Constructed Wetlands in the Hospitality Industry

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The hospitality industry is increasing its awareness of how the integration of nature-based solutions can decrease its environmental impact while maintaining or increasing the service level of the sector. Constructed wetlands (CWs) constitute a promising sustainable solution for proper in situ domestic wastewater treatment but its use in the hospitality industry is scattered among both the technical and scientific literature. The research was to collect an updated profile of CWs implemented as wastewater treatment technologies in hospitality units worldwide, with the ultimate aim of creating a database containing information on the location, treatment design, and performance of these systems for use as a reference tool for future stakeholders.

Keywords: hospitality industry ; constructed wetlands ; nature-based solution

1. Free Water Surface Flow Constructed Wetlands

FWSCWs aim to replicate the naturally occurring processes of a natural wetland, marsh, or swamp, in which wastewater flows above a sealed substrate to prevent seeping into the surroundings. Planted macrophytes are either emergent, submerged, or floating, and treatment occurs through the wetland bed and plant components [1]. Low construction, maintenance, and energy costs are advantages of this type of CW design, although the fact that wastewater is exposed to the atmosphere increases the possibility of mosquito breeding [2].

A lab-scale experiment evaluating the weight variation of *Salvinia molesta* plants on wastewater phytoremediation was set in Malaysia using wastewater samples from a university campus that included a laundry area, toilets, hostels, restaurants, staff quarters, offices, and a hotel. The experimental design consisted of three tanks built with acrylic plastic sheets, with the dimensions of 670 mm × 420 mm × 220 mm (L × W × H), where different weights of *S. molesta* (70 g, 140 g, and 280 g) were planted. A t-shaped structure installed in the middle of the tanks served as a flowing guide, and the inlet was installed above the outlet to maintain the water level. The performance of different weights of *S. molesta* plants in wastewater treatment was observed for 14 days at a 24-h retention time. For inlet concentrations varying from 2.53 to 3.52 mg/L for phosphate (PO_4^{3-}), 10.79 to 11.00 mg/L for ammonia nitrogen (NH_3), and 4.2 to 4.4 mg/L for NO_3^-, removal efficiencies reached 97.7% for turbidity, 99.7% for PO_4^{3-}, 99% for NH_3, and 90.6% for NO_3^- for the *S. molesta* system planted with the highest weight (280 g) [3]. It should be noted that, despite the design simplicity, FWSCWs present some disadvantages, such as higher land requirements, the risk of human exposure, and long-term operational issues, if plant litter is not removed and substrate maintenance is not performed [1][2].

2. Horizontal Subsurface Flow Constructed Wetlands

The configuration most widely reported in the reviewed literature was HSFCWs, representing 56% of the CW typology. As it was implemented worldwide, studies were retrieved from China, Costa Rica, India, Italy, Mexico, Poland, Portugal, and Spain. HSFCW advantages stem from their low energy requirements for operation, low construction and maintenance costs, and little need for specialized labor [1][4][5]. In Portugal, **Figure 1** shows a CW for wastewater treatment. The system consists of a septic tank followed by a HSFCW and a pond installed in a rural tourism hotel [4]. The flow design was 4.1 m^3/d of domestic wastewater for occupation rates ranging from 6 to 40 persons. The CW surface area was 40.5 m^2, and the system was planted with a polyculture of *Canna flaccida*, *Canna indica*, *Zantedeschia aethiopica*, *Watsonia borbonica*, and *Agapanthus africanus* in an expanded clay substrate. The treatment system achieved removal rates of 95.1% for TSS, 93.8% for COD, 94.0% for BOD_5, 72.8% for TP, and 43.5% for NH_3 from an average COD loading rate of 156 kg/ha·d and BOD_5 loading of 66 kg/ha·d. The CW was also shown to be efficient at removing fecal indicator bacteria, with removal rates for total coliforms and *Escherichia coli* of up to 3.0 log10 [4]. In 2017, Calheiros et al. [6] reported a decrease in fecal bacteria indicator counts, with a special focus on *E. coli* since, in general, they were not detected in relation to an inlet of 3.0 ± 0.9 log CFU/mL. Total coliform counts and fecal coliforms also decrease up to 3 log in relation to an inlet of 5.3 ± 0.8 log CFU/mL for total coliforms and 5.3 ± 0.7 log CFU/mL for fecal coliforms.

Figure 1. Horizontal flow constructed wetland installed in a rural tourism unit for wastewater treatment; (**a**,**b**): landscape integration; (**c**,**d**): constructed wetland in two different times of the year.

With the goal of better understanding the route of pathogenic bacteria and indicator organisms in CWs, the system was again analyzed by Calheiros et al. [7]. Pathogenic indicators of *E. coli* achieved reduction rates of up to 2 log at the outlet, Enterobacteriaceae achieved reduction rates of up to 3 log, *Salmonella* spp. was never detected at the outlet, and *Listeria monocytogenes* was detected in only one sampling [7]. Later, in order to address the dynamics of the arbuscular mycorrhizal fungi communities colonizing the roots of *C. indica*, *C. flaccida*, and *W. borbonica*, Calheiros et al. [8] again analyzed the same CW, reporting removal efficiencies of 88% for TSS, 91% for COD, 66% for PO_4^{3-}, and 48% for NH_4^+ for a BOD/COD ratio between 0.3 and 0.8. In general, higher values of COD and BOD_5 were registered in hot seasons, corresponding to the increase in overnight accommodations.

After being in operation for more than 5 years, Calheiros et al.'s [9] system continued to report constant removal rates of up to 87% for COD and BOD_5, up to 99% for TSS, up to 91% for PO_4^{3-}, and up to 97% for NH_4^+ and NO_3^-. These studies documented the long-term operation of a nature-based solution applied in the hospitality industry, showing that CWs have the ability to decrease the toxicity of wastewater from small tourism units and reinforcing the notion that CW can be a sustainable nature-based solution for treating domestic wastewater [9].

Fattoria Baggiolino is a farm holiday site located 25 km from Florence, Italy, which is inhabited by the owners from November through to March and marketed for weekly rentals from early March through to October; this is a type of countryside tourism promoted in remote areas of Italy, which are usually far away from centralized wastewater solutions [2]. The onsite wastewater treatment consisted of one Imhoff tank and two septic tanks, where effluent lines were combined into a single-bed HSFCW. The wastewater production was approximately 30 PE, with a mean organic loading rate of 4.2 g COD/m^2·d, for an accommodation capacity of 24 beds, and after the onsite treatment, the effluent was discharged for sub-irrigation [10]. The surface area of the CW was 108 m^2, and it was designed to produce treated wastewater that complies with the discharged water quality limits outlined by The Regional Environmental Protection Agency of Tuscany and the Scandicci (TSS 90–95%, BOD_5 90–99%, NH_4^+ 40–50%, TP 30–50%, fecal coliforms 98–99.99%). The net construction price of the completed plant in 2002 was EUR 10,864, with operational costs estimated at approximately EUR 230 per year, or EUR 0.19 per m^3 of treated wastewater [11].

Similarly, a HSFCW was chosen as a decentralized wastewater treatment solution for a camping site called "La Cava", also in Italy. The accommodation capacity was 24 beds and 48 tents; eight people permanently live at the site. Wastewater was segregated into two parallel lines: one for graywater and the other for blackwater. Graywater was treated at a flow rate of 9.5 m^3/d, passing first through a degreaser, followed by a one-cell HSFCW with a surface area of 115 m^2 and planted with reeds. Blackwater was treated at a lower average flow rate of 6.5 m^3/d, passing first through a septic tank and then flowing into a one-cell HSFCW planted with reeds, whose surface area was 126 m^2. The segregation of fluxes allowed for safe reuse of the treated graywater, which was pumped back to the buildings for toilet flushing, while treated blackwater was reused for drop irrigation in green areas [11]. For blackwater, COD achieved high average reductions of 89% and an average organic loading rate of 11 g COD m^2/d; TKN achieved an 84% reduction, TP average removal rate was 99%, and NH_4^+ averaged a 55% reduction. As for graywater, for an average organic loading of 36 g COD m^2/d, the average COD removal rates were 40%, while TKN averaged 96%, NH_4^+ averaged 99%, and TP averaged 95% [11].

In China, a full-scale wastewater treatment system was developed at a touristic household farm in Wuhan. The system consisted of four treatment units: a regulation-size pond, iron-carbon micro-electrolysis (ICME) reactors, sedimentation tanks, and a two cell HSFCW with a surface area of 1000 m^2. The ICME reactors were composed of three consecutives units: the first two for micro-electrolysis and the third as a deposit unit in which sludge and activated carbon particles are trapped before being recirculated back to the ICME. Forced aeration to the first two ICME units allowed for the maintenance of the aerobic environment to enhance ammonia oxidation efficiency. As for the HSFCW, the bed media was composed of geotextiles, loess, and gravel; planted with Calamus, cattail (*Typha orientalis*), and reed (*Phragmites*); and embellished by little iris and *Thalia dealbata* [12]. During the sampling period, the average wastewater flow was 150 m^3/d in winter and 400 m^3/d in summer (below the design flow of 600 m^3/d). After choosing the optimal conditions (a Fe-C/water ratio of 1:1, an initial pH of 4, and a Fe-C/water ratio of 1:4) the CW reduced COD, BOD_5, and NH_4^+ in the final effluent to the range of 8.8–28.3 mg/L, 2.7–5.7 mg/L, and 0.4–1.5 mg/L, respectively, which satisfied the environmental quality standards for surface water in China [12].

In Costa Rica, a biogarden system was built to treat wastewater generated at a hotel. The system comprised septic tanks and grease traps for sewage and graywater pre-treatment, followed by seven HSFCWs. The hotel’s maximum capacity was 141 people, with the high tourism seasons occurring from December to February and July to September. Raw water was extracted from a well at an average of 16 m^3/d and used by the hotel guests, employees, restaurant, laundry room, greenhouse, artificial pond, and swimming pool [13]. As observed by Pérez-Salazar et al. [13], the average pollutant loads in all influents were close to or higher than the permitted discharge limits in Costa Rica of 50 mg/L and 150 mg/L for BOD_5 and COD, respectively [14]. Thus, wastewater pre-treatment was not sufficient to meet the national criteria and, given that there were no municipal wastewater treatment solutions in the area, the biogarden system was created. Each CW cell had an average area of 12 m^2 and contained river cobble as a support material, gravel as a bed, and *Cyperus papyrus* and *Heliconia* sp. plants. The average removal rates for BOD_5, COD, and TSS was 80%, 66%, and 72%, respectively, thus producing an effluent in compliance with current national legislation. The study also demonstrated that this system was able to cope with significant load variations between the high and low tourist seasons and/or between the rainy and dry seasons [13].

In Spain, a HSFCW system was set up to treat 11 m^3/d of domestic wastewater generated from a hotel. The system consists of two septic tanks in series, from which the effluent is distributed to two parallel beds (each 187.5 m^2). Bed 1 remained unplanted, while common reed (*P. australis*, [Cav.] Trin. ex Steudel) was planted in bed 2; however, the development of the macrophytes was very poor. Thus, for data interpretation, the author considered both beds as unplanted. The CW influent TSS and BOD_5 averages were 120 mg/L and 410 mg/L, respectively, and average removal rates of 54% for BOD_5 and 36.84% for TSS were achieved. In comparison to the removal rates reported in the literature [1][15], this system presented lower efficiencies. García et al. [16] pointed to four possible explanations: (1) because data were obtained during the first year of operation, it is possible that the biofilm did not develop, leading to the low degradation of OM; (2) in HSFCW reed beds, studies indicate that to achieve BOD_5 reductions lower than 25–30 mg/L, the areal organic loading rate (AOLR) should be under 6 g BOD/m^2 per day, but in the Vilagrassa hotel, the loading was an average of 13.6 g BOD_5/m^2 per day; therefore, the author points to the possibility that this CW was not well dimensioned; (3) the use of large quantities of disinfectants such as NaOCl in the hotel may have interfered with the beds’ microbiological development; (4) flow design constrictions such as flow short-circuiting [2][16][17][18].

In India, an aquatic macrophyte-based system was established for treating wastewater collected from a nearby hostel, hotel, and houses. Wastewater flowed in subsurface mode at 23 mL/min through three parallel shallow raceways filled with gravel, in which two were planted with C. esculenta and one was operated as an unplanted control. Four experiments —I, II, III, and IV—were conducted in which diluted wastewater concentrations varied from 450 to 1650 mg/L for COD, 3.2 to 5.0 mg/L for NO_3^-, and 2.8 to 4.5 mg/L for PO_4^{3-} [19]. The systems were operated with a retention time of 3.6 days during 10 days, after which the systems were emptied and the second run of the experiment was initiated with untreated wastewater, repeating initial conditions for another 10 days while plants remained in the raceways. Systems I and II were conducted with only one wastewater change on day 10, while the wastewater for systems III and IV was changed every fifth day of the experiment. Therefore, within the entire duration of the experiment (20 days), the wastewater was changed four times for systems II and IV, while the wastewater treatment was changed two times for systems I and II [19]. Between the two nutrients tested, the removal of NO_3^- was better than PO_4^{3-} in all raceways, including the controls, with better (albeit not statistically significant) nutrient removals observed for the planted railways than the controls. A significant reduction in COD was achieved in all raceways, with planted ones performing better than the controls: 85.6% vs. 97.8% for experiment I, 82.3% vs. 90.2% for experiment II, 91.7% vs. 93.5% for experiment II, and 91.2% vs. 94.5% for experiment IV.

In Poland, Pawęska and Kuczewski, [20] presented the efficiency of five small wastewater treatment plants (max. 350 inhabitants) designed to treat domestic sewage after preliminary mechanical treatment in a septic tank. Within these five units, two CW beds were built in Paszków and Mroczeń to treat wastewater coming from an adjoining holiday resort and a primary school for later effluent discharge in adjoining streams. Three main parameters—BOD_5, COD, and TSS—were considered as the main indicators for pollutant reduction, as required by the Ordinance of the Minister of Environment for PE < 2000 [21]. The treatment plants were designed as a hydroponic technology system (for the present purpose, it was considered subsurface flow) in concentric circular trenches, with a depth and diameter of 2 m and the addition of light-expanded clay aggregates (LECA) as filling. In the case of the CW installed in Paszków, it was planted with reeds (*Phragmites* L.) and comprises a total capacity of 4 m^3/d, a surface area of 214.1 m^2, and a total of four beds. The average wastewater inflow characteristics were 114.2 mgO_2 d/m^3 for BOD_5, 499.8 mgO d/m^3 for CODCr, 302.5 mg/dm^3 for TSS, 50.1 mgN d/m^3 for TN, and 7.4 mgP d/m^3 for TP. The respective removal rates were 97.7% for BOD_5, 86.09% for CODCr, 66.35% for TSS, 58.88% for TN, and 56.76% for TP. From the five wastewater treatment plants, the best effluent quality was achieved by CWs, although the TSS limits did not always comply with national legislation. Finally, the results obtained in this study showed lower efficiency than those reported in the literature, with the author suggesting that a design or clogging problem hindered the treatment efficiency [20].

Several subsurface CWs were built in Mexico by using the high biodiversity of plants to treat wastewater flowing from houses, condominiums, restaurants, and small hotels. The treated wastewater was discharged to subsurface drains, and the resulting trials showed a 65–70% decrease in COD, a TSS removal of 44.4%, and a BOD_5 removal of 87.9% [22].

Table 1 shows a BOD_5 average removal rate of 88%. COD presented a slightly higher variation, but the average removal rate was 87%, making OM removal consistent with previously reported values for domestic wastewater [1][21][23][24]. When available, the data reported for nutrients varied considerably, with NH_4^+ varying from 48 to 99%, NH_3^+ from 25 to 99%, PO_4^{3-} from 66 to 91%, and TP from 57 to 99%.

Table 1. Average removal rates efficiencies (%) per HSFCW analyzed from the retrieved papers.

CW Scale	BOD_5	COD	TSS	NH_4^+	NH_3	NO_3	TKN	TN	PO_4^{3-}	TP	References
Real	**94%**	**94%**	**95%**	**N/A**	**44%**	**88%**	**N/A**	**N/A**	**73%**	**73%**	[4]
Real	**>80%**	**>80%**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	[6]
Real	**75%**	**75%**	**83%**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	[7]
Real	**91%**	**91%**	**88%**	**48%**	**N/A**	**N/A**	**N/A**	**N/A**	**66%**	**N/A**	[25]
Real	**87%**	**87%**	**99%**	**97%**	**N/A**	**97%**	**N/A**	**N/A**	**91%**	**87%**	[9]
Real	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	[11] ***Baggiolino tourism farm***
Real	**N/A**	**Black—88%; Gray—40%**	**N/A**	**Black—55%; Gray—99%**	**N/A**	**Black—25%; Gray—98%**	**Black—84%; Gray—96%**	**N/A**	**N/A**	**Black—99%; Gray—95%**	[11] ***La Cava***
Real *	**2.7–5.7 mg/L**	**8.8–28.3 mg/L**	**N/A**	**0.4–1.5 mg/L**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	[20]
Real	**80%**	**66%**	**72%**	**N/A**	**N/A**	**N/A**	**85%**	**N/A**	**76%**	**N/A**	[13]

CW Scale	BOD_5	COD	TSS	NH_4^+	NH_3	NO_3	TKN	TN	PO_4^{3-}	TP	References
Experiment	N/A	Experiment I—85.6 vs. 97.8%, Experiment II—82.3 vs. 90.2%, Experiment III—91.7 vs. 93.5%, Experiment IV—91.2 vs. 94.5% (Unplanted vs. Planted)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	[19]
Real	97%	86%	66%	N/A	N/A	N/A	N/A	59%	N/A	57%	[20]
Real	88%	65–70%	44%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	[26]
Real	54%	37%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	[16]

Note: * Removal results for ideal conditions of pH = 4; Fe-C/water ratio of 1:4; N/A: not available.

3. Vertical Subsurface Flow Constructed Wetlands

VSFCWs were initially developed as a middle stage, after the anaerobic septic tank and before HSFCWs. Their main advantage is related to higher oxygen transfer capacities when compared with horizontal flow CWs, which leads to lower treatment areas and associated constructions costs [1].

The Abetina Reale Shelter is a mountain shelter with a restaurant that is open to the public mainly on weekends and in the summer, meaning that the site is characterized by wastewater load fluctuations. Prior to CW implementation, wastewater was directly discharged into a first-class category river, having only an Imhoff tank for pre-treatment. To improve its wastewater treatment, a buffer tank was installed after a new septic tank, which fed two parallel VSFCW cells (63 + 63 m^2). Designed for a 100 PE and an average organic loading rate of g COD/m^2.d, for discharge on a first-class category river, the following theoretical removal percentages must be complied with (according to The Water Authority): TSS 98–99%, COD 90–97%, BOD_5 90–97%, NH_4^+ 75–85%, TN 60–75%, TP 50–60%, fecal coliforms 99.90–99.99% [11].

In general, the overall mean removal efficiencies of the VSFCW beds were between 52 and 99% for TSS, 48 and 99% for BOD_5, 44 and 95% for COD, 34 and 95% for NH_4^+, 20 and 94% for TN, 21 and 97% for TP, and 26 and 92% for PO_4^{3-}, depending on the VSFCW design [1]. Therefore, it is expected that the Abetina Reale Shelter's CW will comply with The Water Authority's requirements for discharge on a first-class category river.

4. Hybrid Flow Constructed Wetlands

HSFCWs have limited oxygen content, which hinders nitrification processes occurring on their beds, while VSFCWs provide sufficient oxygen transfer, increasing nitrification efficiency but leading to poorer denitrification rates. Hence, mixed wastewater treatments using both typologies can explore the advantages of one type to balance the disadvantages of the other, theoretically leading to a balanced treatment [1][24][27][28].

A hybrid system was installed at "Relais Certosa", a hotel in Florence. It comprised a hybrid design for the secondary treatment of hotel wastewater, starting with primary treatment tanks that fed the HSFCW cell. The effluent continued to flow toward a repartition well that fed two separated chambers of a VSFCW [2][11][26]. The HSFCW cell had a surface area of 160 m^2, while the two VSFCW cells, laid out in parallel, had a total surface area of 180 m^2 (90 m^2 each). The systems used a high-density polyethylene (HDPE) geo-membrane for waterproofing, and while the HSFCW used gravel as substrate, the VSFCW used both sand and gravel. Both CWs were planted with reeds and, after filtration through the VSFCW, a portion of the effluent was discharged to the river while the remainder was stored for reuse [2][11][26]. Designed for a 140 PE and an average organic loading rate of 17.5 g COD/m^2.d at the HSFCW and 2 g COD/m^2.d at the VSFCW, the following theoretical removal percentages must be complied with (as required by The Water Authority) for a first-class category river: COD 94%, BOD_5 95%, TSS 90%, TKN 60%, NH_3 85%, and TP 94%.

In Lloret de Mar, Spain, a HSFCW was integrated into a cascading vertical set-up (vertECO) for decentralized graywater treatment in order to decrease potable water consumption by reusing graywater for toilet flushing, leading to a potable water consumption reduction of 80% per guest per night [29]. Specifically, the design used a vertical set-up with four cascading stages combined with a horizontal subsurface water flow. A time-controlled pump intermittently fed 7 L/min of wastewater from an oxygenated water tank to the top floor of the vertical ecosystem. The horizontal subsurface water flowed through the rhizosphere and was forced by gravity into the next floor, maintaining a saturated wastewater level. A light-expanded clay aggregate was used, as well as oxygenation enhanced by pumping air through perforated hoses in the bottom of the containers in order to promote aerobic microorganisms for efficient rhizosphere degradation processes. The installation stage's top layer was planted with a polyculture of *Cyperus alternifolius* L., *Monstera deliciosa*, *Carex acutiformis*, *Ficus pumila* L., *Juncus inflexus* L., *Philodendron scandens*, *Juncus effuses* L., *Philodendron erubescens*, *Equisetum hyemale* L., *Syngonium podophyllum* S., *Spathiphyllum wallisii*, *Iris laevigata*, *Spathiphyllum wallisii* 'sensation', *Mentha aquatica* L., and *Calathea* sp. [30]. The organic load averages were 158 mgO_2/L for COD and 116 mgO_2/L for BOD_5, with reported average removal efficiencies of more than 90% for COD, BOD_5, TSS, and turbidity, while total organic carbon reached more than 80%. The effluents consistently met the standards for various reuse applications, even at different hydraulic retention times [30]. In terms of organic micropollutants, influent graywater was characterized by high concentrations, but more than 95% were reported to be removed by the vertECO system, such as acetaminophen, ibuprofen, salicylic acid, caffeine, estradiol, progesterone, testosterone, triclosan, and methyl-, ethyl-, and propylparaben. In addition, a more than 80% removal rate was achieved for diclofenac, atenolol, and trimethoprim. Hydrochlorothiazide, sulfamethoxazole, and salbutamol were not reduced by more than 30%. Statistically significant differences were found at different hydraulic retention times for acetaminophen, atenolol, ibuprofen, ethylparaben, ris(2-chloroisopropyl) phosphate, and tris(2-butoxyethyl)phosphate [30].

The vertECO system was again analyzed in 2021, achieving removal rates higher than 84.0% for COD and TSS and higher than 95.4% for turbidity and BOD_5. Therefore, the effluent continued to comply with reuse legislation [5]. Microbiological indicators were also analyzed, with fecal enterococci achieving a log removal of 4, *E. coli* achieving a log removal > 4, and total coliforms achieving a log removal of 2.7.

An installation consisting of an experimental multi-stage CW system was set up at a wastewater treatment plant in Mojacar, Spain. This plant used a lagoon system to treat wastewater from the village and tourist resort area, experiencing pronounced fluctuations in hydraulic and organic load throughout the year. The design consisted of 24 tanks laid out in four series by three stages, with each series replicated. Series 1, 2, and 3 were fed with pre-treated water from an anaerobic stabilization pond, and series 4 was fed with the effluent from the lagoon system. Different hydraulic loads were supplied automatically at regular 60-min intervals [31]. All tanks were planted with emergent macrophytes from nearby wetlands, *P. australis* and *T. dominguensis*. In the first tank (stage 1) in series 1, *Phragmites* was grown on a surface flow CW. The first tank (stage 1) in series 2 and 3 was designed with an upflow VSFCW and planted with *P. australis*. The first tank (stage 1) in series 4 was also planted with *P. australis*, but a HSFCW was used due to the higher oxygen concentration of the influent since it was pre-treated wastewater. The second tank in each series, or stage 2, was designed with a horizontal subsurface flow and planted with *T. dominguensis*. Sand was used in series 1 and 4, while fine gravel was used in series 2 and 3. The removal of TSS was 90% for series 1, 96% for series 2 and 3, and 95% for series 4; the COD removal rates were 87% for series 1 and 2, 78% for series 3, and 70% for series 4; the BOD_5 removal rates were 90% for series 1, 2, and 4 and 88% for series 3. Regarding the TP removal rates, it were 66% for series 1, 55% for series 2, 48% for series 3, and 60% for series 4. TN removal rates were 38% for series 1, 41% for series 2, 23% for series 3, and 78% for series 4 [32]. The third tank (stage 3) in each series was designed with a vertical subsurface flow and planted with *P. australis*. To ensure homogeneous water distribution over the substrate surface, two parallel channels (2 cm wide and 140 cm long) were used approximately 20 cm over the substrate. This design improves water oxygenation. The substrate consisted of coarse gravel and stones combined with a layer of iron filings in series 1. The net treatment area (stages 1, 2, and 3) per PE in terms of hydraulic loading rate was 2.3 m^2 for series 1 and 2, 1.2 m^2 for series 3, and 1.6 m^2 for series 4. The use of sand improved TSS retention; however, because of the risk of clogging, the advantages of the use of sand must be pondered. The addition of iron to the substrate improved phosphorus retention from 55% to 66%. Although the performance of this treatment for organics removal is high, the subsurface flow system does not offer conditions for nitrification. Therefore, if nitrogen has to be removed in the next treatment stage, water oxygenation has to be ensured [31].

Koh Phi island located in Thailand experiences land and energy scarcity, with more than 1 million tourists visiting every year. After the 2004 tsunami, the Danish Government gave a relief grant to Thailand to help re-establish the nation's wastewater management services [21]. The island stakeholders designed a wastewater treatment installation that uses a recovery-based, closed-loop system wherein wastewater is collected, treated, and reused in an integrated system. The system was dimensioned to treat up to 400 m^3/d of mixed blackwater and graywater, where odor control, aesthetics, and social involvement was equally important to the treatment performance; in fact, the creative process garnered a design concept based on a butterfly and a flower, which comprised the application of CW with different operational flows. The wastewater was pumped to siphons which distribute the wastewater in intervals to three VSFCWs, or the first petal of the flower, which has an area of 2300 m^2, being filled with gravel, and planted with *Canna* and *Heliconia*. The flow later goes to three HSFCW cells, the second petal of the flower, which has an area of 750 m^2 and was also filled with gravel and planted with *Canna*. From there, it flows to three surface flow CWs, the wings of the butterfly (which have an area of 750 m^2 and are planted with Papyrus). It then finally arrives to the polishing ponds, or the butterfly's body, which has an area of 200 m^2 [21]. Treated effluent is stored in an underground reservoir for irrigation. The average removal rates were 90.00% for TSS, 91.58% for BOD_5, 38.89% for TKN, 50.00% for NO_3^-, 46.43% for TP, 90.09% for oil and grease, and 92.31% for fecal coliforms. The effluent from the system mostly met the Thai effluent standards for pH, TSS, and TKN, but the effluent BOD_5 concentrations were slightly higher (average 25 mg/L) than the 20 mg/L effluent standard. Also, the outlet concentrations of oil and grease were higher than the 5 mg/L requirement [21]. The installation experienced problems with high concentrations of oil and grease in the effluent, probably due to high influent concentrations as a consequence of illegal connections to the wastewater collection systems and the lack of oil and grease traps at individual residential houses, restaurants, hotels, and other businesses. The lack of grease traps resulted in high levels of oil and grease in the collection system and in the treatment plant, which increased the clogging of the gravel beds [21].

In the Italian region of Castelluccio, the installed wastewater treatment plant was inadequate to support the tourism load, which shifts from less than 50 people during winter up to 1000 or more people during summer. Therefore, a multi-stage CW system consisting of a French scheme, or VSFCW reed bed filters, was installed with an area of 1800 m^2, followed by two parallel free water-pond systems as a polishing stage and a recreational pond holding several rare aquatic plants typical of the Castelluccio plateau. This hybrid configuration permits a considerable reduction in the total surface needed for the treatment and, consequently, a reduction in water loss by evapotranspiration. The removal efficiencies were >90% for TSS, COD, and BOD_5 [22].

Different design typologies were analyzed in the hybrid section. The first used a horizontal flow stage to remove organic matter (OM) and TSS and provide denitrification, followed by a vertical flow stage to enhance OM and suspended solids (SS) removal and increase nitrification [2][11][22]. The Verteco design was developed for the treatment of graywater by using a vertical structure with four cascading stages combined with horizontal water flow and aeration in the root zone in order to enhance nitrification. As for [31] study, different designs were tested, but in general, Stage 1 focused on sedimentation and secondary wastewater treatment with an oxygenated effluent for nitrification. Stage 2 used saturated conditions to enhance denitrification, and stage 3 enhanced the oxygenation of the medium. In this last stage, series 1 contained a thin iron layer to increase phosphorus fixation. The last two hybrid systems used a VSFCW stage first in order to remove OM and TSS and enhance nitrification. The second stage was a HSFCW for denitrification [21] or another VSFCW stage to enhance nitrification [22].

Table 2 presents the reported removal efficiencies (%) for BOD_5, COD, TSS, NH_4^+, NH_3, NO_3^-, TKN, TN, and TP observed in the hybrid CWs. For COD, BOD_5, and TSS, the median removal efficiencies were equal to or above 90%, while the NH_4^+ and NH_3 medians were 78% and 85%, the TN median was 45%, and the TP median was 57%.

Table 2. Average removal rate efficiencies (%) per hybrid subsurface flow constructed wetlands (CWs) analyzed.

CW Scale	BOD_5 (%)	COD (%)	TSS (%)	NH_4^+ (%)	NH_3 (%)	NO_3-N (%)	TKN (%)	TN (%)	TP (%)	References
Real	**95%**	**94%**	**90%**	**N/A**	**85%**	**N/A**	**60%**	**N/A**	**94%**	[11][22][26]
Real	**96%**	**94%**	**91%**	**56%**	**N/A**	**N/A**	**73%**	**43%**	**N/A**	[30]
Pilot	**98%**	**84%**	**86%**	**99%**	**N/A**	**N/A**	**N/A**	**65%**	**N/A**	[5]
Real	**90%**	**81%**	**94%**	**N/A**	**N/A**	**N/A**	**N/A**	**45%**	**57%**	[31]
Real	**92%**	**N/A**	**90%**	**N/A**	**N/A**	**50%**	**39%**	**N/A**	**46%**	[21]
Real	**N/A**	**98%**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	[22]

It is worth noting that the application of CWs for the removal of micropollutants from hotel graywater was also addressed by Zraunig et al. [30]. As expected, there was a high level of influent concentration variability, but the vertECO system was able to remove many Pharmaceutically Active Compounds (PhACs) and endocrine disruptors (EDCs), although others showed more persistence. Therefore, CWs may be a solution for minimizing micropollutant discharge through wastewater, although further research is needed to provide a better understanding of the removal mechanisms of these compounds.

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