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Review

Constructed Wetlands as a Solution for Sustainable Sanitation: A Comprehensive Review on Integrating Climate Change Resilience and Circular Economy

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Abstract: About eighty percent of wastewater is discharged into the environment untreated. Many challenges are decelerating solving the global sanitation problem, such as the financial limitations and lack of technical capacities. Parallel to this, many countries are facing a growing demand on their limited water resources. Higher water demand and limited availability leads to over-abstraction and deterioration in the availability and quality water resources. In this situation, wastewater can be a new water source. Therefore, there is a growing interest in finding low-cost, easy-to-operate and sustainable sanitation solutions. Constructed wetlands (CWs) in recent years have proved their capability in the sanitation sector as an appropriate sanitation system in different contexts, CWs have proved their ability to treat several types of wastewaters for several decades. 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. Several studies have investigated CWs suitability based on different sustainability indices (technical, social, environmental, etc.). In this paper, a comprehensive review covers the definition, types, treatment processes, sustainability criteria, limitations, and challenges of CWs. The paper also focuses on climate change resilience and circular economic approach under the technical and financial criteria, respectively.

Keywords: nature-based solution (NBS); sustainable sanitation; constructed wetland (CW); wastewater treatment; climate change resilience; circular economy

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1. Introduction

Globally, 3.6 billion people lack safely managed water services, including 1.9 billion people with basic services, 580 million with limited services, 616 million using unimproved facilities, and 494 million practicing open defecation [1]. Despite the efforts made and the improvements over the recent decade, the unsafe management of wastewater and excreta continues to present a major risk to both public health and the environment [2]. Around 80% of wastewater is discharged into the environment untreated [3].

The impact of climate change on the global water cycle is well-known, water availability has become more variable and unpredictable, which leads to an increased challenge in providing sustainable access to adequate quality water for human health. Many countries are suffering from water scarcity and are relying on reusing treated wastewater. Most of these countries are developing countries who already suffer from a lack of proper sanitation systems that doubles the problem in these countries. Thus, there is a need for sustainable sanitation systems to protect human health and the environment as well as to provide a source of water that can be used for agriculture and other purposes [1].

Several challenges are slowing the progress of solving the global sanitation problem, such as both the implementation and operational costs. Therefore, there is a growing demand and interest in low-cost and sustainable treatment solutions. The current widespread conventional treatment systems are well known for their high costs, both construction and operational-maintenances cost, their huge energy consumption, and have put the sustainability of conventional systems under question especially for small communities [4]. On the other hand, CWs and nature-based solutions (NBSs) in recent years have proved their valuable role in solving sanitation problems. They have been used as an appropriate system in different contexts either as the main technology or combined with conventional technologies [2,5]. In addition to the cost-effectiveness, CWs can provide environmental and socioeconomic benefits. CWs and NBS play a vital role in achieving many of the sustainable development goals (SDGs) set by the United Nations (UN) in the 2030 agenda, since wastewater and water management is one of the 17 SDGs: SDG 6 is dedicated to water and sanitation and sets out to "ensure availability and sustainable management of water and sanitation for all", CWs are playing an important role in wastewater management and are connected with other SDGs' like SDG 2, 3 and 13 that consider applying CWs as one of the main adaptation measures against climate change [1,4,6].

This paper describes NBSs and their application in the sanitation sector, the paper focuses on CWs as a treatment technology, including the definition of CWs, types of CWs, and treatment mechanisms of CWs with several case studies. The paper analyzes the sustainability of CWs as a sanitation solution (technical, financial, environmental sustainability) with a focus on integrating climate change resilience and a circular economic approach to the technical and financial sustainability. Finally, limitations and challenges in applying CWs in sanitation are considered in this review.

2. Definition of NBSs, CWs Types, and the Usage in a Sanitation System

In 2018, The United Nations World Water Development identified that NBSs are inspired and supported by nature and use or mimic natural processes to contribute to the improved management of water [3]. Therefore, the defining feature of an NBS is not whether an ecosystem used is 'natural', but whether natural processes are being used to achieve a water-related objective. An NBS can involve saving or restoring natural ecosystems and/or the enhancement or creation of natural processes in modified or artificial ecosystems. They can be applied at different levels: micro- (e.g., a dry toilet) or macro- (e.g., landscape) scale [3,4,7,8].

The application of 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 [2,7,9].

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 [7].

3. Treatment Mechanism within CWs

Treatment mechanisms within CWs include biological, physical, and chemical processes. The treatment process occurs from the combination of water, substrate, plants, plants debris and microorganisms [10]. 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 [11–14].

Pollutant removal in CWs occurs in the substrate materials and plant rhizosphere [15]. CWs can efficiently remove the following components from wastewaters: suspended solids, organic matter, excess nutrients as well as the natural remains of pathogens [9,15]. Several applications of CWs in treating industrial wastewater have proved the ability of CWs to remove heavy metals efficiently [16,17]. The major of pollutants and pathogens present in wastewater are suspended solids, organic contents, pathogens, nitrogen and phosphorus, and heavy metals, the removal mechanisms for each are mentioned in Table 1 [7,18].

Table 1. Treatment Mechanisms [7,18].

Main Removing Mechanisms for Pollutant and Pathogen in CWs	
Parameter	**Main Removal Mechanisms**
Suspended solids (SS)	Sedimentation, filtration
Organic matter (OM)	Sedimentation and filtration for the removal of particulate organic matter, biological degradation (aerobic and/or anaerobic) for the removal of dissolved organic matter
Nitrogen (N)	Ammonification and subsequent nitrification and denitrification, plant uptake and export through biomass harvesting
Phosphorus (P)	Adsorption-precipitation reactions driven by filter media properties, plant uptake and export through biomass harvesting
Pathogens	Sedimentation, filtration, natural die-off, predation (carried out by protozoa and metazoa)
Heavy metals	Sedimentation, filtration, adsorption, ion exchange, precipitation, and biological degradation through plants and microbiological metabolism

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 [7,19].

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 [19]. The sedimentation process not only reduces the organic matter, but also removes coliform bacteria [19,20]. 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 [7]. Within the substrate materials, adsorption occurs which is an important process for the removal of phosphorus and heavy metals [21,22].

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 [7,12]. 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 [7,23].

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 [17,18].

4. Classification of CWs

CWs can be divided into two main categories: surface flow and subsurface flow systems. Despite this, there are many wetland classifications in the literatures, but the simplest classification is the subsurface flow (SF) treatment wetlands which are subdivided into horizontal flow (HF) and vertical flow (VF) wetlands depending on the direction of water flow. Free water surface (FWS) wetlands (also known as surface flow wetlands) are densely vegetated units in which the water flows above the media bed, whereas in subsurface flow wetlands the water level is kept below the surface of a porous medium, such as sand, gravel, soil, biochar, or other material [4,7,11]. SF (HF and VF) wetlands are generally used for the secondary treatment of wastewater. VF wetlands used for treating screened raw wastewater have also been introduced and successfully applied, while FWS wetlands are generally used for tertiary wastewater treatment [2,7,11].

A combination of various wetlands, known as hybrid CWs, has also been introduced for the treatment of wastewater, generally this design consists of two stages of several parallel CWs [2,7,8,11,24]. In recent years, more innovations and wide applications have taken place to enhance the performance of CWs, such as aerated CWs, baffled flow CWs, step feeding CWs and circular flow corridor CWs [25]. A diagram for the various types of CWs is shown in Figure 1. While Figures 2–4 show further details of CW types.

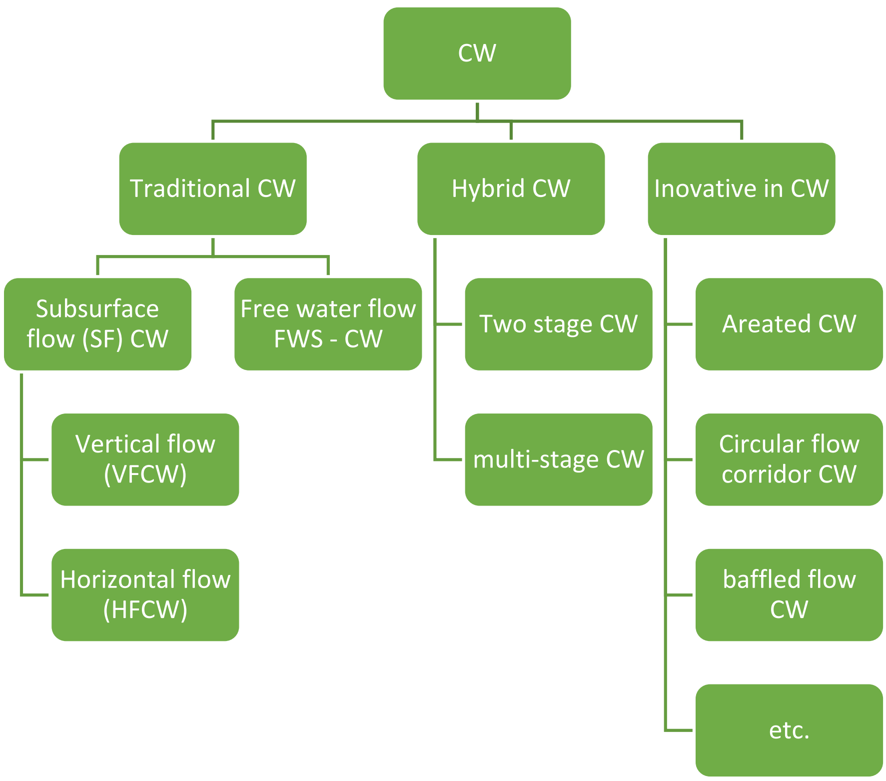

Figure 1. Classification of CWs for wastewater treatment.

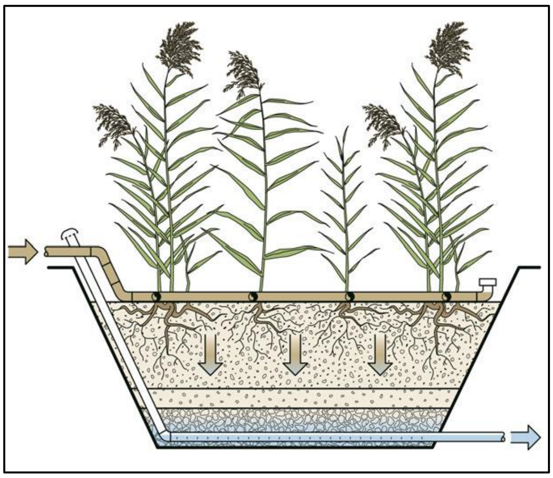

Figure 2. Subsurface vertical flow VFCW [7].

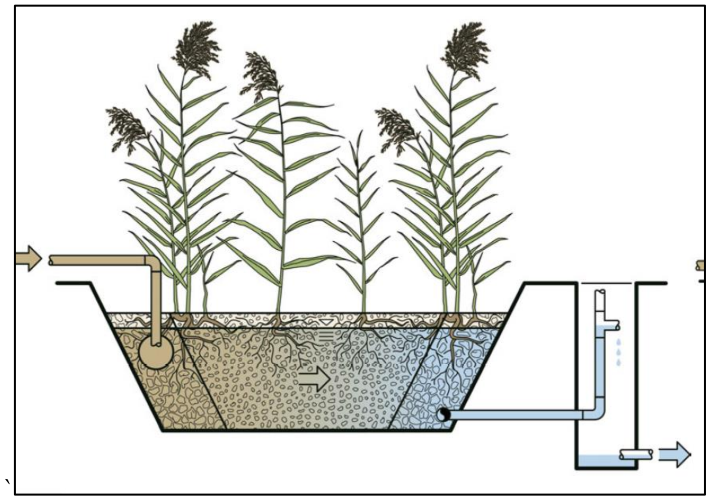

Figure 3. Subsurface horizontal flow HFCW [7].

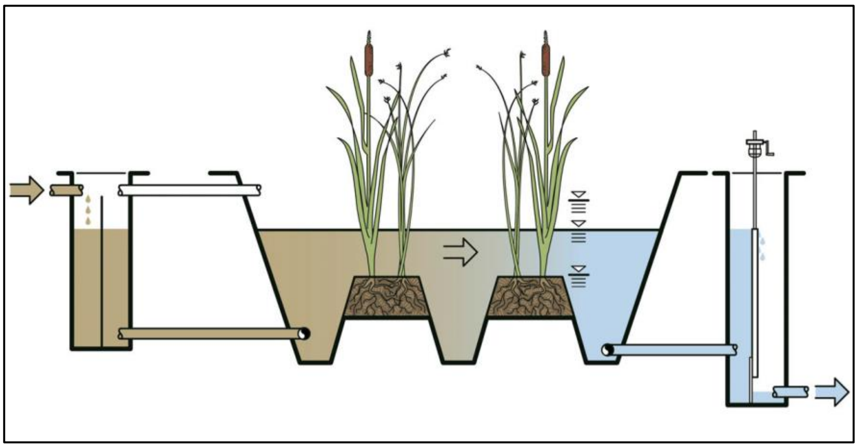

Figure 4. Free water surface horizontal flow FWS-CW [7].

CWs as a Safe Technology

The main goal of having a sanitation system is to protect human health by reducing the possible risk of contacting pathogens and hazardous substances at all points of the sanitation system and to improve hygiene level, nutrition, and livelihood. CWs, as a sanitation solution, have three intervention for human health; (i) several studies have proved the efficiency of CWs in treating wastewater to an acceptable level according to national and international standards, especially as decentralized solutions for scattered communities where they are usually have unimproved/improved onsite sanitation solution [2,26]; (ii) CWs as an affordable and easy-to-operate sanitation solution providing a source of treated wastewater to be used by the community, reducing the pressure on the available water resources needed for human uses, such as hand washing and other hygienic purposes [6,11,27,28]; (iii) natural areas, where CWs can promote physical and mental health, clean air and water, and help enhance human health. Furthermore, NBSs can provide aesthetic appeal and restorative properties, drawing people together and strengthening community ties, people usually find beauty or aesthetic value in various aspects of ecosystems, as reflected in the support for parks, "scenic drives", and through the selection of their residence locations. CWs used for wastewater treatment could be the biophysical characteristics or qualities of species or ecosystems (settings/landscapes/cultural spaces) which people appreciate because of their non-utilitarian qualities [2,7,8,29,30]. The previous reports have encouraged investigation into the sustainability of CWs as a safe treatment technology.

5. CWs and Sustainability

Protecting and promoting human health, through providing a clean environment and breaking disease cycles are the main objectives of any sanitation system. Due to this fact it is highly important to implement a sustainable sanitation solution to achieve that objective in the long-term. A sustainable sanitation system has to be not only economically viable, socially acceptable, and technically and institutionally appropriate, but the system should also protect the environment and the natural resources [31].

Many reports have studied and determined the sustainability criteria and identified different sustainability indices in the sanitation sector. According to Andersson et al. (2016) a sanitation system can be considered sustainable if it is economically viable, socially acceptable, technically and institutionally appropriate, and able to protect the environment and natural resources [32]. This definition has been illustrated by many authors, such as Lennartsson et al. (2009) [33] and Bao et al. (2013) [34].

Many authors have focused on the technically, financial, and social sustainability in sanitation, such as Hashemi (2020) who considered the technical, social, and economic aspects in evaluating the sustainability of sanitation systems [31]. While Han (2017) focused on the technical aspects in evaluation and comparing the sustainability of sanitations systems [35] other studies compared different sanitation systems based on the economic aspects and social approaches toward achieving sustainable sanitation [36,37].

According to Hashemi (2020) sustainable sanitation is a loop-based approach that differs from the current linear concepts of wastewater management, that does not only focus on technology, but also social, environmental, and economic aspects [31]. A sustainability approach in sanitation is a holistic approach. It recognizes that human waste and wastewater are valuable resources. This view comes from considering wastewater as a source of nutrients and water that can be recycled and reused [35,38]. When selecting or designing a new sanitation system, the following sustainability criteria should be considered: (i) health and hygiene, (ii) environment and natural resources, (iii) technology and operation, (iv) financial and economic issues, and (v) socio-cultural and institutional aspects [35,36].

Roland and Arne (2008) illustrated that the main concept of sustainability as more of a direction than a state to reach. Nevertheless, it is critical that sanitation systems are evaluated carefully regarding all dimensions of sustainability to succeed as sustainable sanitation [39].

Based on the aforementioned literature, in this study a deep focus on the technical, social, financial, and environmental sustainability criteria will be considered to evaluate the sustainability of CWs as a sanitation technology.

5.1. Are CWs 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 [4]. 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 [40,41].

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 [42]. 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 [43].

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 [44].

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 [19]. 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 [45]. 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 [46]. 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 [47]. Other examples for different applications of CWs are illustrated in Appendix A.

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 [7,11]. 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 [7,48]. 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. Stefanakis et al. (2014), Nivala et al. (2017), Stefanakis (2019), and Al-Wahaibi et al. (2021) mentioned that only monitoring of the feeding system and harvesting the reeds periodically is required [4,6,7,49].

5.2. Are CWs 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 [3]. 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 [3,26]. 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) [48]. 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. [5].

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 [50].

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 [27,51].

Several studies have monitored the performance of CWs in treating wastewater under the variation of climate change. For instance, Mander et al. (2015), López et al. (2019), and Salimi et al. (2021) studied the impact of climate change on CWs and found that the performance might be affected by the water level within the CWs. This affect can vary between enhancing the aerobic decomposition and the anaerobic decomposition depending on the water level within the CWs. The temperature impacts have also been analyzed and showed an enhancement in photosynthesis processes and the degradation of the wastewater to a certain limit [52–54].

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 [53].

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

5.3. Are CWs 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 [6,26].

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 [8].

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 [55].

5.4. Are CWs 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 [25,48,56–58]. Similarly, energy requirements for CWs are far less than that of conventional WWTPs [58–60].

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 [19]. 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 [61]. 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 [2,62].

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 [43]. 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) [42]. 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) [63]. 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 [2].

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 [40,64].

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 [25,57].

5.5. Are CWs 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 [27]. 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 [65].

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. [27,66]. 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 [67].

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. [68].

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 [19,68,69]. 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 [70]. The nutritional value of 13.31 kg of reeds is equivalent to that of one kilogram of oats [68]. 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.

5.6. Are CWs Environmentally Sustainable?

CWs are multifunctional, providing many benefits to the environment [66]. 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 [3,26]. 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 [71–73]. 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 [74]. 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) [75]. 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 [61]; (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) [76]. 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 [77]. 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 [78].

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% [79].

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 [2,30,41,80].

6. Challenges and Disadvantages

Although there are advantages and the co-benefits of CWs as a sustainable treatment technology, CWs, as with every treatment process have their limitations, these limitations and disadvantages create challenges for applying CWs in sanitation. The main challenges with CWs are summarized in Table 2 (but not limited to).

Table 2. Disadvantages/challenges of applying CWs.

Disadvantage/Challenge	Description	Reference
CWs require more area than the conventional systems	HFCW requires 5–10 m^2/PE, VFCW requires 1–3 m^2/PE, the French CW requires 2.0–2.5 m^2/PE). Limited land availability or cost for sanitation systems can be unaffordable, especially in the urban areas, which makes CWs as unsustainable sanitation solutions in some contexts	[7,81,82].
The accuracy of designs	The performance of CWs is highly affected by the local conditions where the plant is located, this challenge increases with the lack of standard guidelines on design and sizing of recently developed CW types. In addition, unique operation and maintenance guidelines are required for each specific CW.	[2].
The need for preliminary treatment	Preliminary treatment is needed before CWs which requires more costs and more material consumption. Additionally, CWs require more retention time compared to conventional systems, thus more CW beds and more land area are needed.	[4,27,83].
Biomass production	Although the vegetation covers used in CWs have economic value, to produce higher biomass periodical harvesting is required to maintain the removal efficiency of the system. Leading to an increase in the maintenance cost of CWs.	[68].
Varieties of pollutant removals	Each vegetation type has different removal rates for pollutants, few types can be planted at the site, hence removal of all pollutants is difficult.	[2,59]
Longer HRT	The treatment process in CWs requires more time compared with other mechanical treatment processes. CW efficiency might vary seasonally. In the summer, the removal efficiency of many CWs is better when compared to the winter.	[84]
Efficiency and insects	In FWS CW, removal of some pollutants is not efficient for the aquatic phytoremediation, such as heavy metals. In FWS CW mosquito breeding can be a problem if not operated well.	[42,85].
Required proper operation	Although the operation of CWs does not require skilled staff, proper operation and maintenance are needed to avoid clogging problems and to meet the final disposal or reuse standards for the effluent.	[4].

To overcome the previously mentioned challenges, further innovation and research is needed to investigate different design scenarios that minimize the land requirements, such as hybrid systems, aerated CWs, etc. A collective and comparative study of CWs' design and operation guidelines can result in holistic and revised guidelines suitable for different contexts. Further research and cost-effective studies are needed to investigate the possibilities for utilizing the biomass production and reusing the harvested vegetation as a step toward achieving a circular economy.

More researches to investigate the stability of removal efficiencies of different parameters and identifying the main factors that impact the treatment efficiencies are required. Another important area is the analysis of the socioeconomic and environmental contribution/benefits of CWs. Further research might be the analysis of the sustainability of CWs using sustainability tools to support decision makers and stakeholders.

7. Summary and Conclusions

This review illustrates that the sustainability criteria of CWs as a sanitation technology has been fulfilled in many cases and projects. CWs can be applied to treat different types of wastewater with a higher removal percentage of BOD, COD, NH4, TN, TP, heavy metals, etc. CWs have been shown to have removal efficiencies of 80–91% for BOD, 60–85% for COD, and 80–95% for TSS. CWs can be considered as resilient technologies to climate change impacts if operated appropriately; climate change might affect the degradation process and the total emissions but these are limited impacts to the overall efficiency. Economically the review illustrates that CWs require zero or low energy, and low operational and maintenance costs. Approximately, CWs require 1–2% of its capital cost for its operation and maintenance, which is very low compared with other treatment technologies, and can be liked with the circular economic approach thought different interventions, such as the energy productions and nutrients recovery. The review summarizes the benefits of applying CWs to the environment rather than protecting the environment from discharged wastewater, playing an important role in biodiversity restoration and carbon sequestration, and providing a green and aesthetic area with clean air important for human health. CWs can be applied at different levels, centralized, semi-centralized and decentralized and can be applied as a main technology or combined with other technologies. This variety makes CWs fit the national and international institutional requirements and the regulations. Considering the successful and sustainable application of full-scale CWs, future studies need to focus on the comprehensive evaluation of CWs under real-life conditions, optimization of environmental and operational parameters (e.g., influent loads and tidal operation), exploration of novel enhancement technologies and maintenance scenarios. Further research on innovative CWs needs to consider land area requirements, enhancing the removal efficiencies, and circular economy applications with CWs. Furthermore, further research must be conducted to evaluate the non-market value, including a cost-benefit analysis.

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Appendix A

Table A1. Applications and examples of CWs.

#	Case	Application	Treatment Efficiency Removal (%)				References
			COD	BOD	TSS	TN	
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]
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]

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