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Innovative Multistage Constructed Wetland for Municipal Wastewater Treatment and Reuse for Agriculture in Senegal

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Abstract: This paper reports on the performance of using a multistage constructed wetland (CW) to treat municipal raw wastewater and an analysis of its suitability for agricultural irrigation. The pilot plant consists of two stages of vertical flow CWs plus one stage of a horizontal CW built in 2018 with different local materials at the Gaston Berger University Campus, Saint Louis (Senegal). Each CW stage is composed of several filters with different type of media (silex, granite, or river gravel), filtering media depths, and macrophytes (*Phragmites* and *Typha*). The physicochemical and microbiological indicators were monitored over six months at each bed inlet and outlet to evaluate the efficiency and achievements of the Senegalese, European, and WHO regulations/recommendations for disposal or reuse in irrigation. This study demonstrates the viability of this new multistage CW design to treat raw municipal wastewater and produce an effluent of good quality suitable for reuse in agriculture. The removal of organic matter, suspended solids, and nutrients was very high (>95% for SS, BOD_5 and $N-NH_4^+$, >90% for COD and $P-PO_4^{3-}$), as was the reduction of microbiological indicators (fecal coliform reduction >5 log units and helminth egg removal of 100%). First, trends related to the influence of design (the type of gravel, filter depth, and type of macrophyte), operational modes, and the CW treatment efficiency were determined. The use of non-crushed gravel and *Typha* spp. seemed to provide better removal rates. On the contrary, no differences were found between the use of silex or granite gravel. For the studied Senegalese conditions under dry and hot climates, the preliminary results indicate that no resting periods are necessary for vertical flow CWs (VFCWs), thus resulting in a reduction in construction and operation costs. The main outcome of our study is evidence that multistage CWs can provide robust, cost-effective treatments, as well as allow for safe water reuse, which is imperative in areas with severe water scarcity and endemic microbiological waterborne diseases.

Keywords: constructed wetlands; wastewater reuse; agriculture; sanitation; arid regions

1. Introduction

According to the United Nations' 2017 World Water Development Report [1], close to 80% of the wastewater generated by anthropogenic activities returns to nature without being treated or reused. This is not only a problem for the environment but also a major health threat. Increasing urbanization and the changing climate are posing new challenges to municipal water management that require urgent attention worldwide, and the rural and peri-urban areas located on the growth margins of cities are most likely to bear the costs. The integration of decentralized approaches into existing centralized infrastructure is thus essential for achieving sustainable, efficient, and affordable water resource management that is accessible to all. Such approaches are also often better suited to enable the recovery and reuse of valuable water and material resources to meet growing population needs, limit the environmental impacts of growth, and transform cities and towns into agents of sustainable change. The lack of adequate wastewater treatment facilities in Africa poses major threats to both human health and ecosystems. Senegal has one of the most developed water supply sectors in sub-Saharan Africa but still faces important challenges for sanitation, with particular concerns in rural and peri-urban areas [2].

Over the past years, numerous technologies have been developed to treat wastewater but they are often very expensive and too high-tech for small flows, particularly in sub-Saharan areas like Senegal. In this context, the research and implementation of affordable and sustainable wastewater management solutions are needed. On the other hand, in the Sahelian region area, there is structural water scarcity accentuated by climate change; thus, the need for non-conventional water resources for irrigation is crucial for food production, since water availability enhances agricultural performance and food security [3]. Although some pilot projects on treated wastewater reuse have been implemented, this type of reuse is still not common practice in Senegal, since the majority of the population does not have a sanitation system able to produce good quality water [4]. From this perspective, constructed wetlands (CWs) could provide an effective solution to fulfill the legal requirements for low operation and maintenance costs. Although CWs have been used around the world for decades, only pilot tests with dewatering reed beds and surface CWs have been implemented in Senegal [5,6]. Specific challenges and issues were identified prior to the design of the new CW: the technology had to (a) generate good quality treated wastewater suitable for irrigation purposes to solve water scarcity problems, (b) reduce sludge production and the associated management costs, (c) use local materials (gravels, sand, and plants), and (d) adapt to Sahelian conditions (high temperatures, low humidity, sandstorms, specific wastewater characteristics, etc.). To reduce sludge production and disposal, the pilot plant was designed to treat raw wastewater based on the French Reed Bed (FRB) concept. FRBs are a particular CW solution that receives raw wastewater, leading to a high suspended solids, organic matter, and nutrient load. The typical scheme includes a first stage for raw wastewater subdivided into three beds; each bed is periodically fed for 2–4 days, with a resting period of 4–8 days. In this way, proper drying and aerobic oxidation of the sludge layer formed on the top is guaranteed. The second stage usually features a vertical flow CW (VFCW) of two beds fed for 3.5 days, followed by rest for 3.5 days. This technology has been known in France for the past 20 years but remains innovative in many countries outside the French territory. FRB's advantage is that it does not need any primary treatment (no septic tank, only grit removal), further reducing the operation and maintenance cost of nature-based solutions for wastewater treatment (no yearly sludge removal), as long as the rest periods and intermittent feeding are applied to prevent clogging [7,8]. Moreover, the removal efficiency is high, with a relatively low area footprint for nature-based systems. The sludge accumulated in the first stage is mineralized and removed every 10–15 years when it becomes stabilized and suitable for reuse in agriculture as a soil amendment [9]. Despite the high percentage removal of organic matter and nutrients, the standard FRB configurations do not achieve a significant removal of microbial indicators [10,11], thus resulting in a problem in their implementation when reusing wastewater for certain applications that require low pathogen content (e.g., non-restricted irrigation). To address this gap and increase the reduction of bacterial pathogens without adding "conventional" or "advanced" technologies (such as chlorination

and membranes), several design strategies may be adopted, including using a higher medium height for the vertical beds, applying specific granulometries, and adding a horizontal CW (HFCW) with high hydraulic retention times (HRT) as the third stage. Finally, new operational modes were also implemented to adapt the CWs to the specific climatic conditions. Therefore, the new CW offers innovation in all these dimensions. This paper reports on the first 6 months of performance for this multistage CW, as well as an analysis of its suitability for agricultural irrigation reuse.

2. Materials and Methods

2.1. Study Site Presentation

The study was carried out at the full-scale pilot plant constructed inside the University Gaston Berger (UGB) Campus, Saint Louis, Senegal, with an estimated population of around 11,000 students in 2018. The UGB has two social campuses that include 15 student villages and a unitary collective sewerage system. This network collects water from the educational campus, social campuses, university houses, and restaurants and discharges it into the field nearby without any treatment.

The climate of Saint Louis is Sahelian, characterized by hot and dry continental winds and an average annual temperature of 24.5 °C. Temperatures range from 18 °C in January to 40 °C in May. Saint Louis has an average of 250 sun-hours per month, representing an average of 8.5 h per day of sun. The climate is very dry (the average amount of annual precipitation is 265.0 mm) and is characterized by two seasons: the rainy season (hot and humid) that starts in late June and ends in October with large rainfall (up to 100 mm in August) and the dry season lasting from November to May with harmattan winds descending from the desert, causing hot and dusty days with almost zero rainfall [12].

2.2. Pilot Plant Description

The pilot plant was designed by the University of Barcelona, UGB, and the SEDAQUA company (A Coruña, Spain). The construction was carried out by the SALL construction company (Dakar, Senegal) with the collaboration of UGB workers and supervised by GM Construcciones (Lalín, Pontevedra, Spain). The pilot plant receives raw wastewater collected from the UGB's principal sewage pipe with a designed flow of 5 m^3/day corresponding to around 50 PE. This pilot is a hybrid system consisting of a two-stage vertical flow FRB plus a third stage with HFCWs (Figure 1).
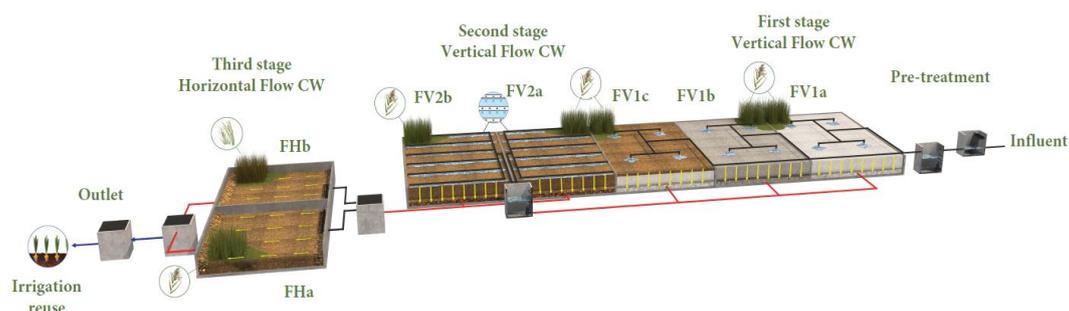

Figure 1. Multistage constructed wetland (CW) layout (prototype, University Gaston Berger (UGB) campus).

The raw wastewater is diverted to a settler tank with bar racks. The pretreated wastewater is then directed to the first storage tank and pumped into the first VFCW stage (3 beds). From the first VFCW stage (total: 72 m^2; each bed is 24 m^2), the outlet water flows to the second storage tank and is then pumped to the second VFCW stage (total: 48 m^2; each bed is 24 m^2). The treated water then flows via gravity towards the third HFCW stage (total: 72 m^2; each bed is 36 m^2). Finally, the treated water from the HFCWs is diverted into a reservoir tank for further water reuse. The first VFCW filters have 3 layers: a filtering layer (70–85 cm high) of different materials, a transition layer (10 cm) of 8–16 mm gravel, and a drainage layer (25 cm) of 25–40 mm gravel. The second VFCWs filters have 3 layers: a filtering layer (70–90 cm high) of washed river sand, a transition layer (10 cm) of 5–15 mm gravel,

and a drainage layer (25 cm) of 25–40 mm gravel. Finally, the third stage of HFCW filters provides a filtration zone with 5–15 mm gravel and a zone for the distribution and drainage area with 40–80 mm gravel. The main design parameters of the hybrid pilot plant are shown in Table 1.

Table 1. Main design characteristics of the filters.

Stage	Filter	Filtering Layer			Plant
		Height (cm)	Material	Granulometry	
1st VFCW	FV1a	70	Silex	3–8 mm	*Phragmites*
	FV1b	70	Granite	3–8 mm	*Phragmites*
	FV1c	15	River gravel	3–8 mm	*Phragmites*
		70	Silex	3–8 mm	
2nd VFCW	FV2a	90	River sand	d10 = 0.27 CU = 3.6	*Phragmites*
	FV2b	70	River sand	d10 = 0.27 CU = 3.6	*Phragmites*
3rd HFCW	FHa	60	Silex	5–15 mm	*Phragmites*
	FHb	60	Silex	5–15 mm	*Typha*

d10: Mesh diameter allowing 10% of the sand mass to pass through (mm); CU: Coefficient of uniformity, ratio d60/d10.

2.3. Experimental Protocol

2.3.1. Operation

The pilot plant was constructed in 2018 and put into operation in December 2019. A summary of the operational parameters is shown in Table 2. The pilot plant received an average flow of 4.5 m^3/day. The VFCWs were operated intermittently by flooding alternated with drainage, and the HFCWs operated via gravity. The daily number of dosing–drainage cycles was 10 for both VFCW stages (10 batches/day, 2 min per batch). For the same flow, two dosing regimens were applied while varying the feeding schedule to study the effects of the resting periods on filter performance. Thus, two operating periods were established: the first one with no resting periods (all filters were fed at the same time) and a second period with a standard FRB feeding–resting period strategy (V1 filters were alternately fed for 3–4 days followed by a rest period of 7 days; V2 filters were alternately fed for 3–4 days followed by a rest period of 7 days).

Table 2. Vertical flow CW (VFCW) operational modes.

	Duration (Months)	VFCW Stage 1			VFCW Stage 2		
		Feed/Rest (days)	HL (cm/day) [1]	Batches Per Day	Feed/Rest (days)	HL (cm/day) [1]	Batches Per Day
Period 1	3	No rest	6	10	No rest	9	10
Period 2	3	3.5/7	18	10	3.5/7	18	10

[1] Filters in operation.

2.3.2. Wastewater Quality Monitoring

A six-month monitoring program (12 series) consisting of grab sample analyses was performed from February to July 2019. Samples were taken in each step of the pilot, including the influent and the effluent of each filter (9 sampling points), and then preserved and stored following the Standard Methods [13]. The pH, Electrical Conductivity (EC) and Temperature (T) were monitored in situ with portable sensors. The Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD_5), Suspended Solids (SS), Total Nitrogen (TN), Ammonia ($N-NH_4^+$), Nitrates ($N-NO_3^-$), Phosphates

(P-PO$_4$$^{3-}$), and Total Phosphorous (TP) were analyzed according to the standard French methods [14] in the Laboratory of Wastewater Treatment and Water Pollution (University Cheikh Anta Diop, Dakar, Senegal). Fecal Coliforms (FC) were enumerated according to the 24-h standardized violet red bile lactose agar (VRBL) method, and the results were expressed as the log$_{10}$ colony-forming units (CFU) per unit of volume. Helminth eggs were quantified according to the standard methods [13].

2.3.3. Data Analysis

Statistical analyses were performed on the raw data using the statistical computer packages Excel 2016 and IBM-SPSS Statistics for Windows. Excel 2016 was used for the descriptive statistics (averages, maximum, minimum, and SD). SPSS 24 was used for an analysis of variance (ANOVA). The analysis of variance was performed to assess the influence of different design and operational variables on the removal of pollutants. Statistical significance was established at $p \leq 0.05$.

3. Results and Discussion

3.1. Multistage CW Performance: Water Quality and the Removal of Physico-Chemical Pollutants

Tables 3 and 4 present the results of the 6-month monitoring of the multistage CW for physico-chemical parameters. The average water quality in the inlets and outlets is displayed in Table 3 and the average percentage removals of each step and total removal (pilot inlet-outlet) are shown in Table 4.

Table 3. Multistage CW average water quality and standard deviation.

Parameters	Pilot Plant Influent	Pre-Treatment Effluent	Vertical Flow CW Outlet First Stage			Vertical Flow CW Outlet Second Stage		Horizontal Flow CW Outlet Third Stage	
			FV1a	FV1b	FV1c	FV2a	FV2b	FHa	FHb
T (°C)	26.3 ± 1.5	27.1 ± 0.8	27.8 ± 0.9	27.2 ± 1.1	27.1 ± 1.4	26.1 ± 0.6	26.2 ± 0.5	24.8 ± 1.0	24.7 ± 1.4
EC (mS/cm)	1331 ± 170	1420 ± 129	1179 ± 91	1314 ± 132	1191 ± 94	888.0 ± 301	1061 ± 122	1056 ± 115	1049 ± 142
pH	7.7 ± 0.2	7.5 ± 0.1	7.8 ± 0.2	8.3 ± 0.1	8.1 ± 0.1	5.7 ± 0.4	5.8 ± 0.4	8.0 ± 0.2	8.0 ± 0.2
SS (mg/L)	718.9 ± 291	388.8 ± 59	59.7 ± 31	64.0 ± 14	49.5 ± 11	11.9 ± 4.2	13.7 ± 4.3	9.6 ± 6.4	5.7 ± 2.3
BOD$_5$ (mg/L)	655.6 ± 106	495.5 ± 85	107.9 ± 68	113.4 ± 57	81.0 ± 32	2.4 ± 1.6	2.3 ± 1.7	3.8 ± 2.7	2.3 ± 1.1
COD (mg/L)	1240 ± 589	1063 ± 293	239.2 ± 58	268.7 ± 83	188.5 ± 31	94.0 ± 36	82.2 ± 39	79.8 ± 39	71.3 ± 33
N-TN (mg/L)	188 ± 82	138.2 ± 29	68.2 ± 17	73.0 ± 19	79.8 ± 8	38.6 ± 21	37.3 ± 17	24.4 ± 6.5	23.0 ± 9.0
N-NH$_4$$^+$ (mg/L)	130.9 ± 68	99.8 ± 21	41.9 ± 11	42.8 ± 13	42.5 ± 14	4.8 ± 2.4	3.5 ± 2.1	4.1 ± 2.4	3.4 ± 2.9
N-NO$_3$$^-$ (mg/L)	4.3 ± 2.5	2.7 ± 1.3	21.4 ± 9.7	18.6 ± 8.6	21.3 ± 11	31.4 ± 12	29.8 ± 11	11.1 ± 3.1	12.5 ± 4.7
P-PO$_4$$^{3-}$ (mg/L)	70.9 ± 43	68.7 ± 39	48.1 ± 25	53.5 ± 21	44.2 ± 23	13.0 ± 5.2	14.6 ± 4.8	5.5 ± 4.1	2.1 ± 1.2

Table 4. Multistage CW performance: percentage removal of pollutants ($n = 12$).

Parameters	Pre-Treatment	Vertical Flow CW First Stage			Vertical Flow CW Second Stage		Horizontal Flow CW Third Stage		Total % Reduction
		FV1a	FV1b	FV1c	FV2a	FV2b	FHa	FHb	
EC	−6.7	16.9	7.5	16.1	19.7	13.6	−3.2	−2.5	**−18.7**
SS	45.9	84.7	83.5	87.3	79.5	76.3	25.1	55.6	**98.3**
BOD$_5$	24.4	78.2	77.1	83.6	97.6	97.7	2.4	3.8	**99.5**
COD	14.2	77.5	74.7	82.3	59.5	64.6	9.4	19.0	**90.7**
TN	26.5	50.6	47.2	42.2	47.6	49.4	35.8	39.4	**80.9**
N-NH$_4$$^+$	23.8	58.0	57.1	57.4	88.7	91.7	1.2	18.1	**95.6**
N-NO$_3$$^-$	37.2	−692	−588	−690	−53.6	−45.8	63.6	59.2	**−304.2**
P-PO$_4$$^{3-}$	3.1	30.1	22.2	35.7	73.3	69.9	60.1	84.5	**90.7**

Influent wastewater presented a typical composition of raw municipal wastewater with minor contributions of industrial wastewater but a high concentration of pollutants compared with the standard values for urban wastewater [15]. These high concentrations can be explained by the low values of water use in Senegal, estimated at between 40 and 80 L/person [16], compared with the higher values in Europe (about 150 L/person) [17]. The high concentrations of nutrients (>100 mg/L for nitrogen and almost 80 mg/L for phosphorous) and high EC are also notable. These results are in

accordance with some other studies of wastewater quality in Senegal [18]. The high concentration of nutrients is explainable partially by the low water consumption per capita but could also be due to the large-scale use of non-biodegradable detergents and body-washing products.

The pretreatment of the multistage CW was designed to remove sand and large particles. One of the challenges was to handle the high quantity of sand in the sewage and sandstorms in the area. Pretreatment effectively removed a large quantity of SS (mainly inorganic particles). The average SS content in the inlet was 718 mg/L with high variations (SD = 306); that in the pretreatment outlet was 388.8 mg/L. The average ratio of SS/VS in the inlet was 55%, while after the pretreatment, the ratio was 78%, thus confirming the settlement of sand and other inorganic solids.

The first stage of VFCWs received an average of 72 g of SS/m^2·day. During operational Period 1 (all filters in operation), each filter received 24 g of SS/m^2·day; in Period 2 (with resting–feeding periods), each filter in operation received 72 g of SS/m^2·day. This value is slightly lower than the values than can support FRBs (up to 150 g of SS/m^2·day for a filter in operation), since part of the SS settled in the pretreatment step. The average organic loads (for COD and BOD_5) were 66 g of COD/m^2·day and 30 g BOD/m^2·day in Period 1 and 199 g COD/m^2·day and 92 of BOD/m^2·day in Period 2. The first stage of the standard FRBs allowed for organic loading rates values up to 180 g BOD_5/m^2.day and 300 g COD/m^2·day [19]. The BOD_5/COD ratio presented average values of 0.45, which indicates intermediate biodegradability [15]. The VFCWs of the first stage presented very good removal percentages for all the physico-chemical parameters. The SS concentration in the filter outlet was much lower (with average removal efficiencies of 84–87%), confirming the excellent filtering capacity of the VFCWs, even though the study was performed at the beginning of the filter's operational life and thus did not feature complete phragmite development or a significant sludge layer forming on the tops of the beds. Therefore, over time, this percentage would likely increase, since the retention of SS on the filter surface improves filtration [20]. Organic matter removal was also very high: 77–83% for BOD_5 and 74–82% for COD. The oxidation of organic matter was very notable, despite the high organic loads, indicating that the hydraulic and organic loading rates could be increased in the first stage, thereby reducing the area footprint needed per PE and reducing the costs. The first-stage vertical filters also nitrified the wastewater (N-NH_4^+ removal of about 57%) producing nitrates, thus confirming the oxidation capacity of the filters due to batch feeding, even in Period 1 with no resting periods. Phosphorus removal ranged from 22 to 35%. Significant percentage differences in removal were observed, depending on the filter material (see Section 3.3).

The second stage involved two beds of sand VFCWs and significantly removed the remaining SS and organic matter and also nitrified the influent, thus generating high-quality effluents and indicating the excellent functionality of the filters. These results (percentage removals of >75% for SS, >97% for BOD_5, >59% for COD, and >88% for N-NH_4^+) are slightly higher than those from other experiences with FRBs under similar hydraulic and organic loads [21]. These results could be explained by the high and constant temperatures in the region. These temperatures would increase the degradation rate kinetics for the removal of organic compounds and nitrification, since the microbiological activity of the attached biomass inside the filters would be enhanced. These results also confirm the excellent performance of the sand filters and sand VFCWs when the filters are designed and operated with proper granulometry and material depths and an adequate hydraulic regime (hydraulic load, feeding cycles, and water distribution on the beds) [21,22]. The high removal of phosphorus on both sand VFCWs is also notable. The retention of phosphorus is comparable with that from systems with a fixed biomass on fine media in the absence of specific materials for phosphorus removal in the first year of functioning [19,22]. Phosphorus was then reduced, averaging 70% removal. Phosphorus removal in VFCWs was mainly due to adsorption and plant uptake [19,23] and is closely related to the physical, chemical, and hydrological properties of the filtering material (which is physically or chemically adsorbed, mainly by ligand exchange). However, a decrease in the concentration of soluble inorganic phosphorus is linked to biological activity, either by macrophyte assimilation or via removal through microbiological processes. In both processes—adsorption and biological phosphorus uptake—the

accumulation capacity is finite. As the CW reaches a stable state, elimination decreases dramatically. Thus, it is expected that this high percentage of removal will decrease in the next few years.

The HFCW stage (one bed planted with *Typha* and one bed planted with *Phragmites*) acts as a polishing stage to reduce the remaining pollution to very low levels for some parameters such as SS or phosphates, providing a percentage reduction between 25–55% and 60–84%, respectively. The HFCWs also partially denitrified the nitrates entering the filters (59–63%) due to the anaerobic/anoxic conditions of the HFCWs. These denitrification processes are possible in the HFCW thanks to the presence of sufficient organic matter (carbon source from the COD) in the influent. However, the pH was not ideal for denitrification; the optimal value is between 7.0 and 8.5 [24], and the average pH in the HFCW inlet was 5.7. Therefore, these unfavorable pH conditions could explain why a higher denitrification percentage was not achieved in the HFCWs. Regarding organic matter, HFCWs did not have as great an influence on the elimination of BOD_5 since the BOD_5 concentration in the inlet was almost below the detection limit. The removal of COD was also very low (9–19%), despite the large retention times of the HFCWs. Almost all the BOD_5 was already degraded in the vertical stages, so the COD treated for HFCWs was more refractory to further bacterial transformation processes occurring in the HFCWs. This COD that was more difficult to degrade could have originated in the campus laboratories or from other campus activities (e.g., mechanical ateliers). Again, significant differences were found between the two HFCWs depending on the plant species (see Section 3.3).

The overall removal of the multistage CW was very high (>95% for SS, BOD_5, and $N\text{-}NH_4^+$; >90% for COD and $P\text{-}PO_4^{3-}$). The EC slightly increased (−18.7%), mainly in the HFCWs, as explained by the evapotranspiration due to the high hydraulic retention times of the horizontal beds. Nitrates increased from 4.3 mg/L in the inlet to 12.5 mg/L at the outlet, thus providing a variation of −304.2%. Almost all the organic nitrogen and ammonia has been nitrified in the VFCWs (first and second stages), providing $N\text{-}NO_3^-$ concentrations of 31 mg/L and 28 mg/L in the VFCWs' second-stage effluents. Although HFCWs efficiently removed nitrogen by denitrification or nitrate plant uptake ($N\text{-}NO_3^-$ removals of 63% and 59%), the horizontal filters were not able to completely denitrify the influent, probably due to the lack of available carbon for the denitrifying bacteria.

3.2. Multistage CW Performance: Enumeration and Removal of Microbiological Indicators

Municipal wastewater in Senegal contains a variety of pathogens, including high concentrations of bacteria and viral helminth eggs, reflecting the carrier state and infection levels in the community. This poses a public health concern with wastewater reuse, especially in endemic regions with a high prevalence of waterborne diseases. The removal of microbiological indicators is thus critical if water reuse is planned. Regarding bacterial indicators (Table 5), the average fecal coliform quantities in the VFCW's first-stage inlet and outlet were 6.7 log CFU/100 mL and 6.5 log CFU/100 mL, respectively, with a removal average of 0.2 Ulog removal. Higher reductions were found in other studies with similar VFCWs at a 65 cm depth. Hydraulic retention time is a key factor in the removal of bacterial indicators, where the higher the retention time, the greater the removal [11]. The water flowed very quickly in the first stage of the VFCWs [12] due to the material (gravel) and the almost negligible surface sludge layer on the tops of the beds. This surface sludge layer can increase the filtration capacity and bacterial indicator removal [20] and was not developed in the pilot during the first year of operation. The average fecal coliform inlet concentration for the second stage of the VFCWs was 6.5 log CFU/100 mL and 3.7 log CFU/100 mL in the outlet, with an average removal of 2.9 Ulog. These values are higher than the usual VFCW removal rates [10,11] but are in accordance with the results of the infiltration–percolation filters at about 1 m depth [25]. The depths, feeding modes, and sand granulometry levels of the second stage VFCWs were based on these infiltration–percolation systems; hence, these design parameters seem to be optimum for the removal of fecal coliforms in VFCWs. The HFCWs removed an average of 1.7 Ulog FC, which is within the usual range of HFCW removal (between 1 and 2 Ulog) [26–28]. A combination of the two stages of VFCWs plus one stage of HFCWs reached 5.6 Ulog in total, providing an outlet quality of about 2×10^2 CFU/100 mL for bacterial

indicators. The raw wastewater presented a high number of nematode eggs (13) (mainly *Ascaris* spp.) that were almost 100% removed in the first stage of CW. The effective removal of *Ascaris* spp. eggs was due to filtration/sedimentation [29].

Table 5. Microbiological indicator (fecal coliforms and nematode eggs) concentration and removal.

Indicator			Inlet	Pre-Treatment	Vertical Flow CW First Stage			Vertical Flow CW Second Stage		Horizontal Flow CW Third Stage		Total
					FV1a	FV1b	FV1c	FV2a	FV2b	FHa	FHb	
FC	Conc [1]. (Ulog/ 100 mL)	Av	7.5	6.7	6.6	6.4	6.4	3.8	3.7	1.8	2.0	
		Max	8.1	7.1	7.1	6.7	6.7	4.5	3.8	2.8	2.1	
		Min	7.2	6.4	6.4	6.0	6.0	3.5	3.5	0.1	2.0	
	Removal	Ulog		0.8	0.1	0.1	0.3	2.9	3.0	1.8	1.7	5.6
N. Eggs	eggs/L	Av	13 [2]	5 [3]	0.7 [3]	0	0	0	0	0	0	
	Removal	%		61	86	100	100	100	100	-	-	100

FC: fecal coliforms; N. eggs: nematode eggs; [1] Concentration; [2] *Ascaris* spp., *Trichuris* spp.; [3] *Ascaris* spp.

3.3. Effect of Operation and Design Parameters

Table 6 presents the effects of the design and operational variables ($p \geq 0.05$) for the removal of specific parameters. The significant differences are represented in gray cells and marked with "S" (significant effect).

Table 6. Effect of the design and operational variables on parameter removal (S = significant effect).

Variable ＼ Parameters	SS	BOD$_5$	COD	N-NH$_4^+$	P-PO$_4^{3-}$	Fecal Coliforms
Filtering Material (FV1a, FV1b, FV1c) (silex, granite, silex + river gravel)	S	S	S	-	S	S
Filtering Media Depth (FV2a, FV2b) (70 cm, 90 cm sand)	-	-	-	-	-	-
Plant Species (FHa, FHb) (*Phragmites, Typha*)	S	S	S	S	S	-
Operational Modes in Vertical Filters (no resting/sequential feeding)	-	-	S	S	-	S

Regarding the gravel material in the first stage of the VFCWs, significant differences were found for FV1c (silex gravel + 15 cm of 3–8 mm river gravel). This filter presented better removal rates for almost all parameters. However, no significant differences were found between FV1a silex and FV1b granite. These results are in accordance with other studies [20] that demonstrated worse performance in VFCWs with crushed gravels or sands. Nevertheless, specific studies may have to be done to interpret these results in detail. For the second stage of the VFCWs, the depth of the sand filters did not present significant differences in any parameters. Both filters offered similarly high removal rates, likely due to the small differences in sand height (20 cm), which was not sufficient to result in any significant effect. The HFCWs planted with *Typha* (FHb) presented better performance than the filters planted with *Phragmites* for all the physico-chemical parameters. Although the literature is not clear on which plant offers better performance in HFCWs [30,31], our results show clear differences that can be attributed to the much higher and more rapid development of *Typha*. Moreover, *Typha* colonized the entire bed in nearly 1 month, while the growth and spread on the bed of *Phragmites* were much less.

Finally, significant differences were found in the two operational modes applied. Better results were apparent when no resting period was used. This is likely because although the hydraulic load for the overall filter stage remained the same, this load was not the same for the filters in operation (see Table 2). In Period 2, the filters operated with sequential feeding (one filter feeding and the other resting), so they received higher water volumes per m^2. Thus, the better results seen when no resting period was applied can be attributed to the higher loads received by the filters in operation.

Clearly, the hydraulic load plays an important role in the removal of some pollutants in VFCWs [32]. The VFCWs of the UGB did not present clogging or oxygenation problems during the study, even without resting periods. This fact was demonstrated by the good water infiltration capacity of the filters, the quality provided, and the nitrification capacity. Therefore, for the studied Senegalese conditions under a dry and hot climate, the preliminary results indicate that no resting periods are necessary. High temperatures and a dry climate would enhance mineralization, as well as the drying of solids and organic matter. This would yield a great reduction in construction and operational costs, since it would not be necessary to construct/operate several beds in parallel. Despite these trends, more studies must be performed to confirm these hypotheses.

3.4. Treated Water Disposal and Reuse on Irrigation for Agriculture

Table 7 compares the quality requirements (Senegalese norms for disposal [33] and EU legislations for water reuse in irrigation [34]) and recommendations (WHO recommendations for water reuse in unrestricted irrigation [35]).

Table 7. CW effluent quality comparison with the Senegalese, EU, and WHO quality requirements or recommendations for disposal and water reuse in irrigation.

Parameters	Horizontal Flow CW Outlet Third Stage		Senegalese Norms for Disposal Media (NS 05-061, 2001)	WHO Recommendations for Water Reuse in Unrestricted Irrigation	European Legislation for Water Reuse in Irrigation
	FHa	FHb			
SS (mg/L)	9.6	5.7	40		10 [a]–35 [b,c,d]
BOD_5 (mg/L)	3.8	2.3	50		10 [a]–25 [b,c,d]
COD (mg/L)	79.8	71.3	200		
TN (mg/L)	24.4	23.0	30		
$N-NH_4^+$ (mg/L)	4.1	3.4			
$N-NO_3^-$ (mg/L)	11.1	12.5			
$P-PO_4^{3-}$ (mg/L)	5.5	2.1	10		
FC (CFU/100 mL)	180	200	2000	1000	10 [a]-100 [b]-1000 [c]-10,000 [d]
Helminth Eggs (eggs/L)	0	0		<1	

[a,b,c,d] Classes of reclaimed water quality and allowed agricultural use and irrigation methods: Class A: All food crops, including root crops consumed raw and food crops where the edible part is in direct contact with reclaimed water. All irrigation methods are allowed. Class B: Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops, and non-food crops, including crops to feed milk- or meat-producing animals. All irrigation methods are allowed. Class C: The same crop category irrigable with the water quality of Class B. Only drip irrigation is permitted. Class D: Industrial, energy, and seeded crops. All irrigation methods allowed.

The CW achieved the quality determined by the Senegalese regulations for discharge in natural environments under all parameters studied. Considering the EU quality requirements for wastewater reuse, the multistage CW achieved the quality required for all uses related to COD and SS. For fecal coliforms, the effluent could be reused for Classes C and D (1000 CFU/100 mL–10,000 CFU/100 mL). Compared with the WHO recommendations, Table 6 shows that multistage CW provides suitable water for reuse in unrestricted irrigation under all parameters (fecal coliforms and helminth eggs). The results demonstrate that the multistage CW allows for safe water reuse in agriculture, which is imperative in areas with severe water scarcity like Senegal. In 2021, it is planned to implement innovative irrigation techniques (based on drip and deficit irrigation) to reuse the treated water for a new green area for leisure at the campus, as well as for agricultural vegetable production (carrots, potatoes, and onions) in the farm nearby.

4. Conclusions

This study demonstrates the viability of combining different types of CW to treat raw municipal wastewater with loads up to 72 g of $SS/m^2 \cdot day$ and 199 g of $COD/m^2 \cdot day$. The combination of the three stages of CWs generated effluent with good quality suitable for discharge in the media or reuse in agriculture. The overall removal of the multistage CW was very high (>95% for SS, BOD_5, and $N-NH_4^+$; >90% for COD and $P-PO_4^{3-}$), as was the reduction of microbiological indicators (fecal coliform reduction > 5 log units and helminth egg removal of 100%).

The results demonstrate the capacity of VFCWs based on the FRB concept to retain SS, oxidate organic matter, and nitrify and remove bacterial indicators if a proper granulometry, filter depth, and operation regime is applied.

First, trends related to the influence of the design (the type of gravel, filter depth, and type of macrophyte), operational modes, and the CW treatment efficiency were determined. The use of non-crushed gravel and *Typha* spp. seemed to provide better removal rates. On the contrary, no differences were found between the use of silex or granite gravel. For the studied Senegalese conditions under dry and hot climates, the preliminary results indicate that no resting periods are necessary for VFCWs, thus resulting in a reduction in construction and operation costs.

To conclude, the main outcome of this study is that this proposed multistage CW design can provide robust, cost-effective treatment, as well as facilitate safe water reuse, which is imperative in areas with severe water scarcity like Senegal.

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