Constructed Wetlands as a Sustainable Sanitation Solution

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The application of nature-based solutions (NBSs) in treating wastewater are treatment wetlands or constructed wetlands (CW). CWs are natural treatment technologies that efficiently treat many different types of wastewater (domestic wastewater, agricultural wastewater, coal drainage wastewater, petroleum refinery wastewater, compost and landfill leachates, fish-pond discharges, industrial wastewater from pulp and paper mills, textile mills, seafood processing). CWs can effectively treat raw wastewater to different levels of treatments and can be used as a primary, secondary, or tertiary treatment. CWs are engineered systems designed to optimize and copy processes found in natural environments thus they are considered as sustainable, environmentally friendly options for wastewater treatment. CWs have low operational and maintenance requirements and have a stable performance with less vulnerability to inflow variation. CWs have proved their ability to treat several types of wastewaters. Several benefits and facts, such as the low construction and operational costs of CWs, low-energy, and less operational requirements, have raised the interests in CWs as a treatment technology. The sustainability of CWs as a sanitation solution (technical, financial, environmental sustainability) is described with a focus on integrating climate change resilience and a circular economic approach to the technical and financial sustainability.

Keywords: constructed wetlands ; wastewater ; nature-based solution ; sustainable sanitation

1. Treatment Mechanism within Constructed Wetlands (CWs)

Treatment mechanisms within constructed wetlands (CWs) include biological, physical, and chemical processes. The treatment process occurs from the combination of water, substrate, plants, plants debris and microorganisms [1]. In conventional wastewater treatment systems the treatment processes consist of a series of separated unit operations, each of them designed for a specific purpose, multiple removal processes can occur in one or two reactors, while the treatment processes in CWs varies from being simple to complicated which makes CWs, in terms of treatment processes, not fully understood [2][3][4][5].

Pollutant removal in CWs occurs in the substrate materials and plant rhizosphere [6]. CWs can efficiently remove the following components from wastewaters: suspended solids, organic matter, excess nutrients as well as the natural remains of pathogens [6][7]. Several applications of CWs in treating industrial wastewater have proved the ability of CWs to remove heavy metals efficiently [8][9]. The major of pollutants and pathogens present in wastewater are suspended solids, organic contents, pathogens, nitrogen and phosphorus.

The vegetation cover and reeds In CWs plays an important role in treating wastewater, their roots and rhizomes provide a proper site for microbial biofilm growth leading to an increase in biological activity per unit area when compared to open water systems, such as lagoons. They distribute the flow, limiting hydraulic short-load, and release small amounts of oxygen and organic carbon compounds into the rooting which can be used for the aerobic and anoxic microbial processes [10][11].

In the substrate materials sedimentation and filtration occur, sedimentation of the suspended particles present in wastewater leads to the removal of pollutants, and higher retention times will help to achieve a higher sedimentation percentage [11]. The sedimentation process not only reduces the organic matter, but also removes coliform bacteria [11][12]. The retained particulates accumulate within the substrates and are consumed by hydrolysis processes, generating an additional load of dissolved organic compounds that can be degraded within the treatment bed [10]. Within the substrate materials, adsorption occurs which is an important process for the removal of phosphorus and heavy metals [13][14].

In most CWs theoretically all the nitrogen removal processes are active, including ammonification, nitrification, denitrification, plant and microbial uptake, nitrogen fixation, nitrate reduction, anaerobic ammonia oxidation, adsorption, desorption, burial, and leaching [3][10]. It is widely accepted that microbially induced transformations of nitrogen, common to other wastewater treatment systems, dominate in CWs, with absorption and plant uptake also present to a limited extent. The nitrogen removal processes are affected by the treatment wetland type, applied loading rate, hydraulic retention time, temperature, plant type and the properties of the substrate materials [10][15].

Regarding heavy metals compared to the conventional treatment methods of removing heavy metals, such as chemical precipitation, ion exchange, adsorption, and membrane filtration CWs have proved their ability to remove heavy metals through several successful applications of treating industrial wastewater. CWs effectively remove heavy metals from wastewater through a combination of physical, chemical, and biological processes. Physical, flocculation, sedimentation, and filtration are the main removal processes able to remove heavy metals from wastewater, the physical process is carried out through the interactions between wastewater containing substrates and plant root systems. Biologically, plants can absorb heavy metals via their root systems, transferring and storing them in other plant tissues in a process called phytoaccumulation; thus, CWs allow the permanent removal of heavy metals by harvesting plant shoots. Furthermore, the microbiological activities of some microorganisms in CWs can remove heavy metals through their metabolism and biosorption. Chemically, several chemical processes to remove heavy metals can occur within CWs such as chemical adsorption, ion exchange, and oxidation [9][16].

2. Constructed Wetlands and Sustainability

2.1. Are Constructed Wetlands Technically Sustainable?

Technical sustainability is an important criterion within the sustainability criteria, as the treatment system should be technically appropriate and perform according to the treatment efficiency required. CWs can treat several types of wastewater and can be used at different stages of treatment, as described before. CWs provide a solution in different contexts, it can be used as a centralized, semi-centralized and decentralized solution [17]. The fact that CWs are easy to operate and maintain can compensate for the lack of technical staff and locally available expertise, particularly for small and medium communities and in low and developing countries [18][19].

Technically, CWs have proved their capacity for treating several types of wastewater, as the main system or a combined technology with conventional systems. For instance, Masi et al. (2017) analyzed French constructed wetlands treating domestic wastewater in Moldova and illustrated the removal efficiency was 86% for both the COD and BOD [20]. Another example where Langergraber et al. (2018) studied a vertical flow small wastewater treatment plant in Austria that serves 40 population equivalents, reported the removal efficiency was 98% for both COD and BOD [21].

In Sicily (Italy) a horizontal flow CW HFCW has been used as a tertiary treatment system after a trickling filter. After five years of study, the HFCW has been used for tertiary treatment with the removal efficiency of TSS, BOD, COD, TN, TP, TC and *E. coli* were 98.21%, 85%, 63%, 71%, 42%, 31%, 98.57% and 98.21%, respectively. HFCW also showed the very effective removal of salmonella and helminth [22].

In Nepal, wastewater treated with CWs achieved a treatment percentage of 90.9% for TSS, 90% for BOD, 48.3% for COD, and 15.3% for TN [11]. While Yoon et al. (2001) illustrated that, in South Korea, wastewater treated with CWs had a removal percentage 90% for TSS, 93.04% for BOD, 41.17% for TP and 19.6% for TN [23]. Another study from China, Liu et al. (2009) found that wastewater treated with *Phragmites australis*, *Typha latifolia* and *Canna indica* plants had the removal percentage of 62.06% for TP, 81.7% for BOD, 73.3% for COD, and 44.3% for TN [24]. In the Netherlands, Verhoeven and Meuleman (1999) found that wastewater treated with *Phragmites australis* plants had a removal percentage of 99% for TSS, 95% for BOD, 80% for COD, 35% TN, and 25% for TP [25]. Other examples for different applications of CWs are illustrated in **Table A1**.

Table A1. Applications and examples of CWs.

			Treatment Efficiency Removal (%)				
#	Case	Application	COD	BOD	TSS	TN	References
1	VF CW FOR POLLUTION CONTROL IN PINGSHAN RIVER WATERSHED, SHENZHEN, CHINA-COMBINED SEWER	Tertiary treatment	40.00	40.00	80.00		[2]
2	TWO-STAGE VF CW AT THE BÄRENKOGELHAUS, AUSTRIA-DOMESTIC WASTEWATER	Secondary treatment	98.03	99.46	97.35	70.60	[43]

#	Case	Application	Treatment Efficiency Removal (%) COD	BOD	TSS	TN	References
3	VF CW FOR MATANY HOSPITAL, UGANDA-DOMESTIC WASTEWATER	Secondary treatment	92.00	99.31	99.87		[86]
4	French VF CW IN ORHEI MUNICIPALITY, MOLDOVA-DOMESTIC WASTEWATER	Primary and secondary treatment using French reed beds	85.59	85.85	96.05		[42]
5	CHALLEX TREATMENT WETLAND: FRENCH CWs FOR DOMESTIC WASTEWATER AND STORMWATER	Primary and secondary treatment beds (FRBs) and VFTWs	96.24	96.21	98.92	91.25	[2,63]
6	TAUPINIÈRE TREATMENT WETLAND: UNSATURATED/SATURATED FRENCH CWs FOR DOMESTIC WASTEWATER IN A TROPICAL AREA	Primary and secondary treatment	95.69	96.68	98.11	68.48	[87]
7	HS FLOW SYSTEM FOR GORGONA PENITENTIARY, ITALY-DOMESTIC WASTEWATER	Secondary treatment	68.44	71.58	29.47	31.25	[13]
8	HS CW IN KARBINCI, REPUBLIC OF NORTH MACEDONIA-DOMESTIC WASTEWATER	Secondary treatment	84.25	88.96			[2]
9	HF CW IN CHELMNÁ, CZECH REPUBLIC-DOMESTIC WASTEWATER	Secondary treatment	80.00	93.26	91.72		[62]
10	FWS CW IN ARCATA, CALIFORNIA, USA-DOMESTIC WASTEWATER	Secondary and tertiary treatment		91.28	93.81		[2,88]
11	FWS CW TERTIARY TREATMENT IN JESI, ITALY-DOMESTIC WASTEWATER	Tertiary treatment	13.16	16.67	76.32	27.06	[2,89]
12	full-scale experimental VF CW with effluent recirculation in OMAN-INDUSTRIAL WASTEWATER	Primary and secondary treatment	98.15	98.81			[49]

It is worth mentioning that despite the absence of clear guidelines in designing CWs, several studies and design concepts have proved their reliability to be used to design CWs to treat several types of wastewater [2][10]. Many authors have illustrated that the easiness and flexibility of design and the possibility of using local materials have made CWs sustainable solutions in different contexts, the high resistance of *phragmites* also plays a vital role in technical sustainability [10][26]. As a technology it has been proven that it has very limited requirements for operation, and the technology does not require skilled labors or experts to operate.

2.2. Are Constructed Wetlands Resilient to Climate Change?

The technical sustainability can be extended to include the technology resilience to climate change impacts. In recent years the need to have a technology and system that can perform efficiently under the climate change impacts has increased. Several studies have compared and analyzed the performance of different sanitation technologies under climate change impacts. NBSs in general and CWs in specific have a wide range of applications to minimizes the impacts of the climate change [27]. For instance, the application of CWs in flood risk reduction plays an important role in protecting valuable infrastructure, NBSs and CWs have contributed to the reduction and mitigating of flood risks through storing water and regulating and managing the land [27][28]. There has been an increasing interest in applying and using CWs to support conventional wastewater treatment plants (WWTP) during heavy rain and flash floods, especially in cases of combined sewer overflow (CSO) [26]. For example, in Gorla Maggiore they implemented a VFCW and FWS-CW to manage the excess runoff and floods to protect the combined sewer system, CWs succeeded in reducing the peak flow by 53% for five peak events and 86% for an event with a return period of 10 years. [29].

CWs helped several WWTPs in treating and managing first flush rain events, especially in industrial areas where the COD concentration increased up to 80% within the first flush [30].

In the urban context, CWs can retain the rainwater to increase the water capacity of the city. Termed the “sponge city”, CWs can store and retain water through roofs, parking areas and public parks, in all cases the application of CWs can protect the economic value of the city such as the infrastructure [31][32].

López et al. (2019) illustrated in their study that the performance of CWs can be regulated at the design phase and during operation of CWs to sustain the removal efficiency under different climate conditions. They illustrated that CWs play an important role in solving problems associated with climate change impacts, such as (i) the increase in pathogen concentration in wastewater due to the rise in global temperatures; (ii) higher precipitation that can lead to an increase in pathogens concentrations resulting from runoff and first flush problems [33].

The above facts and cases illustrate CWs to be a sustainable sanitation technology from a technical point of view.

2.3. Are Constructed Wetlands Socially Acceptable?

Stefanakis (2019) showed in his publication several benefits of using CWs including a series of ecosystem services, such as cooling, biodiversity restoration, and landscaping. From a social point of view, CWs provide solutions to the increasing growth rate of modern cities and peri-urban areas. CWs acting as a green multi-purpose solution for water management and wastewater treatment, have been effectively proven through several worldwide applications to possess multiple environmental and economic advantages. These systems can function as water treatment plants, habitat creation sites, urban wildlife refuges, recreational or educational facilities, landscape engineering and ecological areas [28][34].

The social aspect of CWs is being increasingly improved and validated. The green, aesthetical appearance of CWs compared to conventional WWTP makes CWs more accepted by society. Many enterprises in industries, municipalities, and private companies, etc. choose CWs to treat wastewater generated by their premises to enhance their green profile and integrate CW installation into their social responsibility plan [35].

Zitácuaro-contreras et al. (2021) analyzed the social potential of using plants used in CWs and classified their potential in decorative, artisan, medicinal, and food industries. Consequently, plant species can be used in the elaboration of handicrafts, flower arrangements, and the cultivation of seedlings which can be used at the local market. They illustrated the huge potential for enhancing the social sustainability as they provide several benefits and opportunities for use of the cultivated plant species for generating income. In their case study they mention that 90.5% have a decorative use, and the rest can be used in artisanal activities; they both have the potential to have economic value and use in social and cultural local events [36].

2.4. Are Constructed Wetlands Financially Sustainable?

The limited operational and construction costs compared to the conventional systems, and the fact that the energy required for CWs is far less than the energy requirements of conventional systems have shown the importance when considering CWs as sustainable sanitation solutions, especially as a decentralized solution for scattered communities. Several studies have indicated that CWs have shown several advantages in economic value (construction and operation costs) in comparison to conventional WWTPs [26][37][38][39][40]. Similarly, energy requirements for CWs are far less than that of conventional WWTPs [40][41][42].

Parde et al. (2021) illustrated that CWs are low-cost treatment processes to treat wastewater with low operation and maintenance cost, for example, the operational costs of a CW are equal to 1–2% of plant construction costs [11]. Grinberga and Tilgalis (2011) studied the cost difference between CWs and an activated sludge treatment system and showed that activated sludge constructions costs are 30% higher than the construction costs of CWs, while the maintenance costs for activated sludge treatment systems are almost equal to their construction costs, the maintenance costs for CWs are almost negligible [43]. This fact has been illustrated through many examples and studies like the horizontal flow treatment wetland in CHELMNÁ, Czech Republic where the operational cost was 1500 USD yearly and the capital cost was 23,000 USD [44][45].

Langergraber et al. (2018) calculated the operational cost for two stages of a CW in Austria and found that the operation cost was equal to 3.8% of the total construction cost [21]. While the French CW in Moldova, which treats domestic wastewater for more than twenty-thousand population equivalents, had a construction of 3.4 million euros while the operational cost was 85,000 euros per year (around 2.5% of the total construction costs) [20]. Arias et al. (2014) analyzed a case of a French CW in Challex and found that the construction cost was 1850 million euros while the annual operational cost was 15,000 euros (around 1% of the total implementation costs) [46]. Another example from Italy found the operational cost for the Gorgona CW was 0.5% of the construction costs, and in the Jesi CW the operational cost was 6.7% of the construction costs [44].

Other papers have analyzed the financial and environmental aspects of using CWs for industrial wastewater treatment; Mannino et al. (2008), and Dimuro et al. (2014) used the replacement cost methodology (RCM) for financial analysis and the life cycle assessment (LCA) for environmental assessment, their results indicated that the total value savings calculated for implementing a CW instead of the sequencing batch reactors was $282 million over the project's lifetime. The LCA proved that the lower energy and material inputs of the CW resulted in fewer potential impacts on fuel use, acidification, smog formation, and ozone depletion leading to fewer potential impacts on global warming [18][47].

However, land requirements for CWs might be the most limiting factor for their application, especially when the cost of land is expensive due to limited availability, resources scarcity, and the high population density. This fact is critical for the financial sustainability of CWs. This problem can be solved with innovative ideas, such as artificial aeration CWs; however, this option might increase the lifecycle cost of CWs [37][39].

2.5. Are Constructed Wetlands in Line with a Circular Economy Approach?

The financial sustainability of CWs can be integrated into the circular economic approach. Several recent studies have analyzed and studied CWs in the circular economy and compared it with the linear economic approach for example, Masi et al. (2018) studied the role of CWs within the circular economy and resource recovery paradigm, in their study they illustrated that CWs interfere with the circular economy through water reuse, nutrient recovery, energy, and biomass production and ecosystem services [31]. As an example of nutrients recovery, the French CW or French reed beds (FRBs) with its particular design showed an appropriate performance. FRB contains two stages, the first stage receives the raw wastewater and most of the TSS and organic content creates an organic top layer rich in macronutrients, this is dehydrated and decomposes over time, this humified biomass is then removed from the beds and can be reused as soil conditioner and fertilizer [48]. The second stage of FRB improves the removal efficiency of TSS and organic content and it completes the nitrification process, started in the first stage and attains some denitrification. [31][49]. Sludge drying reed beds (SDRBs) are another example which presents similar processes and the same final product as the FRBs. SDRBs are stabilized sludge load produced by conventional and activated sludge plants. SDRBs have been proven to be the cheapest solution to manage and treat the excess sludge from activated sludge plants, with the potential to reuse the dried sludge as soil conditioner in agriculture [50].

Among energy production the harvested reeds of CWs can be used in energy generation; reeds can be used as an energy source in three ways, combustion, biogas production and biofuel production. [51].

The generated biomass reed has an economical value in agriculture. Reeds have been used for centuries for feeding animals and harvested as a fodder plant. Reeds are still commonly used as a fodder plant for water buffalo, cows, sheep, cattle, goats, horses, and donkeys; for instance, in Scandinavia, the Netherlands and China [11][51][52]. Reeds have a high content of nitrogen, potassium (10.9 g/kg) and manganese (2.65 g/kg) making it a good fodder plant for ruminants [53]. The nutritional value of 13.31 kg of reeds is equivalent to that of one kilogram of oats [51]. Although reeds have a lower nutritional value compared to other fodder plants, they are still a cheap and appropriate source.

In summary, integration of CWs into the circular economy paradigm will lead to the financial and economic sustainability of this system.

2.6. Are Constructed Wetlands Environmentally Sustainable?

CWs are multifunctional, providing many benefits to the environment [49]. Several co-benefits beyond wastewater treatment allow CWs to be considered as sustainable sanitation systems from an environmental point of view, these co-benefits should be evaluated when selecting CWs as a treatment technology [27][28]. CWs play an important role in restoring biodiversity, many researchers have studied how CWs help in restoring biodiversity, concluding that CWs can enable cities to conserve, restore and thrive with nature. CWs are being increasingly integrated into urban development practices. They have the potential to effectively address biodiversity challenges through conserving nature, restoring nature, and mobilizing people [54][55][56]. CWs and NBSs in general help in the process of pollination mainly performed by insects, birds, and bats. Pollination is vital for the development of fruits, vegetables, and seeds [57]. As CWs enhance the biodiversity it therefore plays a main role in pollination.

CWs can regulate the humidity and localized temperatures during hot weather conditions by ventilation and transpiration processes, as illustrated by Baker et al. (2021) [58]. CWs are considered as an adaptation measure to climate change; (i) CWs consume less energy than conventional treatment systems, and thus less emissions are generated [43]; (ii) CWs are important for carbon sequestration during the treatments (physical or biological processes) such as photosynthesis, carbon is removed from the atmosphere and deposited in a reservoir or carbon sinks (such as oceans, forests, or soils) [59]. Several studies have used different tools to evaluate and assess the environmental impact of CWs and to compare it with other treatment technologies. Flores et al. (2019) used the LCA tool to compare the long-term environmental impacts of using CWs to treat winery wastewater compared to other scenarios, including activated sludge treatment systems. The study illustrated that CWs were the most environmentally friendly option; the potential environmental impacts of CWs are 1–10 times lower compared to activated sludge scenarios [60]. CWs are considered as an eco-friendly eTechnology with low energy consumption. De Feo and Ferrara (2017) also used LCA to evaluate and compare between two wastewater treatment systems (activated sludge and CW), they considered three sensitive parameters with the three values resulted in 27 combinations that were evaluated with three different impact assessment methods (IPCC 2007 100 years, ecological footprint and ReCiPe 2008 H). They found that among all scenarios CW was the best environmental choice in 93% of the scenarios [61].

The growing reeds and vegetation cover plays an important role in carbon sequestration through absorbing atmospheric carbon and storing it in their structure. The estimated rate at which the reeds perform this is 3.3 kg/m^2/year with an accuracy of ±15% [62].

The treated water in general is a valuable water resource that can be used for multiple purposes (usually other than domestic), such as agriculture and irrigation, groundwater replenishment, and environmental restoration. Water reuse can provide alternatives to existing water supplies and can be used to enhance water security, sustainability, and resilience [19][44][63][64].

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