Wetlands for Wastewater Treatment

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ABSTRACT: This article provides an update on the wastewater treatment technologies, which utilize natural processes or passive components to remove various pollutants. The focus is on the wetland systems and their applications in wastewater treatment (as an advanced treatment unit or a decentralized system), and nutrient and pollutant removal (heavy and hazardous metals, industrial and emerging pollutants including pharmaceutical and personal care products and endocrine disrupting chemicals). A summary of studies involving the effects of vegetation, wetland design and operation, modeling, hybrid and innovative systems, storm water treatment, sludge treatment, landfill leachate treatment, and pathogen removal is also included.

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Constructed wetlands (CWs) are known for their efficiency as a promising and proven technology for domestic wastewater treatment. CWs treatment is a natural biological process that has been used for more than five decades (Vymazal et al., 2016). Free water surface constructed wetlands (FWSCW), vertical subsurface flow constructed wetlands (VSSFCWs) and horizontal subsurface flow constructed wetlands (HSSFCWs) have been used for wastewater treatment to reduce various pollutants. Wetlands for the treatment of wastewater, sludge, stormwater, and leachate have been evaluated in laboratory, pilot, and full-scale studies. Jiang et al. (2016) provided a review updating the research conducted in wetlands for the year 2016. Various applications of wetlands in wastewater treatment, wetland design, and other factors affecting the performance were discussed.

In Kerala, India, a CW system using a laboratory scale model with the common wetland plant 'Reed' showed removal efficiencies for domestic wastewater treatment of 87.36, 57.93, 83.7, 86.6, 36.66, 98.28, and 61.83 %

respectively for total dissolved solids (TDS), dissolved oxygen (DO), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), Total Kjeldahl Nitrogen (TKN), nitrate, and sulphate respectively (Midhun et al., 2016). Similarly, a low cost laboratory scale integrated constructed wetland (ICW) system planted with native species, *Veronica anagallis-aquatica* sp., was compared with a non-vegetative species at various detention times, and it was found that the vegetated ICW showed higher removal efficiency over non-vegetated system: 69.12% vs. 17.12%, 67.77% vs. 16.04%, 68% vs. 16.48%, 71.19% vs. 6.56%, 71.54% vs. 14.80%, and 72.04% vs. 11.41% for total dissolved solids (TDS), total suspended solids (TSS), phosphates (PO_4), sulfate (SO_4), nitrate (NO_3), and nitrite (NO_2), respectively; while a reduction in bacterial counts and fecal pathogens was also detected in *V. aquatica* wetland at 20 days detention time (Sehar et al., 2016)

Likewise, naturally aerated and artificially aerated CWs using laboratory models filled with filter media were compared to treat domestic wastewater. It was shown that the COD removal efficiency for the artificially aerated vertical flow constructed wetland (VFCW) was 67%, higher than the naturally aerated (49%) (Prasad et al., 2016). Furthermore, a pilot-scale HCW and VCW using selected plant species (*Typha Latifolia*, and Croton Plants) exhibited the best removal efficiencies at an optimum hydraulic residence time (HRT) of 12.8 hrs. (Chandrakanth et al., 2016). The CW reduced the BOD from 370 mg/L to 59.2 mg/L, COD from 480 mg/L to 103 mg/L, Total Solids (TS) from 3200 mg/L to 1820 mg/L, TSS from 500 mg/L to 10 mg/L, and TDS from 2700 mg/L to 1810 mg/L.

The results from an artificial aeration and flow modification of a FWSCW treating wastewater from a school revealed that under low average concentrations of BOD_5 ($BOD_5 < 12.3$ mg/L), artificial aeration and flow modification exhibited a superior potential in improving the removal ratio of BOD_5 and an effective removal of ammonium-nitrogen (NH_4^+-N). (Chyan, Lin, et al., 2016). Furthermore, Wu, Lin et al. (2016) conducted a two-year experiment to examine the variation of CO_2 flux from FWSCW systems treating sewage treatment plant effluent, which showed notable removal efficiencies of COD (74.6–76.6%), NH_4^+-N (92.7–94.4%), TN (60.1–84.7%), and TP (49.3–70.7%). A combination of different treatment methods with CWs also provide an efficient treatment alternative. A treatment system consisting of a septic tank (roughing and primary treatment) and an HSSFCW as a secondary treatment has been proven to be efficient in the medium term for the removal of organic matter and TSS of domestic wastewater (Jácome et al., 2016).

A hybrid CW system consisting of four vertical and one horizontal flow subsurface CWs built for high organic content piggery wastewater treatment in a cold region showed an average purification efficiency of 95 ± 5, 91 ± 7, 89 ± 8, 70 ± 10, 84 ± 15, 90 ± 6, 99 ± 2, and 93 ± 16% for BOD_5, COD, total carbon (TC), TN, NH_4^+-N, TP, total coliform, and TSS, respectively (X. Zhang et al. 2016).

CWs are frequently used for metal removal from wastewater. In order to improve the removal efficiency, influential process parameters must be evaluated. Šíma et al. (2016) examined the removal efficiency of selected metals from municipal wastewater using a HSFCW. The highest removal efficiencies were achieved for zinc and copper (89.8 and 81.5%), respectively, which is where the precipitation of insoluble sulfides (ZnS, CuS) in the vegetation bed and the sulfate removal occurs. Lesser removal efficiencies (43.9, 27.7, and 21.5%) were exhibited for Li, Sr, and Rb, respectively; low removal efficiencies were also achieved for Ni and Co (39.8% and 20.9%). A pilot-scale subsurface compost wetland with a short HRT (7.5–14.5 h) effectively removed Zn from a mine water discharge with a removal efficiency of 67.5%, and a mean volume-adjusted removal rate of 0.92 $g/m^3/d$ (Gandy et al., 2016).

The effect of different hydraulic loading rates (HLR) was evaluated on the pollutant removal efficiency of SVFCWs. For example, Vera et al. (2016) evaluated the influence of two HRT (3.5 d and 7 d) and plant species classified by their species origin in four mesocosm CWs operated in a super-arid area. Results revealed that the HRT substantially improved, in more than 10%, the reduction efficiency of nitrogen and phosphorus forms (TN, NH_4^+-N, TP, PO_4^{-3}-P), the reduction efficiency significantly increased with *Cyperus papyrus* by more than 30%, but only for phosphorus and nitrogen.

On the other hand, Herrera-Cardenas et al. (2016) evaluated the efficiency of HSFCWs in the removal of micropollutants (caffeine, tonalide, galaxolide, alkylphenols and their monoethoxylates and diethoxylates, methyl dihydrojasmonate, sunscreen parsol and UV-15l) from a wastewater treatment plant (WWTP) discharge at mesocosm level. The study evaluated the influence of three variables at three stages (porous media, macrophyte type, and HRT of 1, 3, and 5 days) and the results exhibited a removal efficiency between 70% and 75% of the organic load and that all the micropollutants were reduced at different degrees, from 55% to 99%, with HRT being the process control variable that exhibited major effects on the treatment efficiency. Meanwhile, two HSF pilot scale CW units (one planted and one unplanted) treated secondary cheese whey with several COD influent concentrations (1,200 to 7,200 mg/L), HRT (8, 4, 2 and 1 day) and temperature (2.4 to 32.9 ∘C). The systems effectively reduced COD to 91% and 77.2% for both planted and the unplanted treatment units (Sultana et al., 2016).

CWs can also be used for tertiary wastewater treatment. A study examined the use of four large pilot scale horizontal vertical hybrid constructed wetlands (HF-VFCWs) to treat an effluent to be used for water reuse in Isfahan, Iran. (Haghshenas-Adarmanabadi et al., 2016). The results of a twelve month sampling period showed that the hybrid HF-VFCWs are very efficient in reducing BOD_5 (85 %), COD (80 %), TSS (79 %), NH_4-N (78 %), TP (74 %), and fecal coliforms (99 %). Butterworth et al. (2016) explored oxygen transfer theory, nitrification in existing CWs, and the main process control factors to be considered when applying the technology for tertiary treatment upgrades. The potential for effective ammonia removal in CWs was apparent once adequate oxygen is supplied to allow aerobic environments to predominate in the bed through loading reduction in horizontal flow constructed wetlands (HFCWs).

Mateus et al. (2016) studied the feasibility of using the source of biological energy source crop *Saccharum officinarum* (sugarcane) as vegetation and mineral wastes in four HSF pilot-scale CWs designed for the nutrients removal. Planted wetlands demonstrated removal efficiencies better than the unplanted unit, showing e efficiencies of 77% ± 4% for total phosphorus and 60% ± 12% for total nitrogen, and planted CW filled with chipped limestone 68% ± 3% for total phosphorus and 58% ± 7% for total nitrogen for one year of monitoring data. Also, Rozema, Rozema et al. (2016) assessed performance results from VFCW treating (16,620 L day^{-1} in each unit) winery wastewater and domestic wastewater at a winegrower in Ontario, Canada, with an average HLR of 22.3 mm/d and an average COD surface loading rate (SLR) of 34.0 $g/m^2/d$. Average high removal efficiencies were: for COD was 99%, 99% for carbonaceous COD, 98%TSS, 83% TP, 94% TKN, and 85% NH_4^+-N.

The role of microorganisms in the removal of contaminants in CWs is a very significant aspect of the treatment process. Wu, Han et al. (2016) studied the composition and diversity of microbes in a full-scale ICW system (three CWs in series) and examined how microbial assembly were formed by the structures and physicochemical properties of the sediments. Study results exhibited that the microbial phenotypes were more varied in the full-scale ICW than in single CWs, which contributed to the removal of organic matter and nitrogen (Wu et al., 2016). He, Guan et al. (2016) also studied the bacterial and archaeal communities in a surface water constructed wetland (SWCW) using Illumina high-throughput sequencing. The diversity and structure of both bacterial and archaeal communities demonstrated a notable spatio-temporal difference. Likewise, Syranidou et al. (2016) examined the potential of indigenous endophytic bacteria to enhance the removal efficiency of the wetland helophyte *Juncus acutus* to treat mixed pollution containing emerging organic pollutants and metals. Immunization with indigenous endophytic bacteria and specifically the consortium was shown to have enhancing effects on the plant in terms of pollutant removal and stress mitigation, proving a promising potential to improve performance in CW systems at a large scale. Microbial nitrogen removal pathways in planted (*Canna indica* L.) and unplanted IVCWs study demonstrated that nitrifying, anammox, and denitrifying bacteria were distributed in both down flow and up flow columns of the IVCWs, with the anammox process having the most N removal pathway (55.6–60.0%) in the IVCWs (Hu et al., 2016).

The use of CWs as a secondary treatment for domestic wastewater is a very appropriate technology to the needs of rural communities due to low or no power consumption, minimum operation and maintenance requirements, no noises, no offensive odors, and no presence of disease vectors (mosquitoes, etc.) (Jácome et al., 2016). For example, results from a study by Lu et al. (2016) of different CWs using four different fillers (maifanite, steel slag, bamboo charcoal, and limestone) to treat rural household sewage showed that removal efficiencies obtained good effect in meeting the effluent water quality requirements.

Wetlands for Nutrient Removal

CWs have been confirmed to be sustainable, low operating cost, and energy-efficient systems for reducing nutrient loads in wastewater. Numerous studies have confirmed the nutrient removal capability of wetlands. Single-stage CWs are considered to have a low removal efficiency for N, but control of plant species in the treatment process of CWs possibly through its effect on O_2 supply and study results proves that ammonia oxidizing archaea (AOA) improves NH_3 oxidation (Paranychianakis et al., 2016). A study examined the relations among emergent macrophyte productivity, composition of plant community, and N uptake at a 42 ha CW, showing the effect of macrophyte community composition on N processing (Weller et al., 2016). Hu, He, Ma et al. (2016) investigated the microbial N removal pathways in planted (*Canna indica L.*) and unplanted IVCWs. The nitrification, anammox, and denitrification rates were highest (18.90, 11.75, and 7.84 nmol N g^{-1} h^{-1}, respectively) in the lower-flow column of the planted IVCWs with anammox process being the main N removal pathway (55.6-60.0%).

Basic Oxygen Furnace (BOF) steel slag aggregate was studied in batch and column experiments to assess its potential use as a substrate in CWs to identify the key P removal mechanisms of BOF steel slag (Blanco et al., 2016). Batch tests with BOF slag aggregates and increasing initial phosphate concentrations displayed phosphate removal efficiencies among 84 and 99% and phosphate removal capabilities from 0.12 to 8.78 mg P/g slag. Similarly, Park et al. (2016) examined the improvement of P removal while attaining near-neutral pH (7 S.U.) in aqueous solution using steel slags and ferronickel slag (FNS) for application to CWs. Mixed slags at the BOFS-R: FNS ratio of 7:3 were applied to CWs, could achieve high P removal efficiency and near-neutral pH for meeting the acceptable drinking water quality discharge standard.

Full and intermittent aeration were studied in a pilot plant of three HSSFCWs treating primary effluent wastewater; one unit was aerated; one intermittently aerated (with a set limit of 0.5 mg/L of DO within the bed) and no aeration in the remaining unit as a control (Uggetti et al., 2016). Intermittent aeration was the most efficient operating process and the coexistence of aerobic and anoxic conditions supported by the intermittent aeration lead to the highest COD (66%), ammonium (99%) and total nitrogen (79%) removal efficiencies.

In Eastern Canada and the Northeastern USA, a performance data review of 21 studies was conducted in which 25 full-scale CWs that treated agricultural wastewater showed the following average removal efficiencies: BOD_5 81%, TSS 83%, TKN 75%, NH_4^+-N 76%, NO_3^--N 42%, and TP 64% (Rozema, VanderZaag, et al., 2016). In Icrisat, India, Datta et al. (2016) studied two full scale FWSCWs operating under similar hydraulic loadings. The initial treatment cells were vegetated with *Typha* and second treatment cells were vegetated with water hyacinth (CW-1) in one of the CWs and with water lettuce (CW-2) in the other. Results showed a steady removal efficiency of 35–40% for ammonia-nitrogen in both CWs. Results from a study that evaluated the efficiency of sand media modified with biochar and two plant species (*Melaleuca quinquenervia* and *Cymbopogon citratus*) in removing TP from sewage effluent in CWs showed a removal of TP reduction in the mesocosms loaded with SCW and septage ranged from 42 to 91% and 30 to 83%, respectively, and for PO_4-P ranged from 43 to 92% and 35 to 85% for SCW and septage, respectively (Rozari et al., 2016).

In a study focused on analyzing the relationship between the abundance of nitrogen-removing microorganisms and water quality limits of effluents, the treatment performance of an IVCW and N removal mechanism showed high removal efficiencies of NH_4^+-N (above 90%), TN (55–90%) and TOC (above 95%) under 2, 4, 6, 8 C/N ratios, in the IVCW pilot system (Fu et al., 2016). A subsurface and surface flow CWs system with a facultative pond for wastewater treatment showed a nutrient and COD removal performed by the cumulative treatment system in the study period of 50%, 55%, and 75% for NH_4+-N, TP and TN, COD, respectively (Sartori et al., 2016). Wang, Ding et al. (2016) study showed that an increase dosage of Polyvinyl alcohol (PVA)-immobilized pellets nitrifier accelerated NH_4 -N removal in CWs; with removal efficiencies of 46% NH -N, 43% TN, and 65% COD, which were significantly higher than control, while type of plants has also played a critical role in nitrification. Conclusions from a self-supplying carbon source CW study revealed that the addition of plant fermentation broth greatly improved the nitrate removal rate (Zhang et al., 2016). A study (Zheng et al., 2016) concerning the interspecific competition of *Phragmites* and *Typha* in two large CWs showed that although plants nutrient uptake accounted for a higher rate of the N removal in FWSCW, that in the subsurface flow accounted for a higher rate of the phosphorous removal. Hu, He, Wang et al., (2016) study confirmed that plant uptake and microbial conversion were the main mechanisms of NH_4+ removal in planted IVCWs (95% removal efficiency). Similarly, a sub-surface horizontal flow CWs with effluent recirculation combined with intermittent artificial aeration to treat high alkaline stripped effluent (pH > 10), reduced TN by 71% (K. He et al., 2016). Moreover, Khajah and Babatunde (2016) explored a new route of nitrogen removal called the Complete Autotrophic Nitrogen Removal Over Nitrite process (CANON) in a single stage tidal flow CW system and found that by combining the control of oxygen supply (internal recirculation, six cycles a day) and high influent inorganic carbon concentration of 150 mg/L. the CWs achieved ammonium and TN removal of 98% and 67%, respectively, from synthetic domestic wastewater.

CWs can be a reliable technology for denitrification on wastewater treatment. Zhai, Rahaman et al. (2016) evaluated a complex microbial consortium responsible for the nitrogen removal in a full-scale hybrid CW receiving municipal sewage based on the use of illumina high-throughput sequencer, 15N isotopic tracer, and three years of physicochemical analysis. The study confirmed the existence and activity of two anammox bacteria: *Candidatus* ‘*Anammoxoglobus propionicus’* and ‘*Brocadia fulgida’* in a full-scale CW and also found that simultaneous autotrophic and heterotrophic denitrification and anammox processes contributed together to the nitrogen removal. A study of the effects of Fe^{2+} and carbon to nitrogen ratio (C/N) on denitrification in CWs revealed that NO_3 removal efficiency was mostly improved by adding Fe^{2+} at low C/N ratio, but when Fe^{2+} was added at higher C/N ratios, denitrification was not significant (Song et al., 2016). Furthermore, Wang, Huang et al. (2016) explored nitrogen transformation and related microbic characteristics in a modified single stage tidal flow CW at five different shunt ratios. Shunt ratio significantly affected nitrogen removal during operation of the TFCW with the adoption of a modified step-feeding mode. When the shunt ratio was 1:2, TFCW had the best pollutant removal performance for TN.

Studies that examine the role of artificial aeration in nutrient removal in CWs were also evaluated. Wu, Lv et al. (2016) assessed whether the improved configuration of vertical up flow CWs coupled with aeration in the center part and effluent recirculation can strengthen the treatment performance of high strength anaerobic digestate supernatant. Removal efficiencies for NH_4^+-N, TN and COD were 92%, 69%, and 69%, respectively. Also, external aeration and intermittent circulation improved the nitrogen removal performance of SSFCW in landscape garden ponds (Chyan, Jhu, et al., 2016). Fan, Zhang, et al. (2016) evaluated the long-term enhanced removal efficiency of organics and nitrogen in SSFCWs with and without intermittent aeration. The high and long-term were attained in experimental intermittently aerated SSFCW compared with non-aerated SSFCW (95.6% COD, 96.1% NH_4^+-N, and 85.8% TN).

Bateganya et al. (2016) assessed the performance of SSFCWs as hotspots of nutrient transformation and removal processes between the WWTP and the receiving CW in Kampala, Uganda. *C. papyrus* coupled with batch loading improved aerobic conditions and removal rate concerning the removal of TSS, organics, and nutrients; and SSFCWs may not operate as individual treatment units, they could be a viable option and a user friendly technology alternative at a local level. Fan, Chen et al. (2016) examined the variations in abundance and structure of ammonia-oxidizing prokaryotes (ammonium-oxidizing archaea and bacteria (AOA and AOB), respectively) and how these can be related to nutrient exhaustion, by comparing a series of treatment compartments in two CWs in Taiwan. The study estimated that AOA may be more critical than AOB for reducing nutrients in the CWs.

Plant absorption is another key process for the removal of nutrients in wastewater. Borges et al. (2016) analyzed denitrification and uptake by plants in CWs with the application of 50 gm^{-3} of nitrate in a CW system composed of six units operated in batch mode and three of those units received ethanol as carbon source. The range of nitrate-nitrogen removal (in stage 1) was 11.7%–54.8% for wetlands without an ethanol source and 98.0%–99.9% for wetlands receiving the external carbon source; while on stage 2, NO_3^- removals were 3.6%–15.7% for wetlands without ethanol source and 94.7%–97.5% for wetlands with ethanol added to the system, also resulting in increased nitrite concentrations from the treatment process (Borges et al., 2016).

Wetlands for Pathogens and Viruses Removal

There are approximately 60 known general types of waterborne human pathogens including virus, bacterial pathogens, protozoa, and multicellular eukaryotic parasite (Wu, Carvalho et al., 2016). Most of these pathogens can survive in wetlands for a prolonged period of time. Although CWs have shown to be highly efficient in the removal of organic matter and nutrients, pathogen removal is seldom the main target in these systems (Alexandros and Akratos, 2016). Rachmadi et al. (2016) investigated several human enteric viruses as well as a plant virus, pepper mild mottle virus (PMMoV) in two SFW. Higher concentrations of PMMoV were discovered in the inlet of wetlands for all the viruses tested (10^4 to 10^7 genome copies/L), but exhibited almost no removal; the enteric virus ranged from 1 to 3 $\log_{10}$; and the polyomavirus were almost completely removed (Rachmadi et al., 2016). On the other hand, Nemhtow et al. (2016) studied the removal of microbial pathogens from pig manure in a sludge treatment wetland. Petterson et al. (2016) reported that the annualized probability of infection estimates with the benchmark (1 x 10^{-4}) indicated that viral pathogens were the primary concern after evaluating three-full-scale stormwater treatment systems on the pathogen removal efficacy.

Vegetation plays an important role in the removal of pathogens in wetlands. *Typha latifolia*, *Cyperus papyrus*, *Cyperus alternifolius*, and *Phragmites mauritianus* have shown to remove more than 98% of both Salmonella species and E.coli (Kipasika et al., 2016). *C. alternifolius* and *T. latifolia* have shown to be more effective than *C. papyrus* and the least effective is *P. mauritianus*. *Daphnia magna* is another type of plant used in CWs for biofiltration that can reduce the survival of enteric bacteria associated with fecal pollution (Norgaard and Roslev, 2016). Furthermore, Vivant et al. (2016) treated effluent from a wastewater treatment plant on a vegetated (*Typha* or *Phragmites*) wetland, and they noticed that the E. coli hardly survived in the vegetated areas during the colder season. In contrast, Sheludchenko et al. (2016) used CWs as a post-treatment system for pathogen removal (following treatment within a maturation pond), which resulted in a limited removal of viable bacteria with the CWs.

Anaerobically treated effluent is often nutrient-rich and contains high concentration of unacceptable pathogens, which usually requires a post-treatment step as CWs (Valipour and Ahn, 2016). Unfortunately, living organisms in wetlands can be affected by this treated effluent, such is the case of the parasitism found in *Sander lucioperca* (Percidae) (Movahed et al., 2016; Gupta and Kaur, 2016). Ibekwe et al. (2016) used CWs for the removal of pathogens and nutrients from swine waste. Canonical correspondence analysis (CCA) demonstrated that different bacterial populations were significantly impacted by ammonium, phosphate, COD, TSS, and TDS removal, with 54% of the removal rate explained by $NH_4^+PO_4^{3-}$ (Ibekwe et al., 2016).

The restoration of aquatic macrophytes can increase bacteria diversity and the surface quantity of biofilms and therefore bacteria diversity (Pang et al. 2016). Waller and Bruland (2016) investigated the ability of CWs to treat fecal indicator bacteria (thermotolerant coliforms and enterococci) during low and high precipitation conditions, and it was observed that the levels of both coliforms and enterococci increased during storm events due to the increased mobilization of sediment. Furthermore, Sartori et al. (2016) reported a removal of E. coli that ranged from 98% during quiescence season to more than 99% in growing season (2-3 orders of magnitude).

Wetlands for Emerging Pollutants Removal

Emerging contaminants (endocrine disrupting chemicals, pharmaceutical, and personal care products) are considered harmful to human health, aquatic life, and ecosystems; and often difficult to remove by conventional treatment methods. The discharges of treated wastewater are one of the major sources of trace organic contaminants (TrOCs) in the aquatic environment, so there is an urgent need to assess and compare the removal efficiencies of the most widely used wastewater treatment technologies for the elimination of these compounds from sewage (Melvin and Leusch, 2016). Constructed wetlands can be used as an alternative method to reduce emerging contaminants efficiently. Pesticides are one category of the EDCs that can be successfully removed by wetlands.

A study by Lv, Zhang, Zhang et al. (2016) investigated the removal of the pesticides imazalil and tebuconazole at representative concentration levels (10 and 100 μg/L) in saturated CW planted with five wetland plant species (*Typha latifolia*, *Phragmites australis*, *Iris pseudacorus*, *Juncus effunisus* and *Berula erecta*) at various HLRs during the summer and winter. The study results showed that imazalil and tebuconazole removal varied greatly with the season and plant species, and pesticides removal was performed by substrate sorption with low phytoaccumulation, and nitrifiers may perform an active role in the biodegradation of these pesticides. Likewise, Lv, Zhang, Casas et al. (2016) research compared the removal of the two pesticides, imazalil and tebuconazole, by four wetland plants (*Typha latifolia*, *Phragmites australis*, *Iris pseudacorus* and *Juncus effusus*),aiming to understand the possible removal mechanisms. Results from the 24-day study 24-day showed that the tebuconazole removal efficiencies (25%–41%) were comparatively lower than those for imazalil (46%–96%) for all plant species (Lv, Zhang, Casas, et al., 2016).

An integrated CW system based on the synergetic action of solar photocatalytic oxidation with pilot scale surface flow CWs used for the purification of wastewater contaminated with pesticides, specifically the herbicide clopyalid, showed that emerging pollutants at low concentrations can be effectively degraded and estrogenic activity can be significantly reduced (Berberidou et al., 2016). Furthermore, a ditch with a package of straw placed in its centre and a vegetated pond installed in grass cover bands showed removal efficiencies monitored for Isoproturon and 2,4-MCPA ranging from 61.0 to 100 %, but lower removal efficiencies ranging from 1.4 to 43.9 % were observed for boscalid and tebuconazole (Vallee et al., 2016). Three integrated recirculating constructed wetlands (IRCWs) planted with and without *Cyperus alternifolius*, with Iron (Fe)-impregnated biochar added as a main substrate efficiently removed four pesticides (chlorpyrifos, endosulfan, fenvalerate, diuron) (Tang et al., 2016). Maximum pesticide removals (99%) were attained when Fe-impregnated biochar was introduced to the IRCW, followed by the planted (64%–99%) and plant-free IRCW

(45%–99%). A study by Maillard et al. (2016) concerning the impact of batch flow versus continuous flow methods on the elimination of the chiral herbicide *S*-metolachlor (*S*-MET) and hydrological tracers (bromide, uranine and sulforhodamine B) in CWs showed that plant uptake, sorption, photodegradation, and presumably biodegradation were prominent under batch mode. Meanwhile, Stang et al. (2016) focused their study on the dynamics that oversee the interaction between aquatic macrophytes and pesticides in aqueous environments and the study demonstrated that sorption and desorption of pesticides to and from aquatic macrophytes and macrophytes can characterize a temporary reduction for pesticides.

The analysis of the responses and suitability of a plant (*Canna indica*), substrate enzymes and microbial communities in bench scale HSCWs loaded with different concentrations of the Triazophos (TAP) pesticide)(0, 0.1, 0.5, and 5 mg/L) indicated that TAP stimulated the activities of superoxide dismutase (SOD) and peroxidase (POD) in the *C. indica* roots(Wu, Feng, et al., 2016).

Phenolic compounds are classified as priority pollutants due to toxic and carcinogenic effects, thus, they should be removed from water sources. Current experience suggests that CWs can effectively remove a series of several phenolic compounds from sewage, even at high concentrations (Stefanakis and Thullner, 2016). Six pilot scale CW units of two types, HSF and VF, designed for the removal of five EDCs: Bisphenol A (BPA), Nonylphenol (NP), Nonylphenol monoethoxylate (NP_1EO), Nonylphenol diethoxylate (NP_2EO), and Triclosan (TCS) exhibited enhanced removal efficiencies for, NP_1EO, BPA, and NP_2EO in HSF-R by 51.4%, 49.6%, and 48.4%, respectively, in HSF-C was 99.0%,50.0%, and 66.0%, and in HSF-Z 98.9%, 55.4% and 80.3%, respectively. In the VFCWs, the average removal efficiencies were: −12.5%, 45.6%, 41.5% and 72.2% in VF-R, 96.2%60.0%, 99.0% and 99.8% in VF-C, and 95.6%, 59.0%, 98.7% and 99.8% in VF-Z for NP, BPA NP_1EO, NP_2 EO, respectively (Papaevangelou, Gikas, Tsihrintzis, Antonopoulou et al., 2016).

CWs have the capability of removing pharmaceutical, and personal care products (PPCPs) in large quantities, including pharmaceutical drugs, cosmetics, and fragrances. A wetland with *P. stratiotes,* and *E. crassipe* efficiently removed six pharmaceuticals drugs and PPCPs, including ibuprofen (IBU), carbamazepine (CBZ), sulfamethoxazole (SMX), sulfadiazine (DIA), sulfa-methazone (SMZ), and triclosan (TRI) using an HRT of 13 d, but the efficiency was much lower at higher concentrations due to the toxic effect of PPCPs to wetland plants (Lin, and Li., 2016).

Yan, Feng et al. (2016) studied the potential of CWs in removing the pharmaceutically active compounds (phACs) (car- bamazepine, sulfamethoxazole, ofloxacin, and roxithromycin) and the effects of phACs on the photosynthesis and antioxidant enzymes of *Cyperus alternifolius* in CWs. A two-stage CW (adsorption of the CW medium surface followed by slower process of interaction with plants and microorganisms) improved the removal of PhACs in CWs and demonstrated that *C. alternifolius* can uptake and withstand certain PhACs (Yan, Feng, et al., 2016). Similarly, Yan, Gao et al. (2016)

analyzed *C. alternifolius* leaves exposed to PhACs in CWs, which showed that *C. alternifolius* can tolerate multiple PhACs up to 500 µg/L and be useful for phytoremediation.

HSFCWs planted with cattail and unplanted control mesocosms showed a significant removal efficiency ($p < .05$), enhancing the planted mesocosms (78.5%) when compared to those in the unplanted beds (57.9%) (Zhang, Luo, et al., 2016). Three rural CWs used for the treatment of 32 multi-class PPCPs showed removal efficiencies that exhibited large variability between 11 and 100% for anti-inflammatories, 37 and 99% for β-blockers, and 18 and 95% for diuretics (Chen, Vymazal et al. 2016).

An investigation by Li, Wu et al. (2016) evaluated the bacteria associated with co-metabolic and metabolic degradation of ibuprofen in a horizontal SFCW system by high-throughput pyrosequencing analysis and revealed that the plants promoted the microbial degradation of ibuprofen, especially at the downstream zones of wetland. In a similar study, Li, Zhang et al. (2016) studied the removal mechanisms of ibuprofen related with plants in a HSSFCW and the findings provided an understanding into the processes of phytoextraction, phytotransformation, and rhizodegradation of ibuprofen by *Typha angustifolia*. Nowrotek et al. (2016) studied a CW start-up for removal of diclofenac (DCF) and sulfamethoxazole (SMX) in planted and unplanted microcosm down flow (DF)-CWs and observed a moderate removal efficiency for DCF (approx. 50%) and relatively low efficiency of SMX (24-30%).

Free water surface CWs are also extensively used for effective removal of antibiotics and hormones such as estrogens, progesterone, and testosterone. The removal of antibiotics in CWs can be accomplished through physicochemical decomposition, adsorption by wetland soil and plants, photodegradation, and biodegradation (Choi et al. 2016). HSFCWs planted with *Cyperus alternifolius* L. with various design parameters significantly reduced 7 antibiotics and 18 antibiotic resistant genes in domestic wastewater (with 17.9% to 98.5% of removal rate), while those for the total antibiotic resistance genes (ARGs) varied between 50.0% and 85.8% by the mesocosm-scale CWs (Chen, Wei, et al., 2016). Nine CWs microcosms (divided into three treatment units) significantly reduced the antibiotics enrofloxacin and oxytetracycline (>99%) in nine weeks of CWs treatment of aquaculture wastewater fed with 100 µg/L of each selected antibiotic (Bôto et al., 2016). Furthermore, a CW with *Juncus acutus* L efficiently removed antibiotics (CIP and SMX), bisphenol A (BPA), and heavy metals after 28 days, without *J. acutu* showing traceable phytotoxicity symptoms, in higher concentrations than those that are usually detected in industrial or hospital sewage (Christofilopoulos et al., 2016).

CWs used to treat antibiotics in livestock wastewater showed average removal efficiencies of 85% for sulfamet-hazine (SMA), 81.86% for sulfathiazole (SFI), 49.43% for sulfamethoxazole (SMZ), 29.47% for chlortetracycline (CTC), and 27.26% for enrofloxacin (EFX), while trimethoprim (TMP), tetracycline (TC), and tetracycline (TC) were hardly removed. (Choi et al., 2016).

A study by Dong et al. (2016) examined the occurrence and removal efficiency of 19 antibiotics (including four macrolides, eight sulfonamides, three fluoroquinolones, three tetracyclines, and trimethoprim) four treatment systems: two ecological CWs and stabilization pond (SP), an activated sludge (AS) treatment plant, and a micro-power (MP) biofilm system.. Study results displayed the AS and CW outperforming the MP and SP treatment systems and the AS outperformed the CW process in terms of antibiotics removal. Both AS and CW processes showed better performance in summer than in winter, indicating biological degradation and temperature could play an important role in antibiotics removal (Dong et al., 2016). Dai et al. (2016) examined the efficiency of 12 pilot-scale CWs with different configurations on the removal of hormones estrone and estradiol from raw domestic sewage. Estrogens were more effectively removed by the 12 CWs during summer and even during the winter, experiment showed that target estrogens were efficiently removed by wetland substrate under anoxic conditions through exothermic sorption and degradation. (Dai, Yang, et al., 2016).

CWs have also been evaluated for the removal of surfactant emerging contaminants in greywater. Studies were conducted on HFCW and VFCW systems for the treatment of 2.5 m^3/day of greywater with an HRT ranging from 8.9 days to 14.9 days (Ramprasad and Philip, 2016). Removal efficiencies monitored over a year for the emerging contaminants Sodium dodecyl sulphate (SDS), propylene glycol (PG) and trimethyl amine (TMA) for various operating parameters for HFCW were around 89%, 95% and 98%, respectively, and for HFCW, were 85%, 90% and 95% for SDS, PG and TMA, respectively.

Wetlands for Stormwater Treatment

CWs can reduce stormwater volume and improve water quality, including the removal of soluble reactive phosphorus which can be improved by extending infiltration versus surface flow (Vacca et al., 2016). Niu et al. (2016) studied a free water surface wetland to control non-point source pollution from stormwater. As the stormwater went through the wetland, TSS, TCOD, TN, and TP were reduced by 85%, 57%, 6%, and 68% on average, respectively. Hartshorn et al. (2016) combined floating treatment wetlands with stormwater detention basins to enhance nutrient removal with CWs in addition to the benefits of flood mitigation, downstream erosion control, and improved aesthetics, and recreational uses of wet detention basins. Additionally, Adyel et al. (2016) assessed the nutrient attenuation ability of SCWs that combined surface flow and laterite-based subsurface flow attenuating up to 62% TN and 99% TP loads during dry weather and 76% TN and 27-68% TP during episodic flow pulses. Zhao, Zhao et al. (2016) constructed a lab-scale baffled HSSFCW. with adsorptive media/substrate to treat highway runoff. In terms of adsorption efficiency, vesuvianite was found to have the highest removal efficiency of 86.5%, 68.1%, 78.25%, 95.2%, and 64.85% for TSS, COD, TKN, NH_4^+-N, and TP respectively.

Merriman et al. (2016) monitored a stormwater constructed wetland (SCW) during the first year after construction and reported the potential of the SCW in volume reduction, TSS, and oxidized nitrogen ($NO_{2,\ 3}$) treatment. Total ammoniacal nitrogen (TAN), organic nitrogen (ON), TP, and TN were fully developed after the first growing season. On the other hand, Al Rubaei et al. (2016) monitored the performance of SCWs during 19 years, treating 320-ha urban catchment. Stormwater was still effectively treated after 19 years, removing 89-96% concentrations of Cd, Cu, Pb, Zb, TSS, and TP with only required maintenance for sediment removal. Further, Karjalainen et al. (2016) studied the use of wetlands to remove peat extraction contaminants found in runoff. They noticed that it did not only mitigate the negative effects on downstream water bodies, but that they also remained functional 14 years later.

According to Natarajan and Davis (2016), a wetland can be formed from a transitioned infiltration basin (or failed infiltration basin), which can control storm runoff and volumes by occasionally reducing the downstream hydrologic and pollutant loads. Li et al. (2016) examined the purification capabilities of HSFCW and integrated flow (wave pattern flow) constructed wetlands (IFCW) systems on urban rainwater runoff. Results showed that the purification effect of IFCW is 7% higher than that of the HSFCW; however, this study just investigated the purification effect of constructed wetlands. Yi et al. (2016), on the other hand, accomplished a 92.47% removal of phenanthrene from industrial runoff using a pilot-scale horizontal subsurface flow constructed wetland (HSSFCW) through enzyme activity and soil microbial community structure concluding that Proteobacteria and Bacteroidetes were the dominant phyla of the bacteria community, which may be related to the biodegradation of phenanthrene. In addition, SCWs have shown potential for removing fecal pathogens, such as E. coli, somatic coliphages, and *Clostridium perfringens* in runoff (Petterson et al., 2016).

Stormwater constructed wetlands (SCWs) can also serve as habitat for living organisms. Scheffers and Paszkowski (2016), compared amphibians in SCWs with those of natural wetlands. They noticed that egg masses, larvae, and metamorphs were lower inSCWs than in natural wetlands; however, metamorphs exhibited larger body size in SCWs.

Vegetation in Wetlands

Roy et al. (2016) affirmed that the basin morphometry of constructed wetlands is not typical of naturally formed wetlands, which explains the difference in vegetation composition. Interestingly, they determined that plant community composition is a better indicator than species richness when monitoring wetland conditions. Therefore, several studies have been presented on the selection of the most suitable plant communities for CWs. Sieben, Collins, Corry, et al. (2016) presented an overview and classification of the vegetation in specific type of wetland habitats in semi-arid regions of South Africa. From the two types of resilience (altered hydrology and physical human disturbance), it was concluded that terrestrial species are the most resilient to hydrological impacts when compared to those of hydric species. Also in South Africa, Pretorius and Brown (2016) studied the main drivers of vegetation species in different types of wetlands and determined that the substrate type and hydrological regime are the major determinants of vegetation communities. It is suggested that the different types of wetlands should be evaluated individually for better results because vegetation composition vary with the wetland type (Pretorius and Brown, 2016). In addition, the growth of tall indigenous vegetation in wetlands can be used as fibers for construction and traditional crafts; therefore, the immoderate use of these wetlands may accelerate their deterioration (Sieben, Nyambeni, et al., 2016).

An area of consideration in wastewater treatment is the role of microfauna in bacteria and pollutant removal in CWs. Microfauna community structure can be affected by vegetation and flow type (Pedescoll et al., 2016; Meng et al., 2016). *Typha angustifolia* and *Phragmites australis* are two different types of microfauna used in CWs. Carballeira et al. (2016) investigated the influence of plants and plant species on the treatment efficiency of shallow horizontal subsurface flow CWs treating municipal wastewater. The five CW units in parallel consisted of an unplanted CW and the other four were planted with (a specie per CW) J. *effussus*, *Iris pseudacorus*, *Thypha latifolia*, and *P. australis*; which resulted in a removal of 89-93% TSS, 83-88% COD, and 90-95% BOD_5. The highest removal of BOD_5 (94%) was noticed in the CW planted with *P. australis*, and they concluded that the effect of plants on the removal efficiency of organic matter was loading rate dependent (Caballeira et al, 2016). Surprisingly, *P. australis* has been considered an invasive species in south central Nebraska, USA (Mykleby et al. 2016). Rodriguez and Brisson (2016) explored the effect of combining *P. australis and Phalaris arundinacea* to improve pollutant removal; however, no evidence of treatment improvement was found when combining both species. On the other hand, Klomjek (2016) investigated pollutant removal using a vertical subsurface flow CW planted with Giant Napier grass (*Pennisetum purpureum* cv. King grass) and Dwarf Napier grass (*Pennisetum purpureum* cv. Mott), which resulted in more than 70% removal of COD and TKN with 2 and 5 cm/d hydraulic loading rate (HLR). Moreover, Turker et al. (2016) investigated the role of plants and vegetation composition in CWs on the boron removal. The results indicated that a maximum of 64% removal of boron can be achieved by a monoculture CW planted with *T. latifolia*. Zhao, Cie et al. (2016) performed a lab-scale study to select a suitable wetland plant species for the removal of triclosan. They noticed that emergent plants can remove more than 90% of triclosan, while floating plants showed the lowest stable process with approximately 80% removal (Zhao, Cie et al., 2016). Although this study showed promising data, a higher scale should be evaluated before its application.

Vegetation in CWs also plays an important role in the removal of nutrients from wastewater. However, the removal efficiency mainly depends on the type of plants. For example, Leung et al. (2016) compared efficiency of CWs on treating mangrove plants (*Aegiceras corniculatum* and *Bruguiera gymnorrhiza*) and non-mangrove plants (*Acorus calamus*, *Canna indica*, and *Phragmites australis*) in different cultural arrangements. Mangrove CWs planted with *A. corniculatum* showed higher application values than the non-mangrove CWs to treat toxic wastewater. Similarly, Ge (2016) investigated the influence of seasonal change on contaminants removal and harvesting on three floating treatment wetlands (FTWs) planted with emergent macrophytes. *Thalia dealbata* outperformed *C. indica* and *Lythrum salicaria* in the removal of total nitrogen (69.96%) and total phosphorus (82.4%) from urban stormwater runoff sewage. Additionally, water hyacinth plant has also shown significant ability to remove nutrients from wastewater (Patil et al., 2016).

Due to the fact that most of the world's water is saline and there are numerous coastal wetlands, salt-tolerant plants are very important for wetland ecosystem management. Sieben, Collins, Mtshali, et al. (2016) described 29 saline wetland communities and further summarized them into 15 communities, which were mainly vegetated with salt-tolerant lawn grasses, sedges, and halophytic shrubs. It was discovered that wetness has the highest effect in the vegetation patterns as it is negatively correlated with electrical conductivity. Additionally, sodium was found to have the greatest influence on species composition. According to Jones, Stagg, et al. (2016), tidal saline wetland systems experience anthropogenic and natural hydrologic alterations that affect the success of plant regeneration; however, macrophytes accomplish this regeneration through combination of vegetative propagation and sexual reproduction. Macrophytes have also shown capabilities for carbon accumulation or sequestration (Means et al., 2016; White and Visser, 2016). Means et al. (2016) estimated a carbon storage potential of 344 g C/m^2 in the most diverse mesocosms (four different plant species) and 610 g C/m^2 in monoculture ones. In monocultures, *Juncus effusus* and *Mimulus ringens* stored more carbon as biomass than the other species, *Carex vulpinoidea* and *Eleocharis obtuse*.

In order to provide an effective tool for the evaluation of long term natural wetland conditions in Eastern Africa, Moges, Beyene, Kelbessa et al. (2016) developed a plant-based index of biological integrity that included 122 plant species belonging to 37 families, and therefore, facilitate the management of wetlands. Agricultural and urban impaired wetland types showed higher level of species richness due to the anthropogenic activities that enhance the establishment of colonizer species, which exterminate native plant species. In the United States, erosion is a major problem for CWs, which is degrading playa-wetlands in this semi-arid country. Haukos et al. (2016) evaluated the effectiveness of vegetative buffers surrounding playa-wetlands in removing metal, nutrients, and dissolved/suspended solids from runoff. Buffers removed about 70% of P, 78% N, 83% TSS, and 58% TDS suggesting that vegetation buffers could be an economical conservation tool for playa-wetlands (Haukos et al., 2016).

Wetlands for Pollutant Removal

Studies that evaluated or improved removal performance of pollutants in CWs were reviewed (Verma et al., 2016). Heavy metal pollution on an aquatic ecosystem due to anthropogenic activities poses a major threat to its viability and environmental sustainability. CWs for domestic wastewater treatment in a school and single-family residence showed to be efficient for Cu and Zn (between

25% to 75% for Cu; and between 0% to 100% for Zn) removal (Schirmer et al., 2016). The wetland physical medium (gravel and sand filter) allied to the biological system (macrophyte) was shown to be the major factor responsible for better metal removal rates.

Rezania et al. (2016) studied the phyto-accumulation potential of four species of free-floating macrophytes: *Pistia stratiotes*, *Eicchornia spp*., *Lemna spp*. and *Salvinia spp*. Phytofiltration (rhizofiltration) was the only method used for heavy metal uptake from water. The removal efficiency of free-floating aquatic plants was better than submerged and emergent plants. Moreover, Verma et al. (2016) studied the metal accumulation potential of Cd, Fe and the biochemical aspects of aquatic macrophytes *Eichhornia crassipes* and *Trapa natans* as model phytoremediation tools. *Eichhornia crassipes* and *Trapa natans* have great potential to remove heavy metals by phytoremediation and can be utilized for the mitigation of heavy metals contamination in an applied ecosystem.

Furthermore, Syukor et al. (2016) showed that the combination of Limnocharis flava and Tyha angustifolia and longer retention period (13 days) improved heavy metal removal of copper (79.07%), magnesium (68%),, cadmium (61.07%) , chromium (69.17%),, nickel (74.87%), iron, (81.17%), lead, (62.07%) and zinc 63%). . CWs with fifteen wetland plant species were studied for the treatment of moderate and heavy Cd-polluted sewage (0.5 mg/L and 1.0 mg/L, respectively), exhibited Cd removal efficiencies of more than 90%, 23.5%, and 16.8% for 0.5 and 1.0 mg/L^{-1} Cd concentrations in wastewater, respectively (Liu, Zhang, et al., 2016). Leachate generated in compositing facilities usually contains high concentrations of heavy metals that are seriously harmful to the environment and public health (Bakhshoodeh et al., 2016). A HFCW with vetiver plants treating the leachate from a composting facility showed an average removal efficiency for heavy metals between 29.7 and 52.7%, in this ascending order of Cr > Cd > Cu > Ni > Zn > Pb (Bakhshoodeh et al., 2016).

Türker, Türe, Böcük, Çiçek et al. (2016) analyzed the effects of plants and vegetation composition on boron (B) removal pathways and the role of plants on physicochemical parameter of wastewater in CWs under ambient conditions in the world's largest B reserve area. The maximum B removal was attained by a monoculture CW planted with *T. latifolia* with ae removal efficiency of 64%, while the lowest B removal efficiency (38.1% removal rate) was measured in unplanted unit during the experimental period. On the other hand, Vymazal et al. (2016) examined the quantity of heavy metals sequestered in the aboveground biomass of *Phragmites australis*, revealing that the quantity of heavy metals accumulated in the plant biomass represents often only minor fraction of the inflow annual load, but in other studies, this fraction is rather high, particularly for zinc (up to 59%), more rarely for cadmium (55%) and chromium (38%).

CWs have also been proven technology in the treatment of organic pollutants present in wastewater. Al-isawi et al. (2016) evaluated for the first time the optimal performance of a six year VFCW system treating domestic sewage and the subsequent recycling of the outflow for chilies irrigation (De Cayenne; *Capsicum annuum*) grown in a greenhouse. VFCWs subject to hydrocarbon pollution provided marginal wastewater treatment. However, Ballesteros et al. (2016) evaluated the performance of a surface flow type CW for the removal of benzene from contaminated water from a leaking underground petroleum storage and determined the efficacy of a common reed plant *Phragmites karka* in benzene removal. Planted and unplanted CWs were acclimated with benzene for 16 weeks and tested for an 8-d hydraulic retention time at benzene levels of 66 and 45 mg/L. The planted CW performed better (47% planted vs 31% unplanted) and gave reliable and stable results. Furthermore, artificially aerated and non-aerated CWs significantly reduced nitrobenzene (NB) from 140 mg/L to less than 2 mg/L, a removal of 98%; but once the influent NB concentration increased to 280 mg/L, the artificial aerated wetland had a higher removal efficiency (82%) when compared to that of the unaerated wetland (71%); while with glucose enhanced the NB removal to 95% in the artificial aerated wetlands and 92% in the unaerated (Kirui et al., 2016). Wang, Gu et al. (2016) evaluated the performance of plant and immobilized microbes on pyrene removal and soil microbial functional diversity of co-contaminated soil. The removal ratios of pyrene in the soil with plant, soil with immobilized microbes and soil with both were 51.5 ± 0.69%, 55.2 ± 3.8%, 63.2 ± 1.29% respectively, and were higher than soil control (CK) (31.2 ± 1.5%). Huang et al. (2016) also found an effective approach to treat PAH-contaminated wetlands performing an isolation of two strains (*Pseudomonas putida* PYR1 and *Acinetobacter baumannii* INP1). The cells of PYR1 and INP1 were immobilized in cinder beads for pyrene and indeno (1,2,3-cd) pyrene biodegradation in wetland; which reduced 70.7% and 80.9% of pyrene and indeno (1,2,3-cd) pyrene respectively, while the free cells reduced only 58.2% and 55.3% after 30 days of operation.

The presence of sulfate in wastewater effluent is a challenge for wastewater treatment and water reuse. Chen, Wen et al. (2016) investigated sulfur (S) removal and its conversion in five batch CWs treating secondary effluent. The results showed that the plant cattail (*Typha latifolia*) had an insignificant effect on sulfate removal, while the carbon-rich litter produced a significant improvement in sulfate removal.

A study evaluated the treatment performance of a CW used to treat disinfection by-products precursors. The results showed average removal efficiencies for COD, NH_4^+-N, TN, dissolved organic carbon (DOC), ultraviolet absorbance at 254 nm (UV_{254}), THMs, and HAAs were 38.40%, 41.70%, 25.90%, 30.96%, 47.58%, −20.52%, and 25.22% respectively (Yang, Lu, et al., 2016). A constructed microbial fuel cell coupled constructed wetland (CW-MFC) for Methyl Orange (MO) (an azo dye) decolorization and further removal, showed a MO decolorization rate of open and closed-circuit CW-MFC were 75.59% and 87.60%, respectively, while the N,N-Dimethyl-p-phenylenediamine (DMPD) removal rate in the anode layer of open and closed-circuit CW-MFC were 84.96% and 96.33%, respectively (Z. Fang et al., 2016).

Wetlands Design and Operations

Various treatment configurations and a wide range of treatment capabilities make CWs a sustainable on-site approach for sewage treatment. A three stage simulated CW developed to evaluate the removal efficiency of plants in wetlands exhibited high removal efficiencies for TDS (67.27%), TSS (86.10%), BOD (87.81%), NO_3-N (81.28%), and PO_4-P (83.54%) at a detention time of 72-hrs (Upadhyay, Bankoti, et al., 2016).

Weerakoon et al. (2016) studied the effects of HLR variation on the removal of pollutants in three continuous VSSFCWs beds packed with 10 –20 mm gravel media, installed in a tropical region. The performance of these wetland mesocosms showed that both systems can provide a significant pollutant removal with a buffering capacity of HLR up to 25 cm/day. Moreover, a simulated HFCW with gravel medium and aquatic plants *Typha latifolia* and *Polygonum hydropiper* improved the removal efficiency of BOD_5, TDS, TSS, PO_4^{3-}-P, and total nitrogen in CW planted with *T. latifolia* by 88.20, 61.9, 72.12, 74.23 and 66.78%; however, with *P. hydropiper*, reductions were 79.47, 53.47, 55.46, 60.40 and 52.87%, respectively, at 8 d retention time (Upadhyay, Singh et al., 2016). Similarly, three VFCWs operated under different regimes for almost 3 years treating wastewater from a university campus proved higher removal capacity and better performance than the unplanted one; and seems to operate better under warmer conditions (Papaevangelou, Gikas, and Tsihrintzis 2016).

A study conducted by Babatunde et al. (2016) revealed that the design and configuration of multi-stage SSFCWs may influence the treatment performance and the microbial composition in the systems evaluated. Results indicated similar removal efficiencies can be achieved using either a 3 or 4 stage configuration when organic loading rates are up to 100 g BOD_5/ (m^2 ·day). . In removing P, the effect of changes in configuration was less noticeable. Based on the study performance results, at least 80% P removal can be achieved for loadings up to 10 g P/(m^2·day).

The influence of DO as an important parameter in the pollutant removal efficiency of CWs was also examined. A study introduced a comprehensive analysis of DO supply and distribution characteristics in different types of CWs (Liu, Hu, et al., 2016). The study concluded that atmospheric reaeration (AR) served a key role in oxygen intensification. Similarly, two laboratory-scale VFCWs combined with algal pond displayed greater contaminant removal from wastewater at low temperatures; due to oxygen enrichment and DO increase by algae via photosynthesis (Zhao, Song, et al., 2016).Furthermore, Araya et al. (2016) proved that intermittent artificial aeration enhanced the oxidation conditions in CWs and varying the support media from gravel to natural zeolite significantly improved the NH^+_4 −N removal efficiency by up to 60%. In another study, intermittently aerated VFCWs operated at different aeration times (between 1 h/d to 10 h/d) and aeration rates (between 0.1 L/min to 2.0 L/min) revealed that the optimum aeration time and aeration rate were 4 h/d and 1.0 L/min, which could generate the proper aerobic and anoxic areas in CWs with higher removal of COD (97.2%), NH_4^+-N (98.4%) and TN (90.6%) attained at the same time during the experiment (Wu, Fan, Zhang, Ngo, Guo, Hu et al., 2016).

A VSSF-CW for sewage effluent treatment in an eight-month experiment under different operating conditions including: vegetation, media type (gravel or vermiculite), and mode of sewage feeding (continuous or batch), showed that plants had a significant effect ($P < 0.05$) on the removal efficiency of all pollutants (Abdelhakeem et al., 2016). The type of media is an important factor for the removal of NH_4^+, TP, and dissolved phosphorus (DP) while the mode of feeding had no significant effect in removing COD, BOD, TP, and DP under all tested conditions and the batch mode of feeding had a significant ($P < 0.05$) effect only on TSS. Furthermore, Kadaverugu et al. (2016) studied the importance of sand, marble chips, and wetland plant *Typha latifolia* in prototype CWs developed in polyvinyl chloride columns at varying HRTs for wastewater effluent reuse in agriculture. Organic pollutants (BOD_5 and COD) concentrations were reduced by sand and *Typha latifolia*, and turbidity and phosphates were significantly reduced by the sand through filtration and adsorption, while sulfates were significantly reduced by marble chips (Kadaverugu et al., 2016).

The porous media in CWs may suffer from gradual clogging that may result in hydraulic failure and/or loss of treatment efficiency. Aiello et al. (2016) analyzed the hydraulic aspects of HSSFCWs to investigate the clogging phenomena through *in situ* measurements of hydraulic conductivity of the gravel bed, quantification of accumulated clog matter and flow paths visualization by means of tracer tests. One bed had been operating for eight years while the other two were operated for two years. Despite a lower hydraulic conductivity of the porous media and higher concentrations of total solids in the oldest CW, these results should be indicative of some degree of medium clogging, the treatment performance remained largely unaffected after eight years of operation.

The performance of CWs in wastewater treatment may be influenced by evapotranspiration (ET). A pilot HSSFCW composed of three separate units, one planted with *Cyperus alternifolius* L., one planted with *Typha latifolia L.*, and an unplanted unit was treating domestic wastewater from an activated-sludge wastewater treatment plant. The *T. latifolia*-unit showed higher cumulative evapotranspiration rates (3579 mm) than the *C. alternifolius*-unit (3142 mm) (Tuttolomondo et al., 2016).

Wetland Modeling

Several models have been developed and/or modified to understand and enhance wetland management practices. Important decisions are often made based on prediction-model responses. These predictions often prevent or better prepare for catastrophic events. For example, the Dynamic Interactive Vulnerability Assessment Wetland Change Model (DIVA_WCM) predicted a loss of 46-59% of global coastal wetland stocks by 2100, with 50 cm of sea-level rise (Spencer et al., 2016). Response surface methodology (RSM) three factor central composite design (CCD) was applied to predict the experimental variables of palm oil mill secondary effluent (POMSE) concentration, Vetiver plant density, and time (Darajeh et al., 2016). The results confirmed that the empirical model derived from RSM can be used to describe the relationship between the independent variables and response (Darajeh et al., 2016). Furthermore, aquatic ecological models are used for ecosystem management of wetlands and for pollution control due to the fact that they can simulate material flows and structural ecosystems (Zhao, Liu, et al., 2016). An aquatic ecological model was developed using the STELLA (Structural Thinking, Experiential Learning Laboratory with Animations) modeling software, demonstrating that the simulation precision of the model is sufficient to reflect the trend of changes in the aquatic ecological indexes (Zhao, Liu, et al., 2016). Jones, Hawkins, et al. (2016) concluded that the use of model-based indices of biological integrity for wetland plants can increase confidence in wetland assessments by reducing assessment errors associated with natural variation in plant metrics.

Two generic models for evapotranspiration, a regression model and a machine learning-based Relevance Vector Machine (RVM) model were developed with a robust latter to analyze the insignificant effect of drainage on evapotranspiration in the temperate region wetlands, which applies to those in the subtropic (Wu, Shukla, et al., 2016). The developed models can aid predicting differences in evapotranspiration for future climate change scenarios. Besides, Rengers et al. (2016) investigated the Computational Fluid Dynamics (CFD) simulations of a modified constructed wetland system (EvaTAC), which consists of an evapotranspiration and treatment chamber. This model determines empirical effects of geometric and flow parameters on the hydraulic performance and the effluent pollutant fraction in HSFCWs (Rengers et al., 2016). Sharifi et al. (2016), on the other hand, modified the Soil and Water Assessment Tool (SWAT) model to better represent NO_3^- cycling in wetland soils with various degrees of water holding capacity. This modification enhanced the model capabilities of calibrating paired watersheds simultaneously within a single framework. Similarly, Sun, Bernard-Shannin, et al. (2016) modified SWAT model to be combined with Landscape Unit Darcy model, (SWAT-LUD). SWAT-LUD model simulated the nitrate and water input from the soil profile both spatially and temporally. In addition, SWAT has been modified to better represent riparian depressional wetlands (SWATrw); thus, SWATrw integrates a more flexible wetland morphometric formula to model wetland-river interaction (Rahman et al., 2016).

Due to the high amount of nutrient loads in wetlands different models have been used for its reduction. A dual-objective reservoir operation optimization model was used to improve nutrients (mainly N and P) assimilative capacities in downstream plant-dominated wetlands (Xu, Yang, et al., 2016). The model mainly considers holistic mass balances in the wetland system, but does not include the spatial distribution of nutrients. Also, the MacCormack finite difference method for solving the contaminant port equations of wetland model, wetland solute transport dynamics (WETSAND), uses the implicit finite difference method to solve the coupled advection-dispersion-reaction equations for the nutrient cycling (Kazezyilmaz-Alhan and Medina, 2016). Another useful tool in wetland management is the Lake Okeechobee

Environment Model (LOEM-CW), a water quality model that was developed for simulating water quality processes including the nutrient cycling, submerged aquatic vegetation, and emergent aquatic vegetation in CWS (Ji and Jin, 2016).

Wetlands are often used as a tertiary treatment for wastewater treated effluent from a variety of sources and are expected to remove any remaining contaminants. Different models have demonstrated to efficiently simulate and predict the treatment of these pollutants. The CWM1 biokinetic model provided by HYDRUS Wetland Module has been used to study the response of hourly and daily sudden loads in a HFCWs (Rizzo and Langergraber, 2016). This biokinetic model is used to simulate the aerobic, anoxic, and anaerobic pollutant removal processes in HFCWs. Additionally, Constructed Wetland 2D (CW2D) – is a biokinetic model that describes microbial dynamics and transformation and degradation processes in SFCWs and can be implemented in HYDRUS for application on CWs treating combined sewer overflow (Palfy et al., 2016). In order to quantify removal pathways in wetland environments, Alvarez-Zaldivar et al. (2016) developed a reactive transport model (RTM) that includes the transition from oxidation to reductive dehalogenation of *cis*-1,2-dichloroethene and corresponding carbon isotope signatures. The Variable Residence Time (VART)-based model, also called VART-BOD model, simulated BOD removal processes in CWs with fee water surface (Deng et al., 2016).

Fuzzy Risk Assessment Model (FRAM) uses remote sensing and Geographic Information System (GIS) tools to identify areas with varying intensity of wetland conversion risk. Sarkar et al. (2016) used FRM in two stages, FUZZY c-Means (FCM) was used in the first stage to classified satellite data and in stage two, model relevance over 13 study sites was studied through questionnaire-based field survey. The combination Fuzzy-stochastic two-stage and GIS model can also be used to identify the optimal spatially distributed network of CWs for non-point source pollution control (Dai, Guo, et al., 2016).

The Steven Institute of Technology Estuarine and Coastal Ocean Model (sECOM) is a three-dimensional, free-surface, hydrostatic, primitive equation model which can be applied to oceanic, coastal, and estuarine waters used by Marsooli et al. (2016) to include vegetation effects on mean flow and turbulence quantities. They added vegetative source and sink terms to the transport equations of the Mellor-Yamada turbulence closure model. Lawler et al. (2016) investigated the impact of spatial scaling, mesh resolution, storm characteristics, and bottom friction on storm surge in wetland areas using the coupled hydrodynamic-wave model (ADCIR+SWAN). A simulation-based-water-environment management model with Laplace scenario analysis (SWML) was designed for planning regional sustainability in compound wetland ecosystem, and it can be used for probability of each scenario occurrence under insufficient data availability (Zeng et al., 2016).

Due to the degradation of wetland ecosystem in China, Sun, Lin et al. (2016) assessed the health level of wetland ecosystem using the pressure-state-response (PSR) model by synthesizing remote sensing and statistical data.

The basis of this model is the causal-effect relationships, such as human activities, human unsustainable consumption modes, or economic systems exert some pressures on the environment (Sun, Lin, et al., 2016).

Ghosh et al. (2016), used NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) 250 m and 500 m images. They used Wide Dynamic Range Vegetation Index (WDRVI) for MODIS 250 m and Visible Atmospheric Resistant Index (VARI) for MODIS 500 m to map biophysical characteristics of tidal wetlands. The synthetic aperture radar (SAR) imagery helped to identify seasonal variations in radar backscattering coefficient for reed marshes and rice fields (Zhang et al., 2016). The use of multi-mode SAR can improve the reliability of the water-level retrieval scheme to better capture spatial distribution of hydrological patterns (Zhang et al., 2016). While Samso et al. (2016) developed a mathematical model using COMSOL Multiphysics™ and Matlab® to simulate bio-clogging effects in HFCWs. Pal and Jaffe (2016) used a methanogenesis model based on Michaelis-Menten and Monod kinetics to study the interaction between hydrogen (H_2) and methane (CH_4) dynamics in wetland sediments. Li et al. (2016) presented a novel model based on an earlier biogeophysical model, $CH4MOD_{wetland}$, which can be used to simulate CH_4 emissions from boreal and artic treeless wetlands.

Other Areas of Consideration

Studies have shown that temperature influences the efficiency of nitrification and denitrification in the wastewater treatment. A combined VFCW and polishing pond system showed a removal efficiency for TN of only 12.7%, and in the polishing pond during the summer period, content of total nitrogen in treated sewages was further decreased by nearly 50% (Myszograj et al., 2016). However, during the winter period, the polishing pond fulfilled mainly retention role and thus did not improve effectiveness of the whole system. .Similarly, Zhao, Yang et al. (2016) investigated the bioaugmentation effect on a pilot-scale CW system for nitrogen removal under cold temperature (10 °C) and compound microbial inoculate enrichment and application. Results showed a 10% higher removal efficiency of ammonia and TN compared to a control (unbioaugmented) group. Oon et al. (2016) evaluated the effects of circuit connection, organic loading rates, and electrode spacing on the treatment performance of an up-flow constructed wetland–microbial fuel cell (UFCW–MFC) for successful wastewater treatment and bioelectricity generation. The average removal efficiencies (1-day HRT) for COD, NO_3^- and NH_4^+ were 99%, 46%, and 96%, respectively. Despite larger electrode spacing, the voltage outputs from Anode 2 (A2) (30 cm) (having a maximum power density and Coulombic efficiency of 93 mW/m^3 and 1.42%, respectively) and Anode 3 (A3) (45 cm) were higher than from Anode 1 (A1) (15 cm) as a result of insufficient fuel supply to A1 (Oon et al., 2016).

pH levels in wastewater can also affect the treatment performance of wetlands. Higgins et al. (2016) examined the use of CWs with *Phragmites australis* to effectively buffer the alkalinity in bauxite-residue leachate (pH>12) and results showed that metals concentrations within the vegetation biomass were less than critical phytotoxic levels and also demonstrated the capacity for *P. australis* of growing in bauxite-residue leachate-inundated growth media without negative effects.

Similarly, Buckley et al. (2016) examined CW conferred mechanisms (water quality dilution, contact with CO_2, and substrate type) for treating bauxite residue leachates to concentrations permitted for discharge and the study demonstrated that substantial reductions in solution pH can be attained depending on the diluting water quality (but concentrations achieved may not always be appropriate for direct discharge) and additional reductions occur with carbonation and soil contact. Furthermore, Mojiri, et al. (2016) studied co-treating landfill leachate and municipal wastewater by using a newly designed CW system with *Typha domingensis*, which contains two substrate layers of adsorbents: ZELIAC and zeolite. At optimal contact time (50.2 h) and leachate to wastewater mixing ratio (20.0%), reduction efficiencies of color, COD, NH_4-N, Ni, and Cd concentrations were 90.3%, 86.7%, 99.2%, 86.0%, and 87.1%, respectively.

CWs have also been studied for sludge treatment. Three VFCWs with different macrophytes (*Zizaniopsis bonariensis*; *Cyperus Papyrus*; and *Thypha domingensis*), were used to treat anaerobic sludge dewatering with medium-high solids loading rate (150 kg total solids/m^2-year) (Magri et al., 2016). When recirculation was introduced, it was possible to reduce the amount of final effluent produced by evapotranspiration and promote additional treatment of sludge water, which attained characteristics for safety disposal in the environment with average COD, ammonium nitrogen and phosphorus concentrations of 137 mg/L, 5 mg/L, and 2 mg/L respectively.

Adeniran et al. (2016) examined the quantity of biogas produced for energy use from an anaerobic digester of a CW. After a period of 148 days, the average of the percentages of methane (CH_4), CO_2, Hydrogen Sulphide (H_2S) and Carbon monoxide (CO) were 60.97±8.38%, 33.93±6.31%, 1.03±4.45%, and 0.25±2.11% respectively, with the mean rate of biogas production was found to be 641.83±88.26 m^3/day.) In northeast Italy, a pilot hybrid SSFCW + floating treatment wetland line treating digestate liquid fraction (DLF) showed a removal efficiencies of 57.9% for COD, 64.6% for TN, 65.1% for NH_4-N, 35.6% for NO_3-N, 49.2% for TP, 45.1% for PO_4-P in subsurface flow line (SSL), and of 89.2% for COD, 90.0% for TN, 89.0% for NH_4-N, 93.8% for NO_3 -N, 50.3% for TP, 49.9% for PO_4-P respectively in floating treatment wetland line (FTWL) (Maucieri et al., 2016).

During the summer, intensive photosynthesis of submerged plants in surface-flow CW could cause pH to rise, which may have detrimental effects on emergent plants. An investigation of nitrogen biological removal in lab-scale SFCW at different pH levels showed that TN removal efficiency was reduced from 76.3% to 51.8% with pH increase from 7.5 to 10.5, which was primarily attributed to plant adaptation, decay and inhibition of microbial processes (i.e., nitrite-oxidizing bacteria and denitrifiers) (Yin et al., 2016).

CWs used for the treatment of swine wastewater may possibly trap substantial amounts of carbon. A marsh-pond-marsh design wetland treatment showed that the effectiveness of this CW system was highly dependent on soil carbon content and organic matter turnover rate, proving to be large sinks for stable C forms (Reddy et al., 2016). Furthermore, Pal, Manna et al. (2016) concluded that soil of East Kolkata Wetland (EKW) stored high quantity of carbon and composite tannery wastewater was the main contributor, and the efficiency of carbon storage of the EKW ecosystem contributes to the preservation and restoration of this sensitive ecosystem.

A comparison of a conventional wastewater treatment system and a wetland for attenuation of the pesticide fipronil showed that conventional treatment to be unsuitable for reducing overall toxicity. However, CW removed both parental fipronil and the sum of fipronil-related compounds with efficiencies of 44 ± 4% and 47 ± 13%, respectively (Supowit et al., 2016). A newly CW in north Wales, UK contributed to the improvement of the water quality of a reservoir, showing a removal efficiency of 72% of initial NO_3^-, 53% of initial phosphate PO_4^{3-}, and 35% of initial BOD; while inorganic nutrients decreased, the DOC outputs increase, suggesting that CWs represent a source for DOC (Scholz et al., 2016).

The use of wetlands for wastewater treatment to help mitigate the effects of climate change has been researched A study conducted by Lavrni et al. (2016) examined the potential of CWs to treat domestic wastewater and produce an effluent that will be suitable for reuse in agriculture as a potential mitigating alternative of water source, due to climate change impacts to streams and other sources of water. In general, CWs had trouble reaching the strictest standards of Southern European countries (Greece, Italy, Portugal, and Spain) especially regarding microbiological limits, but their effluents are found to be appropriate for reuse in areas that do not require high water quality. Furthermore, Walters et al. (2016) evaluated the long-term performance of wetlands identified in the Eagle Creek Watershed in central Indiana, U.S. to decrease a range of high flows estimated from future climate setups. Wetlands proved to be a proved solution for peak flow reduction. In Eastern Sicily, Italy, a HSSFCW system used for tertiary treatment of sanitary wastewater for irrigation of vegetable crops did not present potential environmental impacts, as evidenced by the *Escherichia coli* content found in reuse effluent would not present a risk for rotavirus infection (Castorina et al., 2016).

Innovative & Hybrid Wetlands

An individual hybrid wastewater treatment installation consisting of a classic three-chambered 6 m^3 septic tank, a vertical flow (VF) trickling bed filled with Keramzyt granules, a special wetland bed, and a permeable pond proved to be very effective and reliable for the treatment of wastewater generated at a mountain eco-tourist farm in Krynica-Zdrój, Poland (Jucerski et al., 2016). Jóźwiakowski et al., 2016 studied the use of three hybrid treatment wetlands for wastewater treatment in two national parks in Poland. The CWs consisted of three steps: (i) mechanical treatment in three septic tank compartments, (ii) biological treatment in two or three stages of vertical and horizontal beds, and (iii) phosphorus inactivation in p-filter with calcium-silica rock. Results showed the three hybrid CWs produced very low concentrations of pollutants in the final discharges; in compliance with the stringent limits for wastewater treatment in national parks areas in Poland (Jóźwiakowski et al., 2016). Furthermore, results from a full-scale vertical-baffled flow wetlands (VBFWs) with artificial aeration and HSFWs suggested that this new hybrid CW can achieve TN and TP removal rates of approximately 65% (Zhai, Xiao, et al., 2016). A study (Türker, Türe, Böcük, Yakar, et al., 2016) evaluated a sustainable prototype engineered wetland to prevent boron (B) mine effluent from spilling into contiguous waterways in the largest B reserve in the world. Mean B concentrations in mine effluent were significantly reduced from 17.5 to 5.7mg/L after passing through the wetland with an HRT of 14 days.

On the other hand, a vertical up flow CW with microbial fuel cell (MFC) integrated into a dewatered alum sludge (DAS) with power activated carbon showed that the inclusion of power activated carbon improved the removal efficiencies of COD, TN, and reactive phosphate ; more significantly (Xu, Zhao et al., 2016). Moreover, three aerated HSSFCWs treating high-strength anaerobic digestate supernatant with intermittent aeration (1 hr. on:1 hr. off) significantly enhanced nitrification with ammonium removal efficiency of 90%, but limited a TN removal efficiency of 53% (Guo et al., 2016). Glucose addition further improved the TN removal efficiency to 82%. Torrijos et al. (2016) tested several configurations of single pass wetland systems (HF + HF, VF + VF, VF + HF), the by-pass (Bp(VF + HF)) arrangement (with feeding by-pass) and the effluent recirculation (R(HF + VF)) system (with effluent recirculation) for the treatment of synthetic domestic wastewater. Single pass wetland systems exhibited a TN removal efficiency below 50% at 0.6–1.2 g TN/m^2 d, 30–50% removal efficiency by-pass in Bp (VF + HF) system increased TN removal efficiency up to 60%, but recirculation improved stability and TN removal rates up to 80% at 8 g TN/m^2-d.

A study of two lab-scale baffled SSFCWs with gravel-wood chips-slag and gravel-slag-wood chips, at different intermittent aeration conditions revealed that gravel-slag-wood chips can extend aerobic/anaerobic alternating environments to gravel and slag zones and maintained anaerobic condition in the subsequent wood chip section (Li, Chi, et al., 2016). Adequate carbon source supply to the CWs resulted in high removals of COD (97%), NH_4^+-N (95%), and TN (94%) in BSFCWs at 2 h aeration per day

Three duplex-CWs with compartments of Control, Aerated and Recirculating, removed primarily organic matter, solids and NH_4^+–N, pathogens, and TN in both compartment (Zapater et al., 2016). However, effluent COD and BOD_5 concentrations remained above 30 mg/L in all compartments due to the short HRT in the VFCW, while only the Control and the Aerated systems met the TN European discharge guidelines.

Integrated wastewater treatment technologies provide a reliable alternative to increase pollutant removal performance in treatment systems. Personnaz et al. (2016) assessed an initial establishment (15 months) of a 2,000 m^2 integrated constructed FWS wetland with sewage treatment ponds established in Helidon Queensland, Australia, to compare the effluent quality results with rival conventional sewage treatment plants (STP). Post establishment results showed a BOD of 10 mg/L; SS of 20 mg/L; pH of 7–8 despite the influent BOD and TSS levels being well above the values used for the system design, demonstrating that FWS wetlands can easily integrate into existing or new sewage pond systems to reliable treatment outcomes. Moreover, Alemu et al. (2016) also concluded that the use of an integrated pilot wastewater treatment system composed of an anaerobic sequence batch reactor (SBR) followed by CWs exhibited an effective treatment performance of tannery wastewater with overall removal efficiencies of 96.6 % of COD, 90.4 % of TN, 97 % of NH_4^+-N, 81.8 % of SO_4^{2-}, 99% of S^{2-}, 98.5 % of total Cr, 86 % of EC, and 99.9 % of pathogens. Additionally, the SBR anaerobic unit generated biogas at a rate of 26.2 to 36 m^3/day (Zapater et al., 2016)

He, Wang et al. (2016) developed an innovative system by installing CW and biofilm-electrode reactor (CWBER) to solve the problem of low denitrification rates in CWs treating low C/N ratio sewage. Results revealed that the optimal operating conditions were C/N = 0.75–1, I = 15 mA, HRT = 12 h, and pH = 7.5; which produced the highest removal efficiencies of NO_3-N and TN at 63.03% and 98.11% for CW-BER., Also, the CWBER enhancive removal efficiency for TN and NO3-N was 23.26% and 24.20%, respectively (He, Wang et al., 2016). A study by Hang et al. (2016) examined the denitrification performance of different plant carbon sources and the effect of dosing method and pretreatment and found that the addition of plant carbon source for all types of CWs. In addition, bioreactors can enhance the nitrate removal efficiency to some degree.

Chyan, Lu et al. (2016) to treat eutrophic landscape water under low pollutant levels and high hydraulic volume loading using an embedded SSFCW with three species of aquatic plants. Field results showed that SSFCW efficiently treat the eutrophic water and preserved the landscape water. Corbella et al. (2016) quantified the effect of water level changes on the performance of two microbial fuel cells (MFC) implemented in HSSFCW treating domestic sewage. Cell voltage (E_{cell}) and the relative distance between the cathode and the water level were documented for one year and results showed that E_{cell} was significantly affected by the relative distance between the cathode and the water level, concluding that the performance of MFC implemented in HSSFCW is highly dependent on plants evapotranspiration. Ijaz et al. (2016) showed the promising role that endophytes play in enhancing the capability of plants to restore the quality of industrial and sewage wastewater by reducing polluting factors, with maximum reductions in COD and BOD_5 of 87%, and 87.5%, respectively. The CWs long term operation has revealed low removal efficiency during winter. An improved laboratory batch CW consisting water celery with the addition of *Tubifex tubifex* significantly enhanced wastewater treatment with removal efficiencies for nitrate (NO_3^-–N), TN and NH_4^+–N of 97.58%, 85.10% and 56.93% respectively (Kan et al., 2016).

Onsite Treatment

Conventional WWTPs generally require high capital investments and long-term budgets to cover the costs of the plants' operation and maintenance. CWs are commonly known of being a cost-effective onsite treatment alternative, since they can eliminate a wide range of pollutants with low capital and operational costs. A HFCW used for the treatment of wastewater in remote houses showed high removal efficiencies, for the first and the second year of study, for BOD_5 (96.4%, 92.0%), COD (84.6%, 77.7%), TS (94.8%, 89.9%), TN (79.5%, 66.0%), NH_4^+-N (98.8%, 86.6%), and TP (83.7%, 82.8%) (Andreo-Martinez et al., 2016). Similarly, Gajewska et al. (2016) conducted pre-feasibility analysis of different approaches for wastewater management in a settlement of 180 persons and concluded that the choice of method for wastewater treatment with wetlands in scattered development should be based on the following criteria: (i) environmental criteria, (ii) technical criteria (simplicity of operation and maintenance as well as fail safety), (iii) economic criteria, and (iv) reliability of operation.

More than 50% of pollutants found in lake waters in China are derived from rural non-point sources, resulting from untreated domestic wastewater released in rivers that feed into the lakes (Gu et al., 2016). An undercurrent CW pilot system to treat wastewaters from the Wucheng lakeside area showed average removal efficiencies of 42.86% COD, 29.46% NH_3-N, 31.35% TN and 21.75% TP (Gu et al., 2016). In Brazil, a full scale two-stage VFCW treating sludge from septic tanks collected in a city showed the following results in three operating strategies (OS1: after sludge application, the percolate generated in CW1 was immediately flows to CW2 for post-treatment, without any retention time in both units; OS2: the percolate from CW1 was retained for 6 days for initial treatment, after which it was sent to CW2 for post- treatment, without any retention; and OS3: percolate from CW1 was retained for 6 days for initial treatment, after which it was sent to W2 for post-treatment, with an HRT of 7 days): OS1 achieved median removal efficiencies of 81%, 74%, 68% and 42% of COD, BOD_5, TKN, and TS respectively; during OS2, the removals were 90%, 97% 78%, and 71% of COD, BOD_5, TKN, and TS respectively; and during OS3, the removals were 94%, 90% 87%, and 68% of COD, BOD_5, TKN, and TS, respectively(Lopez-Avila et al., 2016). OS3 provided the best results for COD and TKN removal.

Four different full-scale wastewater technologies (extended aeration system (EAS), rotating biological contactor (RBC), a CW, and a waste stabilization pond (WSP) used in small communities for more than 10 years treating ECs (sunscreen compounds, fragrances, pharmaceuticals, antiseptics, flame retardants, surfactants, and plasticizers) showed removal efficiencies of 42% for the CW, 62% for the EAS, 63% for the RBC, and 82% for the WSP (Matamoros et al., 2016).

To improve organics and nitrogen removal, Wu, Fan, Zhang, Ngo, Guo, Liang et al. (2016) studied SSFCWs with sludge-ceramsite substrate for decentralized domestic wastewater treatment in different operational modes (with and without intermittent aeration. Higher removals for COD (97.2%), NH_4^+-N (98.9%) , and TN (85.8%) were obtained concurrently in the intermittent-aerated CW system using sludge-ceramsite substrate compared with non-aerated CW.

In Poland, a VFCW treating the sewage from a fruit and vegetable industry showed a reduction of 68.2% for BOD_5, 79.3% for COD, and 60.2% for TP (Puchlik et al., 2016). Moreover, a study of four different bio-beds (three planted and one unplanted) filled with pea gravel, sand, clay, red soil, and charcoal in different ratios showed high removal efficiencies in BOD_5 (89 %), COD (81 %), carbonate (100 %), sulphate (77 %), sodium (77 %), and potassium (74 %) (Shrinithivihahshini et al., 2016).

A semi-batch VFCW was examined for residential bathroom graywater treatment (3-hr treatment) in a single-family home. The system produced an effluent with turbidity of 0.3 NTU and BOD 3.1 mg/L that met graywater reuse guidelines for nonpotable applications (with disinfection) (Yu et al., 2016). Similarly, Kamtekar and Verma (2016) also reported that the use of CWs for greywater treatment is a cost-effective and efficient alternative with high removal efficiencies for COD (98%), BOD_5 (84%), and TSS (84%).

In Germany, three pilot-scale CWs (two planted, one unplanted) were evaluated for the removal of contaminated groundwater containing methyl *tert*-butyl ether (MTBE), benzene and ammonia in a pump-and-treat remediation research facility (Stefanakis et al., 2016). In two of the beds, a solution of phenol and *m*-cresol was injected into the groundwater inflow. Results showed a complete removal of the two phenolic compounds in the beds without any variation in MTBE or benzene removal rates. Constructed wetlands have been used to treat different types of wastewaters including, but not limited to, domestic, industrial, stormwater runoff, agricultural and mining wastewater. Studies discussed in this paper confirm their treatment efficiencies and sustainability of this technology for broader applications.

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