOD_5, 72% for COD, 37% for TP, 50% for TN and 80% for non ionic surfactants. The system was designed for an organic loading of 24 g BOD_5 m^{-2} d^{-1} but the actual average loading was more than twice higher.

10.3. Olive mills effluents

Olive mill wastewaters (OMWs) are generated in two-phase olive oil production processes along with olive pomace or in three-phase olive oil production alone (Coskun et al., 2010). OMWs are often acidic and usually contain very high concentrations of organics and suspended solids (Table 1) together with high concentrations of phenols, oils and grease and fatty acids (Coskun et al., 2010).

Table 17
Concentrations of diluted olive mill wastewater in the inflow and outflow from vertical flow constructed wetlands and comparison with unplanted unit.

	Inflow	Outflow		
		Unplanted	*Typha*	*Cyperus*
COD ($mg L^{-1}$)	2,882	821	762	749
PO_4-P ($mg L^{-1}$)	68.8	3.46	3.14	2.79
NH_4-N ($mg L^{-1}$)	0.81	0.50	0.42	0.51

Different disposal and treatment methods include incineration, stabilization ponds, thermal concentration, direct discharge to the soil (Ün et al., 2006) aerobic and anaerobic biological treatment (Ammary, 2005), nanofiltration and reverse osmosis (Coskun et al., 2010), electrooxidation (Un et al., 2008), electrocoagulation (Ün et al., 2006). However, most methods are very expensive and give rise to sludge or other by products which need to be disposed or must undergo another treatment (Piotrowska et al., 2006).

Yalcuk et al. (2010) described the use of vertical flow CWs mesocosms planted with *T. latifolia* and *Cyperus alternifolius* for treatment of olive mill wastewater in Turkey. The VF CWs were filled with layers of gravel at the bottom, zeolite and sand on the top. Because of very high concentrations in the raw wastewater, the feed water was diluted by tap water. The results are shown in Table 17.

Grafias et al. (2010) reported on the use of combination of VF CW and electrochemical oxidation in a pilot scale system in Greece. At the organic loading rate of 15 g COD m^{-2} d^{-1} the removal of 86% for COD and 77% for color was further enhanced by electrochemical oxidation to 95% and 94%, respectively. The reverse scheme yielded only 81% COD and 58% color removals.

Herouvim et al. (2011) examined a pilot-scale cascade of vertical flow CWs for treatment of olive mill effluent in Greece. The cascade consisted of four beds filled with various filtration porous materials such as cobbles medium and fine gravel and sand. The hydraulic retention time was very short (1 h), and therefore, the surface loads were extremely high (6589 g COD m^{-2} d^{-1}, 175 g TKN m^{-2} d^{-1}, 20 g ortho-P m^{-2} d^{-1}). Despite high loads, the average removal efficiencies of the system were 73% for COD, 75% for phenols, 75% for TKN, 72% for NH_4-N and 87% for ortho-P with respective inflow concentrations of 14,200 mg L^{-1}, 2841 mg L^{-1}, 506 mg L^{-1}, 123 mg L^{-1} and 95 mg L^{-1}.

Two FWS constructed wetlands were tested at Skalani near Iraklio, Crete, Greece (Kapellakis et al., 2012). Each bed occupied an area of 45.5 m^2 and was filled with gravel and planted with *P. australis*. The removal was very high (Table 18) and was improved by recirculation.

Table 18
Treatment performance of FWS constructed wetland treating diluted olive mill wastewater in Crete, Greece. CW1-without recirculation, CW2-with recirculation. Data from Kapellakis et al. (2012).

	Inflow	CW1		CW2	
	($mg L^{-1}$)	Outflow ($mg L^{-1}$)	Removal (%)	Outflow ($mg L^{-1}$)	Removal (%)
COD	6680	1330	80	686	90
TSS	2362	396	83	46.6	98
TP	43.65	8.8	80	6.6	85
TKN	137	30.2	78	17.7	87
NH_4-N	16.2	7.6	53	7.3	55
NO_3-N	3.6	2.2	40	1.7	52
Phenols	1,065	276	74	140	87

10.4. Fish and seafood processing

Fish and seafood industry generate large volumes of wastewater but the volumes reported in the literature fluctuates widely between 2.9 and 228 $m^3 t^{-1}$ fish processed (Sirianuntapiboon and Srikul, 2006; Chowdhury et al., 2010). The volume and concentration of pollutants in wastewaters from fish processing industry depends mainly on the raw fish composition, additive used, processing water source and the unit process. As a result, the concentrations of BOD_5, COD, TSS and TKN vary widely (Table 1). The main components of fish processing wastewater are lipids and proteins (Chowdhury et al., 2010). Also, the pH values vary from 3.8 to 10 depending on the technology and fish species processed. Fish processing wastewaters always contain high concentrations of fat, oil and grease (FOG). Concentrations of FOG are usually found in hundreds of mg L^{-1} but may amount up to 4000 mg L^{-1} (Balslev-Olesen et al., 1990; Chowdhury et al., 2010).

Fish and seafood processing wastewaters are usually treated by a many aerobic (e.g., activated sludge, rotating biological contactors, trickling filters, and aerobic ponds) and anaerobic (e.g., UASB, fluidized bed reactor, anaerobic fixed filter, and anaerobic fixed film) systems (Chowdhury et al., 2010).

White (1994) reported on the use of a HF constructed wetlands for seafood processor wastewater in Alabama, USA. Two wetlands were 1 m wide, 4 m long and filled with a 0.3 m layer of crushed limestone (2.5–5 cm diameter). One wetland was planted with *P. australis* and the other with *S. alterniflora*. At HLRs varying from 1.28 to 4.27 cm d^{-1}, the inflow concentrations of BOD_5 and ammonia of 125 mg L^{-1} and 95 mg L^{-1} were reduced to respective outflow concentrations of 7–11 mg L^{-1} and 5–54 mg L^{-1}. The HLR had much greater influence on removal of ammonia than BOD_5.

Sohsalam et al. (2008) carried out the experiments aimed at the treatment of seafood wastewater in mesocosm FWS CWs in Thailand. The authors compared six different plant species, *Cyperus involucratus*, *Canna siamensis*, *Heliconia* spp., *Hymenocallis littoralis*, *T. angustifolia* and *Thalia deabata*. The raw seafood wastewater was diluted (1:1) with treated wastewater from the existing three-stage facility at seafood factory consisting of a solids separation, stabilization pond and aerated lagoon. The average inflow concentrations varied between 332 and 389 mg L^{-1} for BOD_5, 54–124 mg L^{-1} for TSS, 31–58 mg L^{-1} for ammonia, 95–124 mg L^{-1} for TN and 58–63 mg L^{-1} for TP. All macrophytes units were able to meet limits imposed by Thai government, i.e., 20 mg L^{-1} BOD_5, 100 mg L^{-1} TN and 50 mg L^{-1} TSS at 5-day hydraulic retention time. Average removal efficiencies varied between 91 and 99% for BOD_5, 52–90% for TSS, 72–92% for TN and 72–77% for TP.

10.5. Sugar industry

The beet sugar factory wastewaters usually have high concentrations of organics (Table 1). Conventional treatment methods of sugar factory wastewater include preliminary filtration and sedimentation for suspended solids reduction, flow and load equalization and advanced biological treatment, typically anaerobic followed by aerobic steps and nutrient removal (Farhadian et al., 2007; Güven et al., 2009). Another option is lagooning which is economically less demanding but large space requirements, odor problems and inadequate sealing may pose an environmental risk. Also electrochemical treatment has drawn more attention recently (Güven et al., 2009).

Molasses is a by-product of sugar industry which is currently being used to produce ethanol in several countries, such as Thailand, Taiwan, India and Brazil. This process generates large amount of spent wash water which is usually treated by anaerobic digestion followed by aerobic treatment in activated sludge system or trickling filter. Besides organics, molasses wastewater usually contains high concentrations of nitrogen, phosphorus and potassium and it is dark brown in color (Sohsalam and Sirianuntapiboon, 2008).

During the period 1989–1993 a FWS CW was built at the American Crystal Sugar Company (ACSC), Hillsboro, North Dakota, USA, sugar beet refinery (Anderson, 1996). The existing treatment system consisting of primary clarification, anaerobic lagoon and activated sludge was not able to meet the discharge standards and CW was designed to upgrade the system. The FWS CW consisted of 7 cells with a total surface area of 23.5 ha, 15.2 ha treated water storage reservoir and a 7.5 ha meadow polishing section. The cells were planted with *T. latifolia*, *T. angustifolia*, *S. acutus*, *P. australis* and *Carex* sp. The designed flow was 5678 $m^3 d^{-1}$ but during the monitoring period July–September 1995, the flow varied between 3331 and 3889 $m^3 d^{-1}$. The average inflow BOD_5, TSS, TKN, NH_3 and TP concentrations of 99 mg L^{-1}, 80 mg L^{-1}, 36 mg L^{-1}, 22.3 mg L^{-1} and 1.57 mg L^{-1} were reduced to 4.4 mg L^{-1}, 12 mg L^{-1}, 5.1 mg L^{-1}, 0.31 mg L^{-1} and 0.88 mg L^{-1}, respectively.

In 1993 another 64.8 ha FWS CW was built for effluent polishing at ACSCs refinery located at Dayton, North Dakota near Canadian border (Anderson, 1996). The system consisted of four 16.2 ha parallel cells planted with *Typha*. At Dayton, CW provided similar removal efficiencies for BOD_5, TSS and NH_3 as CW at Hillsboro. However, it was necessary to keep the HLR below 1.5 cm d^{-1} in order to meet the discharge limits for NH_3 (10 mg L^{-1}).

During the mid-1990s, VF constructed wetland was used to treat sugar beet processing waters at Kidderminster, UK (Morris and Herbert, 1998; Morris, 1999). The system consisted of a three-cell first stage (total surface area of 143 m^2) followed by four-cell second stage (total area of 260 m^2). Warm wastewaters during the beet processing season showed good removals of 87%, 88% and 80% for COD, TSS and NH_4-N, respectively, at the HLR of 2.5–7.4 cm d^{-1}. During the non-processing period during the cold weather, respective removals amounted to 74%, 88% and 93% at the HLR of 17.4–18.6 cm d^{-1}.

In western Kenya, Bojcevska et al. (2006) evaluated the use of FWS constructed wetland for treatment of sugar factory effluent. The original treatment system consisted of 12 serial ponds, each 100 m × 35 m. In 2002, FWS CW consisting of eight cells (3 m × 20 m each) planted with *C. papyrus* (4 cells) and *Echinochloa pyramidalis* (4 cells) operated under two HLRs, 22.5 cm d^{-1} and 7.5 cm d^{-1}. The removal efficiency was similar for both plants with the exception of ammonia, which was removed substantially more in the *Cyperus* cell (44%) as compared to *Echinochloa* cell (22%) at the HLR of 7.5 cm d^{-1}. The removal efficiencies for TP, NH_4^+-N and TSS varied between 21 and 29%, 22 and 44%, and 64 and 76%, respectively. Area specific removals of TP, TSS and NH_4^+-N were higher in the high-load CWs than in the low-load ones, but the relative removal was slightly lower.

10.6. Potato processing

Constructed wetlands were used to upgrade existing conventional treatment technologies in potato starch industry in the Netherlands (De Zeeuw et al., 1990). In 1986, two HF CWs (surface areas 230 m^2 and 115 m^2) were built and planted with *P. australis*. The experiments were carried out in three stages with different wastewater characteristics. During the first period, anaerobically pretreated potato starch wastewater was used at HLR of 2.7 cm d^{-1}. The system achieved 48% removal of COD and 16% TKN at the loadings of 54 g COD $m^{-2} d^{-1}$ and 11.9 g TKN $m^{-2} d^{-1}$. During the second period, chemical wastewater from starch derivatization was fed in the system at the HLR of 1.4 cm d^{-1}. The system removed only 11% of COD at the inflow loading rate of 44 g COD $m^{-2} d^{-1}$. Low removal efficiency could have been the result of presence of toxic compounds which developed during the chemical processes.

During the last period, diluted starch manufacturing wastewater was used at the HLR of 1 cm d^{-1}. Removal efficiencies amounted to 92% for COD and 91% for TKN. However, the inflow loadings were only 12 g COD m^{-2} d^{-1} and 1.1 g TKN m^{-2} d^{-1}. In 1987, a small VF CW (surface area 6 m^2) was used to treat anaerobically pretreated starch manufacturing wastewater with COD and TKN concentrations of 2000 mg L^{-1} and 500 mg L^{-1}, respectively (De Zeeuw et al., 1990). The system was able to remove as much as 40 g COD m^{-2} d^{-1} and 10 g TKN m^{-2} d^{-1} with no hydraulic problems. Based on these promising results a 1500 m^2 VF CW was built (De Zeeuw et al., 1990).

Based on the results obtained for a pilot-scale constructed wetland for treatment of potato processing wastewater (Kadlec et al., 1997) a full scale constructed wetland was built in Connell, Washington, USA, in 1995 (Burgoon et al., 1999). The system consisted of primary clarifier, 10 ha FWS CW, 4 ha VF CW and 2 ha FWS CW. The first wetland is designed for sedimentation and mineralization, the second stage is primarily designed for oxidation of organics and nitrogen and the last wetland is designed for denitrification. The FWS CWs were planted with *Typha* sp. and two species of *Scirpus*. The VF CW was left unplanted and was operated rather as intermittent sand filter. The average flow during the period April 1997–April 1998 was 4840 m^3 d^{-1}. The average water temperature at the outflow from the last constructed wetland varied between 13 °C and 16 °C during the period April–October and between 4 °C and 6 °C during the period November–March. The results shown in Table 19 indicated very good treatment efficiency. There was no difference in treatment efficiency between summer and winter periods with the exception of winter when removal of nitrogen exceeded that from the summer. The primary goal to reduce TN by 53% was achieved in order to reach nitrogen load allowable for irrigation of crops.

Kato et al. (2010) reported on the use of hybrid constructed wetland for treatment of potato starch processing wastewaters in Japan. The system consisted of five beds in series in the sequence of VF (990 m^2) – VF (510 m^2) – VF (294 m^2) – HF (210 m^2) – VF (147 m^2), giving a total surface area of 2151 m^2. Pumice gravel was used for 1st, 2nd and 4th stages, while pumice sand was used for the 3rd and 5th stages. The treatment performance of the system over two years of operation was very good (Table 20) despite high organic and nitrogen loadings – 176 g COD m^{-2} d^{-1} and 13.4 g TN m^{-2} d^{-1}, respectively.

In Thailand, Sohsalam and Sirianuntapiboon (2008) reported on the use a small experimental FWS CWs for treatment of molasses wastewater. The wetlands were planted with *C. involucratus*, *T. angustifolia* and *Thalia dealbata* and were operated under various organic loading rates (612–1213 kg BOD_5 ha^{-1} d^{-1}). The removal of pollutants was the highest at the lowest loading rate and BOD_5, COD, TSS, TN and TP removal amounted to 89%, 68%, 93%, 80% and 76%, respectively. There was only small variation of treatment efficiency among wetlands with various plants.

Table 19
Average pollutant concentrations and treatment efficiency of a constructed wetland treating high strength potato processing wastewater in Connell, Washington, USA during the period April 1997–March 1998. Data from Burgoon et al. (1999).

	Inflow (mg L^{-1})	FWS1 $_{out}$ (mg L^{-1})	VF_{out} (mg L^{-1})	$FWS2_{out}$ (mg L^{-1})	Storage (mg L^{-1})	Efficiency (%)
COD	2528	304	172	224	167	93
TSS	327	49	32	43	56	83
TN	165	136	113	80	75	54
Org. N	60.5	16.5	28.5	20	12.5	80
NH_4-N	103	118	45	50	54	47
NO_3-N	1.5	1.0	40	11	8.0	
pH	6.15	7.55	6–95	7.30	7.75	

Table 20
Treatment performance of a hybrid constructed wetland treating wastewaters from starch production in Japan. Chemical parameters in mg L^{-1}, efficiency in %. Data from Kato et al. (2010).

	Inflow	$VF1_{out}$	$VF2_{out}$	$VF3_{out}$	HF_{out}	$VF4_{out}$	Efficiency
COD	54,065	29,095	11,138	5184	4364	3214	94
TN	4118	2187	1054	615	555	424	90
NH_4-N	1311	1225	839	505	502	369	72
TP	338	118	58	37	30	25	93

10.7. Mixed food

Vrhovšek et al. (1996) reported on the use of HF constructed wetland for treatment of food processing plant (without specific details) in Slovenia. The system consisted of two beds (78 m^2 each) in series filled with find sand, coarse and calcareous soil in the ratio of 3:6:1 and 3:5:2 in the first and second beds, respectively. The first bed was planted with *Carex gracilis* (Slim sedge) and the second one with *P. australis*. The average inflow COD and BOD_5 concentrations of 3674 mg L^{-1} and 962 mg L^{-1}, respectively, were reduced by 92% and 89%, respectively, at the average HLR of 3.2 cm d^{-1}. Also, removal of orthophosphate, ammonium-N and nitrate-N were high and amounted on average to 96%, 86% and 65%, respectively.

A 70 m^2 HF constructed wetland was used to treat domestic (75%) and wastewaters produced by seasonal food processing (cheese, tomato sauce, apple and grape juice, olive oil etc., 25%) near Florence in Tuscany, Italy (Pucci et al., 2000). The wetland was filled with gravel (d_{10} = 8 mm) and planted with *P. australis*. The treatment performance results are shown in Table 21.

11. Laundry

Sostar-Turk et al. (2005) pointed out that laundry process, including water-washing processes and dual-phase washing, use significant amounts of water. On the average, a laundry uses 15 L of water to process 1 kg of work (Ciabatti et al., 2009). The quality of wastewater depends on the origin with the highest values occurring from dirty items containing oils, heavy metals or other dangerous substances. Higher concentrations of pollutants are found in hospital laundry wastewater which contains flood remains, blood and urine. Laundry wastewaters from household items is the less polluted. The laundry wastewaters always contain high concentrations of both anionic (MBAS) and non-ionic (BIAS) surfactants. Pitter (2009) reported these concentrations up to 90 mg L^{-1}. Linear alkylbenzene sulfonates (LAS) are the most widely used synthetic anionic surfactants. They account for 28% of the total production of synthetic surfactants in Western Europe, Japan and the United States (Huang et al., 2004) and due to its

Table 21
Treatment performance of HF constructed wetland Poggio Antico, Tuscany, Italy. Microbial parameters in CFU 100 mL^{-1}. Data from Pucci et al. (2000).

Parameter	Concentration (mg L^{-1})		Efficiency (%)
	Inflow	Outflow	
COD	1105	110	90.0
TSS	145	27.6	81.0
TP	17.1	14.1	17.5
NH_4-N	25.6	11.5	55.1
MBAS (Tensides)	6.1	0.96	84.3
Fecal coliforms	340,000	800	99.8
Total coliforms	1,000,000	9250	99.1
Fecal streptococci	1,900,000	4000	99.8
Escherichia coli	200,000	550	99.7

high-volume use in laundry and cleaning products, LAS is a ubiquitous water contaminant.

Del Bubba et al. (2000) reported on the use of a pilot-scale HF constructed wetland planted with *P. australis* in Florence, Italy, to study LAS removal. At HLR of 3.7 cm d^{-1} the removal of LAS amounted to 94.2% and 99.7% for filtered and unfiltered samples with the respective outflow concentrations of 0.9 and 0.06 mg L^{-1}. When the inflow concentrations were increased, the removal effect remained unchanged. The inflow/outflow concentrations were 65/1.8 mg L^{-1} and 278/0.18 mg L^{-1} for filtered and unfiltered samples, respectively. High LAS removal was observed even at temperatures as low as 5–9 °C.

Billore et al. (2002) found in a 300 m^2 pilot scale HF constructed wetland receiving the sewage from the Ravindranagar residential colony in Ujjain, India that the longer chain alkyl LAS homologues were degraded to a greater extent than that of the shorter alkyl chains. The removal of C_{10}, C_{11}, C_{12} and C_{13} LAS homologues were removed to 43.4%, 61.3%, 75.7% and 87.7%, respectively. Also Thomas et al. (2003) found in three HF constructed wetlands in the U.K. that the longer alkyl chain homologues were removed to a greater extent than the shorter alkyl chain homologues in the order $C_{13} > C_{12} > C_{11} > C_{10}$. This decrease has been found by other authors and has been attributed to the differences in the degree to which the homologues are adsorbed onto suspended particles and different biodegradation rates (Swisher, 1987; Painter and Zabel, 1989). The increased biodegradation rate and adsorption are related to the increased hydrophobicity due to longer alkyl chains (Swisher, 1987). Faster rate of degradation of the longer chain homologues has been confirmed for all LAS chain lengths from C_6 to C_{16} (Swisher, 1987; Terzic et al., 1992; Prats et al., 1993).

Huang et al. (2004) studied the removal of LAS in a pilot-scale HC CW in Barcelona, Spain. The authors concluded that the highest rates of LAS oxidation were observed in shallow beds where a more oxidized environment occurred. They also observed that biodegradation of LAS and sulfophenyl carboxylate biointermediates occurred under sulfate-reducing and mixed conditions, i.e., sulfate reducing and denitrification. C_{13} LAS homologues were generally removed to a higher extent than the shorter alkyl chain counterparts. These results supported those reported by Billore et al. (2002). The removal has also been found to be temperature and HLR dependent. The dependence of LAS removal on HLR and seasons was also reported by Thomas et al. (2003) and Kantawanichkul and Wara-Aswapati (2005).

Davison et al. (2005) reported the use of HF constructed wetland planted with a mixture of *T. orientalis* and *Bolboschoenus fluviatilis* (Marsh clubrush) for the treatment of commercial laundry wastewater at The Channon, Australia. At the HRT of 6.1 days the removal of BOD_5, TSS, TN and TP amounted to 61%, 83%, 62% and 32%, respectively.

12. Chemical industry

One of the largest HF constructed wetlands in Europe was built in 1990 at the air products chemical works at Billingham, Teeside, United Kingdom (Sands et al., 2000). The plant is producing alcohols for the plastics and detergent industries, phenol/acetone and derivatives for plastics, detergents, pharmaceuticals and flame-retardant purposes and amines and derivatives for drugs, detergents, paper treatment, agrochemicals and animal feedstock additives. Seven beds planted with *P. australis* with a total area of 49,000 m^2 is filled with soil.

Haberl et al. (2003) reported on the use of vertical flow CW to treat wastewaters from an industrial complex in Estarreja, Portugal producing organic chemicals such as nitrobenzene (NB), aniline (ANL), suphanilic acid (SA), and nitric acid (NA). Influent is dominated by ANL and SA but dinitrophenol (DNP), trinitrophenol (TNP) could also be found. The system consists of four vertical flow beds (each 72 m long and 35 m wide with a depth of 0.8 m) filled with 20 cm of gravel, 20 cm of coarse sand and 40 cm sandy-clay. The average flow was 10 m^3 h^{-1} resulted in a HLR of 2.4 cm d^{-1}. The system performed with high efficiency and the inflow concentrations of ANL, NB, DNP, TNP and SA of 250, 60, 2, 30 and 180 mg L^{-1} were reduced to 2, 1, <0.01, <0.05 and 2 mg L^{-1}, respectively. Dias et al. (2006) mentioned that in 1998, HF CW (1500 m^2) was added to existing vertical flow constructed wetland to treat wastewaters rich in nitrates from the production of nitric acid.

13. Mixed industrial

Wang et al. (1994) described the use of a hybrid constructed wetland for treatment of mixed industrial wastewaters at Yantian Industry Area in Baoan District, Shengzhen City, China. The system consisted of three parallel Water hyacinth (*Eichhornia crassipes*) wetlands (total surface area 825 m^2) followed by two HF CWs (total area 1610 m^2) planted with *P. australis*. At a HLR of 36.5 cm d^{-1} the average inflow COD, BOD_5, TSS, TN and TP concentrations of 456 mg L^{-1}, 189 mg L^{-1}, 232 mg L^{-1}, 22.3 mg L^{-1} and 4.7 mg L^{-1} were reduced to 88 mg L^{-1}, 59 mg L^{-1}, 3.2 mg L^{-1}, 15.5 mg L^{-1} and 1.8 mg L^{-1}, respectively.

Chen et al. (2006) reported on the use of experimental FWS constructed wetlands for treatment of wastewaters from the industrial park in Taiwan. The results indicated higher treatment performance for units planted with macrophytes as compared to units without vegetation. Also, treatment unit with *P. australis* was superior to those planted with *T. orientalis*, *Pistia stratiotes* and *I. aquatica*. At the optimum HRT of 5 days, the removal efficiencies amounted to 61% for COD, 89% for BOD_5, 81% for SS, 35% for TP and 53% for NH_4-N with respective outflow concentrations of 67 mg L^{-1}, 9 mg L^{-1}, 17 mg L^{-1}, 45 mg L^{-1} and 14 mg L^{-1}.

Khan et al. (2009) reported the use of FWS constructed wetland to treat industrial wastewater from Gadoon Amazai Industrial Estate, Swabi, Pakistan, one of the largest industrial estates in the country. It has textile, chemicals, ghee and cooking oil, marble, steel, plastic, soap and detergent industries. FWS constructed wetland with a total area of 4146 m^2 was divided into seven cells and planted with variety of emergent (*T. latifolia*, *Scirpus cyperinus*, *Carex aquatilis*, *P. australis*, *Juncus articulatus*, *Alisma plantago-aquatica*, *Polygonum glabrum*), submerged (*Ceratophyllum demersum*) and free floating (*Lemna gibba*, *E. crassipes*, *P. stratiotes*) species. The results indicated very good performance (Fig. 5) and removal efficiencies amounted to 41% for Ni, 48% for Cu, 50% for Pb, 74% for Fe, 89% for Cr and 92% for Cd.

Zupančič Justin et al. (2009) used a VF-2 × HF-VF hybrid constructed wetlands to treat wastewaters from the food-processing department responsible for the production of wine

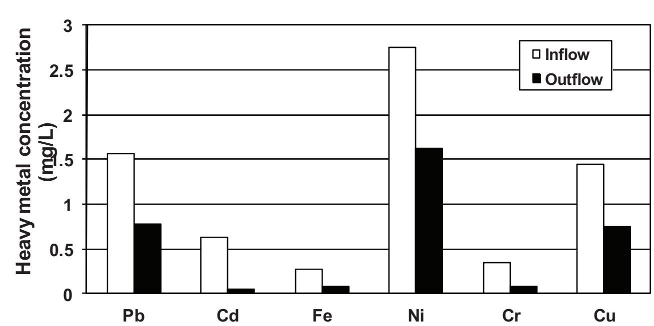

Fig. 5. Removal of heavy metals from industrial wastewater from Gadoon Amazai Industrial Estate, Swabi, Pakistan. Data from Khan et al. (2009).

Table 22
Mean treatment efficiency of a hybrid treatment systems treating mixed industrial wastewaters during the two year period. Based on Zupančič Justin et al. (2009).

	Inflow ($mg L^{-1}$)	Outflow ($mg L^{-1}$)	Efficiency (%)
COD	854	284	67
BOD_5	346	118	66
NH_4-N	5.9	4.5	24
Norg.-N	5.3	0.9	83
Phosphate	2.3	0.9	62
Anionic tenzides	25.4	8.3	67
TSS	0.5	0.7	

and apple vinegar and from the chemical department in which the packing of detergents and soaps are carried out. The system consisted of four beds with a total area of 730 m^2, filled with a mixture of washed river sand with size fractions of 4/8 mm and 8/16 mm and fine sand 0/4 mm. The beds were lined with HDPE, the VF beds were planted with *C. acutiformis*, two middle HF beds were planted with *P. australis*. The outflow from a hybrid CW was discharged into polishing lagoon (437 m^3) planted with *Carex* spp., *T. latifolia* and *Sparganium oocarpum*. The treatment efficiency of the system is presented in Table 22.

14. Miscellaneous

14.1. Explosives

Small scale FWS constructed wetlands planted with *T. angustifolia* (narrow leaved cattail) were used to remediate explosives-contaminated surface and groundwater at the Army Ammunition Plant in Tennessee where explosives were produced between 1942 and 1978 (Best et al., 2000). The wetlands were quite effective and removal of TNT (2,4,6-trinitrotoluene), 2,4DNT (2,4-dinitrotoluene) and 2,6DNT (2,6-dinitrotoluene) amounted to 79%, 58% and 61%, respectively. The removal efficiency was substantially higher as compared to unplanted modules in which respective removal efficiencies were only 57%, 3% and 53%.

In another Army Ammunition Plant in Tennessee, HF and FWS CWs were used to remove various explosives from contaminated water (Behrends et al., 2000b). The FWS CW consisted of two trenches (24 m × 9.4 m). The HF CW consisted of two beds connected in series. The first cell (32 m × 11 m) was kept in anaerobic conditions by addition of milk replacement starter while the second cell (11 m × 11 m) was kept aerobic by aeration. The results indicated that HF CWs was superior to FWS CW in terms of treatment efficiency. The FWS cells suffered from problems with plant establishment due to photodegradation of explosives which inhibited photosynthesis by coloring the water a dark red.

14.2. Steel production wastewater

Yang and Hu (2005) used a HF mesocosm for treatment of steel mill wastewaters in Taiwan. The wetland was filled with gravel, planted with *P. australis* and *T. orientalis* and operated at a HLR of 2.6 cm d^{-1} and HRT of 7 days. The removal efficiency for COD and TP amounted to 50% and 6%, respectively, and most heavy metals were not below the detection limit in the discharged water.

Xu et al. (2009) reported the use of lab scale VF constructed wetlands (one CW filled with manganese ore, one filled with gravel) for removal of manganese and iron in the reclamation of steel wastewater. The treatment efficiency of the manganese ore wetland outperformed the wetland filled with gravel for all monitored parameters (Fe, Mn, COD, turbidity, NH_4-N and TP). The removal of both Fe and Mn was very effective with effluent concentrations of both elements below 0.05 mg L^{-1}. The authors also examined a pilot scale HF CW filled with gravel with 0.5 m long manganese ore zone which formed only 4% of the total substrate volume. The system achieved removal of 91% of Fe and 81% of Mn. Huang et al. (2011) tested a 91 m^2 HF CW to treat wastewaters from a steel enterprise of Baosteel Co. Ltd., in China. The filtration material was a mixture of gravel and manganese ore (9:1) and the vegetation was composed of common reed (*P. australis*), cattail (*Typha* sp.) and windmill grass (*Chloris verticillata*). The inflow concentrations of 26 mg L^{-1} COD, 1.73 mg L^{-1} N-NH_4, 1.6 mg L^{-1} total iron and 0.53 mg L^{-1} manganese were reduced to 5.9 mg L^{-1}, 0.4 mg L^{-1}, 0.05 mg L^{-1} and 0.04 mg L^{-1}, respectively. The effluent from the constructed wetland was further treated by ultrafiltration and reverse osmosis.

14.3. Wood industry

Woodwaste is defined in British Columbia's Waste Management Act includes hog fuel, mill ends, wood chips, bark and sawdust. In 1998, six FWS constructed wetlands (surface area of 96 m^2 of each wetland) were built in British Columbia, Canada to treat woodwaste leachte (Frankowski and Hall, 2000; Masbough et al., 2005). The wetlands were planted with cattail (*T. latifolia*). The inflow BOD, COD, volatile fatty acids (VFA) and, tannins and lignins concentrations of 2584 mg L^{-1}, 3600 mg L^{-1}, 603 mg L^{-1} and 1069 mg L^{-1} were reduced by 60, 50, 69 and 42%, respectively. Tao and Hall (2004) and Tao et al. (2006) reported on the use of FWS constructed wetlands planted with *T. latifolia* (broadleaved cattail) to treat woodwaste leachate generated by precipitation on an uncovered woodwaste pile, including trimmings, off-specification wood chips, sawdust, and shredded bark and roots from several cedar processing mills in British Columbia, Canada. The leachate had low pH of 4.3, high concentrations of COD (6068 mg L^{-1} on average), and tannins and lignins (1839 mg L^{-1} on average). Mass reduction efficiencies of COD and tannins/lignins increased significantly with HRT when diluted leachate was used. When less diluted leachate was used, only a slight increase of the efficiency was observed with increasing HRT. Also, reduction rates increased linearly with mass loading up to 0.4 kg m^{-3} d^{-1} COD and 0.13 kg m^{-3} d^{-1} tannins/lignins (Tao et al., 2006).

14.4. Coke plant effluents

Coke is a high quality fuel for iron and steel industry. It is carbonized from coal at temperatures between 900 and 1100 °C in the absence of air. Volatile compounds such as benzene, toluene, anthracene and naphtalene are released during coke carbonization and are concentrated in the so-called coke plant wastewater (Zhao et al., 2009). Coke plant effluents also contain high concentrations of ammonia, cyanide, thiocyanate, phenols and various heterocyclic compounds (Li et al., 2003; Marañón et al., 2008). The concentrations of pollutants in a coke plant effluents varies (Table 1) as a function of the types of coal used and the different modification of the process employed to manufacture the coke (Marañón et al., 2008).

Jardinier et al. (2001) reported on the use of the pilot scale two-stage HF constructed wetland to treat coke plant effluents in France. The total area of the system was 24 m^2, the beds were filled with gravel (6–12 mm, porosity 35%, 70% SiO_2 and 30% CaO) and planted with *P. australis*. The coke plant effluent, i.e., constructed wetlands influent, was rich in nitrogen (70–100 mg L^{-1}) and the removal amounted to 37%. The authors concluded that HF constructed wetland may be a valid method to substantially decrease nitrogen concentrations and also to retain some metals and PAHs.

14.5. Coal gasification

Effluents produced by many electric generating facilities are usually contaminated with a number of metals and metalloids (Ye et al., 2001). Ye et al. (2003) tested FWS constructed wetland units filled with a mixture of sand and organic-based potted medium to treat the effluent from the sour water stripper of a coal gasification plant in Indiana, USA. In addition to metals and metalloids, this water contained high concentrations of the toxic anion selenocyanate ($SeCN^-$) instead of selenate or selenite, less toxic compounds usually present in other electric utility effluents (Ye et al., 2001). The results revealed that the wetland units substantially reduced the concentrations of selenium, arsenic, boron and cyanide by 64%, 47%, 31% and 3%, respectively. In terms of mass removal, the respective values were 79%, 67%, 57% and 54%. It has also been found that the most of the retained pollutants were retained in the sediment. Of the 14 native species used in the experiment, *T. latifolia*, *T. dealbata* (Thalia) and *Polypogon monspeliensis* (Rabbitfoot grass) exhibited no growth retardation and were highly tolerant of the contaminants.

14.6. Lignite pyrolysis

Wiessner et al. (1999) used HF constructed wetland to treat wastewaters from lignite pyrolysis in Germany. In the past, large amounts of lignite pyrolysis wastewater were deposited either partially or completely untreated in various ecosystems such as groundwater aquifers, surface waters or open-cast coal mines in eastern Germany. Conventional methods of treatment such as extraction, ammonia striping, adsorption or wet oxidation cannot be used for technical or economical reasons (Kuschk et al., 1994). The HF constructed wetlands with an area of 125 m^2 (25 m × 5 m) was filled with clayey sand and planted with *P. australis*, *T. latifolia* and *Schoenoplectus tabernaemontani* from inflow to outflow. The wetland was fed with a wastewater from a 9-ha wastewater pond with a total volume of about 25 million m^3 which was created by filling of a former open-cast coal mine for several decades. The inflow N-NH_4 and COD concentrations were 56 mg L^{-1} and 658 mg L^{-1}, respectively. The results indicated that removal of ammonia was very high (0.63 g N-NH_4 m^{-2} d^{-1}) but the system proved not to be efficient in removal of organics. However, the calculations showed that the use of a constructed wetland system as a part of remediation project could be useful, especially for removal of ammonia.

14.7. Tool industry

Di Luca et al. (2009) and Maine et al. (2009) reported on the use of FWS CW in Argentina to treat wastewater from metallurgical industry. A FWS constructed wetland planted with *T. domingensis* was 50 long, 40 m wide and 0.3–0.6 m deep and was designed to treat both sewage and wastewater from a tool factory. The primary target of treatment was the removal of heavy metals, namely Cr, Ni, Zn and Fe. The removal efficiencies varied among seasons from 82 to 99%, 54 to 64%, 56 to 67% and 96 to 99%, respectively. The construction of the wetland was preceded by experiments with a pilot-scale wetland (Hadad et al., 2006) and experiments aimed at the efficiency of various plant species (Maine et al., 2007).

14.8. Flower farm

Kingfisher constructed wetland near Lake Naivaska in Kenya was built in 2005 to treat a mixture of wastewaters from a flower farm (Kimani et al., 2012). The wastewaters include those from a pack house where the plants are graded and packed for export, from the bio-control agents houses, laundry, staff canteen and washing waters. The CW consists of a HF bed and subsequent three FWS cells (no area size provided by the authors). The HF cell is planted with *Canna* sp., *Hydrocotyle* sp. and *Cyperus* sp. while FWS cells are dominated by *Pistia* sp. and emergent species along the perimeter. The inflow concentrations of 233 mg L^{-1} TSS, 138 mg L^{-1} BOD_5, 569 mg L^{-1} COD, 5.1 mg L^{-1} TN and 5.1 mg L^{-1} TP were reduced to 23 mg L^{-1}, 72 mg L^{-1}, 186 mg L^{-1}, 2.0 mg L^{-1} and 2.6 mg L^{-1}, respectively. According to the authors, the CW was highly efficient in reducing pollutants concentrations and the CWs have the potential for amelioration of point sources of pollution around the Lake Naivasha.

15. Summary

In Table 23, examples of the use of constructed wetlands for various industrial effluents are summarized. The survey has revealed that all types of constructed wetlands have been used with most systems being either free water surface constructed wetlands with emergent vegetation or horizontal subsurface flow constructed wetlands. The use of vertical flow constructed wetlands for treatment of industrial wastewaters has been less frequent so far. However, vertical flow constructed wetlands have been successfully used for treatment of olive mills wastewaters

Table 23
Examples of the use of constructed wetlands for treatment of industrial wastewaters with treatment efficiency of major target parameters and hydraulic loading rate (HLR), wherever available. The references order is made according to the date of publication.

Type of wastewater	Type of CW	Location	References	HLR (cm d^{-1})	Treatment efficiency (%)
Refinery	HF	South Africa	Wood and Hensman (1989)		
	FWS	USA	Litchfield (1993)	1.2	BOD 98, COD 93, NH_4-N 84, Phenol 99, OG 99
	FWS	China	Xianfa and Chuncai (1994)	47	BOD 50, TSS 44, TN 19, TP 68
	FWS	Hungary	Lakatos (1998)	1.4–1.7	
	FWS	USA	Hawkins et al. (1997)	12.8–128	BOD 79, TSS 95, OG 74, TPH 92, Al 86
	FWS	USA	Gillepsie et al. (2000)	0.1	Zn 65
	FWS	USA	Huddleston et al. (2000)	6.4	BOD 86, NH_4-N 94
	HF	Canada	Moore et al. (2000)	2	C_5–C_{12} 100 (aerated), 30–100 (non-aerated)
	HF	USA	Wallace (2002a)	2.8	BOD 99, NH_4-N 98
	HF	UK	Chapple et al. (2002)		DRO (C_{10}–C_{40}) 99.9
	VF	USA	Haberl et al. (2003)	3.4–6.8	Benz 65, BTEX 66, TPH 93, MTBE 18
	FWS	China	Ji et al. (2004, 2007),)		BOD 83, COD 76, mineral oils 92, TKN 66
	HF, FWS	Taiwan	Yang and Hu (2005)	2.0–5.0	COD 30–50, TN 48–80, TP 50–60
	VF	Pakistan	Aslam et al. (2007)	10	BOD 51, COD 50, TSS 47, TN 53, Cu 47
	FWS-HF	USA	Wallace and Kadlec (2005)		Benzene, BTEX, GRO – below detection limit
	FWS-VF	USA	Wallace et al., 2011	13	Benzene 87, toluene 77, As 98, Fe 87
	FWS	Hungary	Czudar et al. (2011)	1.3–1.6	BOD 59, COD 54, TN 22, TP 43

Table 23 (*Continued*)

Type of wastewater	Type of CW	Location	References	HLR ($cm\,d^{-1}$)	Treatment efficiency (%)
Pulp and paper	HF	USA	Thut (1990a)		NH_4-N 31–88, TSS 55–68, TP 14–31
	HF	USA	Thut (1990b, 1993),)	15	BOD 80–90
	HF	USA	Hammer et al. (1993)	3.1–9.4	BOD 27–58
	HF	USA	Boyd et al. (1993)		BOD 67–84
	FWS	USA	Tettleton et al. (1993)		BOD 6–7, TSS 33–81, TP 32–53, NO_3-N 64–80
	FWS	USA	Knight et al. (1994)		
	FWS	USA	Hatano et al. (1994)		BOD 18–33, TSS 51
	FWS	China	Xianfa and Chuncai (1994)	1.5	BOD 38, TSS 84, TN 29, TP 54
	HF	Kenya	Abira et al. (2005)		Phenol 81–89
	FWS	USA	Kadlec and Wallace (2009)	22	BOD 77, TSS 48
	HF	India	Choudhary et al. (2010)	1.9	Resin and fatty acids 92–96
Tannery	FWS	Turkey	Kucuk et al. (2003)		COD 30, NH_4-N 95, Cr 45–55
	HF	Portugal	Calheiros et al. (2007, 2009),)	3.0–6.0	BOD 48, COD 59, TSS 72, TKN 25
	HF	Portugal	Calheiros et al. (2012)	6	BOD 73, COD 65, TSS 65, NH_4-N 73, TKN 75
	HF	Tanzania	Kaseva and Mbuligwe (2010)	10	Cr 99.8, turbidity 71
	VF-HF-VF	Bangladesh	Saeed et al. (2012)	6	BOD 98, COD 98, TSS 55, TP 87, NH_4-N 86
Textile	HF	Australia	Davies and Cottingham (1992)	9.6	TSS >88
	VF	UK	Pervez et al. (2000)		Acid blue 113, reactive blue 171, both 98
	HF	Tanzania	Mbuligwe (2005)	45	COD 68–72, color 72–77, sulfate 53–59
	VF	Portugal	Davies et al. (2005)		COD 64, TOC 71, AO7 74
	VF-HF	Slovenia	Bulc (2006)	1.25	BOD 66, COD 84, TSS 93, TN 52, color 90
	VF (upflow)	Japan	Ong et al. (2009)	6	AO7 96
	HF	Italy	Fibbi et al. (2011)	13.3	Cr 40–50
Aquaculture	HF	USA	Zachritz and Jacquez (1993)	790	
	FWS	USA	Schwartz and Boyd (1995)	7.7–9.1	BOD 65, TSS 89, TP 86, NO_3-N 74, NH_4-N 47
	HF, VF	USA	Summerfelt et al. (1999)	1.35	BOD 98, COD 94–92, TKN 86–89, TP 82–87
	VF	USA	Behrends et al. (2000a)		BOD 99, COD 99, TN 96, NH_4-N 86, TP 84
	HF	Canada	Comeau et al. (2001)	21.2	TSS >95, TP >80
	FWS-HF	Taiwan	Lin et al., 2002, 2003, 2005	1.8–13.5	BOD 24, NH_4-N 86–98, TP 32–71, TSS 71
	HF	Germany	Schulz et al. (2003)	100–500	COD 64–74, TSS 97, TP 49–69, TN 21–42
	HF	Canada	Naylor et al. (2003)	3	
	FWS	USA	Michael (2003)	7.9	BOD 82, TP 82, NH_4-N 75, TSS 91
	HF	Australia	Lembery et al. (2006)	0.7	TN 69, TP 89, NaCl 55
	HF	Canada	Chazarenc et al. (2007)	4.2	COD 94, TSS 81, TKN 80, TP 56
	VF	China	Li et al. (2007)	16–39	BOD 71, TSS 82, NH_4-N 62, NO_3-N 68, TP 20
	HF	Germany	Sindilariu et al. (2008)	650	BOD 72, COD 55, TSS 85, TP 43, NH_4-N 61
	HF	USA	Zachritz et al. (2008)	303	COD 12.5, TSS 90, NO_3-N 76, NH_3-N 7.5
	VF	Canada	Snow et al. (2010)		BOD 53, COD 56, TSS 39, TP 58
	VF	China	Snow et al. (2010)	23–34	BOD 56, COD 26, TSS 58, TP 17, TN 48
	VF-HF	China	Shi et al. (2011)	86	COD 27, TSS 66, TN 67, TP 24, NO_3-N 59
	HF, VF	Vietnam	Konnerup et al. (2011)	75–300	BOD 50, COD 50
Winery	HF	USA	Shepherd et al. (2001)		COD 98, TSS 97, S^{2-}99, TKN 78, phenols 100
	VF	Germany	Müller et al. (2002)		
	Not specified	France	Rochard et al. (2002)		
	HF	Italy	Masi et al. (2002)	3.7	BOD 92, COD 88, TN 58, NH_4-N 54
	HF-FWS	Italy	Masi et al. (2002)	2.6	BOD 99, COD 98, TSS 89, TN 81, TP 72
	VF-HF-FWS	Italy	Masi et al. (2002)	2.3	BOD 93, COD 92, TSS 75, TN 90, NH_4-N 90
	HF	USA	Grismer et al. (2003)	3.1	COD 49–79, TSS 30–85, TKN 25–66, Tannin 46–78, S^{2-} 20–78 (lower values for crush period)
	HF	South Africa	Sheridan et al. (2006)		
	HF	South Africa	Mulidzi (2007, 2010),)	2.5–4.5	COD 60–83
	VF-HF-FWS	Italy	Zanieri et al. (2010)	2.3	COD 98, S^{2-}91, TP 60
	HF	Italy	Rochard et al. (2010)	48	COD 95
	VF-HF	Spain	Serrano et al. (2011)	1.95	BOD 70, COD 71, TSS 87, TKN, 52, PO_4^{3-} 17
	HF	USA	Grismer and Shepherd (2011)		COD 97–99, TSS 76–91
Distillery	HF	India	Billore et al. (2001)	2.7	BOD 84, COD 64, TKN 59, TP 79
	HF	Mexico	Olguín et al. (2008)	4.0–8.0	BOD 85, COD 80, TKN 75, NO_3-N 57, NH_4-N 2–10, SO_4^{2-}69
	HF	UK	Murphy et al. (2009)	58	Cu 53–85
Brewery	FWS	USA	Kadlec and Wallace (2009)		
	HF	South Africa	Crous and Britz (2010)		COD 20, NH_4-N 80, NO_3-N 86, PO_4-P 33
Abattoir	HF	Australia	Finlayson and Chick (1983)		TSS 83–89, TN 42–75, TP 68–79
	HF	Australia	Finlayson et al. (1990)		TKN 51–72, TP 37–69
	HF	New Zealand	Van Oostrom and Cooper (1990)	3.3–7.2	COD 65, TSS 90, NH_3-N 20, TN 18

Table 23 (*Continued*)

Type of wastewater	Type of CW	Location	References	HLR (cm d^{-1})	Treatment efficiency (%)
	FWS	New Zealand	Van Oostrom and Cooper (1994)	4.6	COD 42, TSS 94, TN 30, Nox-N 37
	HF	Mexico	Rivera et al. (1997)	5.7	BOD 77, COD 74, TSS 44, org-N 48
	HF	Ecuador	Lavigne and Jankiewicz (2000)	1.7	BOD 98, COD 98, TSS 99, NH_4-N 82, PO_4-P 94
	FWS	Canada	Goulet and Sérodes (2000)	1.4	BOD 85, TSS 95, TKN 66, NH_4-N 54, TP 74
	HF	Lithuania	Gasiunas et al. (2005)	5.3	BOD 96, TSS 93, TP 79, TN 65
	VF-HF	Poland	Soroko (2005)	0.6	BOD 97, COD 97, TSS 94, TN 74, NH_4-N 99
Dairy/cheese	HF	Denmark	Schierup et al. (1990)	2.6	BOD 91, TSS 91, NH_4-N 74, TN 80, TP 81
	HF, VF upflow	New Zealand	Tanner (1992)		BOD 70–90, TSS 40–90,TN 40–90, TP 30–80
	HF	USA	Wallace (2002b)	2.7	BOD 34 (97 with aeration), TN 44 (74)
	HF	Germany	Kern and Brettar (2002)	0.1–0.15	NH_4-N 92, org-N 81
	HF	Italy	Mantovi et al. (2003)	4.4, 2.5	BOD 94, COD 92, TSS 91, TN 49, NH_4-N-9, org-N 79, TP 61
	HF	France	Khalil et al. (2005)	2.5	BOD 50, TOC 70, TSS 62, TKN 40
	VF-VF-HF	France	Reeb and Werckmann (2005)		
	HF	Lithuania	Gasiunas at al. (2005)	1.5–2.4	BOD 97, COD 95, TSS 96, TP 58, TN 71
	HF	Italy	Gorra et al. (2007)		BOD 75, orgN 24, NH_4-N 27
	HF	Italy	Mantovi et al. (2007)	2.6	BOD 98, COD 97, TSS 94, TP 45, TKN 62, NH_4-N-64
	VF-VF-HF-VF	Japan	Kato et al. (2010)	0.7–2.0	COD 93–96, TN 63–89, NH_4-N 62–82, TP 70–88
	VF-HF	Italy	Comino et al. (2011)	10	BOD 55, COD 72 TSS 60, TP 30, TN 50
Olive mill	VF	Turkey	Yalcuk et al. (2010)	10	COD 74, PO_4-P 94, NH_4-N 43
	VF	Greece	Grafias et al. (2010)		COD 86, color 77
	VF	Greece	Herouvim et al. (2011)		COD 73, phenol 75, TKN 75, NH_4-N 72, PO_4-P 87
	FWS	Greece	Kapellakis et al. (2012)	0.7–1.0	COD 85, TSS 90, TP 83, TKN 83, Phenol 80 NH_4-N 54, NO_3-N 46
Fish/Seafood	HF	USA	White (1994)	1.3–4.3	BOD 91-94, NH_4-N 43–95
	FWS	Thailand	Sohsalam et al. (2008)	7.9–39.5	BOD 91–99, TSS 52–90, TN 72–92, TP 72–77
Sugar industry	FWS	USA	Anderson (1996)	1.4–1.7	BOD 96, TSS 85, TKN 86, $NH_3$99, TP 44
	VF	UK	Morris and Herbert (1998)	2.5–7.4	COD 87, TSS 88, NH_4-N 80
	FWS	Kenya	Bojcevska et al. (2006)	7.5–22.5	TSS 64-76, TP 21-29, NH_4-N 22–44
	FWS	Thailand	Sohsalam and Sirianunpatiboon (2008)		BOD 89, COD 68, TSS 93, TN 80, TP 76
Potato industry	HF	Netherlands	De Zeeuw et al. (1990)	1.0–2.7	COD 11–92, TKN 16–91
	FWS-VF-FWS	USA	Burgoon et al. (1999)	3	COD 93, TSS 83, TN 54, org N 80, NH_4-N 47
	3xVF-HF-VF	Japan	Kato et al. (2010)	0.3–1.0	COD 94, TN 90, NH_4-N 72, TP 83
Mixed food	HF	Slovenia	Vrhovšek et al. (1996)	3.2	BOD 89, COD 92, $PO_4$96, NH_4-N 86 NO_3-N 65
	HF	Italy	Pucci et al. (2000)		COD 90, TSS 81, NH_4-N 55, TP 18
Laundry	HF	Italy	Del Bubba et al. (2000)	3.7	LAS 94–99
	HF	India	Billore et al. (2002)		LAS 43–88
	HF	UK	Thomas et al. (2003)		
	HF	Spain	Thomas et al. (2003)		
	HF	Australia	Davison et al. (2005)		BOD 61, TSS 83, TN 62, TP 32
	HF	Thailand	Kantawanichkul and Wara-Aswapati (2005)		
Chemical industry	HF	UK	Sands et al. (2002)		
	VF	Portugal	Haberl et al. (2003)	2.4	Aniline 99, nitrobenezene 98, sulphanilic acid 99, trinitrophenol >99
	HF	Portugal	Dias et al. (2006)		
Mixed industrial	FWS-HF	China	Wang et al. (1994)	36.5	BOD 69, COD 81, TSS 899, TN 30, TP 62
	FWS	Taiwan	Chen et al. (2006)	10	BOD 89, COD 61, TSS 81, NH_4-N 53, TP 35
	FWS	Pakistan	Khan et al. (2009)	19	Ni 41, Cu 48, PB 50, Fe 74, Cr 89, Cd 92
	VF-HF-VF	Slovenia	Zupanič Justin et al. (2009)		BOD 66, COD 67, NH_4-N 24, orgN 83, $PO_4$62
Explosives	FWS	USA	Best et al. (2000)		TNT 79, 2,4DNT 58, 2,6DNT 61
	FWS, HF	USA	Behrends et al. (2000b)		
Steel industry	HF	Taiwan	Yang and Hu (2005)	2.6	COD 50, TP 6
	VF	China	Xu et al. (2009)		COD 55, NH_4-N 67, TP 93, Fe 97, Mn 93
	HF	China	Huang et al. (2011)	1.8	COD 77, NH_4-N 77, Fe 94, Mn 81
Woodwaste	FWS	Canada	Masbough et al. (2005)		BOD 60, COD 50, VFA 69, tannins/lignins 42
	FWS	Canada	Tao and Hall (2004)	1.2–4.7	COD 6–31, VFA 35–98, tannins/lignins 1–17
Coke plant effluent	HF	France	Jardinier et al. (2001)	3.1	COD 35–52, TSS 94–96, TN 37,

Table 23 (*Continued*)

Type of wastewater	Type of CW	Location	References	HLR ($cm\,d^{-1}$)	Treatment efficiency (%)
Coal gasification	FWS	USA	Ye et al. (2003)	0.9	Se, 64, As 47, B 31, cyanide 3
Lignite pyrolysis	HF	Germany	Wiessner et al. (1999)	2.2	
Tool industry	FWS	Argentina	Di Luca et al. (2009)	5	BOD 87, COD 87, TP 44, Cr 82–99, Ni 54–64, Zn 56–76, Fe 96–99
Flower farm	HF-FWS	Kenya	Kimani et al. (2012)		BOD 87, COD 67, TSS 90, TN 61, 49

and also in hybrid constructed wetlands. The results of the survey also indicated that several wastewaters such as distillery and laundry effluents have been treated only in horizontal flow constructed wetlands so far. The treatment technology of constructed wetlands has evolved in a reliable technology which is nowadays successfully used for many types of industrial effluents.

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