

Review

Sustainable Management and Successful Application of Constructed Wetlands: A Critical Review

Angela Gorgoglione ^{1,*}  and Vincenzo Torretta ² 

¹ Department of Fluid Mechanics and Environmental Engineering (IMFIA), College of Engineering, Universidad de la República, Julio Herrera y Reissig 565, 11300 Montevideo, Uruguay

² Department of Theoretical and Applied Sciences, Università degli Studi dell'Insubria, G.B. Vico 46, 21100 Varese, Italy; vincenzo.torretta@uninsubria.it

* Correspondence: agorgoglione@fing.edu.uy

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Abstract: Constructed wetlands (CWs) are affordable and reliable green technologies for the treatment of various types of wastewater. Compared to conventional treatment systems, CWs offer an environmental-friendly approach, are low cost, have fewer operational and maintenance requirements, and have a high potential for being applied in developing countries; particularly in small rural communities. However, the sustainable management and successful application of these systems remain a challenge. Therefore, after briefly giving basic information on wetlands and summarizing the classification and use of current CWs, this study aims to provide sustainable solutions for the performance and applications of CWs. To accomplish this objective, design and management parameters of CWs, including macrophyte species, media types, water level, hydraulic retention time (HRT), and hydraulic loading rate (HLR), are discussed. The current study collects and presents results of more than 120 case studies from around the world. This work provides a tool for researchers and decision-makers for using CWs to treat wastewater in a particular area. This study presents an aid for informed analysis, decision-making, and communication.

Keywords: constructed wetlands; design and operation; macrophyte; substrate; hydraulic conditions; sustainability; treatment system; artificial wetland

1. Introduction

In the last few decades, constructed wetlands (CWs) have been widely used to treat several types of wastewater such as domestic sewage, industrial effluent, agricultural wastewater, landfill leachate, polluted river water, and urban runoff [1–5]. The studies conducted by Seidel in the 1960s [6–10] and by Kickuth in the 1970s [11–13] in Germany, are considered the kick-off research on CWs. Since then, much research has been done, and the technology has evolved, which has made CWs more feasible from the operational point of view.

Several studies have focused on the design, development, and the performance of CWs [14,15], and on the ability of these engineered systems to remove specific pollutants (organic compounds, suspended solids, nutrients, heavy metals, benzene, toluene, ethylene, xylene—BTEX), pharmaceutical contaminants, pathogens, etc.) from wastewater [3,16–18]. However, there are fewer studies on the sustainable operation and successful application of these systems. Therefore, this topic remains a challenge. CWs' sustainability is influenced by several factors including vegetation, media types, and hydraulics/hydrology. In particular, plant species and substrate material are critical influencing factors to the pollutant removal ability of CWs. They are considered the primary biological components of CWs and, as such, directly or indirectly modify the processes of primary pollutant removal over time [19–21]. Moreover, the treatment performance of CWs is based on optimal operating parameters (i.e., water

depth, hydraulic retention time (HRT), and pollutant load). The variation of these parameters affects the efficiency of contaminant removal [22–24]. Furthermore, a variety of pollutant removal processes (e.g., sedimentation, filtration, precipitation, volatilization, adsorption, plant uptake, and various microbial processes) are directly and/or indirectly influenced by the different environmental conditions, both inside and outside the CWs. Such environmental conditions are, for instance, temperature, availability of dissolved oxygen (DO) and organic carbon source, operation strategies, pH, and redox conditions [3,25,26].

It is worth noting that previous research has almost exclusively focused on how to improve and optimize the efficiency of the treatment performances of CWs [22,24,27]. However, there is still a gap in the understanding of these technology systems, since the current research only focuses on achieving sustained levels of water quality enhancement. This gap in information may result in reduced use of CWs. Before undertaking expensive experimental studies to gather and analyze additional steps to the treatment performance, it is necessary first to understand what enhancement in operation and application of CWs would result if we develop an in-depth knowledge of these systems. This thorough understanding should allow for converting these “man-made” wetlands into sustainable solutions for wastewater treatment made for each particular area. Therefore, to promote and develop sustainable operations and successful application of CWs, it is necessary to review and discuss recent information on the sustainability of these treatment technology systems.

Based on these considerations, this work aims to categorize and provide an overall review of the applications of CWs for wastewater in recent years. In addition, it analyzes the developments in CWs considering plants, substrates selection, and operational parameters in order to optimize the sustainability of wastewater treatments. The conceptual framework of this study is made for incorporating future research considerations aimed to improve the sustainability of CWs. By collecting the results of more than 120 case studies from around the world, this review will allow decision-makers and researchers to assess and quantify the most sustainable solution for CWs wastewater treatment in a particular area. This study presents a useful tool for decision-making, informed analysis, and communication.

With the aim of avoiding repetition throughout the manuscript, the following synonyms will be used to indicate CW: artificial wetland, treatment system, constructed shallow water system, artificial shallow water system.

The remainder of this review is organized as follows. In Section 2, the well-known definition and classification of CWs based on hydrologic factors are summarized. In Section 3, the importance of the knowledge of the wastewater type that a specific area may produce is highlighted. In Section 4, a thorough description and in-depth analysis of the parameters that contribute to sustainable design and maintenance of CWs is reported. Consideration on the sustainability of CWs and main conclusions are presented in Section 5.

2. Research Methodology

Considering the objective of this study, research was focused on published articles where an experimental-scale or field-scale artificial wetland was design, built and studied.

Search parameters included the results of multiple web-based libraries [28–32] using the same keywords reported after the abstract section. The studies selected and cited in this manuscript are between the years 1960 and 2018. Non-peer-reviewed articles were excluded from the selection.

An initial extensive comparison of field and experimental treatment systems was performed. Not all data acquired were found in sufficient quantity or quality to be reported. Therefore, it was chosen to address the following factors only: system type, wastewater type, substrate used, plant species, and HRT.

3. Definition and Classifications of Constructed Wetlands

CWs may be classified according to several design criteria. The three most important parameters are hydrology (open water surface flow and subsurface flow); type of macrophytic growth (emergent, submerged, floating-leaved, and free-floating); and flow path in sub-surface wetlands (horizontal and vertical). It is possible to combine different types of CWs, creating hybrid systems, which utilize the particular advantages of the individual systems [33,34]. Descriptions of several types of CWs are reported in the following paragraphs.

3.1. Constructed Wetlands with Horizontal Subsurface Flow

The horizontal subsurface flow (HSSF) systems are characterized by tanks waterproofed with plastic membranes, filled with inert material of appropriate particle size (e.g., gravel), in which emergent macrophytes develop their roots (*Phragmites australis* is commonly used, even though it is considered an invasive weed in some countries), as schematically represented in Figure 1a.

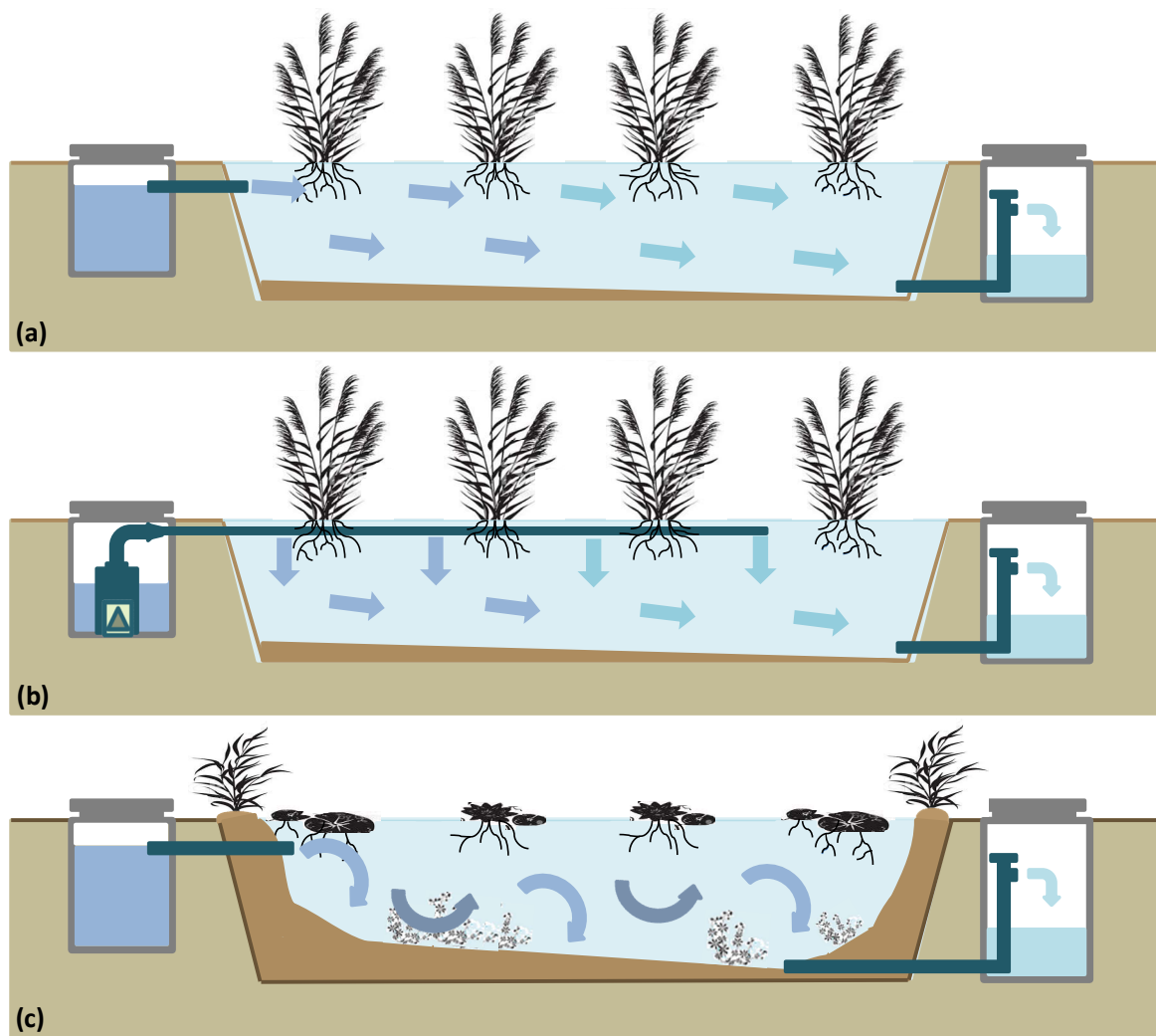


Figure 1. Schematic representation of a CW with (a) HSSF; (b) VSSF; and (c) FWS (arrows indicate the general flow pattern).

The water flow is continuously maintained below the surface of the inert material. This creates a predominantly anoxic environment, rich in aerobic micro-sites in close proximity to plant roots, which operate as oxygen transfer systems from the atmosphere to the inside of the filter bed. The redox conditions of this system allow it to be highly elastic, versatile and efficient with the various types of wastewater that need to be treated, and with the variations of the pollutant content. In these systems, the wastewater passes through the inert material and is in contact with the macrophytes' rhizosphere. The organic and nitrogen matter is degraded by the microbial action, while phosphorus and heavy metals are adsorbed by the inert material.

The plant species contribute to the purification process, firstly, by favoring the development of an active aerobic microbial population in the rhizosphere and, secondly, through the action of atmospheric oxygen pumping from the emerged part of the root system to the surrounding ground portion. This creates better oxidation of the wastewater and creation of alternating aerobic, anoxic, and anaerobic zones. Such conditions allow the development of several families of specific microorganisms and the almost complete disappearance of pathogens, as they are particularly sensitive to the rapid changes in dissolved oxygen content.

HSSF systems are not very tolerant of cold climates. In fact, their performances are always reduced under these weather conditions. These systems keep the septic influent warm with insulation to maximize the functioning of microorganisms and, therefore, maintain treatment performance constant during the season. Dead plant material is also used as a natural insulation layer and protects the filter bed during winter. For systems implemented in areas with unusually cold weather, it is good practice to lower the water level in the tank to prevent freezing.

High organic removal efficiencies can be reached with traditional HSSF CWs. With respect to nitrogen, the limited oxygen availability in some zones decreases nitrification rates and, in turn, the nitrogen removal performance despite rapid denitrification. Considering phosphorous, its removal mechanisms are mainly physical (e.g., precipitation with Ca^{2+} , Al^{3+} or Fe^{3+} that may be present in the soil material), so they are not influenced by oxygen concentration.

The plants most used in HSSF systems are emergent macrophytes like *Phragmites* sp., *Typha* sp., *Scirpus* (*Schoenoplectus*) sp., *Phalaris arundinacea*, and *Iris* sp. It was found that, besides the macrophyte species mentioned above, local species, which are easily available and grow well under local climatic conditions are regularly used in HSSF CWs.

3.2. Constructed Wetlands with Vertical Subsurface Flow

The geometrical configuration and physical layout of the vertical subsurface flow (VSSF) systems is very similar to the one of HSSF (Figure 1b).

The main difference between HSSF and VSSF systems is how the wastewater flows through the inert medium. While in HSSF systems there is a continuous inlet and a flow in the horizontal direction, in VSSF systems the effluent is introduced into the tanks in a discontinuous way and flows in the vertical direction. The intermittent inlet, with the filling and emptying cycles, creates the conditions of a "batch" reactor. It often requires at least two tanks in parallel, which operate with an alternating flow, so it is possible to adjust the timing of re-oxygenation of the bed by varying the frequency and quantity of the hydraulic load of the wastewater input.

The filling medium of this type of systems is made of inert particles finer than the HSSF system to allow a slow water percolation and, thus, a distribution as homogeneous as possible on the entire surface of the bed. The coarse sands used in VSSF systems have suitable hydraulic conductivity for the slow vertical filtration, and they offer a ratio between volume and surface area higher than gravel used in HSSF systems, to facilitate the biomass attachment.

The intermittent supply of the wastewater, associated with a substrate with various particle sizes, facilitates the drainage in the medium; which is alternately in conditions of deficient or excess oxygen. Therefore, the higher aeration of the substrate increases the aerobic processes such as the removal of organic matter and nitrification.

Since the traditional VSSF CWs provide an ideal environment for aerobic bacterial respiration, it shows better organic removal treatment performance from pre-treated domestic wastewater than traditional HSSF CWs. With respect to nitrogen, the excess of oxygen increases the nitrification process eliminating more nitrogen or, at least, converting the main part in ammoniacal nitrogen. Considering phosphorous, the performance is very similar to one of the HSSF CW.

Depending on the climate, *Phragmites australis* (reed), *Typha* sp. (cattails), and *Echinochloa pyramidalis* are common plant options for VSSF systems.

3.3. Constructed Wetlands with Free Water Surface

The free water surface (FWS) systems are organized with tanks or channels that are naturally or artificially waterproofed, in which the water level is constantly maintained above the surface of the medium (Figure 1c), with a water depth that typically ranges between 0.3 and 0.6 m.

The flow follows a path that includes the inlet area and all areas of the system until reaching one or more outlets. The regions characterized by low water depth, with low flow velocity and the presence of plant bodies, standardize the flow through the formation of a multitude of small channels that simulate the behavior of a plug flow reactor. The primary design goals of an FWS system are to ensure the contact of the wastewater with the active biologic surface of the system, to allow an efficient HRT of the wastewater in the system, and to prevent the formation of hydraulic short-circuits [35].

In these systems, the mechanisms of pollutant removal attempt to reproduce those processes that characterize natural wetlands for pathogenic organisms, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), suspended solids, nutrients, heavy metals, and other micropollutant removal. Organic and nitrogenous substances are mainly removed by biological processes under oxygenated conditions (at the surface) or anoxic conditions (in depth). While the suspended solids can on one hand be removed (by sedimentation and/or filtration through plants), on the other hand, they can be created (for example for the presence of microalgae, fragmentation of plant tissues, production of phytoplankton, formation of chemical precipitates). Phosphorus removal is small and occurs through adsorption, complexation, and precipitation processes. The FWS systems show very high performance in pathogenic microorganism removal. However, this efficiency has extreme variability mainly due to the complex combination of physical, chemical and biological processes that affect the removal mechanisms, such as the attachment of microorganisms on the sediment, UV radiation in the deeper areas not occupied by vegetation, and the presence of colonies of birds that can cause the contribution of feces [36]. Finally, heavy metals may be removed through processes like the uptake by the plants, physical–chemical interactions with the ground, or the formation of complexes and resulting precipitation [37].

The plants most used in FWS systems are common marsh species such as *Scirpus* sp., *Eleocharis* sp., *Cyperus* sp., *Glyceria maxima*, *Juncus* sp., *Phragmites australis*, *Phalaris arundinacea*, and *Typha* sp. Most FWS systems use a single species or a surface species in combination with submerged species.

A comparison of some advantages and disadvantages of the three different types of CWs are listed in Table 1.

Table 1. Advantages and disadvantages of HSSF, VSSF, and FWS CWs.

Advantages	Disadvantages
HSSF CWs	
Long flowing distances possible; nutrient gradients can establish	Higher area demand
Nitrification and denitrification possible	Careful calculation of hydraulics necessary for optimal O ₂ -supply
Formation of humic acids for N and P removal	Equal wastewater supply is complicated
Longer life cycle	
VSSF CWs	
Smaller area demand	Short flow distances
Good oxygen supply - good nitrification	Poor denitrification
Simple hydraulics	Higher technical demands
High purification performance from the beginning	Loss of performance esp. in P-removal (saturation)
FWS CWs	
Addition to the “green space” in a community	Higher area demand
BOD, TSS, COD, metals, and organic material removal in a reasonable detention time	Anoxic environment—poor nitrification
N and P removal in a significantly longer detention time	Mosquito production
Minimization of mechanical equipment, energy, and skilled operator requirements	

4. Types of Wastewater Treated

For an efficient and sustainable selection of CWs for a particular area, a thorough understanding of the type of wastewater being treated is necessary. CWs have long been used primarily for the treatment of municipal or domestic wastewaters. However, at present, they are utilized for other wastewaters including agricultural, industrial, and several runoff waters.

4.1. Municipal Wastewater

HSSF CWs are commonly used to treat domestic (single house or households) and municipal (clusters of houses or community) sewage as both secondary and tertiary treatment stages. The “typical” composition of municipal wastewaters is reported in the study of Kadlec and Knight of 1996: BOD₅ = 220 mg L^{−1}, COD = 500 mg L^{−1}, TSS = 220 mg L^{−1}, NH₄-N = 25 mg L^{−1}, NO_x-N = 0 mg L^{−1}, N_{org} = 15 mg L^{−1}, TKN = 40 mg L^{−1}, TP = 8 mg L^{−1} [38]. It is worth noting that HSSF CWs can successfully treat wastewaters with low concentrations of organics. For instance, conventional treatment systems such as activated sludge cannot treat wastewater with low organic concentrations (usually less than 50–80 mg/L BOD₅). By considering all the case studies included in this work, it is possible to calculate an average of the treatment performance in terms of removed load (RL) (kg/ha d) of HSSF CWs treating municipal and domestic wastewaters: BOD_{5 RL} = 77.6, COD_{RL} = 149, TSS_{RL} = 83, TN_{RL} = 10, NH₄-N_{RL} = 5.3, TP_{RL} = 1.9 [39,40]. Besides pollutants usually detected in municipal wastewaters, HSSF CWs were also used for removal of linear alkylbenzene sulfonates [41–43] and pharmaceuticals [44] from the sewage.

4.2. Industrial Wastewaters

A variety of industrial wastewaters have been treated in CWs. Vymazal [39] classified them on the basis of the industrial processes: petrochemical and chemical industries; pulp and paper, textile and tannery industries; abattoir and meat processing effluents; food processing; wineries and distilleries. Treatment of contaminated waters from the petrochemical industry is aimed at removal of various hydrocarbons including diesel range organics, BTEX [17,45,46]. One of the most extensive horizontal flow (HF) CWs in Europe (total area of 49,000 m²) was built at the Air Products chemical works at Billingham, Teeside, United Kingdom [47]. The use of HSSF CWs for the treatment of tannery wastewaters is relatively new, and experiments were carried out in Turkey, Portugal, Greece, and

the USA [48–51]. The use HSSF CWs for the treatment of textile wastewaters was carried out as early as the late 1980s and early 1990s in Germany [52] and Australia [53]. The first experiments to treat abattoir wastewaters were reported by Finlayson et al. [54] from Australia. The most recent ones were conducted in Lithuania by Gasiunas and Strusevičius [55], and Gasiunas et al. [56], who presented the results from an 1880 m² HF CW designed to treat meat-processing wastewaters. One of the first reports on the use of HF CW for food-processing sewage was by White [57] on seafood processor wastewater. Recently, HSSF CWs have been used to treat cheese-processing wastewaters. Mantovi et al. [58] described the use of HF CWs to treat wastewaters from the production of Italian cheese “Parmigiano-Reggiano” (400 m², 10.5 m³ d^{−1}) and “Grana Padano” (2700 m², 70 m³ d^{−1}). The treatment efficiency in both systems was very high and amounted to 94%, 96%, 98%, 62% and 45% for TSS, COD, BOD₅, TKN, and TP, respectively. In addition, the reduction of vegetable fats and oils was very high; the inflow concentrations of 59 mg L^{−1} (Parmigiano) and 167 mg L^{−1} (Grana Padano) were reduced to 1 and 2 mg L^{−1}, respectively. Winery wastewaters are characterized by a high content of organics (up to 45,000 mg L^{−1} BOD₅) and solids, high acidity, and significant variations in seasonal flow production [59,60]. In addition, the winery wastewaters are characterized by low N/C and P/C ratios. Cork boiling wastewater is known for its high content of phenolic compounds and toxic nature. Gomes et al. [61] evaluated the total phenolic compounds (TPh) removal over a 2.5-year monitoring period, in an HSSF CW planted with *Phragmites australis*. Average TPh removal reached 69.1%, with respective mass removal rates up to 0.5 g/m²/d.

4.3. Agricultural Wastewaters

Wastewater from feedlot operations is commonly treated with FWS CWs with a series of lagoons as a pretreatment step (separation of settleable solids, digestion of solids, and treatment of the liquid portion) [40,62]. HSSF CWs are used to a lesser extent, but many excellent examples could be found in the scientific literature [39,63–66]. In Table 2, an average treatment performance for HSSF CWs treating wastewaters from agro-industrial operations is presented. This average was calculated by considering all the case studies included in this work. The inflow concentrations are much lower as compared to raw wastewaters because of intensive pretreatment. On the contrary, Rozena et al. [67], declared that there is no one CW design (HSSF, VSSF, FWS) that is the most effective for agricultural wastewater, so hybrid designs may prove to be the most efficient and practical.

Table 2. Average treatment performance of HSSF CW treating agricultural wastewater. (Adapted from [39]).

	Concentration (mg/L)		Eff. (%)	n *	Loading (kg/ha d)			n *
	In	Out			In	Out	Rem	
BOD ₅	464	183	68.2	43(19)	541	294	246	43(18)
COD	871	327	63	38(17)	1239	602	637	37(17)
TSS	516	180	76.9	56(26)	1430	779	651	54(23)
TN	116	57.5	51.3	31(13)	68	42	26	31(13)
NH ₄ -N	71.5	39.6	33.8	45(18)	74.6	19	55.6	45(18)
TP	19.8	8.5	54.3	44(18)	13.7	7	6.7	44(18)

In = inflow to a vegetated bed. Out = final outflow. Rem = removed load. * The number denotes the number of annual means with a number of systems in parentheses.

4.4. Stormwater Runoff

Agricultural and urban runoff represent the two most common polluted storm waters that threaten the quality of surface waters [68–71]. For this reason, many studies have classified stormwater runoff from urban regions as a contribution to non-point source pollution to surface water [72,73]. An example of HSSF CWs used to treat agriculture stormwater runoff was reported by Zhou et al. [74]. The average total nitrogen (TN) inflow concentration was approximately 22 mg L^{−1} in which about

80% was nitrate, 10% ammonia and 10% organic nitrogen. The removal varied between 27% and 80% depending on the HRT.

For treatment of urban stormwater runoff, FWS CWs are mostly used. Walker et al. [75], in their two-year field study, used a FWS design to treat stormwater runoff from an existing urban area in Queensland, Australia. However, there are some examples of the utilization of HSSF and VSSF designs as well. For instance, Geary et al. [76] reported on the use of an HSSF CW to treat urban runoff from a 21 ha urban catchment at Blue Haven, Australia. Scholz et al. [77], assessed over two years the treatment efficiencies of VF wetland filters containing macrophytes and granular media of different adsorption capacities.

Stormwater monitoring campaigns usually provide records of pollutants by measuring the event mean concentration (EMC), defined as [78]:

$$EMC = \frac{\sum_{i=1}^n C_i V_i}{V} \quad (1)$$

where V is the total runoff volume per event (L), V_i is the runoff volume during time period i (L), C_i is the pollutant concentration during time period i (mg/L), and n is the total number of samples during a single storm event.

Knowing EMC, it is possible to evaluate the pollutant concentration removal efficiency (CRE) and the efficiency ratio (ER). CRE calculates the reduction in pollutant concentration for a given stormwater treatment device, while ER is described in terms of the average pollutant EMCs calculated over the duration of the analyzed storm events for a given stormwater treatment device. They are respectively defined as:

$$CRE = \frac{\sum \left(\frac{EMC_{in} - EMC_{out}}{EMC_{in}} \right)}{\text{no of events}} \quad (2)$$

$$ER = 1 - \left(\frac{\mu_{EMC_{out}}}{\mu_{EMC_{in}}} \right) \quad (3)$$

where EMC_{in} and EMC_{out} are respectively the pollutant EMCs measured at the inlet and outlet of the system, $\mu_{EMC_{in}}$ and $\mu_{EMC_{out}}$ represent the mean of EMCs measured respectively at the inlets and at the outlets of the CW.

Walker et al. [75] calculated these two efficiencies by taking into account some of the common pollutants detected in urban runoff (TSS, TN, TP, $\text{NH}_3\text{-N}$, $\text{NO}_3\text{-N}$, $\text{NO}_x\text{-N}$), measured over two years (Table 3).

Table 3. CREs and ERs of FWS system treating urban runoff (Adapted from [75]).

	TSS	TN	TP	$\text{NH}_3\text{-N}$	$\text{NO}_3\text{-N}$	$\text{NO}_x\text{-N}$
CRE $\pm$ std. dev. [%]	58 $\pm$ 29	7 $\pm$ 48	33 $\pm$ 33	45 $\pm$ 140	50 $\pm$ 33	49 $\pm$ 33
ER [%]	81	17	52	8	47	47

5. Sustainability of the Design and Management of Constructed Wetlands

After understanding the type of wastewater, it is then possible to consider the factors that contribute to improving the sustainability of CWs. Factors to be considered include the site, plant and substrate selection, water level, wastewater type, HRT, hydraulic loading rate (HLR), installation, operation and maintenance procedures. These parameters have been investigated experimentally [51], by using modeling [79–81] and Artificial Neural Networks [82]. In particular, factors such as plant selection, substrate selection, and hydraulic conditions (water level, HLR, and HRT) are critical in creating a viable CW system and achieve the sustainable treatment performance. In the following paragraphs, the importance of these factors is described.

5.1. Plant Selection

Macrophytes are common in wetlands and are considered a significant design element in natural and constructed systems [83,84]. The plant species used in natural treatment systems are plants that commonly live in wetlands (aquatic and hydrophilic plants), adapted to grow in soils that are moderately or constantly saturated. The presence or absence of these macrophytes often delineates CWs as green technology [85]. Wetland plants can adsorb pollutants from the wastewater and accumulate them in their tissue in addition to providing microorganisms in the system with a complimentary growing environment [86]. Furthermore, these plants are able to transfer oxygen from their roots to the rhizosphere, creating aerobic conditions that enhance the contaminant degradation in the system.

The selection of plant species needs to take into account factors such as the climatic conditions of the site, the characteristics of the wastewater to be treated, and the effluent quality required. On the basis of these considerations, Rozena et al. [67], in their review, found that *Typha* spp. tends to be most commonly used in Northeastern–North America. The most suited vegetation to the proposed CW system should be selected by taking into account adaptability to the saturation conditions of the terrain, the growth potential of roots and their oxygen carrying capacity, the high capacity of photosynthetic activity, the tolerance to high pollutant concentrations, disease resistance, and management requirements. On the basis of these considerations, only a few plant species have been widely used in CWs [87]. Macrophytes frequently employed in CW treatments include emergent plants, submerged plants, floating-leaved plants, and free-floating plants. The most common and used emergent species we found included *Typha* spp. (Typhaceae), *Phragmites* spp. (Poaceae), *Iris* spp. (Iridaceae), *Scirpus* spp. (Cyperaceae), *Juncus* spp. (Juncaceae), and *Eleocharis* spp. (Spikerush). The most frequently used submerged plants are *Hydrilla verticillata*, *Vallisneria natans*, *Ceratophyllum demersum*, *Myriophyllum verticillatum*, and *Potamogeton crispus*. The main floating-leaved plants are *Nymphoides peltata*, *Nymphaea tetragona*, *Trapa bispinosa*, and *Marsilea quadrifolia*. The free-floating plants are *Eichhornia crassipes*, *Salvinia natans*, *Hydrocharis dubia* and *Lemna minor* [21]. Considering that plants are one of the leading factors influencing water quality in wetlands, numerous studies were performed on the uptake capacity of plants in CWs. Plant uptake ability may differ according to different technical parameters, such as system configurations, retention times, loading rates, wastewater types and climatic conditions [3]. The impact of plants regarding nitrogen and phosphorus removals is considered high, accounting for 15–80% N and 24–80% P [88,89]. However, several researchers found that it was lower and within the range of 14.29–51.89% of total nitrogen removal, and 10.76–34.17% of total phosphorus removal, respectively [90,91]. Regarding heavy metal removal, Ha et al. [92] evaluated the accumulating capability of *Eleocharis acicularis* in different concentrations of In, Ag, Pb, Cu, Cd, and Zn, and the results showed that *E. acicularis* had an excellent ability to accumulate metals from water. In addition, Ranieri et al. [17] reported the removal of more than 60% of BTEX from wastewater at an HRT higher than 100 h by *Phragmites australis* and *Typha latifolia*.

A summary of the plant contributions to the CW systems is presented in Table 4.

Table 4. Summary of mycophyte roles in CWs.

Role of Mycophytes	Source
Roots: physical effects	
Filtering effect	[93]
Improved hydraulic conductivity	[94,95]
Reduced velocity	[93]
Prevention from clogging	[96]
Roots: microorganisms	
Surface for attachment	[93,94]
Oxygen	[93,94,97–100]
Uptake function	
Nutrients	[88–91]
Metals	[92,101]
BTEX	[17,102]
Evapotranspiration	
Increased water loss	[103,104]

5.2. Substrate Selection

Substrate materials have a strong influence on the movement of water through CW (hydraulic conductivity) and on plant growth. These materials provide a vast surface area for microorganisms to attach additionally to plant biomass (roots, stems, and leaves) and also act either as a filtration and/or adsorption medium for pollutants [105]. Both the chemical soil composition and physical parameters—such as particle size distributions, pore spaces, degree of irregularity—and the coefficient of permeability, are the key criteria influencing treatment performance [106]. For this reason, the selection of optimal substrates is determined in terms of the hydraulic permeability and capacity for adsorbing pollutants. Poor hydraulic conductivity would lead to the clogging of systems, with the consequent severe reduction in the effectiveness of the system. Low adsorption by substrates could also negatively influence the long-term removal performance of CWs [107]. Wu et al. [21] summarized several studies carried out on the selection of wetland substrates, in particular for sustainable phosphorus removal from wastewater. Ionized ammonia can be removed from wastewater through exchange with soil strata, detritus, humic substances, and organic and inorganic sediments or else fixed within the clay lattice in CWs [106]. On the other hand, adsorbed ammonium binds loosely to the materials and can be released effortlessly in response to changes in water chemistry [108]. Numerous studies have been carried out to assess the impact of different substrates used to enhance pollutant adsorption capacity. Meng et al. [26] confirmed the results obtained from previous research [3,4,109], which evaluated the use of different media substrates such as rice husk and organic mulch on system efficiency. The results showed that these media improved nitrogen removal due to organic carbon content. However, these results contradicted those of others regarding the use of expensive substrate materials to improve the CW performance. For example, the use of granular activated carbon did not enhance the adsorption capacity of CW media [14]. Furthermore, the use of zeolite and bauxite media did not provide a significant improvement in CW system efficiency as reported by Stefanakis and Tsihrintzis [110].

Frequently used substrates include natural material, artificial media and industrial by-products (Table 5). Outcomes from these studies suggest that substrates such as sand, gravel, and rock are poor for long-term phosphorus storage, while synthetic and industrial products with high phosphorus sorption capacity and hydraulic conductivity may be more effective alternative substrates in CWs.

Table 5. Substrates commonly selected for CW wastewater treatment (Adapted from [21]).

Type of Substrate	Source
Natural material	
Sand	[4]
Gavel	[111]
Clay	[111]
Calcite	[112]
Marble	[19]
Vermiculite	[19]
Bentonite	[113]
Dolomite	[112]
Limestone	[114]
Shell	[115]
Shale	[4]
Peat	[4]
Wollastonite	[116]
Maerl	[4]
Zeolite	[117]
Industrial by-product	
Slag	[16]
Fly ash	[113]
Coal cinder	[118]
Alum sludge	[119]
Hollow brick crumbs	[118]
Moleanos limestone	[120]
Wollastonite tailings	[121]
Oil palm shell	[122]
Synthetic products	
Activated carbon	[118]
Lightweight aggregates	[4]
Compost	[4]
Calcium silicate hydrate	[20]
Ceramsite	[20]

5.3. Hydraulic Conditions

The water level is an essential element in determining which plant types will become established [123], and it also affects the biochemical reactions responsible for removing contaminants by changing the redox status and dissolved oxygen level in CWs [21]. By comparing 0.27 m deep wetland beds with 0.5 m deep wetland beds, García et al. [124] showed that differences occur in the transformations of pollutants within systems of different depths. In addition, experiments conducted by Aguirre et al. [125], with the aim of investigating the effect of water depth on organic matter removal efficiency in HF CWs, concluded that the relative contribution of different metabolic pathways varied with water depth. Hydrology is another primary factor in controlling CW efficiency. Flow rate should be monitored to accomplish a satisfactory treatment performance [126].

HRT is one of the few operational factors that can be controlled in CWs. For example, a critical BOD removal efficiency can be obtained at an HRT shorter than one day, while the system efficiency will be enhanced at an HRT of about seven days, as shown by Reed and Brown [127]. Based on this, HRT is an important factor that affects the efficiency of the CW treatment, which is usually decided by designers. Despite the advantage of enhancing the treatment efficiency, when increasing the HRT, this can also be considered as the main disadvantage for large wetland areas, particularly when land availability is restricted [128]. The optimal design of HLR and HRT plays a significant role in the removal efficiency of CWs. Greater HLR promotes quicker passage of wastewater through the media, thus reducing the optimum contact time. A proper microbial community may be established in CWs and have suitable contact time to remove pollutants at a longer HRT [3,21,129]. Toet et al. [130] found

positive nitrogen removal in CWs with an HRT of 0.8 days compared results with a 0.3 day HRT. Furthermore, the effect of HRT may differ between CWs depending on the dominant plant species and temperature, as those factors can affect the hydraulic efficiency of wetlands. In a long-term experiment, Cui et al. [16] observed a minor decrease of ammonium and TN removal from domestic wastewater in vertical flow (VF) CWs when HLR changed from 7 to 21 cm/d. Mean ammonium removal decreased from 65% to 60%, and TN reduced from 30% to 20%.

Proper organization and maintenance of a wetland system are essential to ensure the following objectives: (i) achieve and maintain the pollutant removal efficiency established in the design phase; (ii) minimize malfunctions and maximize environmental protection and economic savings; (iii) maximize species efficiency and longevity.

6. Useful Considerations and Conclusions

After years of studies and implementations, the scientific community has widely recognized that CWs are a reliable treatment technology. This review demonstrates that the advances in the design and operation of CWs accomplished over the years have significantly increased pollutant removal efficiency, and the sustainable application of this treatment system has also been significantly improved. In Table 6, recommendations on the design and operation parameters of CWs are presented.

Table 6. Recommendations on the design and operation parameters.

Parameter	Recommendation
Plant selection	Native plant species
Substrate selection	Synthetic and industrial products
Water level (m)	0.27–0.5
HRT (day)	1–7

Considering the increasingly stringent water quality standards for wastewater treatments and water quality worldwide, CWs have some limitations, and future studies and development work are necessary. In particular, as it is represented in Figure 2:

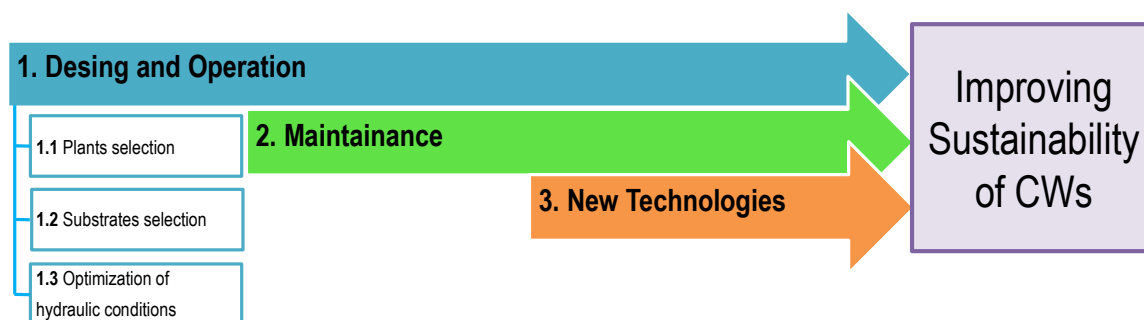


Figure 2. Considerations for improving the sustainability of CWs.

Wetland macrophytes (1.1 in Figure 2) and substrates (1.2 in Figure 2) represent two factors that influence the efficiency of pollutant removal in CWs. More attention should be given to appropriate plant species selection studied for CWs in temperate and cold climates. An intensive evaluation of differences between species and season is also needed. In addition, some non-conventional wetland media, characterized by high sorption capacity, should be studied and used for CWs. Moreover, the review of the design and operating parameters shows that the optimal treatment performance is vitally dependent on environmental, hydraulic and operating conditions (1.3 in Figure 2). Therefore, understanding how to manage and optimize these conditions warrants more investigation.

Additional research on the critical pathways and mechanisms corresponding to higher pollutant removal should be taken into consideration. The review of design and operation parameters (plant and

substrate selection, and hydraulic conditions) shows that the optimal treatment performance is crucially dependent on hydraulic, environmental, and operating conditions. Therefore, if an optimization of the design and management of these systems wants to be accomplished, further studies on the aspects above mentioned would be needed.

For the sake of clarification, it is worth mentioning that as well as studies on design and operation parameters, additional research on maintenance processes (2. in Figure 2) and new strategies and technologies (3. in Figure 2) is necessary for sustainable CW systems and water quality improvement.

Taking into account the efficient and sustainable implementation of full-scale CWs, future studies should focus on a comprehensive assessment of plants and substrates in field trials under real conditions, optimization of environmental and operational parameters, exploration of novel enhancement technologies and maintenance strategies.

New studies will provide information that will increase the successful application and sustainability of CWs.

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