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Review

Constructed Wetlands for the Wastewater Treatment: A Review of Italian Case Studies

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Abstract: Wastewater is one of the major sources of pollution in aquatic environments and its treatment is crucial to reduce risk and increase clean water availability. Constructed wetlands (CWs) are one of the most efficient, environmentally friendly, and less costly techniques for this purpose. This review aims to assess the state of the art on the use of CWs in removing environmental pollutants from wastewater in Italy in order to improve the current situation and provide background for future research and development work. To evaluate the CWs performances, 76 research works (2001–2023) were examined, and the parameters considered were the type of wastewater treated, pollutants removed, macrophytes, and the kinds of CWs utilized. The pollutant removal efficiencies of all CWs reviewed showed remarkable potential, even though there are biotic and abiotic factor-driven performance variations among them. The number of articles published showed an increasing trend over time, indicating the research progress of the application of CWs in wastewater treatment. This review highlighted that most of the investigated case studies referred to pilot CWs. This finding suggests that much more large-scale experiments should be conducted in the future to confirm the potential of CWs in eliminating pollutants from wastewater.

Keywords: constructed wetlands; wastewater; water pollution; phytoremediation; Italy

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1. Introduction

Environmental degradation can be caused by both anthropogenic and natural sources of pollution. Anthropogenic pollution associated with the industrial and agricultural sectors, for instance, is contributing immensely to environmental deterioration, especially in the aquatic ecosystem [1,2]. Domestic and municipal wastewater, sewage from wastewater treatment plants, urban runoff, livestock wastewater, stormwater, and landfill leachate are other major sources of pollution to the aquatic environments. If wastewater coming out from these sources is released into a natural water body without proper treatment, it results in an algae bloom [3,4] that affects aquatic biodiversity [5]. Moreover, it can contaminate soil and groundwater, endangering human health [6]. Consequently, the remediation of polluted water is vital to both reduce such risk and increase clean water availability. Indeed, as recently highlighted by [7], wastewater treatment could contribute to achieving 11 out of 17 sustainable development goals (SDGs) adopted by the United Nations, considerably reducing the global water crisis. Nowadays, the use of green technologies for such purposes is increasing due to (i) their ability to reduce pollution without compromising environmental sustainability and (ii) low implementation and maintenance costs [8]. Among these emerging green technologies, phytoremediation is being recognized as a promising, low-risk, and environmentally friendly in situ clean-up method, where plants are used to decontaminate the environment by eliminating, holding, or providing nontoxic contaminants in soil or water [9–11]. Phytoremediation was successfully used in constructed wetlands (CWs), an artificially built pollutant removal method that utilizes the combined contribution of substrates, macrophytes, and microbial community [9]. CWs are designed and built engineering systems that use the natural processes of emergent/floating/submerged wetland plants, saturated or unsaturated substrates/soils, and associated microbial communities built for water pollution control [12–14]. They are synthetic systems that have been designed to resemble the biological, chemical, and physical processes that take place in natural wetlands [15].

With the use of CWs, wastewater remediation can be conducted more affordably, sustainably, and easily, with a high rate of nutrient recovery, and minimal maintenance/operation costs [16–19] in an eco-friendly way [20,21]. CWs are capable of treating wastewater from different sources such as municipal, livestock, industrial, agricultural, domestic, acid-mine waste, storm run-off, and landfill leachate [22–29]. Numerous harmful chemicals, including antibiotics, heavy metals, landfill leachate, textile dyes, pesticides, hormones, petroleum, and explosives are removed or degraded by the phytoremediation technique [30]. With the help of CWs, a variety of pollutants can be eliminated from wastewater, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SSs), total Kjeldahl nitrogen (TKN), total phosphorus (TP), total coliforms (TCs), and metals by microbial degradation, plant absorption, substrate adsorption, and filtering by the packed media and biological predation [26,31].

This review article focuses on the research works conducted with different kinds of CWs, macrophytes, and substrates in Italy from the year 2001 to 2023, in order (i) to assess the current status about the use of CWs for wastewater treatment, and (ii) to provide useful information for future researchers. The bibliographic research was conducted using some of the most important popular and scientific search engines (Scopus, ScienceDirect, Web of Science, SpringerLink, Google Scholar, and ResearchGate) by entering different keywords, i.e., CWs, wastewater, and Italy.

2. Classification of CWs

CWs are divided into three classes based on the water flow regime [25]: free water surface flow (FWS) CWs, sub-surface flow (SSF) CWs, and hybrid systems (Figure 1).

2.1. Free Water Surface Flow (FWS) CWs

In this system, the wastewater flows through a shallow, planted basin or channel. It has exposed water surfaces and macrophytes that simulate natural wetlands [32], and as a result, high wildlife diversity is expected (insects, molluscs, birds, mammals, etc.) within the large land area required [33]. FWS CWs are reportedly employed less frequently due to the significant risk of human exposure to pathogens [34]. However, it can be utilized in rural areas where access to land is typically better than in urban areas. The wastewater being treated here must have effectively completed secondary or tertiary treatment elsewhere to avoid the system becoming clogged with solids. TSS, COD, BOD_5, and pathogens, such as bacteria and viruses, can all be removed with an effectiveness of greater than 70% [35].

2.2. Sub-Surface Flow (SSF) CWs

It is a type of CWs, the porous substrate media allows the wastewater to flow either horizontally or vertically beneath the surface. According to [36], SSF CWs are efficient in carbon and nitrogen compound removal because of the aerobic nature of the media. SSF CWs usually classified into two, depending on the direction of the water flow: horizontal sub-surface flow (HSSF) and vertical sub-surface flow (VSSF) CWs [37].

2.2.1. Horizontal Sub-Surface Flow (HSSF) CWs

In HSSF CWs, the wastewater moves horizontally below the surface through the substrate media, plant roots, and rhizomes towards the system outlet [24]. According to [38], unlike the FWS CWs, HSSF CWs require a small land area but with high investment costs. HSSF CWs are poor in removing ammonia nitrogen (nitrification) but because of anoxic and anaerobic conditions, they can treat nitrate nitrogen (denitrification) very well [15]. TSS, BOD_5, and COD were reported to be effectively removed by HSSF CWs at rates of 83.9%, 79.2%, and 72.1%, respectively [25].

2.2.2. Vertical Sub-Surface Flow (VSSF) CWs

The wastewater in VSSF CWs moves vertically either as an up-flow or downflow [39] movement. In a downflow movement, wastewater is applied intermittently (with filling and draining) and it inundates the surface before entering the system through gravity [40,41]. As wastewater passes through the medium (substrate), air enters the pores and facilitates the nitrification process [42], hence improving pollutant removal efficiency. This process can be further improved by inserting aeration pipes in the system [35]. Clogging in this system may be caused by degraded macrophytes, pollutants, and particles in the system affecting the hydraulic conductivity that influences the treatment process [43]. VSSF CWs are well-aerated (aerobic condition); therefore, ammonia nitrogen is removed through the nitrification process but not nitrate nitrogen because of the absence of denitrification [15]. According to [25], TSS, BOD_5, and COD removal efficiencies for VSSF CWs were found to be 81.8%, 80.0%, and 78.7%, respectively.

2.3. Hybrid CWs

Hybrid system is a combination of various types of CWs. This system is capable of removing ammonia, nitrate, and total nitrogen from different types of wastewater by combining VSSF CWs with HSSF CWs [44]. The very high pollutant removal efficiency of hybrid CWs is due to the presence of aerobic, anaerobic, and anoxic phases [24,32,45]. Hybrid systems outperform single-stage systems in the removal of TSS (91.2%), BOD_5 (82.7%), NH_4-N (77.6%), TN (73.3%), and TP (69.9%), as well as other contaminants, when compared to other types of treatment wetlands [25].

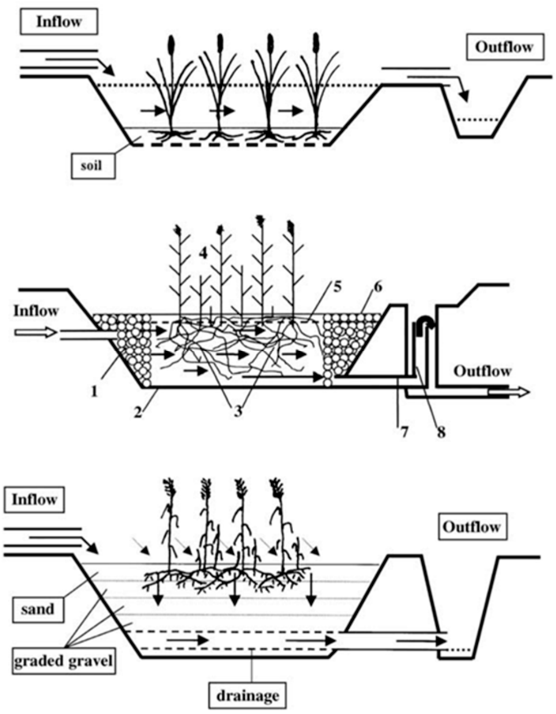

Figure 1. Top to bottom, CW with free water surface (FWS), CW with horizontal sub-surface flow (HSSF, HF), 1 inflow distribution zone filled with large stones; 2 impermeable layer; 3 filtration material; 4 vegetation; 5 water level in the bed; 6 outflow collection zone; 7 drainage pipe; 8 outflow structure with water level adjustment, CW with vertical sub-surface flow (VSSF, VF) (Vymazal, 2007) [39].

2.4. Macrophytes

Wetland plants are classified as emergent plants, floating leaf macrophytes, submerged plants, and freely floating macrophytes [46]. Macrophytes are components of the CW treatment systems that play major roles in the breakdown and removal of nutrients and other contaminants. Aquatic macrophytes are widely employed in wastewater treatment because they grow more quickly, produce more biomass, and have a higher capacity to absorb and store pollutants [47,48]. Through photosynthesis, macrophytes in CWs can also act as a reliable source of energy (carbon from root exudates) for microorganisms [17], and in the rhizosphere, macrophytes offer surfaces and oxygen for the growth of microorganisms [49]. *Phragmites australis*, *Typha latifolia*, *Lemina minor*, *Arundo donax*, *Cyperus alternifolius*, *Canna indica*, and *Cyperus papyrus* are some of the aquatic plants used in wastewater treatment.

2.5. Substrate

The substrate in CWs is usually constituted of soil, sand, gravel, or organic matter such as compost [50]. It is a crucial component of CWs performing several functions, including the following: physical support for wetland plants [51]; controls hydraulic conductivity and plant growth [52]; removal of pollutants by ion exchange, adsorption, precipitation, and complexation [49,53,54]; electron donor function for metabolism and denitrification; and carrier function for microorganisms. For such reasons, CWs substrate has a big impact on the implementation costs, as well as the effectiveness and sustainability of the treatment [51]. Specifically, the substrate in CWs strongly affects the performance of microorganisms by providing aerobic and anaerobic zones that promote denitrification, nitrification, adsorption, ion exchange, and precipitation processes with organic carbon as an accessible energy source [13,55,56].

3. Discussion

The application of CWs in wastewater treatment becomes more common in different parts of the world. Similarly, this review found that the number of published results in the first 11 years (2001–2011) was small in number than the following 12 years (2012–2023), showing how familiar the CWs technique becomes in Italy. Of the 76 articles reviewed, 2 were about laboratory experiments, 30 were large-scale experiments, and the remaining 44 referred to pilot projects. It has been reported that the pollutant removal efficiencies of all the CWs reviewed in this article showed remarkable potential, even though there are biotic/abiotic (physical, chemical, and biological processes) factor-driven performance variations among them. For instance, photolytic degradation, sorption, plant uptake, microbial degradation, type of CWs, plant type, operational mode, soil matrix, hydraulic retention time, hydraulic loading rate, research location, climate, etc. might have caused the observed removal efficiency differences among the CWs. Table 1 summarizes the types of CWs, locations, plants used, wastewater treated, pollutants, and their removal efficiency (RE%), which are the common operational parameters reported in all the 76 reviewed articles.

Biotic and abiotic factors can have a significant effect on the pollutant removal efficiency of CWs. For instance, according to [57], nutrient removal is controlled by the pH of the treatment system in CWs. A reduction in the NH_4^+-N removal rate from 7.8 ± 1.2 g/m^3/d to 6.4 ± 1.3 g/m^3/d corresponding to a reduction in pH from 8.1 to 7.6 was reported [58]. Similarly, research results indicated significant differences in wastewater treatment capacities among plants [59–61]. Some researchers [62] reported removals of ammonium and phosphate ions from a pig industry effluent that ranged between 59–84% and 32–92%, respectively, in CWs with *Phragmites australis,* and 62–75% and 7–68% in CWs with *Typha latifolia.* In the same manner, differences in the removal of pollutants among plants were also observed in this review. For example, the benzene removal potential (%) of a horizontal subsurface CW in South Italy showed different values using *Phragmites australis* (39.78%) and *Typha latifolia* (35.14%) [63]. The types of microorganisms present in a CW also affect the removal efficiency. Organic matter biodegradation is correlated to autotrophic and heterotrophic bacteria, fungi, yeast, and protozoa [64,65]. The presence or absence of these microorganisms in the CWs of the reviewed Italian works possibly contributed to the observed performance variations.

Temperature determines the rate of metabolic activities and impacts microbial populations [66]. Ref. [67] stated a significant ($p < 0.05$) positive impact of temperature on the rate of organic matter degradation, nitrification, and denitrification processes in less time. The success of treatment in a CW often declines at cold temperatures, mostly due to decreased biotic activity [15]. For instance, the rate of ammonium oxidation is greatly reduced when the temperature drops below 10 °C [68]. Moreover, ref. [69] reported 7% and 9% improved removal efficiencies of ammonia nitrogen and nitrate nitrogen, respectively, in constructed wetlands in summer than in winter. The reviewed Italian case studies were conducted under different temperatures and seasons, which are expected to cause performance variations.

Hydraulic retention time or the amount of time contaminants are in contact with the substrate and the rhizosphere of plants is widely known to be a significant controlling element in determining the effectiveness of pollutant removal [33,70,71]. Ref. [67] confirmed a decrease in organic matter (as BOD and total suspended solid) and nitrogen removal efficiency with a reduced hydraulic retention time because of less contact time of pollutants in the system. Ref. [72] recommended a 6-day hydraulic residence time for the acceptable level of treatment of COD, BOD, TN, and TP in horizontal subsurface flow CWs. However, the case studies reviewed here were conducted under different hydraulic retention times contributing to the observed difference in removal efficiencies.

Hydraulic loading rate, i.e., the quantity of wastewater supplied to the CWs system, affects the removal potentials. When there is a large increase in hydraulic load, the contact time between wastewater and biofilms is typically reduced, thus influencing the nitrogen and organics removal rates. According to [67], when hydraulic loading was increased from 31 mm/d to 146 mm/d, the mean organics and nitrogen removal efficiency decreased from 84% to 63%, and 84% to 16%, respectively. As there were different hydraulic loading rates utilized in the reviewed Italian cases, the pollutant removal potentials of the CWs have also resulted in various values.

The quantity of dissolved oxygen (DO) in the system has an impact on the nutrient removal process. According to [73], NO_3^--N was eliminated at a lower DO concentration of 0.5 mg/L, while the removal rate decreased at higher DO concentrations. A total nitrogen (TN) elimination effectiveness of 70% was reported at DO levels of 0.15–0.2 mg/L [73]. In the reviewed works, both horizontal and vertical CWs were utilized, which have different levels of dissolved oxygen that directly control the microbial activities affecting the pollutant removal potentials. The substrate and wastewater feeding mode also affect the pollutant removal efficiency of CWs by enhancing oxygen transfer.

In this reviewed work, *Phragmites australis*, *Typha latifolia*, *Arundo donax*, and *Cyperus alternifolius* are the most frequently used plant species in the experiments treating various wastewaters. These experiments were conducted at different levels (laboratory, pilot, or large scale) depending on the area/volume of the CWs used. There were more pilot-scale studies than large-scale or laboratory-size studies. Similarly, the types of wastewater treated were also different; Urban/municipal/domestic wastewater being the most frequently treated ones, followed by effluent from wastewater treatment plants, agricultural wastewater, and swine/dairy wastewater. Horizontal subsurface CWs have been utilized more repeatedly than vertical and hybrid CW systems. Moreover, numerous contaminants were eliminated from various wastewaters utilizing CWs. COD (chemical oxygen demand), TN (total nitrogen), TSS (total suspended solids), BOD (biological oxygen demand), and TP (total phosphorus) were the major pollutants removed (based on their frequency) in the reviewed works.

Table 1. Summary of research works performed on the application of constructed wetlands on wastewater treatment in Italy.

Type of CWs	Location	Research Scale	Plants Used	Wastewater Type	Pollutants and Removal Efficiency (RE %)	Ref.
Combined (Lagoons and CWs)	S. Italy	pilot	*Typha latifolia*	Swine wastewater	TSS and OM; (99%), TN; (80–95%)	[74]
Surface flow	N. E. Italy	pilot	*Phragmites australis*, *Typha latifolia*	Agricultural drainage	TN; (58 kg/ha discharged out), TN input was 526 kg/ha	[75]
HF and VF	E. Sicily	pilot	*Phragmites* sp.	Municipal effluents	TSS; (85%), BOD_5; (65%), COD; (75%), TN; (42%) and TP; (32%)	[76]
HSS	S. Italy	pilot	*Phragmites australis*	Dairy wastewater and domestic sewage	COD; (91.9%), BOD_5; (93.7%), TN; (48%), TP; (60.6%), Nitrates;-Low conc., Chlorides; (48.7%), Sulfates; (87.8%), Cd; (23.7%), Cr; (51.6%), Cu; (79.4%), Ni; (58.6%), Pb; (69.6%), Zn; (85.7%), Total coliforms; (99.6%), *E. coli*; (99.7%), Faecal streptococci; (98.8%)	[77]
Tanks	N. E. Italy	pilot	*Phragmites australis*	Perfluoroalkyl acids	50% reduction in PFAAs	[78]
HSS	S. Italy	pilot	*Phragmites australis*, *Typha latifolia*	Benzene solution	Benzene; (39.78%) for the *Phragmites* field and (35.14%) for the *Typha* field	[63]
Hybrid (HF and VF)	C. Italy	large	*Phragmites australis*	Domestic wastewater	COD; (83–95%), TSS; (68–93%), NH_4^+; (78–98%), pathogen elimination (3–5 logs)	[79]
CW	N. C. Italy	lab	*Phragmites australis*	Urban and industrial wastewater	Fe; (95%), Zn; (73%), Cu; (61%) (with batch experiment), and Cu; (46–80%), Fe; (70–100%), Zn; (65–85%) (with column system)	[80]
HSS	S. Italy	pilot	*Vetiveria zizanoides*, *Miscanthus x giganteus*, *Arundo donax*, *Phragmites australis*	Wastewater from the treatment plant	TSS; COD; NH_4^+; TN; PO_4; and *E.coli*, respectively, by; *Vetiveria zizanoides;* (86%), (62%), (51%), (59%), (25%), (2.7%): *Myscanthus x giganteus;* (86%), (61%), (52%), (57%), (20%), (2.8%) *Arundo donax;* (89%), (59%), (53%), (56%), (28%), (2.8%): *Phragmites australis;* (88%), (63%), (57%), (61%), (29%), (3.1%)	[81]
Hybrid (HF and VF)	N. Italy	pilot	*Aster tripolium* L. *Juncus maritimus Lam.*, *Typha latifolia*	Agricultural effluent (anaerobic digester)	COD; (76%), nitrate; (86%), ammonia; (87%), P; (87%) with 50 L/d inlet flow COD; (88%), nitrate; (73%), ammonia; (98%), P; (99%) with 200 L/d inlet flow	[82]
VSS	W. Sicily	pilot	*Phragmites australis*, *Arundo donax*	First-flush stormwater	BOD_5; (75–83%), COD; (65–69%), TN; (60–66%), Cu; (25–66%), Zn; (38–63%), *E. coli*; concentration levels < 100 (CFU 100 mL^{-1})	[83]

Table 1. *Cont.*

Type of CWs	Location	Research Scale	Plants Used	Wastewater Type	Pollutants and Removal Efficiency (RE %)	Ref.
HSS	E. Sicily	large	*Phragmites australis, Typha latifolia*	Urban wastewater	TSS; BOD_5; COD; TN; NH_4^+; and TP; in CW1, CW2, and CW3, respectively; CW1; (77%), (62%), (63%), (48%), (42%), (25%): CW2; (80%), (63%), (66%),(44%), (40%), (24%): CW3; (81%), (61%), (59%), (44%), (39%), (20%)	[84]
VSS, free water system	N. Italy	large	*Phragmites australis*	Combined sewer overflow	COD; (87%), NH_4^+ (93%)	[85]
Hybrid (HF and VF)	C. Italy	large	*Phragmites australis*	Mixed (grey/black) wastewater	COD; (94%), BOD_5; (95%), TSS; (84%), NH_4^+; (86%), TN; (60%), TP; (94%), Total coliforms; faecal coliforms; faecal streptococci; and *E. coli*; ranged (99.93–99.99%)	[86]
VF and HF	N. Italy	pilot	*Juncus maritimus, Typha latifolia, Cyperus papyrus*	Industrial wastewater	The RE in Inlet, VSS flow A, VSS flow B, and HSS flow, respectively, for; COD; (18 ± 2%), (15 ± 1%), (14 ± 1%), (7 ± 1%): Zn; (418 ± 1%), (64.1 ± 9.5%), (112 ± 10%), (87.3 ± 9.5%) Fe; (348.09 ± 25.476%), (13.5 ± 19.0%), (24.9 ± 19.0%), (6.53 ± 18.98%): NO_3^- (18.9 ± 1.0%), (17.9 ± 0.8%), (17.6 ± 0.83%), (48 ± 0.76%)	[87]
HSS	S. Italy	large	—	Dairy wastewater	COD; (94.3%)	[88]
HSS	C. Italy	large	*Phragmites australis*	Agro-industrial wastewater	COD; (93%), TSS; (81%), Ammonium; (55%), Nitrates; (40%) TP; (20%), TN; (0.3%), total coliforms; (99.1%), faecal coliforms; (99.7%), faecal streptococci; (99.8%), *E. Coli.*; (99.7%)	[89]
VF and HF	N. C. Italy	pilot	*Phragmites australis*	Landfill leachates	COD; reduction range (0–30%), ammonia; (50–80%), nitrite; (20–26%)	[90]
HSS	N. C. Italy	large	*Phragmites australis*	Activated sludge effluent	Removals of hexavalent/trivalent chromium; (72%) and (26%), respectively.	[91]
HSS	S. Italy	pilot	*Cyperus papyrus, Vetiveria zizanoides, Miscanthus x giganteus, Arundo donax, Phragmites australis*	municipal wastewater	TSS; COD; and *E. coli.*; ranged (82–88%), (60–64%), and (2.7–3.1%) U log, respectively. TN; (64%), NH_4-N; (61%), PO_4-P; (31%)	[92]

Table 1. *Cont.*

Type of CWs	Location	Research Scale	Plants Used	Wastewater Type	Pollutants and Removal Efficiency (RE %)	Ref.
HSS	S. Italy	pilot	*Cyperus alternifolius* L., *Typha latifolia*	Treated urban wastewater	*Typha latifolia*-based RE of TSS; BOD_5; COD; TKN; N-NH_4; TP; (64.3%), (72.4%), (75.7%), (51.6%), (49.6%), (47.9%): *C. alternifolius* based RE of TSS; BOD_5; COD; TKN; N-NH_4; TP; (47%), (64.8%), (66.6%), (36.1%), (38.3%), (31.7%), respectively. *E. coli*; RE did not exceed (89.5%)	[93]
HSS	S. Italy	large	*Phragmites australis*, *Typha*	Treatment plant effluent	TSS; BOD_5; COD; TN; in (H-SSF) CW2; (74 ± 12%), (64 ± 15%), (67 ± 19%), (51± 26%): (H-SSF) CW3; (79 ± 10%), (58 ± 19%), (58 ± 19%), (42 ± 17%): (H-SSF) CW4; (74 ± 13%), (54 ± 23%), (57 ± 20%), (44 ± 23%): Ammonia removal (51%) for H-SSF2, (42%) for H-SSF3 and (44%) for H-SSF4	[94]
Constructed surface flow	N. E. Italy	large	*Phragmites australis*, *Typha latifolia*	Agricultural drainage	N; (90%)	[95]
FRB, VF, free water	C. Italy	pilot	*Phragmites australis*	Treatment plant wastewater	COD; BOD_5; TN; N-NH_4^+; TP; and TSS; were (>80%)	[96]
Wall cascade (WC)	N.E. Italy	pilot	*Mentha aquatica* L., *Oenanthe javanica*, *Lysimachia nummularia* L.	Kitchen grey waters	COD; (86%), BOD_5; (83%), MBAS; (anionic surfactants) (82%), TKN; (57%) and N-NH_4; (43%)	[97]
Hybrid (VF and HF)	–	pilot	*Aster tripoloium*, *Typha latifolia*	Artificially grey water	COD; (95%) (inside the V-SSF vegetated tank)	[98]
HF and VF	S. Italy	pilot	*Phragmites australis*	wastewater treatment plant effluent	TSS; (>85%), BOD_5; (74%), COD; (61%), TN; (54%), Nitrate; (87%), TP; (57%) in *Phragmites australis* covered beds. Faecal coliforms; *E. coli*; and faecal streptococci; (>97%)	[99]
HF	S. Italy	pilot	*Arundo donax* L., *Cyperus alternifolius* L.	Urban wastewater	BOD_5; (70–72%), COD; (61–67%), TKN; (47–50%), TP; (43–45%), Pathogen; load removal (90%)	[100]
HF	–	lab	*Phragmites australis*, *Carex oshimensis*, *Cyperus papyrus*	Grey water	Turbidity; (>92%), TSS; (>85%), COD; (>89%), BOD_5; (>88%)	[101]
HF (H-SSF1 and H-SSF2)	S. Italy	large	*Phragmites australis*	Treatment plant effluent	TSS; COD; BOD; (80%), (63%), (58%) for H-SSF1 and (67%), (38%), (41%) for H-SSF2	[102]

Table 1. *Cont.*

Type of CWs	Location	Research Scale	Plants Used	Wastewater Type	Pollutants and Removal Efficiency (RE %)	Ref.
Hybrid (HF and VF)	S. Italy	large	*Phragmites australis, Iris pseudacorus, Cyperus papyrus var. siculus, Canna indica, Typha latifolia*	Effluent from a tertiary treatment unit	TSS; (95.8 ± 1.4%), BOD_5; (93.2 ± 3.6%), COD; (92.7 ± 6.8%), TP; as PO_4 (P-PO_4) (26.7 ± 11.2%), N; as NH_4 (N-NH_4) (78.2 ± 30.8%), TN; (55.1 ± 7.1%), N; as NO_3 (N-NO_3) (20.7 ± 8.3%), *E. coli*; (CFU/100 mL) (4 ± 0.7%)	[103]
CW	S. C. Italy	large	*Iris pseudacorus, Juncus effusus, Carex elata, Nymphaea alba*	Domestic sewage	COD; (7.6%), TSS; (6.7%), N-NH_4^+; (92.3%), NO_3^-; (63.3%), *E. coli*; (96.2%)	[104]
Hybrid	S. W. Italy	pilot	*Phragmites australis, Arundo donax, Arundo plinii Turra*	Landfill leachate	COD; (93%), BOD_5; (95%) Ni; (92%)	[105]
Surface flow	N. C. Italy	large	*Phragmites australis, Typha latifolia, Typha angustifolia, Salix alba, Populus alba*	Agricultural drainage	TN; (47%), TP (49%)	[106]
Hybrid	S. Italy	pilot	*Canna indica, Typha latifolia*	Semi-synthetic stormwater	Metals; (Cd, Cr, Fe, Pb, Cu, Zn) (70–98%)	[107]
Constructed surface flow	N. E. Italy	large	*Phragmites australis*	Herbicide runoff	Mitigation effectiveness (98%), i.e., (45–80%) fold lower than the applied concentration	[108]
Hybrid (VF and HF)	N. W. Italy	pilot	*Phragmites australis*	Cheese factory wastewater	RE (minimum-maximum) for TSS; (28–88%), COD; (53–80%), BOD_5; (31–80%), TOC; (25–80%), TP; (10–73%), TN; (40–51%)	[109]
Subsurface flow	N. W. Italy	large	*Phragmites australis, Typha latifolia, Scirpus lacustris*	Dairy wastewater	BOD_5; (>90%), nitrogen (50–60%)	[110]
(HF and VFl), and free water system	C. Italy	large	16 different Tuscany's native macrophytes	Municipal wastewater	Organic load; (86%), TN; (60%), TP; (43%), TSS; (89%), ($NH4^+$); (76%), (4–5) logs pathogens concentration	[111]
Surface flow	N. E. Italy	large	*Typha latifolia, Phragmites australis*	Agricultural drainage	NO_3^-N; (83%), TN; (79%), PO_4-P; (48%), TP; (67%)	[112]
Free water surface	N. E. Italy	large	*Phragmites australis, Typha latifolia, Carex* spp., *Juncus* spp., *Phalaris arundinacea, Mentha aquatic, Iris pseudacorus*	Agricultural drainage waters	TN; (33.3–49.0%), N-NO_3; (32.2–80.5%)	[113]

Table 1. *Cont.*

Type of CWs	Location	Research Scale	Plants Used	Wastewater Type	Pollutants and Removal Efficiency (RE %)	Ref.
HSS	C. Italy	pilot	*Phragmites australis*	Olive oil extraction effluent	COD; (74.1 ± 17.6%), polyphenols (83.4 ± 17.8%)	[114]
HSS, and free water system	C. Italy	large	*Typha latifolia, Myriophyllum spicatum, Phragmites australis, Elodea Canadensis, Ceratophyllum demersum, Lythrum salicaria, Iris pseudacorus, Epilobium hirsutum, Alisma plantago aquatica, Butumus umbellatus*	Winery wastewater	COD; (97.5%), N-NO_2^-; (84.7%), NO_3^-; (39.9%), TP; (45.5%)	[115]
Subsurface VF	C. Italy	pilot	*Zantedeschia aethiopica, Canna indica, Carex hirta, Miscanthus sinensis, Phragmites australis*	Synthetic wastewater (micropollutant)	N; (67.4%), P; (74.4%), Zn; (99.3%), Cu; (99.3%), LAS; (78.3%), Carbamazepine; (61.4%)	[116]
HSS	S. Italy	pilot	*Phragmites australis, Typha latifolia*	Produced wastewater	Paracetamol removals in *phragmites* bed (51.7–99.9%), in *Typha* bed (46.7–>99.9%)	[117]
Surface flow	N. Italy	large	*Phragmites australis, Typha latifolia, Carex* spp.	Agricultural drainage water	TSS; (82%), TN; (78%), NO_3-N; (78%), $NH4^+$-N; (91%)	[118]
Hybrid (VF and HF)	N. E. Italy	pilot	*Canna indica, Symphytum officinale, Phragmites australis*	Piggery wastewater	COD; (79%), TN; (64%), NH_4-N; (63%), NO_3-N; (53%), P; (61%)	[119]
HSS	S. Italy	pilot	*Arundo donax, Cyperus alternifolius*	Pre-treated urban wastewater	TSS; (73.72%), BOD; (67%), COD; (66.21%), TN; (50.33%), NH_4-N; (54.11%), TP; (41.11%). Total coliforms; faecal coliforms; faecal streptococci; and *E.coli;* (89.60%), (88.01%), (83.12%), and (87.67%), respectively.	[120]
V-SSF and H-SSF	N. Italy	pilot	*Phragmites australis*	Domestic wastewaters	TN; (71%), NH_4-N; (94%), TP; (27%) and COD; (92%) in the v-SSF TN; (59%), NH_4-N; (21%), TP; (52%) and COD; (70%) in the h-SSF	[121]

Table 1. *Cont.*

Type of CWs	Location	Research Scale	Plants Used	Wastewater Type	Pollutants and Removal Efficiency (RE %)	Ref.
CWs	C. Italy	large	*Phragmites australis*, *Typha latifolia*, *Lemna minor* L., *Lemna minuta Kunth*, *Sparganium erectum* L., *Carex pendula Huds*, *Salix alba* L., *Populus alba* L.	Municipal wastewater	Sulphates; (50%), (33% in winter) Nitrates; (80%) in winter, (15%) in spring and summer *E. coli*; (82%) in spring, (99%) in autumn	[122]
HSS	S. Italy	pilot	*Cyperus alternifolius*, *Typha latifolia*	wastewater treatment plant effluent	BOD_5; (70.6–68.1%), TKN; (43.9–52.8%), N-NH_4; (43.2–48.0%), TP; (37.8–42.1%), Total coliforms; (80.5–88.7%), Faecal coliforms; (83.5–90.6%), Faecal streptococci; (76.6–83.1%), *E. coli*; (87.3–91.3%)	[123]
(H-SSF1) and (H-SSF2)	N. E. Italy S. Italy	large	*Phragmites australis*	Piggery manure Municipal wastewater	COD; (62.7%), TN; (34.9%), TP; (7.61%) COD; (64.5–45.1%), TN; (44.4–48.1%), TP; (25–37.5%) in Catania (S. Italy)	[124]
HSS	N. Italy	pilot	*Phragmites australis*	Domestic wastewater	Cu; (3.4–9%), Ni; (35 ± 16–25 ± 10%), Zn; (27 ± 9–26 ± 5.4%)	[125]
HSF	S. Italy	pilot	*Phragmites australis*, *Typha latifolia*	BTEX and metals solution	Fe; (88–95%), Cr; (86–90%), Pb; (78–88%): BTEX; (46–57%)	[126]
HSS	S. Italy	large	*Phragmites australis*	municipal wastewater effluent	TSS; BOD_5; COD; TN; and TP; (74 ± 16%), (42 ± 21%), (41 ± 21%), (61 ± 17%), and (50 ± 31%), respectively.	[127]
HSS	S. Italy	pilot	*Phragmites australis*, *Typha latifolia*	Artificial wastewater	Cr; (87%), Pb; (88%), Fe; (92%) in *Phragmites* bed: Cr; (90%), Pb; (87%), Fe; (95%) in *Typha* bed	[128]
CW	C. Italy	pilot	*Phragmites australis*, *Salix matsudana*	Urban wastewater (micro-pollutants)	NP; diclofenac; atenolol; (8.4–100%) in *P. australis* bed while *S. matsudana* preferentially removed NP_1EO, NP_2EO, ketoprofene, and triclosan	[129]
HSS	N. Italy	pilot	*Phragmites australis*	municipal (micro-pollutant)	From 1% for psychiatric drugs to 26% for antihypertensives, on average (16 ± 8%)	[130]
HSSFs CW(1) HSSFs CW(2)	S. Italy	pilot	*Festuca*, *Lolium*, *Pennisetum* spp., *Arundo donax* L., *Cyperus alternifolius* L., *Typha latifolia* L.	Treated wastewater	RE by *T. latifolia* and *C. alternifolius* for TSS; (64–57%), BOD_5; (68–64%), COD; (75–70%), TKN; (51–43%), NH_4-N; (52–41%), TP; (47–38%), Total Coliform; (88–85%), Faecal Coliform; (88–83), Faecal Streptococci; (84–77%), *E.coli*; (90–88%) RE by *A. donax* and *C. alternifolius* for TSS; (74–71%), BOD_5; (70–64%), COD; (71–66%), TKN; (48–45%), TP; (48–42%), Total coliforms; (89–85%), Faecal coliforms; (90–88%), *E. coli*; (88–85%)	[131]

Table 1. *Cont.*

Type of CWs	Location	Research Scale	Plants Used	Wastewater Type	Pollutants and Removal Efficiency (RE %)	Ref.
HSS	S. Italy	pilot	*Cyperus alternifolius*, *Typha latifolia*	Urban wastewater	RE by *C. alternifolius* and *T. latifolia* for TSS; (74.2–77%), BOD; (68–70.5%), COD; (74.2–77%), TKN; (42.7–51.8%), N-NH_4; (42.3–49.4%), TP; (35.6–39%). Total coliforms; (83.6–90.4%), Faecal coliforms; (79.6–88.8%), Faecal streptococci; (76.4–84.1%), *E. coli*; (87.7–92.1%)	[132]
HSS	S. Italy	pilot	*Arundo donax*, *Cyperus alternifolius*	Dairy wastewater	RE by *A. donax* and *C. alternifolius* for TSS; (79.6–76.1%), BOD_5; (61.8–61.4%), COD; (51.5–53.1%), TN; (45.2–41.7%), N-NH_4; (36.7–40.7%), ON; (41.8–41.1%), TP; (49.8–45.7%), Cu; (43.2–39.9%), Ni; (44.7–39.3%), Pb; (58.3–46.3%), Zn; (–/–), Total coliforms; (88.1–83.2%), Faecal streptococci; (83.9–81.3%), *E. coli*; (88.3–86.9%), Salmonella spp; (–/–)	[133]
CWs	N. Italy	large	*Phragmites australis*	River water (heavy metals)	Cr; (36.96 mg/g), Ni; (0.67–2.4 mg/g) but 10 times higher in December	[134]
HSS	S. Italy	large	*Phragmites* sp.	wastewater treatment plant effluent	TSS; (77–92%), BOD_5; (37–72%), COD; (51–79%), *E. coli*; (97–99.5%). Salmonella; and helminth; eggs 100% removed	[135]
Hybrid (VF and HF)	N. E. Italy	large	*Canna indica*, *Phragmites australis*	Synthetic wastewater	TN; (95%), NH_4-N; (95%), NO_3-N; (93%)	[136]
Hybrid (VF and HF)	N. Italy	pilot	*Phragmites australis*	University wastewater	RE by vertical-horizontal CWs for COD; (70.4–40.1%), TSS; (80.4–72.7%), TN; (49.3–88.8%), NO_3—N; (–/–), NO_2^-N; (–/–), TP; (47.3%-88.5%), PO_4^{3-}P (34.2–95.1%), Cl^-; (0–9.7%), Br^-; (33%/-), SO_4^{2-}; (3.5–10.2%). *E. coli*; (74.7–99.7%), Total coliforms; (90.7–93.5%), Enterococcus; (50.1–99.9%)	[137]
HSS	S. Italy	pilot	*Arundo donax*, *Cyperus alternifolius*	Treated urban wastewater	RE by *A. donax* and *C. alternifolius* for TSS; (69.5–64.5%), BOD_5; (57.1–54.2%), COD; (72.9–72%, TKN; (54–51.9%), N-NH_4; (59.7–57.5%), TP; (35.1–36.4%), Cl; (8.8–8.6%), Ca; (28–26%), K; (26.3–21%), Mg; (16.4–11.5%), Na; (9.9–7%)	[138]
HSS	N. C. Italy	large	*Phragmites australis*	Textile wastewater	Hexavalent chromium; (70%)	[139]
HSS	S. Italy	pilot	*Arundo donax*, *Cyperus alternifolius*	Combined dairy and domestic wastewater	RE by *A. donax* and *C. alternifolius* for TSS; (80.69–82.98%), BOD_5; (78.02–75.61%), COD; (62.67–61.12%), TN; (51.84–49.68%), N–NH_4; (45.05–51.51%), ON; (40.51–45.11%), TP; (39.86–38.88%), Cu; (44.11–48.31%), Ni; (35.17–31.03%), Pb; (31.57–36.84%), Zn; (56.25–50.33%)	[140]

Table 1. *Cont.*

Type of CWs	Location	Research Scale	Plants Used	Wastewater Type	Pollutants and Removal Efficiency (RE %)	Ref.
VF	S. E. Italy	pilot	*Phragmites australis*	A mix of 5%, 10%, and 20% landfill leachate	COD; (60.5%), N–NH_4^+; (47.5%) in 5% landfill leachate. N-NO_3^-; (49.4%) in 10% of landfill leachate	[141]
VSS, HSS, and free surface flow	S. Italy	large	*Phragmites australis, Cyperus Papyrus var. Siculus, Canna indica, Iris pseudacorus, Nymphaea alba* L., *Scirpus lacustris* L.	Winery wastewater	TSS; (69%), BOD_5; (78%), COD; (81%), NH_4-N; (57%), TN; (56%), PO_4-P; (38%)	[142]
Hybrid (SSF and floating)	E. Italy	large	*Arundo donax, Phragmites australis*	Digestate liquid fraction from anaerobic digestion plant	COD; (57.9%), TN; (64.6%), NH_4-N; (65.1%), NO_3-N; (35.6%), TP; (49.2%), PO_4-P; (45.1%) in the subsurface flow line and, COD; (89.2%), TN; (90%), NH_4-N; (89%), NO_3-N; (93.8%), TP; (50.3%), PO_4-P; (49.9%) in floating treatment wetland line	[143]
Hybrid (HSS and floating)	N. E. Italy	pilot	*Phragmites australis, Iris pseudacorus*	Municipal wastewater	TN; (74.3%), NH_4-N; (62.1%), NO_3-N; (77.7%), TP; (29.6%), PO_4-P; (37.4%), COD; (46.7%)	[144]
Plastic vertical in-vessel	S. Italy	pilot	*Arundo donax*	Municipal sewage	COD; (78.7–85.7%), TSS; (89–94.9%), TN; (86.1–93.2%), ammonia; (77.4–98.1%). Cu; and Zn; reduced almost to zero	[145]
Microcosm SS	N. E. Italy	large	*Carex elata, Juncus effusus* L., *Phalaris arundinacea, Phragmites australis, Typha latifolia* L.	Artificial wastewater	PO_4-P; removal (86.2%), (48.1%), (37.6%) and (36.0%) for *P. aundinacea, C. elata, J. effusus* and *P. australis* bed, respectively. *T. latifolia* was able to remove more than the PO_4-P load (13.05 g/m^2), with a P uptake: P supplied ratio (21.8%)	[146]
HSS	N. E. Italy	pilot	*Typha angustifolia, Phragmites australis*	Domestic wastewater	Pathogens (98%). TSS; COD; and, BOD_5 (90%). N-NH_4^+; N-NO_3^-; TN; Cl^-; SO_4^{2-};PO_4^{3-} (50%)	[147]
HSS	S. Italy	pilot	*Cyperus alternifolius, Typha latifolia*	Urban wastewater	BOD_5; calculated using concentrations and mass loads in T. *latifolia* (65.5 ± 7.4%) and (70.7 ± 3.8%), respectively. For C. *alternifolius* (60.5 ± 8.9%) and (65.5 ± 5.5%)	[148]

Note: BOD_5—biochemical oxygen demand of 5 days; Br—bromine; BTEX—benzene; toluene; ethylbenzene and xylene; Ca—calcium; Cd—cadmium; CFU—colony forming units; Cl—chlorine; COD—chemical oxygen demand; Cr—chromium; Cu—copper; CWs—constructed wetlands; *E. Coli.—Escherichia Coli*; Fe—iron; FRB—French reed bed; HF—horizontal flow; HSF—horizontal surface flow; HSS—horizontal sub-surface; K—potassium; LAS—linear alkylbenzene sulfonate; MBAS—methylene blue active substance; Mg—magnesium; Na—sodium; NH_4^+—ammonium; NH_4^-N—nitrogen level in ammonium ion; Ni—nickel; N—nitrogen; N-NO_2^-—nitrogen in nitrite; NO_3^-—nitrate; NP1EO—monoethoxylated nonylphenol; NP2EO—diethoxylated nonylphenol; NP—nonylphenol; OM—organic matter; Pb—lead; PFAAS—perfluoroalkyl acids; PO_4^{3-}—phosphate as P; PO_4—phosphate; P—phosphorus; RE—removal efficiency; SO_4^{2-}sulphate; TKN—total Kjeldahl nitrogen; TN—total nitrogen; TOC—total organic carbon; TP—total phosphorus; TSSs—total suspended solids; U log—log units; VF—vertical flow; VSS—vertical sub-surface; Zn—zinc.

The pollutant removal efficiencies of the hybrid CWs in the reviewed case studies were very high compared to the other types of CWs, which are similar to research results reported elsewhere [24,32,45]. The removal efficiency of COD ranged from 53% to 80%, but the highest values (79–97.5%) were obtained in trials with hybrid CWs, which is in line with a recent work that achieved a COD removal of 97.56 ± 1.6% [149]. Similarly, removal efficiency for TN of the reviewed work was between 60% and 66%; however, hybrid CWs managed to increase the performance (64–88%). This result is in agreement with the work of [150], who reported 82.71 ± 3.92% TN removal in an anoxic-aerobic system combined with an integrated vertical-flow constructed wetland.

The removal efficiency of TSS was also very high (89% to 95%), indicating the potential of CWs. This result is supported by the range of values (81.6–97.1%) for TSS removal from anaerobic reactor brewery effluent reported by [151]. Moreover, CWs were able to remove BOD successfully (75–80%), but then again the highest values (93–95%) were recorded in experiments conducted with hybrid CWs. These values are also consistent with reported BOD removal that ranged between 85% and 94% [152]. Even though the removal efficiency for TP was relatively low (10–73%), hybrid CWs gave higher values (47–94%), which is also comparable with the removal percentage (92.28 ± 2.78%) reported by [150].

Heavy metals (Zn, Cu, Pb, Ni) and pathogens (total coliforms, faecal streptococci, *E.coli*.) were also removed in some of the experiments conducted with CWs. For instance, the removal efficiency of Zinc ranged between 65% and 85%; nonetheless, the hybrid CWs resulted in high performances (70–98%). A total reduction in zinc and copper almost closer to zero was also reported [145]. The lead removal efficiency was 78–88%. The hybrid CWs again resulted in high removal potentials (70–98%). The removal efficiency for nickel was between 35 and 58%, but hybrid CWs, in the same way, gave a high value (92%). Removal efficiency for copper ranged from 46 to 80%, then again a removal potential of 99.3% was obtained with hybrid CWs.

4. Conclusions and Future Directions

This article reviewed 76 published results that engage CWs in treating several wastewaters. The experiments were conducted at various times and places, employing different operational parameters. However, it has been attempted to consider and tabulate only the operational parameters reported in all the reviewed works. The number of research outputs published showed an increasing trend over time (23 years), in a way indicating the research progress of the application of CWs in wastewater treatment. The performance of the reviewed works of CWs in treating wastewater in Italy varied considerably because of many biotic and abiotic factors affecting the major biological, physical, and chemical activities going on in the CWs. However, all assessed works of CWs in treating wastewater are considered the best at removing pollutants. The knowledge and skills acquired from these results could be utilized as a foundation for any planned nature-based wastewater treatment activities. It is also worthwhile doing additional large-scale trials to confirm the capability of CWs in eliminating pollutants from wastewater because there is a chance that they will provide different findings from those found in pilot-scale studies.

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