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Review

Recent Advances in Application of Constructed Wetland Technologies for Enhanced Wastewater Treatment

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Abstract

Constructed wetland systems are used as innovative and emerging solutions for environmental protection and restoration as these systems are low-cost and sustainable wastewater treatment systems. Recently, investigations of novel enhancement technologies on various modified constructed wetlands to improve treatment performance have been reported in different literatures. Hence, this review aims to provide an overview of the recent advances in constructed wetland technology considering a wide range of expanded designs, configurations, and combinations with other technologies for the enhancement of wastewater treatment. It is found that the criteria for constructed wetland design and operation include site selection, plant selection, substrate selection, wastewater type, plant material selection, hydraulic loading rate, hydraulic retention time, water depth, operation mood and maintenance procedures are found to be the focuses of the current research on sustainable design of constructed wetlands.

Keywords: Constructed wetland systems, environmental protection, wastewater treatment, sustainability.

Introduction

Water pollution is becoming a serious issue of the entire world due to the rapid population growth, unsuitable treatment technology and inadequate management especially in developing countries (Vymazal, 2011a; Wu *et al.*, 2014). Historically, traditional and centralized sewage treatment systems have been used successfully for water pollution control in most countries (Li *et al.*, 2014). However, these wastewater treatment technologies like activated sludge process, membrane bioreactors and membrane separation, are rather expensive and not entirely feasible for wide spread application in rural areas (Chen *et al.*, 2014). Furthermore, these technologies are limited and insufficient when facing ever more stringent water and wastewater treatment standards (Wu *et al.*, 2013). Thus, constructed wetlands, due to high removal efficiency, low cost, simple operation, and great potential for water and nutrient reuse; have become an increasingly popular option for wastewater treatment (Vymazal, 2007; Kadlec, 2009; Rai *et al.*, 2013). They are engineered wetlands which are designed and constructed to mimic natural wetland systems for treating wastewater (Wu *et al.*, 2015). These systems are mainly comprised of vegetation, substrates, soils, microorganisms and water. As inspired by the simulations on natural wetland, the wastewater purification in a constructed wetland treatment system is achieved by the triple synergistic effects of physical, chemical and biological interactions in natural ecosystems (Saeed and Sun, 2012; Lu *et al.*, 2015). Currently, numerous studies have focused on the design, development, and performance of CWs for the reason that long-term effective treatment performance in CWs and the sustainable operation remain a challenge. On one hand, plant species and media types are crucial influencing factors to the removal performance in CWs as they are considered to be the key component of CWs and change, directly or indirectly, the primary removal processes of pollutant over time (Li *et al.*, 2008). On the other hand, the treatment performance of CWs is critically reliant on the optimal operating parameters (water depth, hydraulic retention time and hydraulic load rate, feeding mode and plan of setups, etc.) (Kadlec and Wallace, 2009; Wu *et al.*, 2014). Additionally, various pollutant removal processes (e.g., sedimentation, filtration, precipitation, volatilization, adsorption, plant uptake, and various microbial processes) are generally directly and/or indirectly influenced by the various internal and external environment conditions such as temperature, availability of dissolved oxygen and organic carbon source, operation strategies, pH and redox conditions in CWs (Calheiros *et al.*, 2009; Chen *et al.*, 2011; Saeed and Sun, 2012; Meng *et al.*, 2014). Moreover, given the fast urbanization and the land protection for crop production, natural passive CWs cannot be fully promoted because of the large area requirement. The number of research groups that study how these factors perform in the contaminant removal in CWs has dramatically increased in recent years (Wu *et al.*, 2014).

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Table 1. Enhancing techniques on hybrid CWs for BOD and COD removal.

CW type	Enhancement techniques	BOD Rem. (%)	COD Rem. (%)	References
VF-HF	Natural ventilation	90.3-99.1		Lee *et al.* (2015)
VF-HF	Ventilation pipe, electric fan air	97.2-97.5		Lee *et al.* (2015)
VF-HF		85	74	Kouki *et al.* (2009)
VF-HF	Varied loading rates	87	83	Herrera-Melia'n *et al.* (2010)
VF-HF		92-96	81-84	Lesage (2006) and Lesage *et al.* (2007)
VF-HF	Multi-layer	93	90	Keffala and Ghrabi (2005)

Similarly, the volume of knowledge and information published in international journals and books on minimizing the influences of these factors and possible solutions suggested to improve the treatment performance has increased considerably. Better understanding of the intensified removal processes responsible for water treatment has expanded concurrently with CW usage and has led to a great variety of designs and configurations, such as aerated subsurface-flow CWs (Nivala *et al*., 2007, 2013), baffled subsurface-flow CWs (Tee *et al*., 2012), and combinations of various types of CWs (Vymazal, 2013a). While much advancement has been made in the contaminant removal processes in CWs over the years, there is still a gap in the understanding of these systems in developing countries. Meanwhile, to date the application and the adoption of CW technology in these countries has been surprisingly slow (Bojcevska and Tonderski, 2007). This paper presents a review of the recent advances in CW technology considering a wide range of expanded designs, configurations, and combinations with other technologies for the enhancement of wastewater treatment.

Recent advancements in pollutant removal by CWs

The criteria for CW design and operation include site selection, plant selection, substrate selection, wastewater type, material selection, hydraulic loading rate (HLR), hydraulic retention time (HRT), water depth, operation mood and maintenance procedures (Akratos *et al*., 2009; Kadlec and Wallace, 2009) and so are the focuses of the current research on sustainable design of CWs (Vymazal, 2011a). With reference to the optimal design of hydraulic loading rate (HLR) and hydraulic retention time (HRT), greater HLR promotes quicker passage of wastewater through the media, thus reducing the optimum contact time. On the contrary, an appropriate microbial community could also be established in CWs and have adequate contact time to get rid of contaminants at an extended HRT (Saeed and Sun, 2012; Yan and Xu, 2014). As selecting plants utilized in CWs is one among the focuses of the present research on sustainable design of CWs, tolerance of waterlogged-anoxic and hyper-eutrophic conditions and capacity of pollutant absorption are recommended besides adaption to extreme climates (Vymazal, 2011b). Among the macrophytes, emergent plants are the main vegetation in FWS and SSF CWs designed for wastewater treatments.

Vymazal (2013b) surveyed emergent plants utilized in FWS CWs, and revealed that *Phragmites australis* is that the most frequent species in Europe and Asia, *Typha latifolia* in North America, *Cyperus papyrus* in Africa, *Phragmites australis* and *Typha domingensis* in Central/South Americas and *Scirpus validus* in Oceania. Similarly, a review of plants used in SSF CWs by Vymazal (2011b) showed that by far the most frequently used plant around the globe is *Phragmites australis* which has been particularly used throughout Europe, Canada, Australia and most parts of Asia and Africa. The feeding mode of influent has been shown to be another important design parameter (Zhang *et al*., 2012). The difference of feeding mode (such as continuous, batch and intermittent) may influence the oxidation–reduction conditions and oxygen transfer and diffusion in wetland systems and, hence, modify the treatment efficiency (Wu *et al*., 2015). Various studies were conducted to evaluate the effect of influent feeding modes on the removal efficiency of CW treatments and explain batch feeding mode help to obtain the better performance than continuous operation (Wu *et al*., 2015) as continuous feeding decreases process of denitrification.

Enhancement of organic matter and emerging contaminant removal by CWs

Compared to the traditional CWs (FWS and HF CW), the VF CW provided a greater supply of oxygen that increased the nitrification rate and the performance of aerobic biological oxidation that resulted in a good removal of biochemical (BOD) and chemical oxygen demand (COD) (Lee *et al.*, 2015). In this review, investigations on the active role of wetland plants and VF-HF CWs for BOD, COD and emergent contaminant removal are presented. The effects of design factors for COD and BOD reduction, such as loading, residence time, temperature, porous media, vegetation, and aeration (Dong *et al*., 2012) are also discussed below. The enhancement of BOD and COD removal in a hybrid constructed wetland under different ventilation methods was assessed by Lee *et al.* (2015) and the results showed that the removal efficiencies of BOD and SS in the effluent were 95.3–99.0% and 88.9–99.1% in the VF-HF CWs with natural ventilation, whereas they were 98.8–98.9% and 97.2–97.5% in the VF-HFCW with a ventilation pipe and an electric fan air blower (Table 1), providing air by the renewable energy of solar and wind power, respectively.

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Enhancement of treatment efficiency of hybrid CWs for municipal sewage wastewater is also indicated by several studies. For instance, in Tunisia a study by Kouki *et al.* (2009) reported on the use of a VF-HF CW in Joogar and showed the treatment efficiency was very high for BOD, COD, TSS and TP with percentage efficiency of 85% and 74% for BOD and COD respectively (Table 1). Herrera-Melia`n *et al.* (2010) also tested a pilot-scale VF -HF CWs in Canary Islands, Spain, under two overall hydraulic loading rates of 3.7 and 7.5 cm d^{-1}. The results revealed very high treatment efficiency in terms of BOD and COD, 87% and 83%, respectively (Table 1). Lesage (2006) and Lesage *et al.* (2007) reported on the use of four VF-HF constructed wetlands in Flemish part of Belgium. The treatment performance of all these systems for BOD and COD is very high with removal efficiency of 92-96% for BOD and 81-84% for COD (Table 1). Other studies tested pilot scale VF-HF CW to demonstrate the effect of plants for removal of nitrogen. The VF bed was filled with coarse gravel at the bottom (25-40 mm), fine gravel in the middle (2-4 mm) and coarse sand at the top (0.15-0.6 mm). HF bed was filled with gravel (5-8 mm). Their results revealed that the system achieved significant reduction of organics, suspended solids, nitrogen and bacteria with the removal efficiency of 93% and 90% for BOD and COD, respectively (Table 1). Caselles-Osorio *et al.* (2011) evaluated *Eriochloa aristata* and *Eleocharis mutate* under tropical conditions. The results show that the rhizosphere of *E. aristata* and of *E. mutate* enhanced the removal of COD, BOD, and other pollutants. Taylor *et al.* (2011) tested 19 species of wetland plants for COD removal under seasonal effects. The study showed that vegetation increases the removal rate of gravel wetlands especially at low temperatures. Stefanakis *et al.* (2012) investigated the effects of design factors for COD and BOD reduction, such as loading, resting period, temperature, porous media, vegetation, and aeration. The results indicated that vegetation plays an important role in pollutant removal. However, the different species exhibited no significant differences.

Emergent organic contaminants such as pharmaceuticals and personal care products (PPCPs) have raised great concern in recent years (Daugthon, 2004). Carbamazepine and clofibric acid are reported as almost showing no removal in the wetlands by previous studies (Park *et al.*, 2009; Matamoros *et al.*, 2009). Recently, it is found that wetland plants Typha spp. (Dordio *et al.*, 2011) and *Phragmites australis* (Dan *et al.*, 2013) actively participated in the removal of carbamazepine, sulfonamides and trimethoprim when used in CW wastewater treatments. The removal of carbamazepine from nutrient solutions by the plants reached values of 56-82% of the initial contents (from 0.5 to 2.0 mg/L) (Dordio *et al.*, 2011; Dan *et al.*, 2013).

Avila *et al.* (2014) also studied the feasibility of hybrid CW systems used for removing emerging organic contaminants under varied HLR, and demonstrated that the removal efficiency for most compounds decreased as the HLR increased.

Enhancement of nitrogen removal

Toet *et al.* (2005) found positive nitrogen removal in CWs with longer HRT (0.8) days comparing with the results with shorter (0.3) days residence time. A low HRT in CWs may be associated with incomplete denitrification of wastewater, and it is reported that nitrogen removal requires a longer HRT compared with that required for removal of organics (Lee *et al.*, 2009). Furthermore, the effect of HRT may differ between CWs depending on the dominant plant species and temperature, as those factors can affect the hydraulic efficiency of wet-lands. Accordingly, in a long-term experiment conducted by Cui *et al.* (2010) observed a minor decrease of ammonium and TN removal from domestic wastewater in VF CWs; when HLR changed from 7 to 21 cm/d. Accordingly mean ammonium removal decreased from 65-60 percent, whereas TN reduced from 30-20%. However, Stefanakis and Tsihrintzis (2012) reported a long term evaluation of fully matured VF CWs for treating synthetic wastewater, and showed that the wetland systems achieved higher nitrogen and organics removal as the HLR increased. Other studies also provided some information on introduction of new substrates in order to optimize the removal of nitrogen and organics. The substrates introduced are; alum sludge, peat, maerl, compost and rice husk (Babatunde *et al.*, 2010; Saeed and Sun, 2012). The mixed (substrate gravel, vermiculite, ceramist and calcium silicate hydrate) was also used in CWs for treating surface water with low nutrients concentration (Lui *et al.*, 2011). These mixed substrates not only have reactive surfaces for microbial attachment, but also could provide a high hydraulic conductivity to avoid short-circuiting in CWs (Wu *et al.*, 2015). The adsorption capacity of zeolite substrates for ammonium removal in CWs has been investigated by Huang *et al.* (2012) and their results showed that the calculated maximum ammonium adsorption of the substrate (11.6 g/kg) was significantly greater than that of volcanic rock (0.21 g/kg). Organic substrates such as wood mulch and gravel–wood mulch are efficient in VF CWs but not in HSSF CWs (Saeed *et al.*, 2011a). A subsequent investigation tested the removal capacities of a wood mulch VF-gravel HSSF-zeolite VF system (Saeed *et al.* 2011b) also revealed mulch and zeolite showed promising prospect as wetland substrates, as both media enhanced the removal of nitrogen and organics. Average NH4-N, TN and BOD_5 removal percentages were over 99%, 72% and 97%, respectively, across all three systems.

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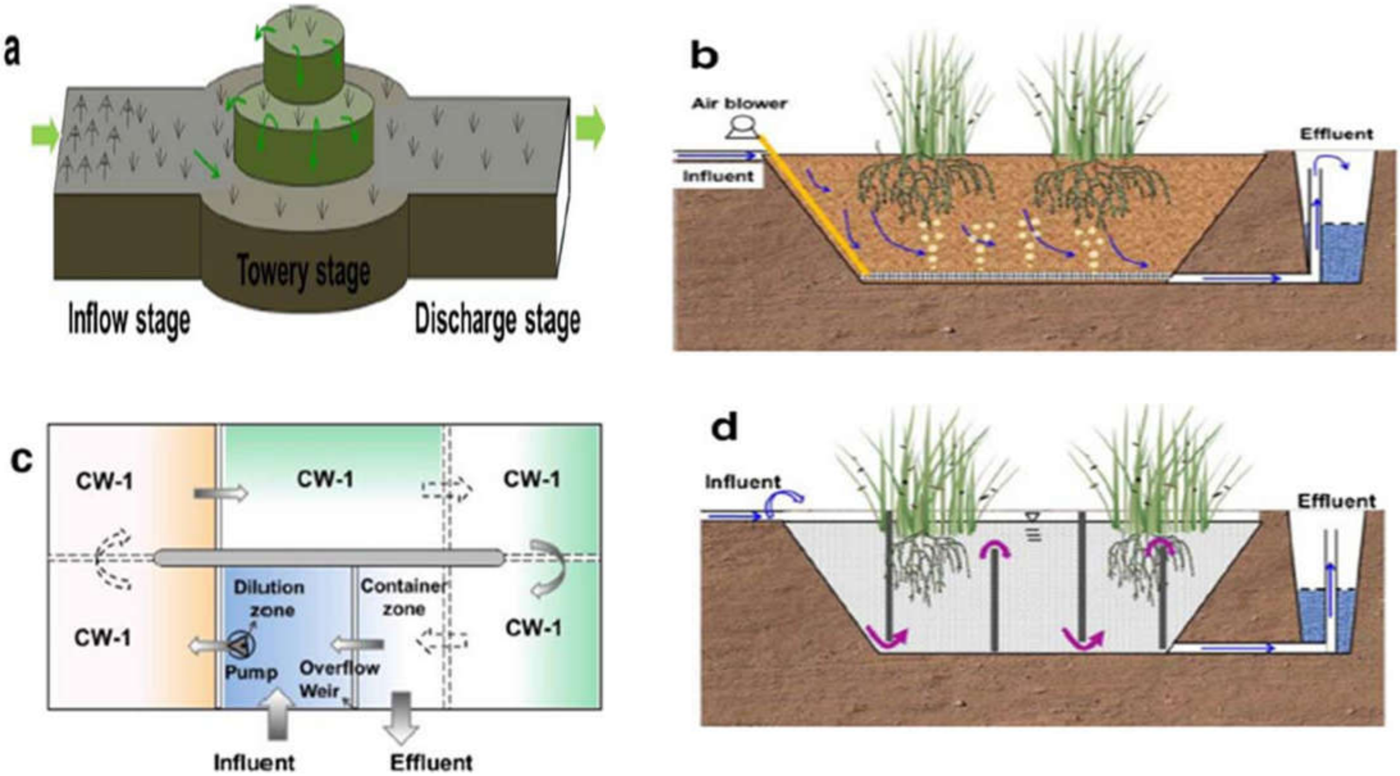
Fig. 1. Schematics and various enhancing techniques applied in CW wastewater treatments. a) Towery hybrid CW modified from Wu *et al*. (2014), b) artificial aeration CW modified from Wu *et al*. (2014), c) circular flow corridor CW modified from Peng *et al*. (2012), d) baffled subsurface flow CW modified from Wu *et al*. (2014).



Wetlands present high nitrification during operation, and both wood mulch and zeolite were more efficient than gravel (Saeed *et al*. 2011b). Tee *et al*. (2012) investigated the feasibility of rice husk-gravel mixed substrate in a new baffled HSSF CW. The roots of vegetation are able to grow deep in rice husks, which provide high uptake and nitrification. Zhang *et al*. (2012) investigated the influence of batch versus continuous flow on the removal efficiencies in tropical SSF CWs. They indicated that the wetlands with batch flow mode showed significantly higher ammonium removal efficiencies (95.2%) compared with the continuously fed systems (80.4%). However, there still exists uncertainty about whether batch operation improves removal efficiencies when compared to continuous feeding mode. Intermittent feeding mode are often considered to boost organics and nitrogen removal in CWs (Saeed and Sun, 2012). Caselles-Osorio *et al*. (2011) evaluated the effect of continuous and intermittent feeding modes on contaminant removal efficiency in SSF CWs, and noted that intermittent feeding improved ammonium removal performances in wetland systems when compared with continuous feeding. Furthermore, the intermittent operation greatly enhanced the ammonium removal efficiency (more than 90%), which may be attributed to more oxidizing conditions in wetlands.

Similarly, the impacts of continuous and intermittent feeding modes on nitrogen removal in FWS and SSF CWs by Jia *et al*. (2011) showed that the intermittent feeding mode enhanced the ammonium removal effectively in SSF CWs without any significant effect for FWS CWs. There are studies that bring solutions for clogging, which are the common problem in treatment wetlands consist of gravel and sand media reed beds using new designs and configurations, such as aerated subsurface-flow CWs (Nivala *et al*., 2012). Bialowiec *et al*. (2011) proved that a novel substrate, lightweight aggregates made from the fly ash from sewage sludge thermal treatment (FASSTT LWA) is better than the conventional gravel substrate in VF CW for N treatment. They found that 25 cm upper FASSTT LWA and 75 cm lower gravel layer is the optimal N treatment combination. A novel towery hybrid (Fig. 1a) CW with three-level stage VF CWs was designed by Zhu *et al.* (2012) to treat livestock wastewater, and the results indicated that average removal rates were >95% for NH_4^+-N that was slightly higher than the removal rates for the ladder-type hybrid CWs in long-term operation. N removal enhancement in a hybrid constructed wetland under different ventilation (Fig. 1b) methods was also assessed by Lee *et al*. (2015) and the results showed that the removal efficiency of TN in the effluent was 19.0–53.3% in the VF-HF CWs with natural

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ventilation, whereas it was 57.5–58.6% in the VF-HF CW with a ventilation pipe and an electric fan air blower, providing air by the renewable energy of solar and wind power, respectively. Moreover, a novel N removal, circular flow corridor CW has been promoted for the secondary treatment of swine wastewater by Peng *et al.* (2012) (Fig. 1c). The authors stated that this operation can enhance interactions between pollutants and microorganisms on the roots of plants and the surface of substrates due to additional oxygen for aerobic microbial activities and a longer retention time. The high-strength swine wastewater has been purified successfully through the special inter-circulation of wastewater in the CWs which consist of several compartments and was connected in an annular corridor. Their results revealed high removal efficiencies of above 93% for COD, NH_4^+-N, and TP at low temperature. Another important issue is the capacity of novel hybrid wetlands. A complex wetland consists of one or more HSSF wetlands and VF wetlands or a combination of horizontal and vertical flowing situation. Tee *et al.* (2012) designed a new baffled HSSF CW (Fig. 1d) where in VF occupies a small area. The study confirmed that complex wetlands provide the advantages of both HSSF and VF CWs and they are efficient for N removal.

Enhancements for phosphorus removal and recovery

A cost-effective and efficient solution for constructed wetlands is the use of a filter medium with high adsorption capacity and high content of the cations like Fe^{3+}, Fe^{2+}, Al^{3+} and Ca^{2+} that are able to precipitate phosphorus (Pereyra, 2015). Several studies were administered on selecting wetland substrates especially for sustainable phosphorus removal from wastewater. The frequently used substrates mainly include natural material, artificial media and industrial by-products with high hydraulic conductivity and phosphorus sorption capacity, such as gravel, sand, clay, calcite, marble, vermiculite, slag, fly ash, bentonite, dolomite, limestone, shell, zeolite, wollastonite, activated carbon, light weight aggregates (Albuquerque *et al.*, 2009; Saeed and Sun, 2012; Chong *et al.*, 2013; Yan and Xu, 2014). Results from these studies also suggest that substrates like sand, gravel, and rock are the poor candidate for long-term phosphorus storage. Xu *et al.* (2006) studied the phosphorus sorption capacity of nine substrates, and showed that sorption capacity of sands varied between 0.13 and 0.29 g/kg. Lai and Lamb (2009) investigated the potential phosphorus removal of using a mixture of fish pond bund material, decomposed granite and river sand as substrate in the CW receiving influent storm water and the theoretical capacity for phosphorus adsorption was determined to be 478-858 mg/kg based on batch incubation experiments. In addition, increasing the proportion of decomposed granite in the substrate mix may enhance the phosphorus sorption capacity considerably, since there are abundant amorphous Fe and Al within the decomposed granite (Lai and Lamb, 2009). Mateus *et al.* (2012) tested the capacity of fragmented Moleanos limestone (FML) as substrate in P treatment. The results of the pilot-scale HSSF wetland experiments confirm that the average P removal rate by FML is 60±7% at a hydraulic loading rate of 40 L $(m^2day)^{-1}$ ± 4 L $(m^2\ day)^{-1}$, which is higher than the average removal rate reported by (Kadlec, 2008 in Mateus *et al.*, 2012). Bruch *et al.* (2011) investigated the P treatment efficiency of three different substrates, lava sand, conventional fluviatile sands, and zeolite mixed with lava sands, in VF CW. According to the experiments, the adsorption capacity of lava sand is not significantly higher than that of conventional fluviatile sands. The tests also confirmed that zeolite increases the sorption ability. Zeolite promotes the hydraulic retention time by increasing the shrinkage and swelling capacity (Bruch *et al.*, 2011). Lindstrom *et al.* (2011) investigated four methods for reducing P internal flow, namely soil dry down, surface addition of alum carbonate, surface addition of calcium carbonate, physical removal of the accreted organic soil under both aerobic and anaerobic water column conditions. The results show that soil dry down and surface alum addition efficiently reduce P internal flow, whereas the other two methods are not as effective. Based on the earlier investigations, the maximum alum-based P removal only occurs during the first few months. Therefore, organic soil removal is the reasonable method for reducing the P flux from the soil and decreasing internal P loading. Zhao *et al.* (2011a) presented a new concept about P treatment and recovery, which describes a system that reuses the by-product alum sludge from a water treatment plant as wetland substrate for domestic wastewater treatment. Alum sludge is commonly disposed in landfills, with little beneficial value. The results illustrate that the alum sludge–based CW was efficient in treating BOD, COD, NH_4^+-N, TN, P, and total P. The removal rates were 57-84%, 36-84%, 49-93%, 11-78%, 75-94% and 73-97%, respectively. After determining the removal capacity of alum sludge-based wetland, Zhao *et al.* (2011b) further investigated the recovery of the alum sludge as an effective and consistent method for recovering P and Al from the dewatered alum sludge cakes (DASC), which were used as substrate in the wetlands. These two investigations proposed the reuse of alum sludge as substrate in CW, and then the recovery of Al and P from the CW substrate for reuse in a water plant and as fertilizer. This concept is a highly completed system for both wastes recycle and wastes treatment. Therefore the concept is match with the image of the multiple benefits of treatment wetlands.

Enhancements for heavy metal removal

Combination of HSSF CW with ultrafiltration-reverse osmosis (UF/RO) as a heavy metal wastewater treatment

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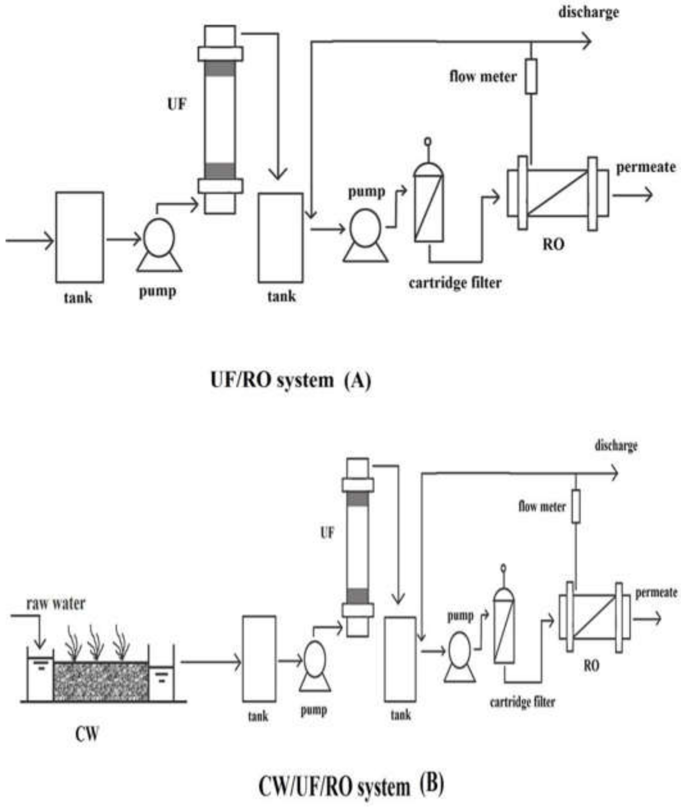
system is suggested by Huang *et al*. (2011). Their study showed that the CW-UF-RO treatment system provides stable treatment effects (Fig. 2). The CW treatment significantly decreased fouling of the RO membrane, avoiding the need for chemical cleaning. The systems were constructed as shown in Fig. 2. In their study, in system A, the wastewater is first treated in the UF process and then directed into the RO process whereas, in system B, wastewater is first introduced into a subsurface flow constructed wetland and then treated in the UF/RO system. Based on the result, the CW effectively reduced the turbidity, COD, and NH_4^+-N. In the wetland, iron and manganese were effectively removed, with 96.9% and 92.5% removal rates, respectively. In the investigation, the surface of the manganese substrate was covered with a bio film, which was the key site for iron and manganese removal. Allende *et al*. (2012) tested gravel, coco-peat, zeolite, and limestone as substrates for VF CWs in treating metals, such as arsenic, boron, and iron. At an average hydraulic loading of 0.073 $m^3(m^2\ d)^{-1}$, limestone exhibited the highest removal rate for arsenic (99%) and iron (98%). In addition, only coco-peat significantly removed boron. From their study, it could be suggested that the removal efficiencies of heavy metals are influenced by the choice of substrates to some extent.

Ha *et al*. (2011) evaluated the accumulating capability of *Eleocharis acicularis* in different concentrations of Ag, Pb, Cu, Cd, and Zn, and the results showed that *E. acicularis* had excellent ability to accumulate metals from water. In addition, Yadav *et al*. (2012) acknowledged that heavy metal bio-concentration varied in several plants species, and below ground biomass removed more metal than above ground biomass. Soda *et al*. (2012) investigated the heavy metal uptake of seven aquatic plants in a FWS CW. The aquatic plants in the experiment exhibited high removal rates for Fe, Cu, Zr, Ag, Sn, and Au. The study also investigated the bio-concentration factors of several metals in two plant species (*Acorus gramineus* and *Cyperus alternifolius*). The results showed that the main CW removed 80% TOC, 18% TN, and 41% NH_4^+-N. Moreover, Fe, Cu, Zr, Ag, Sn, and Al were significantly removed in the main CW system. Peruzzi *et al*. (2011) tested the stabilization of the heavy metal sludge using reed bed sludge treatment wetlands. After 20 days of dehydration and treatment, the sludge became more stable than untreated sludge, which can be used for agricultural purposes. Luca *et al*. (2011) investigated the metal retention and distribution in the sediment of a 5-year-old FWS CW. The stability of the metal compounds in the sediment allows the FWS CW to continue retaining metals in fractions. The reduction rates for Fe, Cr, Ni, and Zn were 98%, 90%, 59%, and 57%, respectively. The study concluded that the wetland was still effective in removing nutrients and metals after 5 years. This result confirms that working time does not limit FWS wetlands.

Fig. 2. Schematic diagrams of the UF/RO system and the CW/UF/RO system (from Huang *et al*., 2011).



Alternative strategies to minimize the CWs footprint

The space required (footprint) of CWs becomes a major disadvantage especially in large cities with high population where there is a limitation of land availability. According to Vymazal (2011a), as a rule of thumb, the area needed by a conventional HF CW is approximately 5 m^2 per population equivalent (PE) while a VF CW requires a lower area demand (1-3 $m^2\ PE^{-1}$; due to its higher bed oxygenation. Calculations of PE followed the Equation (Vymazal, 2011a):

$$1\ PE = 60\ g\ BOD_5\ d^{-1}$$

Where, PE, population equivalent
BOD_5 : 5-day biochemical oxygen demand

In any case, these values are too large when compared for instance with activated sludge systems that require only 0.2-0.4 m^2PE^{-1} (Mburu *et al*., 2013). Thus, innovative CWs are strongly required to meet the treatment requirements within the space that is available or to find alternative conditions to locate the treatment CWs.

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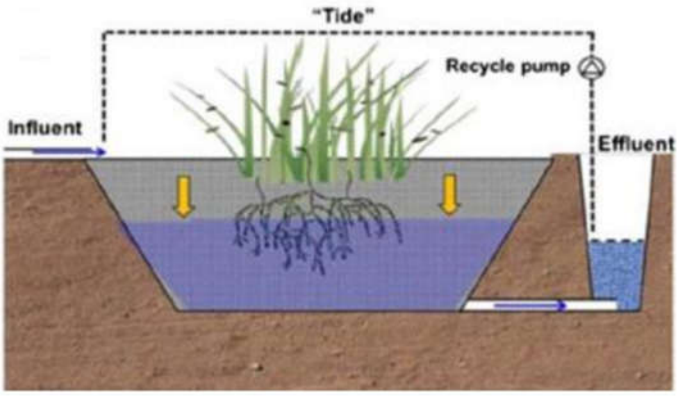
Enhancements to minimize CWs large area requirement

There are reported CWs with less land requirement. Zhai *et al*. (2011) studied a new type of hybrid CW system consisting of both a vertical-baffled flow (VBF) CW and an HSSF CW to treat municipal wastewater in Southern China. The results of their study suggest that this new hybrid CW are able to do removal efficiencies of chemical oxygen demand, suspended solids, ammonia nitrogen, total nitrogen, and total phosphorus of better than 83.6, 95.0, 71.7, 64.5 and 68.1%, respectively, with a particular wetland bed area of 0.70 - 0.93 m^2 PE^{-1}. The land area required for their hybrid CW system is much smaller than that for a conventional HF CW (5 $m^2 PE^{-1}$) and VSSF CWs (1-3$m^2 PE^{-1}$) (Vymazal, 2011a). The recent developments of tidal constructed wetlands (Fig. 3) are other alternative developments to reduce the required land area by CWs (Zhao *et al*., 2004). Tidal flow CWs are systems that by filling and draining wastewater in the bed enhance the entrance of fresh air in to the system. It can work within the same bed, between two beds, with several stages either between CWs or combining technologies (i.e. CW and treatment lagoons) (Pereyra, 2015). To allow the necessary oxygen transfer, the beds must be filled and drained several times per day (~>6 times d^{-1}: Kadlec and Wallace, 2009). The different cycles (filling and draining) allow for different conditions in the bed (aerobic and anoxic/anaerobic) that promotes a highly diverse microbial biomass, without domination of any particular type (Behrends *et al*., 2001). Their study expressed that reciprocating CWs can be>3 m depth in order to increase the fill and drain rates and thus, to reduce the land area requirements. Area reduction is clearly observed in tidal CWs, that require areas of 0.01-0.5 m^2 PE^{-1} (Hu *et al*., 2011; Pereyra, 2015), similar to the footprint required by other technologies for instance with that of activated sludge systems (0.2 -0.4 m^2 PE^{-1}) (Mburu *et al*., 2013).

Conclusion

It has been widely recognized that CWs are reliable treatment technologies for various wastewater treatment implementation. The current review indicates that advances in the design and operation of CWs have greatly increased contaminant removal efficiencies, and the sustainable application of this treatment system has also been improved. For example, the review on plants and substrates selection indicates that wetland macrophytes and substrates are still critical for the sustainable pollutant removal from wastewater in CWs. It should be paid more attention to proper macrophyte species selection (i.e., large biomass production, rich supply of oxygen and carbon compounds, high uptake of pollutants, and tolerance of high pollutant loadings), and for wetland media (natural material, artificial media or industrial by-products) which has high hydraulic conductivity and high sorption capacity.

Fig. 3. Schematic of tidal flow operation (extracted from Zhao *et al.*, 2004).



The review on design and operating parameters shows that the optimal treatment performance is vitally dependent on environmental, hydraulic and operating conditions. Therefore, optimizing these conditions hooked in extensive investigation in future studies. Furthermore, research of the key pathway and mechanism like higher pollutant removal should even be taken into consideration.

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