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Review

The Use of Constructed Wetlands to Treat Effluents for Water Reuse

Sandro Xavier de Campos [1] and Manuel Soto [2,*]

[1] Research Group on Environmental and Sanitary Analytical Chemistry (QAAS), State University of Ponta Grossa (UEPG), Av. General Carlos Cavalcanti, Ponta Grossa 84030-900, PR, Brazil; campos@uepg.br
[2] Department of Chemistry, Faculty of Sciences & CICA, University of A Coruña, E-15008 A Coruña, Galiza, Spain
* Correspondence: m.soto@udc.es; Tel.: +34-647-38-77-69

Abstract: Constructed wetland systems (CWs) are technologies based on natural processes for pollutant removal and have been more and more accepted in the treatment of domestic and industrial wastewater. This study selected and reviewed articles published in the last six years involving the use of different CW conceptions and their association with other technologies to treat different effluents and evaluated the quality of the effluents for reuse. From a total of 81 articles reviewed, 41 presented quantitative data on the quality of the treated effluent in relation to the requirements of the reuse regulations in different countries of the world. CWs can be used to treat gray water and runoff water, as well as domestic and industrial effluents with the purpose of reusing them. While studies on the removal of new chemical and biological substances have increased, challenges are associated with the optimization of CWs to improve the removal of pathogens and new contaminants that have appeared more recently. The potential for the improved removal of those pollutants lies in the association of CWs with conventional and advanced technologies in new configurations. We concluded that studies related to the reuse of effluents using CWs are in constant evolution, with experiments at different scales. The perspectives are promising since CWs are an economic, environmentally friendly, and efficient technology to help in the mitigation of water scarcity problems imposed by climate changes.

Keywords: constructed wetlands; wastewater; runoff; effluent quality; effluent reuse

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1. Introduction

Urban and industrial wastewater discharges remain a major source of pollution worldwide. Urban runoff, stormwater overflows, and untreated sewage discharges are increasingly important sources of pollution. Population growth and the change in annual rainfall patterns associated with climate change make it increasingly difficult to meet the growing demand for recreational, industrial, agricultural, and domestic purposes. Thus, the regeneration of used water with the aim of giving it a second use is increasingly imperative [1,2].

Solutions based on nature, such as constructed wetlands (CWs), offer high possibilities for the sustainable use of water, facilitating its treatment and reuse in situ, as well as contributions to adaptation to climate change through the use and promotion of vegetation, both in urban and rural areas [3,4]. The circular economy criteria and objectives require opting for technologies and configurations that allow the recovery of nutrients and other resources contained in wastewater while allowing the reuse or recycling of the water itself for different uses. CWs offer very interesting benefits regarding both sustainability and circularity [5].

The reuse options are conditioned by the destination that will be given to the treated or pre-treated wastewater. For a few reuse destinations, a pretreatment may be sufficient, while CW effluents can be reused in a greater number of applications by achieving efficiencies similar to or higher than those of conventional treatments in the removal of organic pollutants, while enabling a partial or advanced removal of nutrients, pathogens and persistent pollutants [5,6]. The latter depends on the configuration, type, and operating conditions of the CWs. Pathogenic pollution is one of the factors that limits many of the potential uses of reclaimed water, so it must also be a factor to be considered.

The general objective of this article was the review of the recent scientific literature addressing the quality of the effluents of CWs that treat various types of wastewater, from runoff and gray water to urban and industrial wastewater. A few reviews have been published on the potential of CWs for effluent reuse, either referring to specific geographical areas (Europe; Morocco) or to certain types of effluents, especially urban runoff and sewer overflows [1,4,6], emphasizing the need for a more general review. Specifically, this review aimed to analyze the requirements established in the legislation for the different reuse destinations and the quality of the effluents obtained in CWs. For this, a total of 81 studies published in the last six years, which addressed this objective, were reviewed. Of these, a total of 41 articles had quantitative data on the specific objective of determining the quality of the treated effluent in relation to the requirements of the reuse regulations in the different countries of the world where the studies were carried out. Quantitative data from the last set of articles were presented in tables to facilitate an analysis and comparison, and to allow further discussion. Thus, this work contributes to an update regarding the potential use of CWs as a technology to be adopted or not in the reuse of these different effluents in the context of water scarcity caused by the effects of climate change and the growing requirements of recently adopted reuse regulations. The evaluation of the quality of treated effluents for different uses requires, first of all, the analysis of the regulations that have been established in this respect in recent years. This aspect, as well as a brief description of CWs technology, are addressed in the following sections of this introduction.

1.1. Policies for the Regeneration and Reuse of Wastewater

Starting in the state of California in 1918, countries around the world and international organizations (e.g., World Health Organization—WHO) created their regulations and guidelines to incentivize water reuse practices [7]. In the last two decades, the reuse of different effluents started to be planned in the management of hydric resources in many countries worldwide. Therefore, many regulations in different regions of the planet seek to define the main standards that must be monitored so that the reuse can meet the target proposed without causing environmental problems or presenting risks to the population's health.

According to Santos et al. [8], water reuse regulations advanced in relation to the effects of climate change, pollution, and increased consumption due to the global population growth, which required government planning to incorporate alternative sources in the existing hydric matrices. This type of planning action can only become effective with proper normative instruments that seek the institutionalization of that practice. Not surprisingly, the initial actions were observed in regions that experienced water scarcity such as California (United States of America—USA), Victoria (Australia), China, and Mediterranean countries. However, different regions took different paths due to their specificities and socio-economic development factors. China, for example, is recognized worldwide for their substantial knowledge about water reuse in agriculture, while California and Australia opted for advancing in the adoption of potable water standards. In addition, several regions and global agencies started their own regulation processes with flexible norms and specific objectives such as those proposed by the European Union (EU) and Food and Agriculture Organization (FAO), which aimed at wastewater reuse for irrigation. With the appearance of new scientific and technological advances, countries and their states started to propose their norms with more specific parameters and broadened the possibilities of urban, environmental, and industrial reuse. Table 1 seeks to present in general terms some regulations available in different regions of the world. The socio-economic conditions of developed and developing regions and with greater or lesser water scarcity were taken into account.

Table 1. Applications and parameters for effluent reuse in different regions of the world.

Country	USA [1]	China [2]	EU [3]	Victoria [4]	Spain [5]
Examples of reuse applications	Food crops for human consumption consumed raw [a] Urban reuse: unrestricted [b] Impoundments: unrestricted [c] Indirect potable reuse: Groundwater [d]	Recreational use in rivers and ponds [a] Urban use—Road cleaning [b] Urban use—Municipal landscape [c] Industrial use—Boiler water [d]	Class A—All food crops for direct consumption [a] contact with reclaimed water, consumed raw Class B—Crops for indirect consumption [b] Class C—Crops for indirect consumption drip irrigation [c] Class D- Industrial, energy, and seeded crops [d]	Agricultural food production, consumed raw [a] Domestic garden watering, including [b] Industrial: example, wash-down water [c] Urban (non-potable) controlled public access [d]	Urban use—Irrigation of private gardens [a] Agricultural uses—crops to be eaten raw [b]rage Industrial use—leaning water in the food industry [c] Recreational use—Golf course irrigation [d]
pH	6.0–9.0 [a,b,c]; 6.5–8.5 [d]	6.0–9.0 [a,b,c], 6.5–8.5 [d]	-	6.0–9.0 [a,b,c,d]	-
BOD (mg/L)	≤10 [a,b,c,d]	6 [a]; 15 [b]; 20 [c]; 10 [d]	≤10 [a,b,c,d]	≤10 [a,b]; ≤20 [c,d]	-
Turbidity (NTU)	≤2 [a,b,c,d]	5 [a]; 10 [b,c]; 3 [d]	≤5 [a,b,c,d]	≤2 [a,b]	2 [a]; 15 [c]; 10 [b,d]
TSS	-	-	≤10 [a,b,c,d]	5 [a,b], 35 [c], 30 [d]	10 [a]; 20 [d]; 35 [c];
Total Coliforms (CFU/100 mL)	-	30 [a,b,c,d]	-	-	-
Fecal Coliforms (CFU/100 mL)	Not detectable	5000 [a] 20,000 [d]	≤10 [a], ≤100 [b], ≤1000 [c], ≤10,000 [d]	≤100 [c]; ≤1000 [d]	0 [a]; 100 [b]; 1000 [c]; 200 [d]
Legionella spp.: CFU/L	-	-	<1000 [a,b,c,d]	-	100 [a,c,d]; 1000 [b]
Helminth eggs (egg/L)	-	-	≤1 [a,b,c,d]	-	0.1 [a,b,c,d]
Chlorine Residue (mg/L)	1 [a,b,c,d]	0.05 [a,d]; 1 [b,c]	-	-	-
Color	-	30 [a,b,c,d]	-	-	-
NH_3 -N (mg/L)	-	5 [a]; 10 [b,d]; 20 [c]	-	-	-
NT (mg/L)	-	15 [c]	-	-	-
PT (mg/L)	-	1 [a,b]	-	-	-

Table 1. *Cont.*

Country	Egypt [6]	FAO [7]	Portugal [8]	Cyprus [9]	Greece [10]
Examples of reuse applications	Group A—All types of grass and flowers [a] Group B—All kinds of vegetables manufactured [b] Grupo C—Addition to spray irrigation is not used [c] Group D—Crops for the production of biodiesel [d]	Class A—Irrigation of crops to be eaten uncooked [a] Class B—Irrigation of cereal crops and fodder [b] Class C—Exposure of workers does not occur [c]	Class A—Irrigation of vegetables to be eaten raw [a] Class B—Public parks, gardens, and sport fields [b] Class C—Vegetables to be eaten cooked [c] Class D—Crops to be used as raw material [d]	Crops for human consumption; raw [a] Fodder crops [b] Industrial crops [c] Areas of limited public access [d]	Public access is not expected; industrial crops [a] Industrial use: Ex. Cooling water [b] Unrestricted irrigation crops [c] Urban uses: cemeteries, golf courses, and public parks [d]
pH	-	6.5–8.4 [a,b,c]	-	6.5–8.5 [a,b,c,d]	-
BOD (mg/L)	15 [a], 30 [b], 80 [c], 350 [d]	≤10 [a]; ≤30 [b]; <30 [c];	≤10 [a] ≤ 25 [b,c,d]	≤10 [a,b] ≤ 70 [c,d]	≤10 [b,c,d]
Turbidity (NTU)	5 [a]	≤2 [a]	≤5 [a,b,c,d]	-	-
TSS	15 [a], 30 [b], 50 [c], 300 [d]	≤30 [b,c]	≤10 [a], ≤ 35 [b,c,d]	≤10 [a,b], ≤ 30 [c,d]	≤10 [b,c] ≤ 2 [d]
Total Coliforms (CFU/100 mL)	-	-	-	≤5 [a], ≤ 50 [b], ≤200 [c], ≤1000 [d]	-
Fecal Coliforms (CFU/100 mL)	-	≤14 [a], ≤200 [b,c]	≤10 [a], ≤100 [b], ≤1000 [c], ≤10,000 [d]	-	≤200 [a], ≤5 [b,c,d]
Legionella spp.: CFU/L	-	-	<1000 [a,b,c,d]	-	-
Helminth eggs (egg/L)	-	-	≤1 [a,b,c,d]	-	-
Chlorine Residue (mg/L)	-	-	-	-	-
Color	-	-	-	-	-
NH_3 -N (mg/L)	-	-	-	-	-
NT (mg/L)	-	-	-	15 [a,b,c,d]	-
PT (mg/L)	30	-	5 [a,b,c,d]	2 [a], 10 [b,c,d]	≤15 [a], ≤2 [b,c,d]

Available at (all links accessed on 3 July 2023): [1] https://www.epa.gov/sites/default/files/2019-08/documents/2012-guidelines-water-reuse.pdf; [2] http://www.reclaimedwater.net/; [3] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018PC0337; [4] https://www.epa.vic.gov.au/about-epa/publications/1910-2; [5] https://www.boe.es/eli/es/rd/2007/12/07/1620/con; [6] https://www.eib.org/attachments/registers/156263822.pdf; [7] https://www.fao.org/3/t0551e/t0551e00.htm#Contents; [8] https://diariodarepublica.pt/dr/detalhe/decreto-lei/119-2019-124097549; [9] https://www.moa.gov.cy/moa/environment/environmentnew.nsf/page17_en/page17_en?OpenDocument, [10] https://ypen.gov.gr/. [a,b,c,d] Class of reuse, when not cited unspecified values.

In most of the guidelines, total and fecal coliforms are used as indicator microorganisms for pathogenic microbial quality, while turbidity, BOD, and TSS are used as physico-chemical quality parameters (Table 1). Another piece of evidence is that China keeps one of the most complete regulations in the world regarding the requirements and objectives of water reuse, which contributes to its position in the ranking of users of reused water, reaching around 7.1 billion m^3/year, followed by the USA, where 6.63 billion m^3/year are reused [8]. With the aim of advancing and expanding water reuse, both CW and conventional effluent treatment technologies have been undergoing changes in their configurations, to adapt to increasingly demanding reuse regulations, which almost always requires new innovative approaches.

1.2. Constructed Wetlands

Constructed wetlands (CWs) have been used to treat effluents since the 1960s [9]. Aiming at reproducing the mechanisms involved in several natural processes, CWs are designed selectively with the purpose of obtaining treatment conditions that result in the best quality possible for the final effluent. CWs are treatment systems that include vegetation and suitable bed substrates (i.e., the solid filter medium on which the vegetation is rooted) and flow structures, in addition to the use of a wide variety of microbial flora, which altogether play a crucial role in the removal of pollutants.

Regarding their hydraulic characteristics, CWs can be classified as surface and subsurface flow [9]. Surface flow CWs (SCWs) are very similar to natural wetland zones; however, with a wastewater volume on the substrate, they are not very deep. SCWs are units where wastewater flows over the surface of the substrate, thus forming a water-free layer, which increases oxygen availability and photodegradation processes. Some examples of SCWs are the free-floating and submerged macrophytes, macrophytes with floating leaves, emergent macrophytes, emergent macrophytes floating mats, and the use of trees. The subsurface flow CWs are classified as horizontal (HFCW) and vertical (VFCW), according to the flow direction. In these subsurface flow systems, wastewater flows below the surface of the filter medium, passing through it. VFCW might present a water-saturated or unsaturated substrate, a descending or ascending flow, or the fill and drain system, which is also known as a reciprocating or tidal flow [9]. While in HFCWs and permanently saturated VFCWs an anaerobic or anoxic environment dominates, unsaturated and fill and drain VFCWS can achieve a good oxygenation of the environment and ensure predominant aerobic conditions. In one of the most common arrangements for vertical unsaturated flow systems, the application of sewage occurs intermittently and uniformly on the surface, where it percolates into the filter medium. After passing the effluent, the filter pores are naturally occupied with air, facilitating the maintenance of aerobic conditions in the environment for the oxidative processes that occur in nitrification and also for the oxygenation of organic matter. Unless otherwise noted, in this paper we use the term VFCW to refer to systems with unsaturated conditions.

Many studies have investigated hybrid systems that associate SCW, HFCW, and VFCW (specially unsaturated VFCW) in different arrangements taking advantage of the characteristics of each type of CW to create a more efficient combined system, mainly aiming at the removal of nitrogen, phosphorus, and emergent contaminants. Thus, studies on both single CWs and hybrid CWs by themselves or associated with other conventional or advanced treatment systems have increased noticeably. This occurs because CWs present the advantages of construction and maintenance low cost, being a widely employed technology in developed countries as well as in developing countries.

The literature shows that CWs can treat different effluents with removal results reaching 90% for the main parameters associated with solids and organic matter, obtaining effluents that meet most of the requirements for the different types of reuse [10–15]. However, when a more efficient removal of nutrients (N, P) and pathogens is required, hybrid and combined systems are the most recommended [16–18]. In this way, there are also many studies reporting the possibility of associating CWs with advanced oxidative processes for the removal of emergent contaminants [12–14], even if many of these harmful substances have not been included in the parameters for effluent reuse yet (Table 1).

2. Materials and Methods

This article presents a selection of published studies related to the use of CWs and their advancements aiming to obtain reuse water. The Scopus database was surveyed using the search expressions of constructed wetlands, reuse, quality, and wastewater (all connected by the logical operator "AND"). The expression quality was used aiming to limit the search to studies that presented results or discussions related to the characteristics of effluents on its suitability for reuse, that is to say, in relation to different physical, chemical, and biological parameters. We also sought to relate the quality obtained after the treatment using CWs with reuse regulations. By including the word 'quality', we observed a reduction in the number of studies found from the beginning of the specific publications in 1994 from 621 to 274. Seeking a representative sample of the experiments carried out using CWs and taking into consideration the current effluent reuse criteria, we selected 81 articles published in the last six years (a period from 2018 to 2023).

This paper provides a description of the experiments using CWs considering their main objectives, novel results obtained, and conclusions. In addition, experiments detailing the type of CW, plants, substrates used, removals obtained, and reuse proposals were organized in tables for better visualization. Quantitative data were extracted directly from these articles, when originally available. On other occasions, they were calculated by the authors of this review from other information in the referred article. Articles with results unrelated to regulations and parameters required for water reuse were not included in the tables, so 41 articles were included in the tables. However, some of those articles were included in this report because of their interest in justifying the importance of using CW in the treatment of certain types of effluents and the potential interest for water reuse.

Among the studies published that focused on water reuse, the main focus on the use of CWs as the only treatment or integrated to other technologies was related to runoff, industrial, and domestic water. Due to the specificities of the studies, we decided to dedicate part of the review to the use of CWs in the treatment of domestic gray water and group these studies with the results of the runoff water treatment. Thus, the paper was divided into topics covering studies of CWs dedicated to the reuse of gray water and runoff and studies related to the treatment and reuse of other domestic and industrial effluents.

3. Results and Discussion

3.1. Treatment of Gray Water and Runoff Using CWs for Water Reuse

Gray water is produced from sinks, laundry, and showers and might represent up to 75% of the total domestic wastewater, with approximately 250–300 L generated per person per day in developed countries and 100–120 L in developing countries [2]. Gray water presents a lower concentration of organic matter, nutrients, and pathogens than black water and, consequently, is easier to be treated [15,16].

Considering the diversity of effluents generated and the possibility of proposing decentralized treatment systems, CWs stand out as a suitable technology for the treatment of gray water and runoff aiming at their reuse. Regarding urban runoff, CWs also contribute to the removal of highly toxic contaminants such as heavy metals that might present risk in the reuse of the treated effluent. Due to their landscaping characteristics, for using ornamental plants, experiments are carried out seeking to use CWs in urban spaces, thus enabling the effluent reuse in situ, which is allied to energy production [1,18].

3.1.1. Treatment of Gray Water in CWs

Lakho et al. [15] investigated a system that combined VFCW, filtration, and disinfection for the treatment of gray water from a restaurant in Belgium. The VFCW was built and operated for six months. After going through an activated charcoal system, ultrafiltration, reverse osmosis, ionic exchange membrane, remineralization, and ultraviolet disinfection, the effluent reached a level of potability in accordance with the Belgian potable water regulation and was reused in the restaurant [15]. Another innovation proposed for the use of CW in the treatment of gray water from a restaurant was the operation of a pilot system combining a constructed wetland microbial fuel cell (CWMFC) and a biological filter (FB) for the continuous treatment and recycling of hand washing water [18]. The CWMFC system reached a full bacterial removal for an *E. coli* influent load of 4 log and 432 mg L^{-1} chemical oxygen demand (COD). The final effluent quality met the South-African standards for noble reuse and was also able to generate 4.33 mW m^{-3}-treated effluent. However, those authors [18] reported the need for further studies related to pathogen removal.

Kotsia et al. [19] investigated a VFCW pilot system conceived as a treatment garden, in which they used ornamental plants to treat synthetic gray water aiming to improve the aesthetics and acceptability of the system. A high organic matter removal efficiency was observed; on the other hand, the total phosphorus (TP) removal reduced gradually from 100% during the first year of operation to 15% throughout the second year. Their results showed that *Pittosporum tobira* and *Hedera helix* can grow in VFCW treating gray water without any changes in their physical aspects. The biochemical oxygen demand (BOD) and total suspended solids' (TSSs) final concentration in the effluent was below 10 mg L^{-1} and met the Australian criterion for reuse in toilet flush, except for pathogen quantity. Thus, the use of a simple disinfection system such as the visible ultraviolet (UV/Vis) or chlorination is recommended for the elimination of pathogens [19].

Due to the difficulty of finding large areas needed for the construction of CWs for gray water treatment in urban environments, a solution would be the use of containers for VFCWs. An installation like that might provide the treatment of gray water and their reuse as irrigation water for urban façades, provided that it is followed by a disinfection treatment to comply with irrigation standards set by the WHO [20].

Another great challenge in the use of CWs to treat gray water is the presence of excess personal care products (PCPs) found in water from toilets and showers. Ren et al. [21] developed studies on a pilot scale associating a membrane bioreactor (MBR) and VFCW for gray water PCPs. The removal of PCPs in the MBR was mainly through the adsorption and biodegradation of activated sludge. PCPs were removed >80% in the CW system, through plant uptake and biodegradation, among other mechanisms. The VFCW presented lower removal efficiency in winter since several plants died, which led to a continuous decrease in the number of microorganisms adhered to the roots of the plants and reduction in the oxygen transport capability. Despite that, the final effluent met Chinese reuse requirements regarding organic matter and solids.

In addition to analyzing the efficiency of the removal of the main contaminants, studies have given more and more importance to the phytotoxic effects that gray water effluents reused for the irrigation of different crops might cause. An analysis carried out on gray water effluents from washing machines and kitchen sinks treated using biological minireactors and HFCW showed that tomatoes irrigated with that water did not suffer any negative effects in relation to their growth, photosynthetic activity, hydric state, osmotic potential, or productivity. Moreover, their results showed that treated gray water did not affect soil salinity and even improved plant height. Despite the positive results, those authors recommended further studies to monitor the long-term effect on the soil and health of those consuming the tomatoes [22].

Among the contaminants recently studied, research involving CWs in the treatment of gray water have shown certain concerns with the removal of antibiotic resistant bacteria. Results from the treatment of laundry water using a VFCW showed that an increase ranging between 36.34% and 40.79% in the bacteria resistant to ciproflaxin and ceftriaxone might occur. Another important observation was the strong association of a lack of the degradation of ciproflaxin and ceftriaxone with a lack of the removal of surfactants, which required the use of a disinfection method before the use of the treated water. To guarantee an efficient removal of these surfactants in CWs, an efficient COD removal is also important. In addition, the highest correlation between COD and LAS removal was obtained regarding an organic surface loading rate, suggesting that the area plays a more important role than the volume of the system. *Pseudomonas* spp. predominated in the degradation of such substances [23].

Other studies reported that to meet higher quality requirements for the noble reuse of gray water effluents, the implementation of an pilot advanced system of disinfection is always required [24,25]. With this purpose, an HFCW and ultraviolet-visible (UV/Vis) disinfection were used to treat gray water from the washbasins of a primary school in Morocco. After the treatment, the effluent produced was used to irrigate lawn areas favoring plant growth. With the UV/Vis disinfection in 50 mWs/cm^2, the effluent met the unrestricted irrigation requirements set by the WHO, Morocco, and California (USA), which is one of the strictest guidelines for fecal coliforms (23 CFU/100 mL) [25].

It can be observed in recently published works on the use of CW in gray water treatment that there is a predominance of the use of unsaturated VFCW. This preference may be due to the smaller area required to install these units due to more efficient oxidative processes that also allow for the efficient removal of ammonia.

3.1.2. Treatment of Runoff Water in CWs

Studies related to the treatment of runoff water have shown that those effluents showed a concentration of heavy metals and that the CWs might provide a good efficiency in the removal of such substances. An HFCW-SCW hybrid system built on a pilot scale was used to treat runoff water from the parking lot of a retail shop in Eastern Sicily, Italy [26]. The hybrid system showed good efficiency in the removal of heavy metals, mainly lead (Pb), zinc (Zn), and copper (Cu). The removal efficiency for *Clostridium perfringens* was observed in the HFCW unit. Algi growth occurred in the SCW unit, which reduced the efficiency of the TSS, BOD, and COD removal, compromising the water quality. Preliminary results suggested the reliability of the technology in the treatment of runoff water for urban reuse according to Italian parameters [26].

In another study, Tuttolomondo et al. [27] investigated an VFCW on a pilot scale for the treatment of the first discharge runoff water and verified the effect of such water on the reuse to irrigate pepper and rosemary. Their results showed a good removal of organic matter, nutrients, and heavy metals, such as nickel and chrome. The *Escherichia coli* (*E. coli*) concentrations were low in the effluent and levels were always below 100 CFU/100 mL, reaching the values required for agricultural use. Regarding the plants irrigated, both showed positive results, mainly in relation to metal removal [2].

3.1.3. Main Characteristics of CW Systems Used for the Treatment of Gray Water and Runoff Aiming for Water Reuse

Table 2 summarizes the main characteristics of the studies involving the treatment of gray water and runoff using CWs. Many of these studies were carried out on a pilot or field scale, but some small-scale studies developed in a laboratory were also included. Out of the 10 systems included in Table 2, 3 investigated runoff water and 7 investigated gray water. As for the type of technology, most were simple VFCW (seven cases), while there was one simple HFCW and two hybrid CWs. The vegetable species used were quite diversified, both defined as single-crop or polycrop farming, as well as parallel comparative studies, so that the 10 systems included in Table 2 used 17 different plant species. Out of those, only *Phragmites australis* appeared in three reports and *Typha latifolia* in two reports; the remaining 14 species were found only once in the reports. Gravel was the most frequently used substrate to prepare the CW beds. It could be used alone or in a combination with sand or other materials such as zeolite. There were also reports of the use of volcanic origin substrates, clay, or bioceramics. The HLR of the VFCW systems ranged between 10 and 130 mm/d, with a 63 mm/d (data number, n = 6) average. When comparing VFCW with other types of CW, they present a higher capacity; for this reason, they can operate greater hydraulic and organic loads. However, the reduced appearance of the other technologies in the reports in Table 2 do not allow for a deeper comparison.

Table 2. Main characteristics of systems involving CWs in the treatment of gray water and runoff.

System Number, Type, and Size	Plants	Bed Substrate	HRT, d (HLR, mm d^{-1})	Removal (% or LU (Pathogens))			Reuse	Country
				COD (BOD), TSS, Others [c,d,e,f,g,h,i,j,k]	TN, TP, Others [L]	*E. coli*, TC, EC		
1. HFCW, 12.5 m^2 [a]	*Typha latifolia*	Gravel	6.25 (96)	89 (87), na, 88 [c], 84 [k]	42, 50, 84 [L]	na, na, na	Irrigation of green spaces	Australia
2. HFCW, 1.0 m^2 [a]	*Equisetum giganteum*	Gravel	3.57 (196)	38 (na), na, 35 [k]	na, na	na, na, na	Discharge into soil	Brazil
3. VFCW, 46.80 m^2 [b]	*Phragmites australis; Arundo donax L.*	Silica quartz river gravel	7 (130)	65–69 (75–83), 65.9 [h], 66.7 [i]	na, na	0.94, na, na	Agricultural irrigation; discharge into soil	Italy
4. VFCW, 0.03 m^2 [a]	*Cyperus papyrus*	Clay aggregate	0.09 (768)	99 (na), na	na, na	4.0, na, na	Potable	South Africa
5. VFCW, 0.45 m^2 [a]	*Pittosporum tobira; Hedera Helix; Polygala myrtifolia*	Gravel and sand	na (74–110)	96 (99), 94	na, na	na, 2.2, na	Toilet flushing and washing machines	Australia
6. VFCW, 2.5 m^2 [a]	*Phragmites australis*	Zeolite; lava sand; Rhine sand	na (18–80)	96–98 (85), na	na, 83.4	na, na, na	Irrigation	Germany
7. VFCW, 60 m^2 [a]	-	Lava rock layer	na (50–80)	84 (97), 92,	42, 24	na, na, na	Potable	Belgium
8. VFCW, 0.5 m^2 [a]	*Phragmites australis and Acorus calamus*	Soil Volcanics; Pebble; quartz Sand; Bioceramics	na (80)	73.5 (80), 90 [c], 90 [j]	na, 87, 90 [L]	na, na, na	Reuse non-potable, irrigation	China
9. HCW (HFCW + SCW), 6.75 + 3.5 m^2 [b]	*Canna indica; Typhia Latifolia*	Volcanic gravel	4 (na)	47 (50), na, 60–63 [d], 9- 33 [e], 6–39 [f], 53–90 [g], 30–74 [h], 61–91 [i]	30, 40	1.5, na, na	Irrigation and toilet flushing	Italy
10a. HCW (VFCW + HFCW + HFCW), 0.3 + 0.8 + 2.0 m^2 [a]	*A. gayanus*	granitic gravel	na (75)	90.4 (95.5), 96.8	na, na	2, 2, 2	Irrigation	Africa's Sahel
10b HCW (VFCW + HFCW + HFCW), 0.3 + 0.8 + 2.0 m^2 a	*C. zizanioides*	granitic gravel	na (75)	93.9 (97.5), 98.5	na, na	3, 2, 2	Irrigation	Africa's Sahel
10c HCW (VFCW + HFCW + HFCW), 0.3 + 0.8 + 2.0 m^2 a	*unplanted*	granitic gravel	na (75)	88.7 (94.9), 96.0	na, na	2, 2, 1	Irrigation	Africa's Sahel

References (System number): 1. [25]; 2. [23]; 3. [27]; 4. [18]; 5. [19]; 6. [20]; 7. [17]; 8. [21]; 9. [26]; 10. [24]. Remarks: [a] Grey Water. [b] Stormwater. [c] Turbidity. [d] Cr. [e] Fe. [f] Ni. [g] Pb.[h] Cu. [i] Zn, [j] Personal care products, [k] Surfactants, [L] N−NH_3. *TC, total coliforms, EC: Enterococci*. HCW: hybrid constructed wetland. LU: log units. na: not available.

The VFCW COD removal resulted in 82 ± 18% on average (n = 7). The general BOD_5 and TSS removals were similar or slightly higher than that of COD (85% and 84% on average, with n = 6 and n = 3, for BOD_5 and TSS, respectively). Regarding the removal of nutrients and pathogens, only 4 out of the 10 studies surveyed presented information about these contaminants. Thus, the small number of systems and the variability of factors did not allow us to obtain indicative removal values or the appropriate operating conditions for efficient treatment, highlighting that more research is still needed. Finally, irrigation was the major water destination, reported in 6 out of the 10 studies, followed by use for toilet flushing in 3 reports. Other reported destinations included washing machines and potable water uses.

3.2. Treatment of Domestic Wastewater and Industrial Effluents by CWs for Water Reuse

Despite having been initially designed to treat domestic wastewater on a small scale, recently, CWs have been used to treat effluents from agriculture and dairy industries, winery, tannery, paper, and pulp, among others. Regarding industrial effluents and their reuse, CWs contribute to a system that can treat water containing high organic loads and different contaminants, while producing a small amount of sludge [28,29]. The efficiency of the removal of the main contaminants of domestic and municipal wastewater in CWs is comparable to that of modern technologies of wastewater treatment, such as the activated sludge process (ASP), sequence batch reactor (SBR), mobile bed biofilm reactor (MBBR), upflow anaerobic sludge blanket (UASB), etc. CWs can remove BOD (85–90%), COD (65–80%), TSS (90–95%), TN (65–80%), and TP (35–50%) [30]. Furthermore, if CWs are used in their hybrid configuration and are associated with disinfection systems, they can be highly efficient in removing pathogenic microorganisms. Thus, CWs can contribute the purpose of domestic and industrial wastewater recovery aiming at reusing it, and present the benefits of low maintenance and operational costs, robustness, and efficiency in the removal of several emergent substances that are introduced in the environment by anthropic action every year [31,32].

The use of CWs results in a more acceptable landscape for the population that live around the sewage treatment stations, turning the spaces into gardens, which transform a gray landscape into a green one with gains for the local flora and fauna [33]. In addition, there is evidence that CWs can be used on a real scale by aiming to recover water in places of water shortage such as the Gaza Strip [34].

Therefore, in the last few years, many studies have focused on the use of CWs for the treatment of domestic wastewater aiming at its reuse, mainly as a post-treatment to conventional technologies, to provide greater efficiency and ecological benefits [35].

3.2.1. Efficiency of CWs in the Reuse of Domestic Effluents

Landscape Integration of CWs and Aesthetic Gains from the Use of Ornamental Plants

Studies have been developed showing that CWs operated in large-scale facilities present efficiency in the treatment of effluents and result in ecological and aesthetic gains due to the use of ornamental plants. De Anda et al. [36] studied a unit designed to treat domestic sewage in a large research center in Spain for 2 years. The unit included a septic tank, anaerobic filter, HFCW, and chlorine disinfection. The system also allowed the production of *Agapanthus africanus* as an ornamental plant. Chlorination was required to meet the Spanish guidelines regarding fecal coliform removal for the irrigation of green areas. The water was reused to irrigate grass close to the research center, and the HFCW provided an environment where several species of birds, lizards, butterflies, and bees could live.

A study carried out by Kaushal et al. [37] evaluated three large-scale SCWs used for the treatment of effluents from urban, rural, and industrial facilities for 1.5 years. They investigated the removal of *E. coli*, Enterococci, and total coliforms for agricultural reuse in India. Their results showed that although the microbiological removal was over 70%, it was not possible to meet the requirements for agricultural reuse in India regarding those parameters. Thus, it was necessary to promote a disinfection process. On the other hand, they contributed to the wildlife habitat and improved the aesthetics of previously degraded territories.

Sandoval–Herazo et al. [38] evaluated the process of removing wastewater pollutants on an HFCW microcosm scale using different ornamental plants and substrates obtained from recyclable material. In that experiment, the ornamental plant *Lavandula* sp. was not able to adapt and died 45 days after sowing without producing flowers; the *Spathiphyllum wallisii* produced 12 flowers, while the *Zantedeschia aethiopica* produced 10 flowers. Their results revealed that the use of substrates originated from PET bottles is a viable alternative to be implemented in CWs. The plants *Spathiphyllum wallisii* and *Zantedeschia aethiopica* contributed noticeably to the removal of wastewater pollutants, resulting in good quality for type C agricultural reuse, pursuant to the EU Commission Norms.

HFCWs were used to treat effluents in three resorts located in Thailand. Those HFCWs were designed to receive effluent from a septic tank and decanters. The project included different types of plants aiming to promote a decorative aspect, since it was built in a high circulation area. Despite the effluent having reached Thai standards for reuse in buildings, a low removal of fecal coliforms was observed due to the temperature reaching (30 $\pm$ 5 °C), and a disinfection process had to be added [39].

Dell'osbel et al. [40] evaluated the performance of a pilot hybrid system combining VFCW and HFCW in the treatment of urban effluents. A primary screening treatment and secondary biodigester treatment were employed. The use of five ornamental plants was investigated seeking to aggregate the landscaping potential and better acceptance of the treatment station. The system presented a good capability of removing nutrients from the hybrid system. Pursuant to the Brazilian regulations, the results obtained showed that the final effluent could be used to wash cars and applied to other uses in which the users had direct contact with the water and in which the operator might be exposed to spray aspiration. Achieving the established effluent quality for these uses required recirculation as well as post-treatment disinfection [40].

The Challenge of Eliminating Pathogenic Microorganisms

As verified in previous reports, one of the greatest challenges in the use of CWs was the removal of pathogenic microorganisms, which usually required the use of disinfection to meet the quality requirements for reuse. Thus, a great part of the studies on the domestic effluent treatment using CWs in the last few years has been directed towards this purpose.

Quartaroli et al. [41] compared the use of calcium hypochlorite and sodium hypochlorite as disinfectant agents in a laboratory HFCW system. They carried out batch disinfection tests, using three hypochlorite dosages (5, 10, and 15 mg L^{-1}) and the contact times ranged between 5 and 50 min. All disinfection dosages used showed microorganism final results below 103 CFU/100 mL, meeting the requirements set by FAO for water reuse in agriculture. Trihalomethane was found after disinfection tests; there was also a possibility of the formation of other potentially harmful chlorination byproducts such as haloacetic acids, haloacetonitrile, haloketone, and trichloronitromethane. Therefore, a higher-quality effluent regarding COD removal can be obtained by associating CWs with other treatments to reduce the risk of effluent contamination by those byproducts.

Ali et al. [42] compared the quality of effluents obtained from full-scale HFCW and VFCW as a post-treatment to anaerobic reactors aiming at pathogen removal. Both systems resulted in over 90% removal of the bacterial population. With a tertiary system involving a SCW, a 50% increase was observed in the removal of pathogenic microorganisms, thus enabling the use of such a treated effluent in irrigation.

With a similar objective, Russo et al. [43] used a HFCW as the tertiary treatment of a large-scale sewage treatment station in Italy. Their objective was to obtain a suitable effluent to be used in agriculture, considering the regulations in force in Italy and the European Union. Although CWs have shown a high efficiency in *E. coli* reduction, the results are not enough to meet the limits for the reuse of wastewater in agriculture set by the Italian regulations (10 CFU/100 mL with a maximum value accepted of 100 CFU/100 mL) and were higher than the EU water quality value as required for classes A, B, C, or D. The combination of CW treatments with disinfection by UV treatment was investigated by the same authors [43], who obtained highly effective results with a complete removal of *E. coli*, somatic coliphages, and *C. perfringens* spores. Conversely, low efficiency was observed for enterococci. Thus, although *E. coli* removal from the effluent after the UV treatment met the Italian requirement for reuse, the total removal of enterococci was not possible. Even if neither the Italian regulations nor the EU have set a limit for enterococci, the risk associated with their environmental dispersion is hard to estimate; thus, their removal is needed to obtain better water quality with the least harmful impact to human's health and the environment [43].

Stefanakis et al. [44] verified that one possibility of removing coliforms and enterococci in CW systems involving domestic effluent treatment would be the system aeration. This procedure was implemented in a real-scale VFCW. The effluent was generated from sedimentation tanks and slow biological filters. The number of fecal coliforms, *E. coli*, and enterococci after the aerated VFCW treatment phase met the WHO guidelines for the reuse of wastewater in agriculture and eliminated the need for a final disinfection. A higher efficiency of aerated VFCW in the removal of microbiological contamination when compared to passive CW systems was reported for the first time, which might have implications in the selection of processes and CW technology for reuse. This also shows that aeration might be a new and efficient treatment scheme to be employed in new treatment stations or to update existing ones, seeking to improve pathogen removal. It has been suggested that high concentrations of dissolved oxygen likely alter the characteristics of the microbial consortium, including the development of groups that feed on pathogens [44].

Gonzales-Gustavson et al. [45] investigated the removal of different types of highly pathogenic viruses from an effluent originated in a large-scale domestic sewage treatment station, which included the coagulation, flocculation, and low-pressure UV disinfection phases or SCW as a tertiary treatment. The system served 112,000 inhabitants in Northeastern Spain and the objective of that study was to reuse that water to irrigate vegetables. The SCW was more efficient in reducing virus concentrations compared to the conventional post-treatment, although the effluent showed more variable virus concentrations, probably due to the variability of conditions in the CW. Their results showed that the viral load found in the final effluent did not allow its use in lettuce irrigation according to WHO recommendations. The authors also indicate that the CW land surfaces that would be required to achieve the effluent quality proposed by the WHO would make this option unfeasible in practice for large flows.

Gonzalez-Flo et al. [46] evaluated the performance and quality of water obtained using a combined full-scale system involving an HFCW and chlorine disinfection in Granollers, Barcelona, Spain. The whole system produced over 100 $m^3 \cdot d^{-1}$ reuse water for the irrigation of gardens and streets, and sewage network cleaning. The effluent met the water reuse requirements set by Catalonia for pH, electrical conductivity, TSS, *E. coli*, *Legionella* eggs, and nematoids in 90% of the analyses.

Studies developed in India by Thalla et al. [47] compared the efficiency of real HFCW and VFCW systems allied to disinfection in the treatment of a domestic wastewater with a concentration of 500 mg COD L^{-1} and 300 mg BOD L^{-1}. The VFCW showed better efficiency in the general removal than the HFCW. After chlorination disinfection, the water could be reused according to the American Environmental Protection Agency (EPA) in landscaping, impoundments, building, and industrial reuse such as tower cooling and recirculation, as well as environmental reuse in groundwater recharge [47].

Otter et al. [48] reported a study combining a VFCW with a chlorine generation pilot system in loco. The VFCW received domestic effluent originated from the treatment with activated sludge and from ponds in a Spanish city. The VFCW reduced the chlorine demand in 85%. During the effluent passage through the VFCW, increased conductivity and chlorine concentration were observed due to the planted vegetations' high evapotranspiration rates. The system was considered an alternative of efficient disinfection in decentralized applications of effluent reuse in remote locations with limited access to the electricity network and with restricted requirements for pathogen indicators [48].

Therefore, the disinfection stage associated with CWs is extremely important with a view to using the recovered water for some applications. To this end, chlorination is proposed (the intervention most commonly used) for reuse in urban environments [36,47,48]. For agricultural reuse, care must be taken with residual concentrations, as the presence of chlorine in irrigation water is responsible for contamination of the soil, causing toxicity mainly in the leaves of irrigated crops [49,50].

Use of Microalgae in SCW to Improve the Effluent Quality

When systems including SCW are used, recent studies indicate perspectives to improve the effluent quality based on the use of microalgae. Yehia et al. [51] investigated the treatment of a mixture of domestic effluent with agricultural and industrial material using four pilot SCW units in the presence and absence of microalgae in Northern Egypt (Delta). Their results showed that the best BOD and COD removal was achieved using Chlorella reaching 88% and 84% removal efficiency, respectively. Those authors also reported that Azolla was the microalgae providing the best removal of effluents with the highest TN concentration, while Spirulina was considered to be the most efficient microalgae in the removal of metals such as aluminum (Al), iron (Fe), and manganese (Mn). When compared with other plants used in SCW, microalgae present the advantage of fast growth and ability to absorb nutrients, and good tolerance to temperature changes, in addition to the potential economic benefit of the biomass of the harvested algae. The effluent BOD in all units was below 15 mg L^{-1} for most of the year. This allowed the application of the treated effluent in the irrigation of agricultural products and green landscapes in education and recreation facilities, according to Egyptian regulations.

Some reports indicated that the conventional SCW without microalgae did not meet the requirements for unrestricted irrigation [51]. The combined use of VFCW with microalgae was investigated in the post-treatment of anaerobic reactor effluents [52]. According to the Brazilian regulation ABNT 13969/97, the treated effluent could be reused to wash floors and pavements and irrigate gardens and landscapes. In systems involving large-scale (35,000 m^2) SCW without microalgae, results revealed that there was an increase in the sulfate concentration ($SO_4{}^{-2}$) [53]. Such an increase might be due to the denitrifying bacteria activity, since chemolithoautotrophic bacteria reduce nitrate, while the S-oxidant bacteria oxidize sulfide to return $SO_4{}^{-2}$ during denitrification. This bacterial activity might explain the high NO^{-3} removal and the $SO_4{}^{-2}$ release in CW, which requires post-treatment so that the effluent can be reused [53].

CWs as Post-Treatment of Domestic Effluents

CWs also appear as a good proposal in the post-treatment of domestic effluents in systems involving ponds, UASB reactors, and Imhof tanks, among other technologies. Ergaieg et al. [54] used two HFCW as a post-treatment for maturation ponds in a real-scale tertiary treatment of domestic effluents in Tunisia. The proposal aimed to improve the quality of the water used by farmers in that region regarding the removal of BOD and pathogens. One of the problems found by those authors was the risk of clogging the system due to higher hydraulic loads observed in some moments, which despite meeting the requirements of the Tunisian regulation for reuse as irrigation water, was not in compliance with the WHO regulations regarding coliform removal rates.

Omidinia-Anarkoli et al. [55] studied a pilot-scale hybrid CW (HFCW + VFCW) in the post-treatment of domestic effluents from stabilization ponds. The performance of two substrates and the effect of the presence and absence of plants were compared. When gravel was used as substrate, the VFCW showed maximum BOD removal efficiency. Phosphate removal ($PO_4{}^{-3}$) showed seasonal dependency, and the highest values were observed in hot seasons. Their study also showed that VFCW as a post-treatment for ponds is a solution to obtain effluent for several reuse applications in developing countries that face hydric crisis, such as Iran. The fecal coliform concentrations in the effluent in cold periods tended to be over the maximum standard, while in hot periods they met the reuse requirements [55].

Pinelli et al. [56] studied the use of full-scale SCW in the treatment of effluents originating from irrigated rural areas mixed with the municipal sewage, and compared this treatment with facultative ponds. The system comprised a decanter as a pre-treatment followed by the SCW and solar disinfection. Their results were satisfactory and reached the quality standards imposed by the Egyptian regulations for water reuse.

Gabr [57] described the design of a full-scale treatment system composed of an Imhoff tank and the HFCW post-treatment to obtain water to be reused in agriculture in Dakhla Oasis in the Egypt's Western desert. The installation was designed to serve 5000 people. Darvishmotevalli [58] investigated a treatment involving Imhoff tanks and HFCW aiming at domestic sewage reuse. Despite reaching a removal efficiency over 99%, for intestinal nematode parasites eggs and protozoan cysts, the treatment did not manage to produce suitable effluent for agricultural reuse according to the EU guidelines, due to pathogen concentration, thus requiring an advanced disinfection unit.

A study comparing the VFCW use and its absence as a post-treatment to UASB reactors verified that when the technologies were used separately, they did not achieve water quality to meet the Indian requirements for reuse. However, the UASB reactor removal capacity allied to the VFCW post-treatment reached up to 98% removal regarding organic matter parameters and could be reused [59].

In terms of combining CWs with anaerobic reactors, several applications have gained significant interest [42,52]. Biogas produced from anaerobic reactors could be converted into electricity and used to operate an aerated CW, favoring better performance in the removal of conventional and emerging contaminants. It should be noted that some risks also existed in some integrated processes and deserve attention. For example, although the formation of free chlorine is a fundamental step in the disinfection process adopted, the simultaneous existence of ammonia and free chlorine could produce chloramines which are considered very toxic substances in the environment and for aquatic life [60,61]. Furthermore, some other possible by-products, such as chlorate and perchlorate, are also toxic to humans or deteriorate in the post-treatment process of CW effluents. Therefore, a considerable risk assessment must be carried out in order to select the optimal integrated system in terms of the type of wastewater and the intended reuse purpose.

Hybrid CW Configurations and Combined Technologies Facing Emerging Pollutants Removal

When seeking to use CWs to obtain reuse water without employing other technologies, the best alternative has been found in hybrid configurations. Hybrid CWs have the advantage of combining aerobic, anoxic, and anaerobic environments and related treatment processes. The results show the potential for the long-term operation of hybrid CWs for the treatment of domestic–industrial-mixed wastewater. Studies have shown that when VFCW + HFCW is used to treat domestic wastewater, effluents reached reuse conditions in gardening, agriculture, and cleaning with sanitary purposes [62]. However, even when employing hybrid systems including VFCW + VFCW + HFCW, the salt removal difficulty still remains with increased electrical conductivity in the effluent when the hybrid system is used in a hot climate due to the excess evapotranspiration. The advantage of use in such climate conditions is that the VFCW does not require a resting time, and the effluent can meet quality requirements for use, being classified as Classes C and D according to the EU (irrigation of indirect consumption crops and in drip irrigation), which also results in a reduction in construction and operation costs [63].

Another possibility of optimizing processes involving CWs, reducing the time needed to remove contaminants in VFCW, is the use of biochar from the plant used in the treatment unit. When using biochar obtained from *Phragmits australis*, a significant reduction was observed in fecal coliforms, COD and BOD, and the metals Cu, Mn, Cd, and Al in only

72 h [64]. Those results indicated that the wastewater quality was highly improved by the biochar treatment. However, it was still not enough to reach reuse levels, with stricter requirements regarding the removal of the main physical, chemical, and biological parameters. Moreover, contaminant desorption mechanisms for this type of biochar must be considered in further investigations [64].

In more recent works involving the use of CWs, one of the emerging concerns, due to the changes in the characteristics of the effluents generated by the global population, is related to the removal of emergent contaminants and antibiotic-resistant microorganisms. Miladenov et al. [65] evaluated the removal of emergent contaminants at a trace level by a real system consisting of an aerobic reactor, anaerobic filter, and an HFCW as a tertiary treatment. Those authors investigated some facilities in the USA and South Africa, where the effluent was reused. Only 11 out of 111 compounds were found in the final effluent. However, these included chemical products with harmful effects to human health and to the environment. In addition, new compounds generated during the treatment were found whose toxicity is unknown. Despite being limited to the three systems studied only, those new results showed the need for future monitoring of organic chemical product traces for the reuse of effluents obtained from CWs.

Chen et al. [66] studied the use of a pilot hybrid CW (VFCW + HFCW + SCW) associated with membrane bioreactors, advanced oxidative processes, and UV/Vis disinfection in the removal of antibiotic-resistant genes. They verified that the CW system favored the removal of the existing bacteria (Transposon tnpA, insertion sequence IS91, and integron intI1), but was not enough to eliminate risks. They concluded that to guarantee safety in water reuse, the disinfection system efficiency must be improved.

Cherif et al. [67] proposed a pilot system involving a sequence of treatments to produce noble reuse water with enough quality to be used in fish farming. The system included a membrane biofilter (MBR), a VFCW, sand and activated coal filters, nanofiltration, and reverse osmosis desalinization. Such a combined system enabled water reuse in fish production with increased productivity. However, despite all phases employed, the low removal of emergent contaminants, such as benzotriazole and clarithromycin, showed that the system must be improved, which might include the use of coagulation and flocculation.

The application of hybrid CWs to various wastewaters has demonstrated that the combination could improve pollutant removal efficiency. Hybrid CWs could cover the limitation of each CW. For example, by combining HFCW for VFCW, the desirable condition for the nitrification–denitrification process would be created due to the aerobic, anoxic, and anaerobic environment. Some operational and design parameters such as HLR, bed material, system configuration (number of beds; system layout), influent pollutant concentrations and effluent recirculation can affect the performance of hybrid CWs. It is interesting to note that hybrid CWs are effective in removing organic matter (BOD; COD) and suspended solids, while in terms of pathogens and nutrient removal like N and P components, removal efficiencies depend on system properties and operating conditions.

Main Characteristics of CW Systems Used for the Treatment of Domestic Effluents Intended for Water Reuse

Further details of the studies published and their main characteristics can be observed in Table 3. A great variation is observed in treatment scales ranging between 15,000 m^2 and 0.06 m^2, with the microcosm-scale CWs. Among the 30 plants mentioned in the studies, the growing use of ornamental plants and microalgae has been observed. However, the most used plants were *Phragmites australis* (9) and *Typha latifolia* (5). The technologies appearing in the 23 studies cited in Table 3 are VFCW (7), SCW (6), hybrid CW (7), HFCW (5), and microcosm-scale CW (1). The HRT ranged from hours to over 11 days, with an average of 4.7 ± 5.3 d (n = 20). On the other hand, the HLR ranged from 26 to 1080 mm/d, with the higher HLR in a system involving aerated VFCW.

Table 3. Main characteristics of systems involving CWs in the treatment of domestic effluents.

System Number, Type, Size	Plants	Bed Substrate	HRT, d (HLR, mm d^{-1})	Removal (% or LU (Pathogens)) COD (BOD), TSS, Others [c,d,e,f,g]	TN, TP, Others [h,i]	*E. coli*, TC, EC	Reuse	Country
1. HFCW, 336 m^2 [a]	*Agapanthus africanus*	Volcanic porous rock (tezontle)	11.75 (22.3)	>95 (>95), na	na, na	0.94, 1.09, na	Garden irrigation	Mexico
2. SCW, na [a]	*Typha latifolia; Canna indica*	Gravel and sand	2.5–4 (na)	na, na, na	na, na	0.68, 0.87, 0.90	Garden irrigation	India
3. CW microcosms 0.06 m^2 [a]	*Lavandula sp., Spathiphyllum wallisii, Zantedeschia ethiopica*	Red volcanic gravel (RVG); polyethylene terephthalate (PET)	3 (na)	na (63–68), na	35–50, 35–38	0.41, na, na	Garden irrigation	México
4. SCW, 9.4 m^2 [a]	*Canna indica L.; Bird of Paradise; Sagittaria lancifolia; Lchinodorus*	Sand; Gravel	5 (na)	46–65 (51–76), 48–78, 57–82 [c]	30–48, 40–58	na, na, na	Non-body contact Non-sensitive receiving zones	India
5. HCW (SCW+ VFCW + HFCW), 1.17 + 1.17 + 1.17 m^2 [b]	*Canna x generalis, Equisetum sp., Chrysopogon zizanioides, Hymenachne grumosa and Cyperus papyros nanus*	Bricks of broken clay; gravel	24 (na)	77 (84), na, 99.7 [c]	93.8, 94.0, 93.8 [i]	na, na, na	Car washing and other uses with direct contact	Brazil
6. HFCW, na [b]	*Chrysopogon zizanioides*	Polystyrene, recycled; gravel; thick sand.	na(na)	85 (na), 70	89, na, 81 [i]	na, na, na	Agriculture irrigation	Brazil
7. SCW, 20 m^2 [a]	*Phragmites australis, Sparganium erectum.*	na	5 (na)	41 (54), na	na, na, 67 [j]	na, na, na	Agriculture irrigation	Lebanon
8. VFCW, 0.48 m^2 [a]	*Phragmits australis*	Sand, gravel, biochar	na (200)	71.9 (64.3), na	na, na	0.46, 0.17, na	Agriculture irrigation	Egypt
9a. HCW (VFCW + SCW), 166.8 + 167.4 m^2 [b]	*Typha latifolia, phragmites australis, Vetiver grass, Eichhornia crassipe Centella asiatica. pistia stratiotes*	Gravel; aggregate crush	2 (11.9)	73.6 (76.2), 82	37, na	1.31, na, na	Environmental	Pakistan
9b. HCW.(HFCW + SCW) [b], 123.7 + 107.9 m^2 [b]			1.3 (19.0)	71.5 (72.5), 91	47, na	1.24, na, na	Environmental	Pakistan
10a. HCW (HFCW + VFCW), 9 + 2.25 m^2 [a]	*Phragmites australis*	Gravel	4.1 (10.8)	68.2 (75.7), 84.4	na, na, 19.7 [i]	1.24, na, na	Agriculture irrigation	Iran
10b. HCW (HFCW + VFCW), 9 + 2.25 m^2 [a]	*Phragmites australis*	Pumice	4.1 (7.8)	64.1 (71.6), 85.1	na, na, 4.4 [i]	1.18, na, na	Agriculture irrigation	Iran
11. HCW (HFCW + VFCW + SCW), 360,000–420,000 m^2 [a]	*Calamus, reed water onion*	Gravel	2 (54–62)	na (na), na, 37 [d]	na, na	na, na, na	Agriculture irrigation	China
12. VFCW, 22 m^2 [a]	*Juncus; Phramitis*	na	na (69.3)	44.2 (na), na	na, na, 33.6 [j]	na, na, na	Agriculture irrigation	Tunisia
13. HCW (VFCW + HFCW), 0.78 + 0.78 m^2 [a]	*Canna Indica; Calibanus hookeri*	Gravel; sand; soil	1 (550)	89.9 (92.7), 85.5	na, 88.8, 99.1 [i]	na, na, na	Garden, irrigation, flushing in toilet	India
14. HCW (VFCW + VFCW + HFCW), 72 + 48 +72 m^2 [b]	*Phragmites australis and Typha latifolia*	Silex, granite, or river gravel	na (23.4)	90.7 (99.6), 98.3	80.9, na, 95.6 [h], 90.7 [i]	4.8, na, na	Agriculture irrigation	Senegal
15. VFCW, 0.72 m^2 [b]	*Pistia Stratiotes and Phragmites karka*	Crushed stone Sand, soil	3- 7 (39.7)	90 (>98), 92	89, 80, 70 [i]	na, na, na	Agriculture irrigation	India

Table 3. *Cont.*

System Number, Type, Size	Plants	Bed Substrate	HRT, d (HLR, mm d^{-1})	Removal (% or LU (Pathogens)) COD (BOD), TSS, Others [c,d,e,f,g]	TN, TP, Others [h,i]	*E. coli*, TC, EC	Reuse	Country
16. Aerated saturated VFCW, 1.160 m^2 [a]	*Typha latifolia*	Gravel	0.31 (1078)	22.3 (75.5), 5.6	na, na 89.1 [h], 0.0 [i],	1.29, nd, 1.31	Environmental	United King-dom
17. SCW, 10,000 m^2 [a]	*Phragmites australis; Typha latifolia*	na	na (300)	na (na), na	na, na	2.10, 2.89, na	Agriculture irrigation	Spain
18. SCW 550 m^2 [a]	*Phragmites australis*	na	5 (na)	30–96 [e]; 85–88 [f]; 1–93 [g]	na, na	na, na, na	Garden irrigation; street sewerage cleaning,	Spain
19a. VFCW 0.7 m^2 [b]	*Pennisetum pedicellatum; Cyperus rotundus*	Gravel; sand	1 (357)	66 (90), na	na, na, 84.5 [h], 90 [i]	na, na, na	Landscape, construction, industrial	India
19b. HFCW; 1.45 m^2 [b]	*Pennisetum pedicellatum; Cyperus rotundus*	Gravel; soil	1 (204)	63 (80), na	na, na, 67 [h], 85 [i]	na, na, na	Landscape, construction, industrial	India
20a. SCW, 45 m^2	*Reeds*	na	2 (300)	79 (81), na	60, 69	1.64, 1.82, na	Agriculture irrigation	Egypt
20b. SCW, 45 m^2	*Chlorella*	na	2 (300)	84 (88), na	76, 80	2.32, 2.36, na	Agriculture irrigation	Egypt
20c. SCW, 45 m^2	*Spirulina*	na	2 (300)	82 (87), na	75, 80	2.29, 2.32, na	Agriculture irrigation	Egypt
20d. SCW, 45 m^2	*Azolla*	na	2 (300)	81 (83), na	80, 70	1.86, 2.30, na	Agriculture irrigation	Egypt
21. HCW (ATS + VFCW + VFCW), 0.51 + 0.51 + 0.51 m^2 [b]	*Hymenachne grumosa*	Basaltic gravel; basaltic crushed stone	21 (6.6)	72 (na), 48, 98 [c]	70.1, na, 99.9 [i]	1.26, 5.84, na	Garden irrigation, floor, sidewalk washing	Brazil
22. HFCW, 1321 + 1100 m^2 [a]	*Phragmites australis*	Medium gravel	0.53 (362)	49.4 (54.2), 56.9	56.4, 49.2	1.07, na, na	Agriculture irrigation	Tunisia

References (System number): 1. [36]; 2. [37]; 3. [38]; 4. [39]; 5. [40]; 6. [41]; 7. [53]; 8. [64]; 9. [42]; 10. [55]; 11. [66]; 12. [67]; 13. [62]; 14. [63]; 15. [59]; 16. [44]; 17. [45]; 18. [46]; 19. [47]; 20. [51]; 21. [52]; 22. [54]. Remarks: [a] Municipal Industry wastewater. [b] University wastewater. [c] Turbidity. [d] Antibiotic resistance gene. [e] Pharmaceuticals. [f] Personal care products. [g] Pesticides. [h] $N-NH_3$. [i] $P\text{-}PO_4$. *TC, total coliforms, EC: Enterococci.* [j] Helminth eggs. ATS: Algae turf scrubber. LU: log units. na: not available.

The BOD removal varied between 71.87% (n = 4) in systems involving SCW, 75.17% (n = 4) in HFCW, 79.86 (n = 6) in VFCW, and 82.9% (n = 4) in hybrid systems, which resulted in the achievement of reuse levels for this parameter that appears in all regulations. Out of the 23 studies, 12 cited studies included results on the removal of pathogens, and although some reached 5.87 Log Units (rarely 99.9% removal), many did not reach the limits imposed by reuse regulations and required additional disinfection. Regarding reuse, most systems targeted agriculture irrigation (13). Those were followed by the irrigation of gardens and environmental discharge (3), while car wash, street cleaning, toilet flush, and industrial use were also cited (1).

The reviewed literature showed that CWS and their different configurations are being explored in their potential of improving landscaping aspects of domestic sewage treatment stations. The CW use as post-treatment for conventional technologies enables improvements in the quality of the effluents generated that favor their reuse.

3.2.2. Efficiency of CWs in the Reuse of Industrial Effluents

The studies published reported that CWs are employed in the treatment of effluents of industries such as car manufacturing, oil, tanning and batteries, winery, cooling, brewery, and petrochemical, aiming at the reuse of wastewater. CWs were observed to be quite efficient in the removal of contaminants present in industrial effluents such as heavy metals and toxic organic compounds.

A treatment proposal for the reuse of effluents with heavy metals in a large automobile manufacturer in Italy was developed on a pilot scale using a hybrid CW VF + HFCW [68]. Wastewater collected from industrial and civil buildings was subjected to physical–chemical and biological pre-treatments prior to the hybrid CW system. The authors concluded that the CW systems implemented were highly efficient in the removal of TSS and heavy metals such as Fe (97.9% removal) and Zn (92.9% removal). However, electrical conductivity, alkalinity, and calcium did not meet the requirements for reuse according to the EPA regulations.

Al-Khafaji et al. [69] reported the use of a pilot SCW with duckweeds aiming to remove heavy metals from batteries and tannery industries. Their results revealed efficiency in the removal of Cd, Cr, Ni, and Pb. The duckweed plant is a poor Cd accumulator; however, it is a hyperaccumulator of Pb, Cr, and Ni. Applying an HRT of 3 d, the system removed low percentages of Cd (32.3%), Cr (44.9%), but high percentages of Ni (74.1%), Pb (79.1%), and Zn (92.9%). The effluent final quality, in relation to these parameters, enables its reuse in agriculture. Javeed [66] evaluated the potential of real SCW systems built to treat effluents from tannery and metallurgical industries, mainly regarding the removal of heavy metals from heavily loaded effluents. The removal of metals in each type of effluent proceeded quite similarly, with respect to retention time. For both treatment lines, the mean Ni, Cu, Cr, and Zn removal values were 32%, 48%, 48%, and 57% at 20 days of TRH, respectively, and increased to 88%, 85%, 95% and 94% at 60 d HRT. Seeking to verify the toxicity of the effluent treated, phytotoxicity tests were carried out. Thus, the effluent used in the irrigation of *Abelmoscus esculentus* L. showed a hyperaccumulation trend. However, those values were within the limit accepted by the WHO for the accumulation of metals by plants [70].

There are studies on the use of CW in the treatment of industrial effluents with high organic load such as those from oil, wine, and beer production. Due to the fact that effluents originated from the olive oil production present up to 4000 times more COD and high phenol concentrations, pre-treatment was applied in open tanks for sedimentation or even pH correction. The removal rates of COD, TSS, TKN, and phenol in the pilot VF + SCW hybrid system reached 54.1%, 52.0%, 44.4%, and 60.1%, respectively. On the other hand, the pilot SCW system (with enhanced pre-sedimentation and pH correction) achieved COD, TSS, TKN, and phenol removals of 49.4%, 72.0%, 26.9%, and 51.1%, respectively. Even if a hybrid CW with VFCW + HFCW was used, it was only possible to produce effluent for agricultural reuse in crops that did not require contact, that is, further treatment or lower surface loading rates would be required for more restrict uses [71].

In studies on wine cellars, the use of hybrid CW was investigated regarding agricultural use standards [72]. The treatment system was subjected to a pre-treatment phase (coarse sieving), followed by a Imhoff tank and an equalization tank. The hybrid CW presented a total area of around 230 m^2 and consisted of a VF + HF + SCW bed, producing water for reuse in suitable conditions for food crops to be consumed raw with edible parts produced above the ground, as described by the EU regulation [73]. When treating effluents from a brewery, a system made of an HFCW in two stages was used to produce tomato irrigation water [69]. The HFCW system was used in the post-treatment of an UASB reactor effluent. Those authors observed that the effluent going through the UASB and HFCW treatments reached the irrigation water standard as required by the Ethiopian environment protection agency, showing a high tomato yield capability [74].

Recent studies have also demonstrated the use of CWs in the treatment of effluents to help the production of water to be reused in cooling systems and petrochemical industries. Wagner et al. [70] investigated the use of a pilot hybrid CW (HF + VF + SCW) in the pre-treatment of a membrane system for the reuse of industrial synthetic effluents for tower cooling. The study also verified the removal of phenolic contaminants. Their results showed that the HFCW removed PO_4^{-3}, TSS, and TOC as a result of adsorption and filtration. Regarding VFCWs, they outstood in the removal of phenolic compounds resulting from biodegradation. The SCW did not contribute to the removal of substances and even increased the effluent salinity. However, they provided some options of water storage and habitat for the aesthetic improvement of the unit benefitting the local flora and fauna. Another study developed by the same research group [75] sought the reuse of water from a cooling tower of a system made of green and gray technologies. The treatment plant showed a configuration that included a SCW as a pre-treatment, followed by a system composed of VF + HFCW. After leaving the hybrid CW, the effluent was subjected to nanofiltration, electrochemical oxidation, and reverse osmosis. In addition, they studied the removal of corrosion inhibitors. The pre-treatment using hybrid CWs before the nanofiltration resulted in the removal of phosphate, nitrate, and benzotriazole, but increased TOC and electrical conductivity was also observed. Thus, for the water reuse in cooling towers, the use of reverse osmosis was required [75].

Jain et al. [76] proposed a new pilot CW configuration with a flow deflector (HFCW-FD) for the treatment of wastewater from petrochemical industries and their reuse. Their results revealed that the unit enabled a flow path that was nine times longer, and the use of a filter with a variable depth reduced the total area requirement, and served as a polishing unit. The HFCW-FD made the effluent quality suitable for reuse in irrigation, industrial reuse, and other environmental uses. Thus, the system proposed required less space and maintenance than conventional CWs and managed to produce good quality water for reuse [76].

CWs have been increasingly applied in treating various industrial wastewaters with specific characteristics. Considering the specific characteristics of various industrial effluents with low or high pH, soil materials with a neutralizing ability but low cost for potential use in full projects should be selected. For the use of CW in the treatment of huge industrial effluent flows, the main drawback is the large area that would be required. However, this problem could be minimized by associating it with the economic production of plant biomass and its energy recovery.

Main Characteristics of CW Systems Treating Industrial Effluents Intended for Water Reuse

The main difference in relation to studies on domestic effluents regards the removal of heavy metals originating from industrial activities. The studies listed in Table 4 showed Cr removal ranging between 30.4% and 95.5%, 32.4% for Cd, from 20.3 to 93.2% for Ni, 79.1% for Pb, 24.3–97.0% for Cu, 35.8–95.6% for Zn in SCW systems, and 98.0% for Fe and 92.9 for Zn in VFCW systems. Other examples of removal were reported for phenols, that is, 87.2% in HFCW systems, and from 8% to 20% in the VFCW system. The hybrid CW systems showed great efficacy in the removal of nutrients, obtaining values between 67% and 80% for TN and 95% to 100% for TP. COD removals varied from 20% up to 100% in one HFCW system.

Table 4. Main characteristics of systems involving CWs in the treatment of industrial effluents.

System Number, Type, Size	Plants	Bed Substrate	HRT, d (HLR, mm d^{-1})	Removal (% or LU (Pathogens))			Reuse	Country
				COD (BOD), TSS, Others [h,i,j k,l,m,n,o,p,q,r,s,]	TN, TP, Others [t]	*E. coli*, TC, EC Others [u,v]		
1a. VFCW, 1 m^2 [a]	*Juncus maritimus Lam*	Gravel, sand	na (25)	20 (na), 83.7, 84.6 [n], 96.1 [p], 15.9 [o]	na, na, 95 [t]	na, na, na	Industrial	Italy
1b. VFCW, 1 m^2 [a]	*Typha latifolia*	Gravel, sand	na (25)	20 (na), 98.9, 73.2 [n], 92.8 [p], 9.6 [o]	na, na, 95 [t]	na, na, na	Industrial	Italy
1c. HFCW, 1m^2 [a]	*Cyperus papyrus*	Gravel	4 (50)	60 (na), 99.2, 79.1 [n], 98.1 [p], 29.3 [o]	na, na, 95[99]	na, na, na	Industrial	Italy
2a. HCW (VFCW + SCW), 0.52 + 2.89 m^2 [b]	*Phragmites australis, Typha latifolia*	Carbonate material, gravel, sand, clay	>14 (7.6)	54.1 (na), 52.0, 60.1 [q]	44.4, na	na, na, na	Irrigation	Greece
2b. SCW, 2.89 m^2 [b]	*Typha latifolia*	Clay	14 (7.1)	49.9 (na), 72.0, 51.1 [q]	26.9, na	na, na, na	Irrigation	Greece
3. SCW, 0.3 m^2 [c]	*Lemna minor*	na	3	na, (na), na, 44.9 [i], 32.3 [j], 74.5 [k], 79.1 [l], 92.9 [n]	na, na	na, na, na	Irrigation	Iraq
4. HCW (VFCW + HFCW + SCW), 140 + 60 + 30 m^2 [d]	*Phragmites australis, Cyperus papyrus canna indica,*	Gravel, sand, coarse vulcanic	>9 (13)	81 (78), 69	56, 38, 57 [t]	1.3, 1.6, 0, 1.8	Irrigation	Italy
5. HCW (VFCW + HFCW + SCW), 1.37 + 2.10 + 2.10 m^2 [e]	*Phragmites australis.*	Gravel, sand	5–7 (29)	80–100 (na), na, 60 [r], 80 [s]	80–100, 80–100	na, na, na	Industrial	Netherlands
6. HFCW, 11.4 m^2 [f]	*Cyperus alternifolius, Typha latifolia*	Clay rock	20 (na)	74, (na), 67	66, 61	na, na, na	Irrigation	Ethiopia,
7. SCW, 0.92 m^2 [e]	*Hemarthria compressa*	Alluvial stones	(20–60)	70 (na), 98.3, 35.8–95.6 [n], 30.6–95.5 [i], 24.3–97.1 [m], 20.3–93.2 [k]	na, na	na, na, na	Irrigation	Pakistan
8. HCW (VFCW + HFCW + SCW), 1.37 + 2.10 + 2.10 m^2 [e]	*Phragmites australis*	Gravel, sand	5 (na)	67 (na), na, 90.6 [r]	67, na, 95 [u]	na, na, na	Industrial	Netherlands
9. HFCW, 0.6 m^2 [g]	*Chrysopogon zizanioides*	Gravel, sand, soil	4 (16)	66 (73), 78, 93 [h], 86 [q]	na, na	na, na, na	Irrigation, Industrial	India

References (System number): 1. [68]; 2. [71]; 3. [69]; 4. [72]; 5. [74]; 6. [73]; 7. [70]; 8. [75]; 9. [76]. Remarks: Industries – [a] Automotive, [b] Olive, [c] Tanning and batteries, [d] Winery, [e] Cooling, [f] Brewery, [g] Petrochemical, [h] Turbidity, [i] Cr, [j] Cd, [k] Ni. [l] Pb,[m] Cu, [n] Zn, [o] Cl^-, [p] Fe, [q] Phenol, [r] benzotriazole, [s] acid benzoic [t] N-NH_3, [u] PO4-P, TC, total coliforms, EC: Enterococci, LU: log units. [v] Bacteria indicators, na: not available.

The most widely used substrates were gravel and sand (n = 6). However, clay rock, alluvial stones, carbonate material, and coarse volcanic materials were also mentioned. As for the treatment of domestic sewage, *Phragmites australis* and *Typha latifolia* were the most used plants. Due to the type of industries investigated, with little microbiological contamination, only two reports were found with removal results for those contaminants. Irrigation (n = 6) and industrial (n = 3) were the reuse purposes proposed for the treated effluents.

4. Final Considerations

The advantages and disadvantages of CWs are well known and discussed in numerous reviews [9,12,30]. Low maintenance requirements, good treatment efficiency, and economic feasibility make CWs preferable to other wastewater treatment systems in certain situations. These advantages are manifested in a particular and more pronounced way in the case of decentralized treatment, in areas with less developed sewage network, or when there is a lack of qualified labor. However, CWs are also widely used in many highly developed countries, due to their advantages in sustainability. Multiple removal mechanisms occur in CWs, such as microbial degradation, absorption on the bed substrate, and phytoremediation, among others. Several mechanisms or all of them work simultaneously, resulting in an efficient treatment process [52,68,76]. The high flexibility of CWs allows the implementation of different modifications and intensifications, such as filter media with different properties, different flow regimes, macrophyte species, a combination of different types of CWs (hybrid CWs) or with other treatment systems, effluent recirculation, artificial aeration, etc. This provides them with a great potential to adapt the treatment to the goals of reusing the effluent [13,77,78].

The main drawback of CWs is the high land area required, which can vary from 1 to 8 m^2/hab.·equivalent for a complete secondary and tertiary treatment [9,79], while in the case of using CW as post-treatment, the footprint will be lower. This results in high hydraulic retention times or low hydraulic loading rates for optimum performance. However, in practice very variable values are applied, in the range of 0.3–20 d HRT and 6–300 mm d-1 HLR, excluding some extreme values, as can be observed in Tables 2–4. These wide ranges are the result of very different factors, such as the role of CWs in the global treatment system, the characteristics of the waste water to be treated or the final quality objectives required for reuse.

A drawback common to other technologies is the incomplete degradation of recalcitrant organic matter and other recalcitrant pollutants. This may make it necessary to combine it with other treatment technologies, depending on the objectives of the reuse, as highlighted in the previous sections of this review. However, the great flexibility of CW systems also allows for installations to be adapted to the quality required for the reuse of the effluent, which is highly variable according to the destination (Table 1). For example, nutrient removal is not necessary in most cases of irrigation and agricultural reuse. In this way, the elimination of pathogens, even if it can be high, depending on the type and operating conditions of the CWs, is usually the limiting factor of the effluent quality and the main reason for the need of an additional disinfection post-treatment.

Reports published in the last few years addressing the use of CWs in treatment systems aiming at the reuse of different effluents showed that the studies are promising and that for most parameters defined by the regulations, CWs can achieve the required removal level. Regarding runoff water treatment, studies are mainly directed to the removal of metals and the verification of toxicity in the effluent reuse for the irrigation of different plants. As for gray water, CWs might enable the treatment in loco using ornamental plants to promote better acceptance of sewage reuse, and possibilities of the application of such water in nobler uses when associated with disinfection systems.

Although the removal of pathogens from domestic and municipal wastewater might reach up to 99.9% (3.0 LU), or higher (Table 3), removals were usually in the range from 0.5 to 2.3 LU. Of the total of articles reviewed for CWs treating domestic wastewater, 12 studies contained information on the elimination of pathogenic agents, using various indicators, especially TC, FC, and *E. coli*, and less frequently, enterococci, fecal streptococci, nematode eggs, and viruses. TC and FC were measured simultaneously in six treatment lines. The average removals in these six facilities were 1.68 ± 0.88 LU for TC and 1.58 ± 0.75 LU of FC, observing a good direct correlation between these two parameters (R^2 = 0.94, $p < 0.01$). On the other hand, and considering that *E. coli* is considered an indicator parameter of fecal coliforms, we considered together the data for both indicators (6 studies for *E. coli* and 11 for FC). The elimination of pathogens for this set of facilities (n = 16, either FC or *E. coli*, excluding an outlier of 4.8 LU of FC) was in the range of 0.4–2.3 LU, with an average of 1.28 ± 0.57 LU. Observed pathogen removals were lower than those reported by López et al. [80]. In a review of about 60 systems including CW, these authors found TC and FC removals in the range of 1.2–3.9 UL, with small differences depending on the type of CW, although they were higher in the following order: VFCW < HFCW < HCW [80].

In our revision, pathogen removal was not related to HRT or HLR, which can be explained by the diversity of CW typologies, construction parameters, and operating conditions, in addition to the potential presence of short-circuiting that may cause the actual TRH to be lower than the design TRH [81]. Pathogen removal mechanisms that occur in CWs include antibiotic and antibacterial action, predation, filtration, sedimentation, photodegradation, absorption into the bed substrate, and phytoremediation, among others [80,81]. López et al. [80] reported that the main factors affecting the removal of TC and FC in CWs are the size of the support medium, pH conditions, and the organic matter removal rate. However, there are other factors that influence pathogen reduction, such as design, hydraulic regime, oxygen, environmental conditions, seasonal fluctuation, and the presence and type of vegetation [80,81]. Thus, pathogen removal in CW can be highly unpredictable.

At low influent pathogen concentrations, removals can be expected to be lower [81]. This indicates the difficulty of achieving the very demanding levels of effluent quality for some water reuses in terms of pathogens (Table 1) through the use of CW. In this way, many systems do not manage to meet the requirements imposed by reuse regulations, requiring disinfection using conventional systems such as chlorination or UV/Vis treatment to increase their efficiency. However, the formation of trialomethane due to chlorine use was observed, and the removal of enterococci using ultraviolet radiation was low. Aeration, hybrid configurations, and microalgae contribute to the achievement of more restrictive reuse levels, but the direct consumption crop irrigation standards have not been achieved yet.

The removal of emergent contaminants has been investigated in the CW studies, and even after an association with advanced oxidative processes, it was not possible to remove some types of antibiotic resistant bacteria, corrosion inhibitors, and medicines; therefore, further studies on reuse water monitoring are still required. In the industrial sector, for example, food and car industries, CWs showed efficiency in the treatment of effluents. Most studies have focused on the reduction in heavy metals and phenols from these industrial effluents.

The most frequently used technology involved the use of VFCW due to the possibility of operating with a higher hydraulic load, thus reducing the space needed for its implementation. The most used plants in the treatment of different effluents are *Phragmites australis* and *Typha latifolia*, while sand and gravel are the main substrates employed. When investigating the reuse, although a potability level has been achieved with the integration of CWs to other processes, the most cited possibility of use after the treatments is irrigation.

This systematic review of the recent literature on the treatment of different types of wastewater in CWs mainly included pilot-scale and field studies conducted in 22 countries worldwide. This included the treatment of various types of wastewater, from runoff and gray water to urban and industrial wastewater. Quantitative data on the quality of the obtained effluent were evaluated in comparison with the requirements of the respective regulations for the reuse of the treated effluent. Thus, this review extended the scope of other previous ones that were restricted to specific geographic areas or specific types of wastewater. This review verified that the future of the use of CWs aiming at the reuse of effluents resides in the perspective of their association with conventional and advanced systems of treatment in new facilities to be projected. In addition, studies aimed at the removal of different emerging contaminants should be developed, which can both favor the inclusion of these substances in the reuse regulations and be required by that probable inclusion in the near future. The use of CWs generally represents an aesthetic improvement in the construction of sewage treatment plants. In this regard, it is derived as a general conclusion from the reviewed articles that the use of CWs shows a great potential to increase the acceptance of the reuse of treated effluents by the local population.

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