

Constructed Wetland for Sustainable and Low-Cost Wastewater Treatment: Review Article

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Abstract: There is a growing need for more sustainable wastewater treatment technologies to provide non-conventional water sources. Constructed Wetland systems (CW) are viewed as a low-cost treatment technology with proven treatment efficiency. CWS can treat a variety of contaminants using low energy and natural systems by altering various design parameters. There are two configuration types of constructed wetlands: vertical (VF) and horizontal flow CW (HF). Both configurations have been widely adopted in both large and pilot scale studies with proven records of reasonable wastewater treatment efficiency. The current article reviews the recent development of CW technology and highlights the main achievements and successful applications for wastewater treatment at various locations. The review has indicated that a considerable removal efficiency is attained while using engineered CW systems with variable treatment rates for various pollutants. The treatment efficiency is a function of various parameters including wastewater type, scale dimensions, applied plant and the retention time. The review compared the treatment efficiency for both VF and HF and has revealed that various removal rates of BOD, COD, TSS, TN, TP and NH₄ was attained using both configurations. Yet, the removal efficiency in the case of VF was slightly higher compared with the HF with an average treatment level of 77% and 68% was achieved in both systems, respectively. The review revealed that the CW is an effective and sustainable technology for wastewater treatment with the initial influent level, microbial biofilm, detention time, plant species and configuration among the most dominating parameters that are directly controlling the removal rates.

Keywords: constructed wetland; wastewater treatment; sustainable materials

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1. Introduction

The growing water demand associated with the urban development across the globe has created various socio-economic impacts that add more stress to the limited available natural resources. Global water demand has tripled in the last five decades with the agriculture sector consuming around 80–90% of the available fresh water resources [1]. This in return has triggered the need for non-conventional water resources associated with sustainable water resources management practices, particularly in arid regions including the Arabian Gulf States [2]. Wastewater reuse is among the non-conventional water sources that can fill the water shortage gap. However, this option requires careful attention and design as it is extremely likely governed by the reuse plans that requires ad hoc effluent quality with the desired water use [3]. Therefore, high efficiency treatment systems with no to minimum associated risks are deemed necessary to alleviate any potential negative impacts generated from the various wastewater use applications.

Constructed wetlands (CWs) are fast-growing wastewater treatment technologies designed and constructed to simulate actual physical, chemical and biological processes occurring in natural wetlands [4]. They are manmade wetlands designed to operate and mimic natural wetlands using vegetation, soil and microorganisms, and they may appear as a more ecologically endowed system for wastewater treatment as either a new or restored habitat for native and migratory wildlife [5,6]. The proven advantages in utilizing the CWs for wastewater treatment as green and sustainable technology was discussed by many researchers and resulted in tremendous increases in both research and applications as a result of the simultaneous rise in the environmental sensitivity [3,7,8]. Since CWs utilize natural vegetation and microorganisms, they are viewed as low-cost technologies with low operation and maintenance requirements that can be applied in various socioeconomical conditions [9].

Hence, CWs provide a diverse range of benefits through their functions in the environment and ecosystem sustainability. The economic value of CWs can be divided into four categories based on the benefits, functions and services provided by them: direct, indirect, option and existence values, as shown in Figure 1 [10]. Implementing CW systems widely is an urgent demand and the driving force for improving green environment and sustainable wastewater treatment.

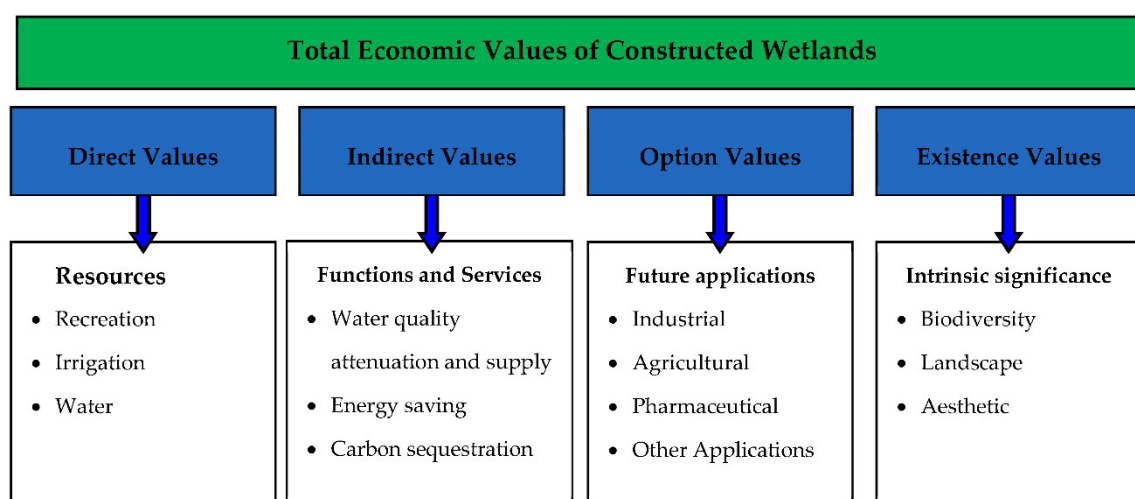


Figure 1. Total economic values of CWs.

One of the crucial advantages of the CW is the introduction of the no-energy requirement that accounts for the main cost input in various wastewater treatment technologies [10]. The passive treatment introduced by the CWs along the new views in wastewater treatment including sustainability and environmental impacts puts them among the most affordable treatment technologies in low income countries [4]. Whereas water flows through the wetland, the contaminants treatment takes place through either physical (sedimentation, filtration, UV exposure), chemical (precipitation, adsorption, volatilization) and/or biological (microbial degradation, microbial nutrient transformations, uptake from water column and root zone, microbial competition and bacterial die-off) processes. CWs are recognized to be effective in treating dissolved organics and suspended solids as well as many other contaminants reported by many researchers [5,11,12]. The recent research has shifted towards examining the applications of constructed wetland technology to treat a wider array of pollutants including metal, dye, organics containing wastewater and heavy metals including iron (Fe), magnesium (Mg), manganese (Mn) and zinc (Zn) [6,13]. Additionally, CW systems were successfully applied to treat phenol compounds and dyes from textile industries, with a considerable level of treatment achieved [13,14].

The treatment of wastewater within a CW takes place once the wastewater passes through the wetland media and the plant rhizosphere. Whereas CW systems mostly provide anaerobic conditions, an aerobic protective film can be formed around the root surface due to the constant release of oxygen by the roots of the helophytes in the rhizosphere [2]. Therefore, the contaminants degradation and treatment occur under both aerobic and anaerobic microorganism presence in the CW [13,15]. Other studies indicated the applicability of CW systems in treating heavy metals, including lead and copper [16].

The current review aims to summarize the recent development of CW technology and critically review the main achievements and successful applications in various geographic locations with the focus on the industrial wastewater treatment. The review investigates the various parameters affecting CW efficiency including wastewater type, plant species, CW configuration and dimensions, retention time and microbial biofilms. A Scopus and Web of Science databases search engine was used to search the literature using the search string: “vertical AND horizontal AND wetland”. The results provided 266 articles for Scopus. This was followed by removing publications in other languages than English. This review mainly aims at reviewing the performance of both VCW and HCW configurations and highlights the relative removal efficiency for certain contaminants.

2. Constructed Wetlands Flow Configurations

Constructed wetlands are characterized by biological activities that are higher than those occurring in conventional treatment systems, which convert various pollutants into non-toxic by-products in the wastewater. Constructed wetlands have also been used for secondary or even tertiary treatments and reuse of wastewater. The treatment procedure involves the flow of wastewater through constructed filtration systems. The treatment is mainly a complex combination of physical, chemical and biological processes that are carried out when wastewater passes through the constructed filtration systems. The treatment process in CWs systems involves the interaction among the wetland media and plants as well as the rate of the microbial organisms activities in addition to other climatic factors [16].

The design methods of CW are based on either volume, which accounts for the hydraulic retention time to ensure optimum pollutant removal, or area-based methods that assess pollutant reduction using the overall wetland areas. A study by [17] reviewed various configurations of CW and determined that the design to be used and applied is highly dependent on various factors, including accessible assets, size, cost, environmental conditions, wastewater quality, treatment level and purpose of treatment. Types of CW are classified based on their hydrology flow direction and selection of CW is based on design complexity, cost and contaminants removal [18]. A better understanding of the wetland's configuration behavior will lead to advanced, reliable and widely used treatment systems.

2.1. Horizontal Flow Constructed Wetlands (HFCWs)

Wastewater flows horizontally in the bed of the HFCW where the wastewater flows into the inlet and flows slowly through the porous medium under the surface of the bed planted with various types of vegetation towards the outlet [5]. The land area requirement for HFCW is the equivalent to about 5–10 m² per person [19]. HCW are very effective in treating various contaminants including organics, suspended solids, microbial pollution and heavy metals [7,9]. Organic compounds are degraded by bacteria under aerobic and anaerobic conditions. The long-term saturation of the bed creates limited opportunity for aeration where the system suffers lack of oxygen transport capacity. Therefore, aerobic decomposition is unlikely to occur in HCWs and contaminants' removal takes place more often through anaerobic processes [20]. This has limited the capacity of HCWs in removing ammonia-N due to the lack of oxygen whilst making HCWs effective in the denitrification process. Meanwhile, HFCWs have shown slightly lower removal efficiency of phosphorus and careful consideration for media selection should be taken into account to

ensure better removal efficiency [10]. Effective pretreatment of wastewater is deemed necessary in the case of HFCWs due to the potential accumulation of leading solids, which may result in bed clogging [21].

2.2. Vertical Flow Constructed Wetlands (VFCWs)

In vertical flow constructed wetlands (VFCWs), wastewater periodically fills the wetland and then drains completely by gravity in a vertical direction [22]. VFCWs require the equivalent of about 1–3 m² land area per person [19,23,24]. Wastewater within the VFCWs is fed intermittently and dispersed along the outlet in large batches; wastewater can then be collected at the bottom through the bed before percolating into a drainage network at the bottom. One main challenge is the limited ability of VFCWs in providing good conditions for denitrification to complete conversion to gaseous nitrogen, which may be released into the environment [15,25]. VFCWs are very effective in treating organics and suspended solids due to the oxidation reduction environment as well as the flow distribution [18]. Contrary to HFCWs, VFCWs are a good option in case of limited land availability [10] and normally preferred in cases of domestic and industrial wastewaters, where they provide enough and reasonable treatment for organic, nitrogen, phosphorus, pathogen removal and solids due to the microbial activity as well as the oxidation reduction environment they provide [9,15,21,26]. One of the design considerations in the case of VFCWs is the proper selection of wetland media where to avoid clogging. Clogging of the VFCW can be due to either the accumulation of the suspended solids and/or due to the high load of the organic matter (OM) and the bacterial growth known as bio-clogging [27]. Extra attention should be paid towards proper media selection as well as pre-treatment processes to ensure even distribution of the wastewater across the wetland surface whilst carefully selecting the optimum hydraulic loading rate. The hydraulic loading rate is defined as the rate at which wastewater is being discharged to the CW treatment system, expressed in depth (or volume) of water per unit area per unit time [21,28,29]. Moreover, another drawback of the VCW compared to the HCW is the heterogenous nature of the influent over the bed, which results in various treatment efficiencies compared to the HWC [30].

2.3. Hybrid Constructed Wetlands

The unique challenges arising from either HCW or VCW configurations have led to the design of a combined wetlands systems known as a hybrid constructed wetland, which aims to reach higher treatment efficiency [31,32]. Several combinations of CW in hybrid systems were tested by many researchers [21,29,33]. This hybrid wetland system has proved to have the combined advantage of both configurations in one set as to complement the processes and result in an more efficient treatment level with less effluent concentration as highlighted by many researchers [21,26,34,35]. The hybrid wetland design consists of parallel VCWs following in a series. Hybrid CWs were developed to complement the efficiency by both VCW and HCW, including the low energy and operation costs, as well as to attain higher treatment efficiency accumulated by both configurations [33,36]. Whereas the VCW segment attains high organic and suspended solids removal and allows for nitrification due to the aerobic environment, the HCW provides the denitrification and further removal of organics and suspended solids. This configuration may vary, and HCWs may be proposed to first remove organics and suspended solids and to allow for denitrification, followed by a VCW bed to further remove the organics and suspended solids and to nitrify ammonia to nitrate. The effluent collected from the VCW can then be reused and sent to a sedimentation tank. The VCW and HCWs configurations are well-known where the sequences can be achieved with any CWS for higher and more effective removal [21]. Additionally, the hybrid wetland system has the potential to treat broader wastewater contaminants, including winery wastewaters, pharmaceuticals and oil fields wastewater [37]. The interaction between various wetland configurations in the

hybrid system allows for aerobic and anaerobic process to better degrade organics as well as enhance the nitrogen removal via nitrification, denitrification and ammonification [37].

3. Case Studies on Constructed Wetlands for Wastewater Treatment Applications

Many real projects have been performed to investigate the effectiveness of CWs technology in treating various types of wastewater [37–40] and as shown in Table 1. CWs were applied to treat municipal and domestic wastewater, industrial mining, agricultural wastewater and leachate from dumping sites. Treated wastewater resulting from CWs can be used for multiple purposes, including aquifer recharge river discharge and recreational purposes. The wetlands were applied to remove various pollutants including BOD, COD, TSS, NH₄, nitrogen and phosphorous and others. The reported removal efficiency showed a varied range of treatment across various CW applications.

Table 1. Different applications of CW in Wastewater Treatment.

Wastewater Type	Location	Type of CW	Reference
Seafood wastewater	Thailand	HF & VF	[41]
Petrochemical	UK	HF & VF	[6]
	USA	HF & VF	[6]
	Taiwan	VF-HF (Hybrid)	[42]
	USA	VF-HF (Hybrid)	[8]
	Turkey	VF-HF (Hybrid)	[7]
	Greece	VF-HF (Hybrid)	[43]
	Denmark	VF-HF (Hybrid)	[44]
	Poland	VF-HF (Hybrid)	[45]
	Mexico	VF-HF (Hybrid)	[10]
	Estonia	VF-HF-FWS-P	[25]
	Thailand	VF-HF-FWS-P	[44]
	Italy	HF-VF-HF-FWS	[21]
	UK	VF-HF(Hybrid)	[6]
	Slovenia	VF-HF	[46]
Canada	HF-FWS	[46]	
Pig farms	China	VF-HF	[47]
	Thailand	VF-HF	[48]
Mining waters	Canada	VF-HF	[49]
	USA	VF-HF	[50]
Textile industry	Australia	VF-HF	[14]
	Pakistan	VF	[22]
Food processing	Slovenia	VF	[46]
	USA	HSFCW	[21]
Hydrocarbons	UK	VF	[51]
Refinery	South Africa	VF-HF(Hybrid)	[50]
	China	VF-HF	[50]
Pulp and paper	USA	HFVF	[50]
Pathogenic microorganisms	UK	VF	[52]
Fishpond effluent	USA	VF-HF	[53]
MTBE Organic	Germany	HF	[54]
Abattoir facility	USA	VF-HF	[50]
	Norway	VF-HF	[50]

VF = vertical flow, HF = horizontal flow, FWS = free water surface, P = pond.

A study of CW to treat landfill leachate by experimental systems showed a significant BOD₅ removal efficiency between 91% and 96% of total nitrogen (TN), as reported by Sim et al. [6]. Meanwhile, a wetland system in Australia- Townsville achieved a slightly lower range (48–67%) of BOD₅ removal, similar to another project, which consisted of four linear channels where a reduction efficiency of about 46% was reported [37]. A pilot U-shaped wetland showed a slightly high BOD₅ reduction of about 67%. The same pilot study reported to have 74%, 65% and 91% removal rate of total nitrogen, ammonia and nitrate-nitrogen, respectively [37]. Another mass balance study to treat the landfill leachate showed that the CW system was able to achieve a significant reduction of the total nitrogen (52%). A pilot-scale horizontal constructed wetland system in Karachi used for domestic sewage treatment monitored for 8 months showed average BOD₅ reductions of 50% [37]. Another study to test the potential application of CWs effluent for crop irrigation showed that the VCW system was able to achieve a reasonable efficiency for most contaminants up to the standard water irrigation quality [29]. CWs have also showed varied efficiency against various parameters. A four-linear-channel wetland reported only 3% of total phosphorus removed in a CW system surface flow compared to a removal of 78% of the suspended solid [8,25]. On the other hand, high total coliforms and fecal coliforms removal efficiency was attained at 93% to 99%, respectively, in a constructed wetland system used for pathogen removal [27].

Furthermore, although CW application in the case of heavy metals showed reasonable removal efficiency, this efficiency varied significantly and showed inconsistent removal on various occasions [30,55]. CW application for heavy metals removal indicated varied efficiency levels, where it was reported that around 55% of chromium (Cr) was removed in CWs, and less efficiency (25%) was observed nickel (Ni) and a significantly low reduction was attained in the case of copper (Cu), where only around 9% removal efficiency was achieved [33]. A slightly higher reduction was reported in the case of zinc (25–87%) and cadmium (Cd 33%) [30,55,56].

4. Kinetics of CWs' Treatment

The treatment efficiency of the CW is normally expressed by the Mass Removal Rate (MRR), which represents the contaminants concentration difference in influent and effluent after subsequent stages of constructed wetland using the following formula:

$$MRR = [(C_{in}Q_{in}) - (C_{out}Q_{out})] / A [g\ m^{-1}] \quad (1)$$

where A is the area of constructed wetland bed [m^2], Q_{in} and Q_{out} are the average influent and effluent flow rates, respectively [$m^3\ d^{-1}$] and C_{in} and C_{out} are average influent and effluent contaminant concentrations, respectively in [$mg\ L^{-1}$] [4]. The removal performance of any CW is a function of the contaminant decay rate where a kinetic experiment is normally conducted to account for the rate that varies from one contaminant to another. This in return determines the detention time that the design of the specific CW should provide to achieve full contaminant decay at the designed rate. First order decay rate is normally assumed and in reference to other parameters [47]. The CW design parameters include retention time, flow rates, surface bed area, contaminant concentrations and the decomposition constant coefficients (k) for wastewater treated in HF and VF beds and are normally obtained by applying the first order equation:

$$(C_{out} / C_{in} = e^{-kT}) \quad (2)$$

where k is the contaminant decay rate in d^{-1} and T is the hydraulic retention time in days.

One of the main drawbacks of the HCW is the limited data about their long-term efficiency [28]. Vymazal, in 2019, reviewed the treatment performance of around 114 HCWs including systems under operation for more than 20 years. The study indicated that HCW systems are very effective in treating organics and SS provided the proper loading rate. This efficiency increases with time, with a removal efficiency of up to 91%

achieved after more than 20 years of operation [28]. Table 2 shows decay rates for various contaminants resulting from pilot and field tests.

Table 2. Decay Rates for Various Contaminants for Wastewater Treatment.

Contaminant	K (d ⁻¹)	Study/Reference
BOD	0.8–1.1	[57]
	0.17–0.22	[58]
	0.86–1.84	[59]
	0.3–6.11	[60]
	0.86	[61]
	0.15–0.29	[45–61]
TN	0.16	[59]
	0.042	[4]
	0.06	[62]
	0.048–0.127	[6]
P	0.09–0.19	[6]
	0.084	[38]
	0.069	[63]
	0.075	[63]
	0.061	[64]
N	0.065	[4]
	0.034	[63]
	0.060	[64]
	0.020	[63]

5. Factors Affecting CWS Efficiency

5.1. Filtration Media

CWs are experiencing various physicochemical and biological processes that facilitate the level of wastewater treatment. Once wastewater flow passes through a certain media of a subsurface flow constructed wetland, the contact results in pollutant removal. Pollutant removal is a function of various parameters, including the detention time, the flow, aeration and many others [4,8]. One of the main factors is the media type which makes the use of CWs advantageous since media can be altered to suite the wastewater quality [65]. Recent studies have investigated the effects of major environmental and operation factors and alternative arrangements of wetland media in multiple-stage wetland systems [66]. The most commonly used CWs media reported in the literature are gravel and cobbles due to their availability, easy accessibility and good hydraulic conductivity [51,67,68]. Media with mixture of gravel, sand, soil or cinder has also attracted more attention since the early 1990s, whereas gravel alone has become the dominating material in the vegetated beds [33]. Yet the rate of gravel use in various applications including CW is much greater than the rate of its replacement, which may lead to severe environmental impact and create the need for other alternate sustainable materials [33]. Soil is used as the main filtration material in many CWs where reasonable efficiencies in removing heavy metals were achieved due to the soil cation exchange, as reported by Zahi et al. [69]. Until now, limited research and ad-hoc studies on alternative wetland materials in wetland systems are available and there is a need to further test other materials including zeolite, slag, fly ash and alum sludge [38,70–72]. The first field study of a pilot-scale CW utilizing alum sludge was proven to ensure high removal efficiency in Ireland [38]. These studies generally reported improved performances in the removal of common pollutants (such as organics, suspended solids and phosphorus) from wastewaters where the removal efficiency of phosphorus in rural domestic wastewater, and the TP removal efficiency were increased to achieve around 81.5% [40,65].

Filtration materials perform an important role in the sub-surface flow of a constructed wetland. The choice of the filtration materials is crucial for hydraulic conductivity and removal of suspended solids and phosphorus. Several researchers investigated [73] the use of different filter media materials such as crushed rock and gravel to deliver appropriate hydraulic conductivity that supports the growth of plants and effective retention of suspended solids [11]. Vymazal [73] collected information and summarized the different non-conventional filtration materials used in various CW Types, as shown in Table 3.

Table 3. Examples of novel filtration materials used in CW are summarized by Vyzamal et al., 2021 [73].

Material	Flow
Clay brick fragments and cork granulates	
Snail shells and coal slags	VF
Rice husk	HF
Rice husk	VF
Waste bricks	VF
Broken bricks	HF
Woodchips and alum sludge	HF
Coco peat, Steel slag and Concrete blocks	VF
Porous slag	Patch CW
Alum sludge and bauxite	HF
Shale ceramicsite	VF
Oyster shell and red soil	VF and HF
Crushed PET bottles	HF
PET bottle residues	HF
Coal cinder	VF

5.2. Pretreatment Availability Prior to CW Systems: Results from Various Literature

Constructed wetlands are appropriate for the treatment of wastewater in small-medium communities or nonpoint source pollution [74]. CWs usually require a physical pretreatment in order to keep the system functioning well and avoid solid precipitation, or a post-treatment depending on the final use of the purified water [75]. One of the main aspects that controls the treatment efficiency of the CWs is quality of the fed wastewater. This quality can be manipulated by providing preliminary treatment prior to the CWs or, alternatively, a post treatment following the CWs. Occasionally, no treatment may be provided. Figure 2 shows a summary of 59 CW projects in China showing the percentage and the type of the preliminary treatment provided for various applications, including industrial applications [68]. The level of treatment within the CWs is a function of various naturally occurring physical, chemical and biological processes that take place within the system and degrade the various pollutants, as a result of the synergetic actions of the system components, i.e., substrate media, plant roots and microbial community [54].

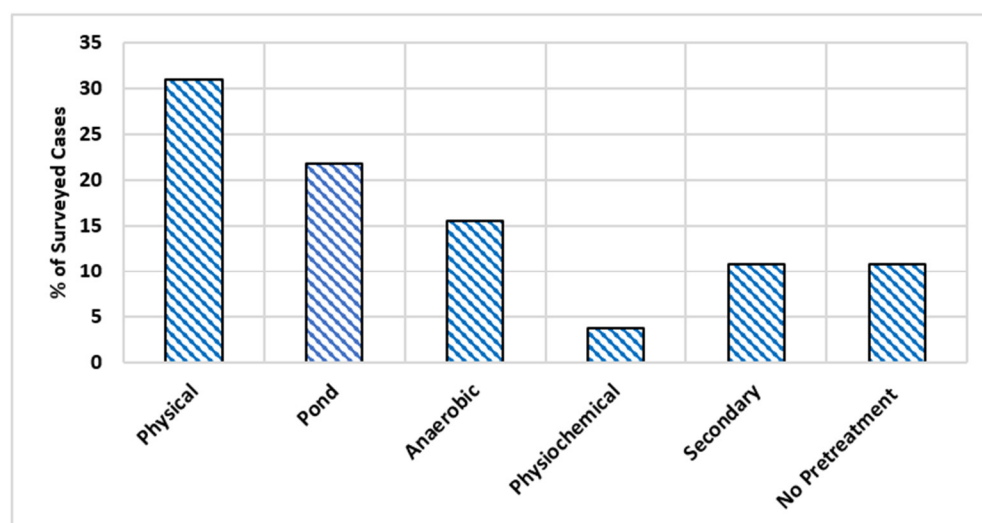


Figure 2. Surveying results of CWs in China presented by June et al., 2011 [70].

5.3. Organic Loading

Organic loading is one of the key parameters that impacts treatment efficiency and also wetland vegetation [76]. The higher the organic load, the lower the treatment efficiency is. Industrial wastewater is characterized by relatively high organic loading due to the high rate of biodegradable substances and solids including oil and grease substances with organic matters such as carbohydrates. It is recommended that CWs proceeded by conventional preliminary treatment, as in the case of industrial wastewater, have the CW at later treatment stages to ensure better efficiency [77]. Organic loading also impacts vegetation growth whereas areas near the inlet of the CWs show less treatment efficiency compared with the outlet. Normally, greater plants growth takes place near the CW outlet due to decreased organic loading [78,79].

5.4. Clogging

Clogging of the CW granular media is one of the main challenges affecting CW performance due to the significant reduction of the infiltration capacity as a result of solids accumulation [80]. To better avoid clogging, several studies have recommended limiting various wastewater parameters that can lead to this phenomena before entering the CW [81,82]. This includes recommended limits for total suspended solids (TSS) and BOD₅, which can indirectly contribute to the solids accumulation whilst biodegrading through microbial growth. Reviews indicated that the average recommended concentrations of BOD₅ and TSS in CWs influents, to reduce clogging, are 3.9 g BOD₅/m² d and 5.4 g TSS/m²d, respectively [80]. Moreover, organic matter content is another factor that may contribute to wetland clogging [83]. A threshold value of less than 5% organic matter content should be maintained, after which a bio-film layer may form on the substrate due to the accumulation of OM, which is viewed as one of the key contributing factors to wetland clogging [83]. However, clogging of wetland systems is relatively complex and highly depends on both the hydraulic characteristics of wastewater as well as the media properties. Although many scientific reviews suggest CW systems to be preceded by a preliminary wastewater treatment system to reduce the clogging effect and limit the solids accumulation, the impact of this treatment is not fully understood [81]. Granular media characteristics include porosity, hydraulic conductivity, potential biofilm formation, rate of solids precipitates, hydraulic retention time and the microbial growth rate [71–82]. Preliminary treatment, hydraulic retention time (HRT), surface loading rate (SLR) and hydraulic conductivity are also among the factors that influence CW treatment efficiency and clogging rate. It was reported that at HRT of 9 ± 7 hours and a relatively low SLR (5.0 g TSS/m² d),

with a hydraulic conductivity of 22–68 m/d, no clogging problem was encountered while treating winery wastewater for the first 5 years of operation [81]. The detachment of microbial substances can develop a thin biofilm that precipitates on the surface of the granular media leading to system clogging. In HCW, clogging is most likely to occur at the inlet of the system, whereas it takes place on the top layers of the [74,81]. One of the main disadvantages of wetland clogging is the reduction of oxygen levels in the wetland, which in turns deters the oxidation process and the bacterial activities, which may result in system failure and reduce the system designed life span by up to more [84].

6. Efficiency Analysis of CW Systems

The review has indicated that the level of performance and efficiency of CW systems vary according to various parameters and functions including the layout, velocity, effluent quality and other configurations. The contaminant removal efficiency of a CW system can be used as a performance indicator that describes the effectiveness of the CW system in removing/reducing wastewater contaminants. A summary of the data collected from the literature for the most repetitive contaminants is plotted in Figures 3–7, with the error bars representing the 95% confidence interval. Overlapping of the confidence intervals implies the similarity in the calculated removal efficiency values between various CW systems. Figures 3–6 present the general trend in average removal efficiencies of each of the most common contaminants in wastewater using various configurations of CW flow systems, including the horizontal flow with laboratory scale (HFL) system, horizontal flow with full site scale (HFS) system, vertical flow with laboratory scale (VFL) system and vertical flow with full site scale (VFS) system, respectively. Figure 7 presents the average removal efficiencies of each system in general. It should be noted that the average removal efficiencies were calculated using collected data from literature about the removal efficiency of each individual contaminant in each system regardless of wastewater source, filtering media type or filter size. Figures titles refer to the type of the system, whether it was horizontal or vertical flow and whether it was a site scale or laboratory scale system.

As can be seen from Figures 3–6, the removal efficiency values fluctuate between 53% and 88% depending on the contaminant type and CW system. As mentioned earlier, the removal efficiency here is used as a performance indicator, which indicates that all systems can effectively reduce any contamination level to an acceptable level with at least 53% efficiency.

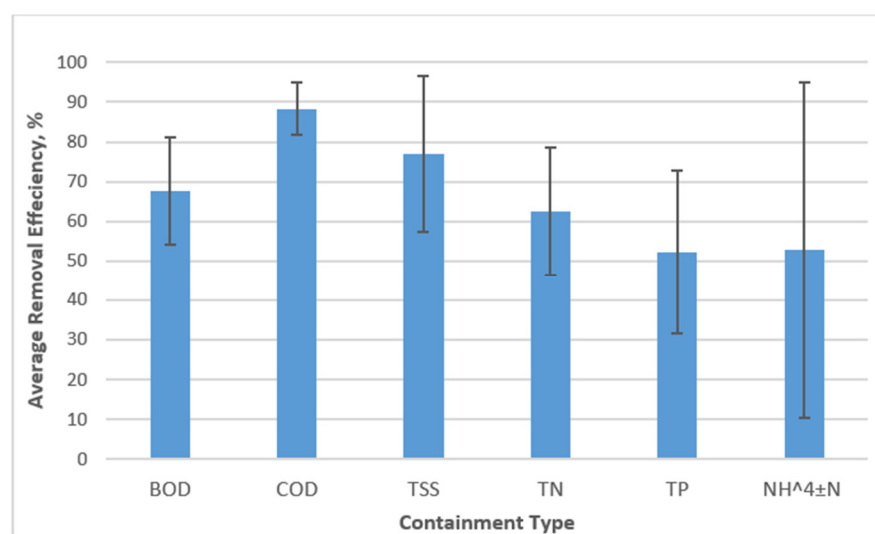


Figure 3. Horizontal flow lab scale systems removal efficiency.

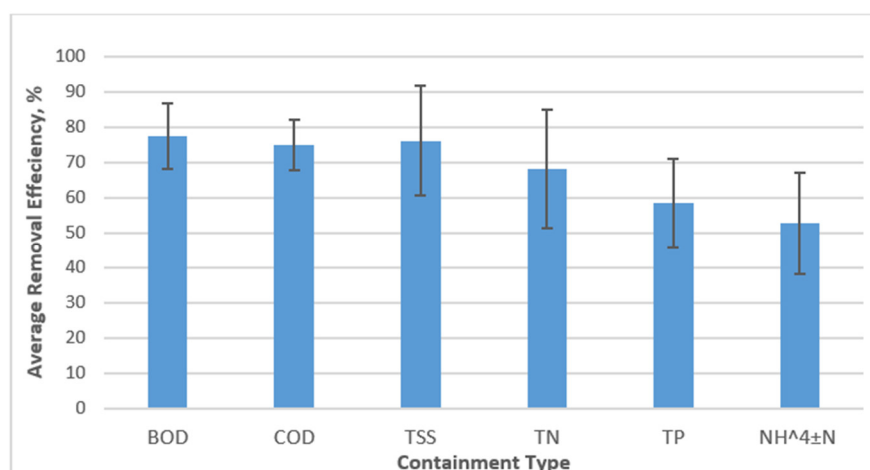


Figure 4. Horizontal flow site systems removal efficiency.

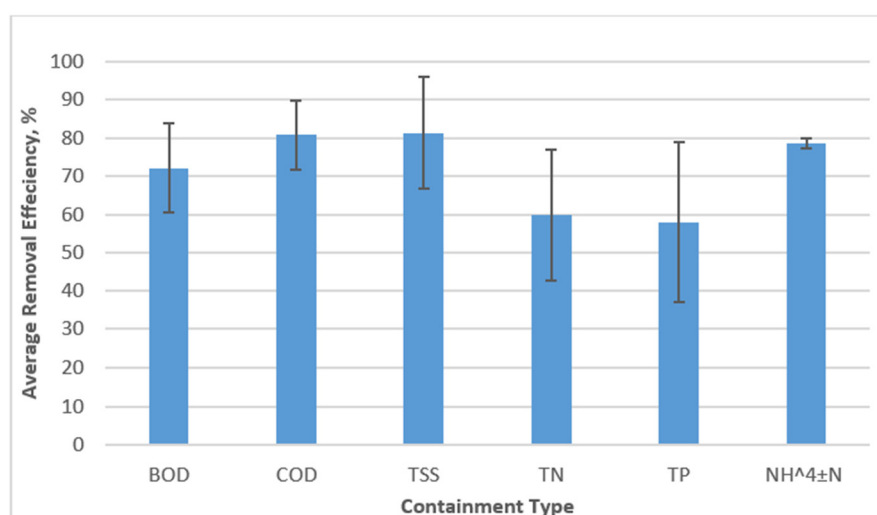


Figure 5. Vertical flow lab scale systems removal efficiency.

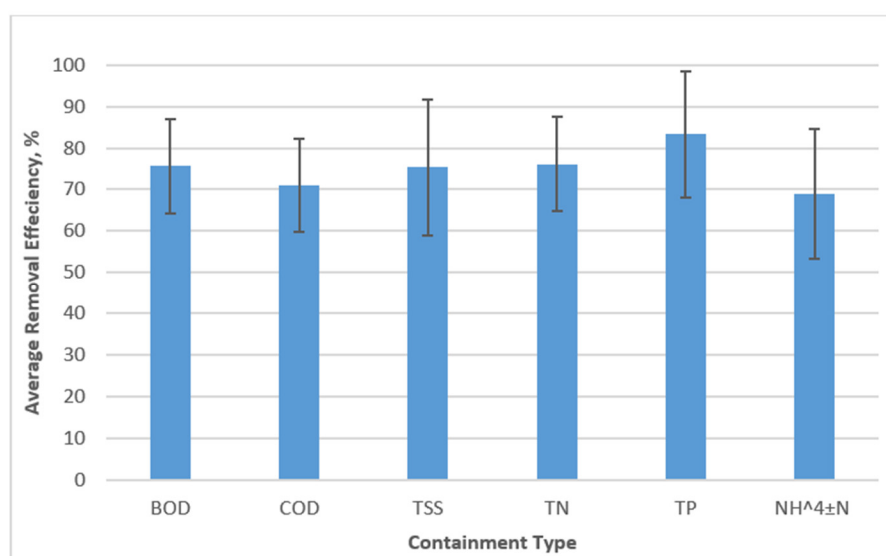


Figure 6. Vertical flow site scale systems removal efficiency.

Additionally, it can be seen from Figure 7 that the overall treatment efficiency of any CW system ranges from 67% to 75%, which indicates an acceptable performance level regardless of wastewater source, filtering media type or filter size.

In general, it can be concluded that CW systems can be successfully used as a sustainable and low-cost wastewater treatment system.

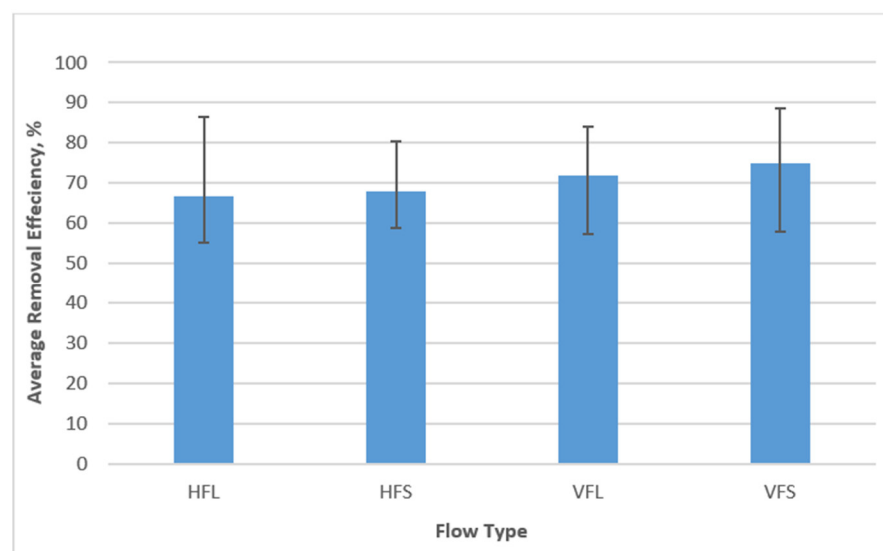


Figure 7. CW systems overall treatment efficiency.

7. Future Research

CW systems have been proven to be sustainable eco-friendly and low-cost technologies compared with many other wastewater treatment technologies, as the system is designed to mimic natural treatment processes in a controlled environment with the advantages of the low to no use of energy. Research and industrial fields still view CW as one of the most suitable wastewater treatment technologies, particularly in the case of small communities. However, the wetland system, as many other technologies, are yet to face various challenges including media selection. Not only does CW media support biofilm and plant growth, but it is also expected to provide good adherence and attachment sites for biofilm growth [85]. Currently, sand and gravel are the most commonly used materials of porous media. Nevertheless, these materials are being utilized at a higher rate than their replacement rates across the globe, leading to a potential environmental impact including coastal erosion events [36]. This has created the need for new sustainable low-cost materials that can replace the current conventional ones. The research has shown a potential for recycled building materials due to their chemical properties, which has not been fully investigated [85]. The use of alternative materials such as agricultural by-products and industrial wastes are among the research areas that require additional research work. Thorough research is necessary for testing special materials, including ceramsite, zeolite and limestone, to diversify the removal of various nutrients as well as enhance the removal efficiency of CWs [68].

Another research area that requires additional investigation in this field is the possibility of utilising the effluent in various applications as well as the need to enhance the operational strategy to increase the removal efficiency and extend the treatment to include a wide array of contamination in constructed wetlands, particularly when applied to industrial wastewater treatment [40]. The impact of various treatment conditions including wastewater temperature and contaminant decay rates are of great concern and are entitled to further research.

Although there seems to be well-established standards and guidelines that co-govern CWs operations, application and maintenance, there seems to be a great challenge when transferring and adopting these guidelines to a different environment with significant climatic variations [27]. The need for large land and native wetland species still represents a real challenge to the CWs, especially where this may not be an option in many cases due to the varied urban design across different countries and the development of ad hoc parameters and strategies for each country, and which is of great interest. Further research is also required to test the tolerance of plants to various contaminant loading levels, as this affects the sustainability and the longevity of the CWs [86].

One of the future research areas that needs more attention is that whereas some countries have achieved an advanced level of the development of CWs systems, and in many cases pilot studies were undertaken, some other countries are still on the brink of the basic laboratory research. Until now, there is limited knowledge on the development of wetland technology, particularly in developing countries and there is a real need for a breakthrough while applying new technologies and materials.

Future research is believed to incorporate new dimensions and the application of nanomaterials in CW systems that can bring innovative wastewater treatment options as well as achieve significant advancements in removal efficiencies. This includes the removal of heavy metals and organic compounds. Investigation of nanomaterials could bring more sustainable and novel approaches to treating a wider array of contaminants within CW systems and allow for more reuse options. This is of particular interest for arid and semi-arid regions where water scarcity marks the main water resources challenge.

8. Concluding Remarks

There has been an evolving trend in the application of CW as a promising eco-friendly and low-cost wastewater treatment technology due to the very low power usage compared with conventional treatment technologies. CW proved to be an effective treatment option particularly in the case of BOD₅, TN, TSS and TP, with removal efficiency ranging between 70–83% in general. There are two main CW configurations, including HCW and VCW, each of which has various advantages and various limiting factors including land availability and initial wastewater quality. Although each configuration faces various challenges, the hybrid CW system is an emerging configuration that combines the advantages of both systems and can provide an aerobic as well as anaerobic environment which suits a wider array of contaminants. One of the main challenges facing CW technology is the potential clogging of the granular media as well as the solid accumulation in either configuration. Clogging can take place due to many factors related to the wastewater hydraulic characteristics, as well as the media properties. The review showed a wide array of contributing factors leading to wetland clogging, including organic matter content, hydraulic retention time, surface loading rate, TSS and BOD₅ concentration and others. The impact of clogging where a thin biofilm layer can precipitate and block the pores of the granular media may result in significant shortening of the wetland life span. Wetland clogging seems to be complex and poorly understood and requires further research and more testing under various conditions.

For efficient CW operation, CW should be utilized as secondary or tertiary treatment technology preceded by preliminary treatment. This preliminary treatment proved to increase the system efficiency while removing various parameters such as TSS and BOD₅ COD, NH₄ and reduces the potential risk of system clogging. The review has indicated that further research is still needed in the field of CW as to better utilize new substrates, including agricultural by-products and industrial wastes materials, plant type and the level of preliminary treatment in case of various contamination events in different conditions.

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