Scientific Research Publishing

Natural Resources, 2024, 15, 1-16
https://www.scirp.org/journal/nr
ISSN Online: 2158-7086
ISSN Print: 2158-706X

Performance of a Horizontal Flow Constructed Reed Bed Filter for Municipal Wastewater Treatment: The Case Study of the Prototype Installed at Gaston Berger University, Saint-Louis, Senegal

Abdou Khafor Ndiaye[1*], Falilou Coundoul[2], Abdoulaye Deme[1], Antonina Torrens Armengol[3], Abdoulaye Senghor[4]

[1]UFR of Applied Sciences and Technology, Gaston Berger University of Senegal, Saint-Louis, Senegal
[2]Polytechnic Institute of Saint-Louis (IPSL), Gaston Berger University of Saint-Louis, Saint-Louis, Senegal
[3]Department of Biology, Healthcare and Environment, Faculty of Pharmacy and Food Sciences, University of Barcelona, Barcelona, Spain
[4]Sanitation Department, Ministry in Charge of Sanitation, Dakar, Senegal

Email: *ndiaye.abdou-khafor@ugb.edu.sn, falilou.coundoul@ugb.edu.sn, abdoulaye.deme@ugb.edu.sn, antoninatorrens@ub.edu, marsenghor@yahoo.fr

How to cite this paper: Ndiaye, A.K., Coundoul, F., Deme, A., Armengol, A.T. and Senghor, A. (2024) Performance of a Horizontal Flow Constructed Reed Bed Filter for Municipal Wastewater Treatment: The Case Study of the Prototype Installed at Gaston Berger University, Saint-Louis, Senegal. *Natural Resources*, **15**, 1-16.
https://doi.org/10.4236/nr.2024.151001

Received: December 1, 2023
Accepted: January 15, 2024
Published: January 18, 2024

Abstract

In Saint-Louis, Senegal, a constructed wetland with horizontal flow reed beds (FHa and FHb) has demonstrated significant efficacy in treating municipal wastewater. Analyzing various treatment stages, the system showed only a slight temperature variation, from an influent average of 26.3˚C to an effluent of 24.7˚C. Electrical conductivity decreased from 1331 mS/cm to 974.5 mS/cm post-primary treatment, with suspended solids (SS) dramatically reduced from 718.9 mg/L to 5.7 mg/L in the final effluent. Biochemical oxygen demand (BOD5) and chemical oxygen demand (COD) saw a notable decrease, from initial levels of 655.6 mg/L and 1240 mg/L to 2.3 mg/L and 71.3 mg/L, respectively. Nitrogenous compounds (N-TN) and phosphates ($P\text{-}PO_4^{3-}$) also decreased significantly, indicating the system's nutrient removal capacity. Microbiological analysis revealed a reduction in fecal coliforms from 7.5 Ulog/100ml to 1.8 Ulog/100ml and a complete elimination of helminth eggs. The presence of Phragmites and Typha was instrumental in enhancing these reductions. The system's compliance with the Senegalese standards for disposal into natural environments, WHO recommendations for unrestricted water reuse in irrigation, and the European legislation for water reuse was established. The effluent quality met the stringent criteria for various classes of agricultural reuse, illustrating the system's potential for sustainable water management. This wetland model presents a robust solution for water-stressed regions, ensuring environmental protection while supporting agricultural needs. The study calls for ongoing research to further refine the system for optimal, reliable wastewater treatment and water resource sustainability.

Keywords

Constructed Wetlands, Horizontal Flow Reed Beds, Wastewater Treatment, Phragmites and Typha Plants, Physicochemical Pollutant Removal, Microbiological Indicators, Fecal Coliforms and Helminth Eggs, Water Quality Improvement, Senegal Water Reuse Standards, Sustainable Water Management, Agricultural Irrigation Reuse, Nutrient Removal Efficiency, Environmental Engineering, Ecological Sanitation Systems

1. Introduction

Sustainable water resource management stands as a paramount concern of our time, responding to the challenges posed by demographic growth and environmental pressures [1]. Within this context, wastewater treatment emerges as a critical domain, offering innovative solutions for ensuring water availability and quality [2]. Among such innovative approaches, horizontal flow constructed reed bed filters have gained increasing interest due to their presumed efficacy in purifying contaminated waters [3]. The African perspective on water management by 2025 aims to promote "the equitable and sustainable use of water for socio-economic development". To effectively achieve this goal, African nations can draw inspiration from other countries facing similar challenges, implementing improved systems to ensure better sanitation for their growing populations. Enhancing sanitation facilities plays a pivotal role in combating poverty and improving the quality of life. Significant disparities in sanitation and wastewater treatment between Africa and other continents persist. It is noted that ten of the countries with the highest levels of open defecation are in Sub-Saharan Africa, where the proportion of the population using safe sanitation facilities is also the lowest at 21% [4]. Constructed reed beds, often associated with natural filtration processes, represent a promising treatment technology. This hybrid method, combining engineering and biological processes, offers substantial benefits in terms of cost and environmental impact. Their ability to remove various pollutants, both physico-chemical and microbiological, makes them a prime candidate for wastewater treatment systems of small and large scales [5]. This study specifically focuses on the efficacy of horizontal flow constructed reed bed filters in the Senegalese context, where water-related concerns are exacerbated by climatic and socio-economic factors. The aim of this study is to evaluate the effectiveness of a wastewater treatment system using horizontal flow constructed reed bed filters, specifically in the Saint-Louis region of Senegal. The system comprises various stages, including manual pre-treatment, French-type horizontal filters (FHa and FHb) associated with different plants (Phragmites and Typha), and a refining step. The Sahelian climate of the region, characterized by high temperatures and low rainfall, presents particular challenges to water treatment. The ultimate goal is to achieve effluent quality that allows for the water's reuse in crop irrigation. Through a thorough analysis of the results obtained in our study, we will seek to determine the viability of applying this technology in the Senegalese context, with a particular emphasis on the reuse of treated water in agriculture. In doing so, we contribute to building a crucial knowledge base for the development of sustainable water management strategies, aligned with the United Nations Sustainable Development Goals (SDGs).

2. Materials and Methods

2.1. Description of the Study Area

The study area is located in the Saint-Louis region of Senegal, specifically within the premises of Gaston Berger University of Saint Louis near the agricultural farm. The university is approximately 12 km from the city of Saint-Louis on the N2 national road leading to Richard-Toll or the Mauritanian border. It is part of the rural community of Gandon and is situated between the two villages Sanar Peulh and Sanar Wolof. The climate of Saint-Louis is Sahelian, with hot, 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 enjoys an average of 250 hours of sunshine per month, about 8.5 hours of sun per day. The climate is characterized by great aridity (with an annual average precipitation of 265.0 mm) and is divided into two distinct seasons: the rainy season (hot and humid) from the end of June to October, with significant rainfall that can reach 100 mm in August, and the dry season from November to May, marked by Harmattan winds from the desert, creating hot, dusty days with almost no precipitation [6]. The goal is to achieve effluent quality that meets the objective of reusing water for crop irrigation. The purification system, shown in 3D in **Figure 1**, consists of a manual cleaning coarse grid, along with a sand cleaner; a first stage of French-type FPR as pretreatment and primary treatment totaling 72 m^2 (3 cells of 24 m^2 each); a second French-type FPR stage (second step), as a secondary treatment of 48 m^2 in total (24 m^2 each); and a third stage (refinement) of horizontal FPR totaling 72 m^2 (two cells of 36 m^2 each). **Table 1** indicates the design characteristics of the filter, highlighting the type of horizontal filter, the specific filter (FHa and FHb), the height of the filter (in cm), the material of the filtration layer (Flint), its granulometry (5 - 15 mm), and finally, the type of plant used as a purifier.

The horizontal filters (FHa and FHb) have similar design features in terms of height, filtration layer material, and granulometry. The main difference lies in the plants associated with each filter, with Phragmites for FHa and Typha for FHb. This plant pairing suggests a possible adaptation of the filter according to specific needs related to the characteristics of the selected plants.

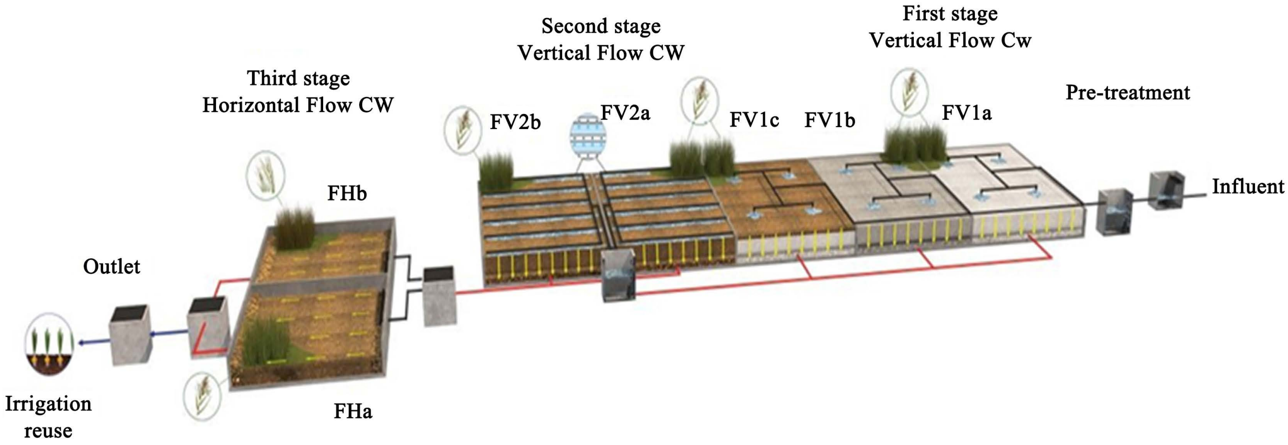

Figure 1. Multistage constructed wetland (CW) layout (prototype, University Gaston Berger (UGB) campus).

Table 1. Main design features of the filter.

Stage	Filter	Filtering layer			Plant
		Height (cm)	Material	Granulometry	
Horizontal filter	FHa	60	Silex	5 - 15 mm	Phragmites
	FHb	60	Silex	5 - 15 mm	Typha

2.2. Sampling and Quality Control

In addition to samples collected from the influent to the prototype and the effluent from the pretreatment device, samples are taken at the inlets and outlets of each filter cell. A monitoring program spanning six months (12 series) and including the analysis of grab samples was conducted from February to July 2019. Samples were collected at each filter in the pilot process, including the influent and effluent of each filter (9 sampling points), and then preserved according to standard methods [7]. The pH, electrical conductivity (EC), and temperature (T) were measured on-site using portable sensors. chemical oxygen demand (COD), biological oxygen demand under five days (BOD5), suspended solids (SS), total nitrogen (TN), ammonia ($N\text{-}NH_4^+$), nitrates ($N\text{-}NO_3^-$), and phosphates ($P\text{-}PO_4^{3-}$) as well as total phosphorus (TP) were analyzed in accordance with standardized French methods NF EN ISO 19458 [8] at the Wastewater Treatment and Water Pollution Laboratory of Cheikh Anta Diop University, in Dakar, Senegal [9]. Fecal coliforms (FC) were counted according to the standardized culture method on lactose bile violet red agar (VRBL) for 24 hours, and the results were expressed in colony-forming units (CFU) in logarithmic base per volume unit. Helminth eggs were quantified according to standard methods [7]. In the remainder of this study, we will focus exclusively on the water quality at the output of the vertical filters.

2.3. Data Analysis

Statistical analyses were performed on the raw data using Excel 2016 and IBM-

SPSS Statistics [10]. Excel 2016 was used for descriptive analyses (means, maximum, minimum, and standard deviation). IBM-SPSS Statistics was utilized to conduct an analysis of variance (ANOVA). The ANOVA was carried out to assess the impact of various design and operational variables on the study outcomes, particularly regarding pollutant reduction. The threshold for statistical significance was set at $p \leq 0.05$.

3. Results

3.1. Water Quality and Physico-Chemical Pollutant Removal

Table 2 presents the results of water quality analysis at different stages of the treatment process, including influent, pretreatment, output from primary and secondary treatments with vertical flow (VF), and outputs from horizontal filters (FHa and FHb). Data are provided for various parameters including temperature (T), electrical conductivity (EC), pH, suspended solids (SS), 5-day biochemical oxygen demand (BOD5), chemical oxygen demand (COD), total nitrogen (N-TN), ammoniacal nitrogen ($N\text{-}NH_4^+$), nitrate ($N\text{-}NO_3^-$), and phosphate ($P\text{-}PO_4^{3-}$). In Table 2 results show an evolution in water quality across five treatment stages. Water temperature remains relatively stable throughout the process, with a slight decrease from 26.3˚C ± 1.5˚C at the inlet to about 24.7˚C ± 1.4˚C at the outlet. The initial electrical conductivity (EC) of 1331 ± 170 mS/cm decreases significantly after treatment (974.5 ± 211.5 mS/cm at the outputs of the first and second vertical flow treatment), then slightly increases to the final values of 1056 ± 115 and 1049 ± 142 mS/cm at the outputs of the FHa and FHb filters. The pH, which starts at 7.7 ± 0.2, drops to 5.75 ± 0.4 after the intermediate stages, then rises to 8.0 ± 0.2 at the final stages, indicating a more alkaline water at the outlet than at the inlet. Suspended solids (SS) show a significant reduction, from 718.9 ± 291 mg/L in the influent water to only 5.7 ± 2.3 mg/L at the FHb outlet. Similarly, 5-day biochemical oxygen demand (BOD5) and chemical oxygen demand

Table 2. Average water quality and associated standard deviation.

Parameters	Influent	Pre-Treatment.	Outlet 1st & 2nd Treatment.	Outlet FHa	Outlet FHb
T (˚C)	26.3 ± 1.5	27.1 ± 0.8	26.15 ± 0.55	24.8 ± 1.0	24.7 ± 1.4
EC (mS/cm)	1331 ± 170	1420 ± 129	974.5 ± 211.5	1056 ± 115	1049 ± 142
pH	7.7 ± 0.2	7.5 ± 0.1	5.75 ± 0.4	8.0 ± 0.2	8.0 ± 0.2
SS (mg/L)	718.9 ± 291	388.8 ± 59	12.8 ± 4.25	9.6 ± 6.4	5.7 ± 2.3
BOD5 (mg/L)	655.6 ± 106	495.5 ± 85	2.35 ± 1.65	3.8 ± 2.7	2.3 ± 1.1
COD (mg/L)	1240 ± 589	1063 ± 293	88.1 ± 37.5	79.8 ± 39	71.3 ± 33
N-TN (mg/L)	188 ± 82	138.2 ± 29	37.95 ± 19.0	24.4 ± 6.5	23.0 ± 9.0
$N\text{-}NH_4^+$ (mg/L)	130.9 ± 68	99.8 ± 21	4.15 ± 2.25	4.1 ± 2.4	3.4 ± 2.9
$N\text{-}NO_3^-$ (mg/L)	4.3 ± 2.5	2.7 ± 1.3	30.6 ± 11.5	11.1 ± 3.1	12.5 ± 4.7
$P\text{-}PO_4^{3-}$ (mg/L)	70.9 ± 43	68.7 ± 39	13.8 ± 5.0	5.5 ± 4.1	2.1 ± 1.2

(COD) decrease drastically, from initial values of 655.6 ± 106 mg/L and 1240 ± 589 mg/L respectively, to 2.3 ± 1.1 mg/L (BOD5) and 71.3 ± 33 mg/L (COD) at the end of treatment. For total nitrogen (N-TN), a reduction from 188 ± 82 mg/L to 23.0 ± 9.0 mg/L is noted at the FHb outlet. Ammonium ($N\text{-}NH_4^+$) also decreases from 130.9 ± 68 mg/L to 3.4 ± 2.9 mg/L. Contrary to these trends, nitrates ($N\text{-}NO_3^-$) increase after pretreatment, from 4.3 ± 2.5 mg/L to 30.6 ± 11.5 mg/L, then decrease in the following stages to reach 12.5 ± 4.7 mg/L.

Finally, phosphate concentration ($P\text{-}PO_4^{3-}$) progressively decreases from 70.9 ± 43 mg/L to 2.1 ± 1.2 mg/L at the FHb outlet, reflecting the treatments efficiency in reducing phosphorus concentrations. These data illustrate the effectiveness of the treatment process in improving water quality by reducing the majority of the measured contaminants, although the transient increase in nitrates requires particular attention.

3.2. Enumeration and Removal of Microbiological Indicators

Table 3 presents monitoring data for two indicators of microbiological contamination, fecal coliforms (FC) and helminth eggs (HE), at different stages of a wastewater treatment process. Data for fecal coliforms are expressed in logarithmic units per 100 milliliters (Ulog/100ml), and results for helminth eggs are in eggs per liter (eggs/L). The "Average" column represents the mean concentration, while "Max" and "Min" represent the observed maximum and minimum values, respectively. The reduction in concentration is also expressed as a percentage. For fecal coliforms (FC), there is a progressive decrease in the average concentration from the influent with 7.5 Ulog/100ml, passing to 6.7 Ulog/100ml after pretreatment, then to 3.75 Ulog/100ml after the first and second treatment, and finally reaching 1.8 and 2 Ulog/100ml at the FHa and FHb outlets, respectively. The maximum variation (Ulog) also decreases, from 0.9 in the influent to 0.3 at the outlet, indicating a reduction in contamination variability. The percentages of FC elimination increase from 11% after pretreatment to 52% and

Table 3. Concentration and elimination of microbiological indicators. FC: fecal coliforms and HE: helminth eggs.

Indicator		Influent	Pre-Treatment	First and second traitement	FHa	FHb
FC concentration (Ulog/100ml) removal	Average	7.5	6.7	3.75	1.8	2
	Max	8.1	7.1	4.15	2.8	2.1
	Min	7.2	6.4	3.5	0.1	2
	Ulog	0.9	0.8	0.6	0.3	0.3
	%		11	44	52	47
HE (eggs/L) removal	Average	13[1]	5[2]	0	0	0
	%		62	100	-	-

[1]Ascaris spp., Trichuris spp; [2]Ascaris spp.

47% for the FHa and FHb outlets, respectively. For helminth eggs (HE), the average concentration at the influent is 13 eggs/L, which is reduced to 5 eggs/L after pretreatment, indicating a 62% elimination. After the first and second treatment, the concentration drops to 0 eggs/L, showing a 100% elimination, which is maintained for the FHa and FHb outlets. These results demonstrate the effectiveness of the treatment process in reducing microbiological indicators. The treatment succeeds in almost completely eliminating helminth eggs and significantly reducing the concentration of fecal coliforms, indicative of a substantial improvement in the microbiological quality of the water. However, a slight increase in FC concentration at the FHb outlet compared to the FHa outlet might warrant investigation to understand and optimize the treatment process at this stage.

4. Discussion

4.1. Physicochemical Pollutant Removal

The changes in various parameters according to the different treatment stages are depicted in **Figure 1**. The values are calculated from the average results presented in **Table 2**, which showcases the performance of a water treatment system in terms of the removal of various pollutants, with observed elimination rates after pretreatment and at the FHa and FHb outlets, based on 12 samples. The influent water, characterized by a typical composition of raw municipal wastewater with a minor contribution from industrial wastewater, presents high concentrations of pollutants compared to standards for urban wastewater [2]. These high concentrations are attributed to the low levels of water use in Senegal (40 - 80 L/person) compared to Europe (about 150 L/person) [11]. Ces concentrations élevées sont attribuées aux faibles niveaux d'utilisation de l'eau au Sénégal (40 - 80 L/personne) par rapport à l'Europe (environ 150 L/personne) [11]. The high nutrient concentrations (N-TN > 100 mg/L, ($P\text{-}PO_4^{3-}$ near 80 mg/L) and high electrical conductivity are also notable and align with other studies on wastewater in Senegal [12]. For EC, the negative values (−6.7%, −8.4%, −7.6%) suggest an increase in conductivity after treatment, which could indicate a concentration of dissolved salts or other conductive ions, a phenomenon that can be explored and contextualized in studies such as [13]. SS shows a substantial reduction, with pretreatment eliminating 45.9% and the FHb outlet displaying the best performance with 55.5%. This efficiency in SS removal is a positive indicator of treatment performance, as discussed in [14]. OD5 presents a reduction of 24.4% after pretreatment, but curiously a negative increase (−61.7%) at the FHa outlet, followed by a slight improvement (2.1%) at the FHb outlet. This increase at FHa could be attributed to unexpected biological or chemical processes and should be analyzed in light of sources such as [15]. Nevertheless, the observation of a negative value for BOD5 elimination rate (−61.7%) at the FHa outlet is peculiar as it suggests an increase in BOD5 rather than a reduction, which would be contrary to the goal of wastewater treatment. Even though this value is obtained relative to the average of the values measured at the outlets of the second treatment by horizontal flow, an increase in BOD5 concentration is noted. This could be due to several factors such as measurement error, sample contamination, internal biological processes (such as the proliferation of bacteria or the decomposition of previously undegraded organic matter, inhibition of degradation by certain chemical components, or unfavorable conditions (pH indicating more alkaline water at the outlet than at the inlet in our experiment), a sudden increase or variation in the inflow rate with a high organic load just before sampling could also explain this peculiar result. To determine the exact cause, it would be necessary to review the sampling, measurement, and analysis procedures, as well as examine the operational conditions of the treatment station at the time of measurement. A repetition of measurements or an analysis of trends over several cycles could help confirm whether this is a one-time anomaly or a systemic problem. For COD, elimination rates remain relatively low, suggesting lesser treatment efficacy for this measure of organic pollution, necessitating further investigation as recommended by [16]. The elimination of total nitrogen (N-TN) and ammonium ($N\text{-}NH_4^+$) shows progressive improvements at different stages, with the best performances observed at the FHb outlet (39.4% and 18.1% respectively). These trends correspond to observations in works like those of [17]. Nitrate ($N\text{-}NO_3^-$) elimination is effective, especially at the FHa and FHb outlets (63.7% and 59.2% respectively), which reflects adequate nitrification, a process also covered in the specialized literature such as [18]. Finally, the elimination of phosphates ($P\text{-}PO_4^{3-}$) is particularly effective at the FHb outlet with 84.8%. This result is very positive as phosphates can contribute to the eutrophication of receiving waters, as explained in [19].

Table 4 and **Figure 2** augment the analysis by presenting the pollutant removal rates across various treatment stages and tracking the progression of different water quality parameters throughout the treatment phases, inclusive of error bars that denote the standard deviation. The results highlight effective suspended solids (SS) elimination and significant reductions in chemical oxygen demand (COD) and biochemical oxygen demand (BOD5). High performance in

Table 4. Pollutant elimination rates.

Parameters	Pre-treatment (%)	Outlet FHa (%)	Outlet FHb (%)
EC (mS/cm)	−6.7	−8.4	−7.6
SS (mg/L)	45.9	25	55.5
BOD5 (mg/L)	24.4	**−61.7**	2.1
COD (mg/L)	14.3	9.4	19.1
N-TN (mg/L)	26.5	35.7	39.4
$N\text{-}NH_4^+$ (mg/L)	23.8	1.2	18.1
$N\text{-}NO_3^-$ (mg/L)	37.2	63.7	59.2
$P\text{-}PO_4^{3-}$ (mg/L)	3.1	60.1	84.8

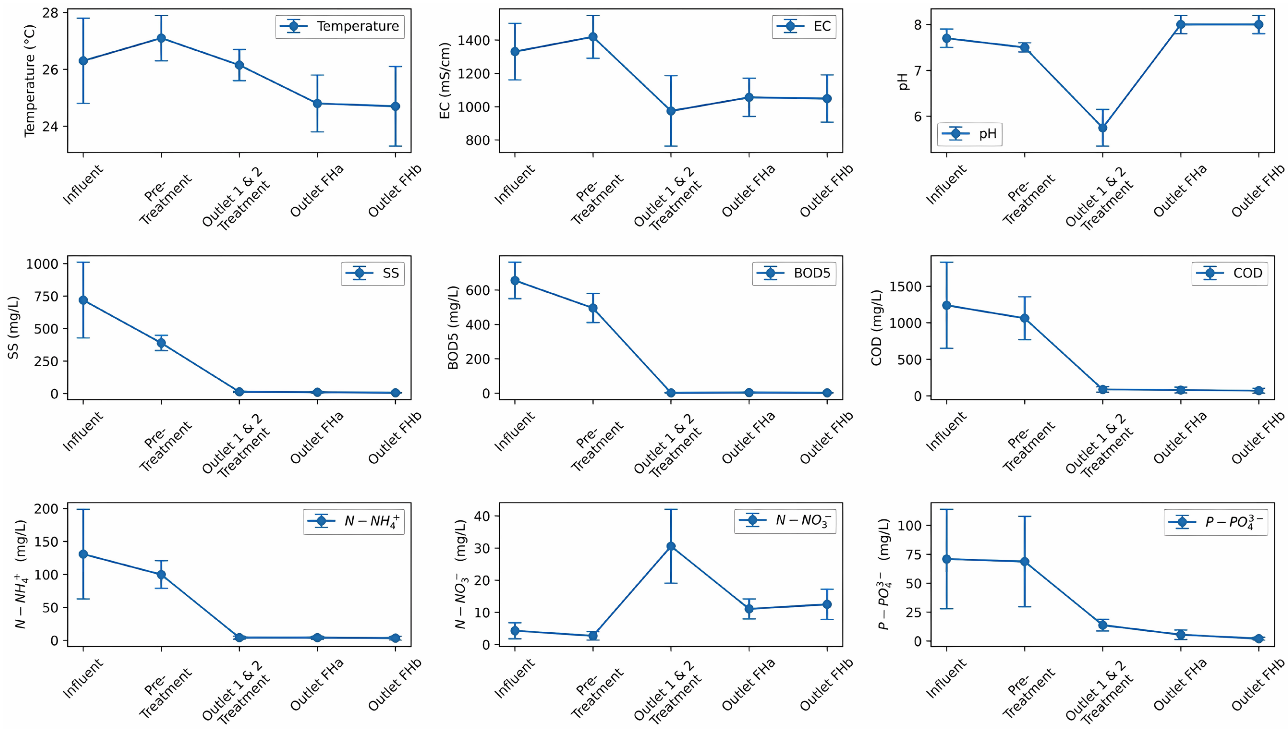

Figure 2. The evolution of various water quality parameters through the different treatment stages, complete with error bars that represent the standard deviation.

the elimination of nitrogenous and phosphorus compounds confirms the system's efficiency in nutrient reduction. The pretreatment step aims to remove sand and large particles in the wastewater, occasionally exacerbated by sandstorms due to the site's geographical positioning [6]. This pretreatment effectively removes a large amount of suspended material, primarily inorganic particles. The second stage involves primary and secondary treatment in reed bed filters with vertical flow, which significantly eliminates suspended materials and organic matter while nitrifying the effluent ($N\text{-}NO_3^-$ > 30 mg/L). These results indicate proper filter operation, with eliminations comparable to other similar experiences [20]. High temperatures in the region enhance the kinetics of degradation, strengthening microbial activity in the sand filters. The strong phosphorus elimination is also noted, although this removal may decrease over time. The filters act as a polishing step, reducing residual pollution to very low levels for certain parameters. However, the suboptimal pH limits denitrification in these FHa and FHb filters. While they are highly effective for certain parameters, their influence on the removal of BOD5 and COD is limited, as these compounds have already been largely degraded in previous stages. Significant differences between the two filters are observed depending on the plant species.

4.2. Removal of Microbiological Indicators

The waters arriving at the pilot treatment station have characteristics typical of municipal wastewater in Senegal. They contain various pathogens, including high concentrations of viral bacteria and helminth eggs, reflecting the carrier state and infection levels in the community. This raises public health concerns in the case of wastewater reuse, particularly in endemic regions with a high prevalence of waterborne diseases. Therefore, the removal of microbiological indicators is crucial if water reuse is considered. The enumeration and removal of microbiological indicators, such as fecal coliforms (FC) and helminth eggs (HE), gauge the effectiveness of the FHa and FHb filters. **Table 3** presents the initial concentrations, removal performance, and characteristic values of the microbiological indicators at different treatment stages. The evolution of the removal rates of fecal coliforms (FC) and helminth eggs (HE) according to the different treatment stages are presented in **Figure 3**. As for fecal coliforms (FC), the average concentration decreases progressively through the treatment stages, from 7.5 Ulog/100ml in the influent to 1.8 Ulog/100ml after the final treatment (FHb). The maximum reduction observed is 6.1 Ulog (from 8.1 to 2 Ulog/100ml), and the minimum is 5.2 Ulog (from 7.2 to 2 Ulog/100ml). The efficiency of elimination increases at each stage, starting at 11% after pretreatment and reaching up to 52% after the first and second treatment. The raw wastewater exhibited a high number of helminth eggs (predominantly Ascaris spp.) which were nearly 100% eliminated in the first stage of the constructed wetland system. The effective removal of Ascaris spp. eggs was due to filtration/sedimentation [21]. The horizontal filters (FHa and FHb) show significant efficacy in reducing fecal coliforms, with reductions up to 1.8 Ulog. This substantial reduction demonstrates the system's efficiency in removing microbiological contaminants. The average fecal coliform concentrations decreased from 7.5 to 1.8 Ulog/100 mL. These values underscore the importance of microbiological contaminant removal to meet water quality standards [22]. Horizontal filters demonstrated notable elimination of helminth eggs, with total removal in both FHa and FHb filters. This suggests particular efficacy in the treatment of parasitic pathogens. The microbiological indicators evaluated, namely fecal coliforms (FC) and helminth eggs (HE),

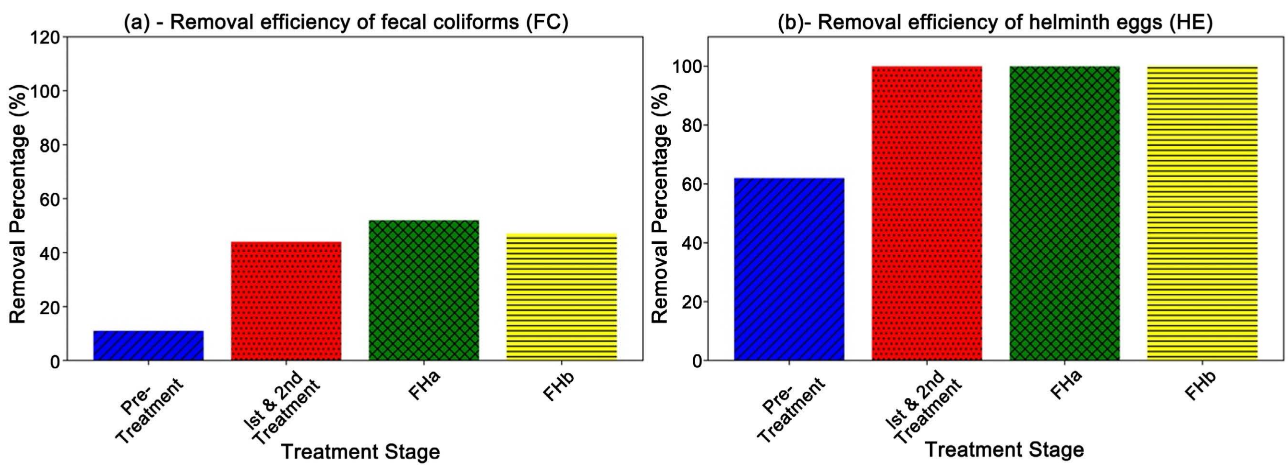

Figure 3. (a) The evolution of the removal rates of FC (fecal coliforms) according to the different stages of treatment; (b) the evolution of the removal rates of HE (helminth eggs) according to the different stages of treatment.

are relevant markers of water microbiological quality. Their monitoring allows for quantifying the horizontal filter's efficacy in reducing health risks associated with fecal and parasitic contamination. In conclusion, the table highlights the positive performance of the FHa and FHb filters in reducing microbiological indicators, with significant results for fecal coliforms and helminth eggs. These observations reinforce the idea that horizontal flow phytoremediation is an effective method in wastewater treatment regarding the elimination of microbiological contaminants. These findings are essential for guiding the design and operational practices of water treatment systems to optimize treated water quality. Further research could explore the specific mechanisms underlying these results, thus contributing to the continuous improvement of water treatment technologies.

4.3. Operating and Design Parameters Effect

Table 5 illustrates the impact of design and operational variables on the removal of various parameters within the system. The letter "S" indicates a significant effect of the variable on the corresponding parameter.

Variables related to plant species, particularly Phragmites (FHa) and Typha (FHb), exhibit a significant effect (S) on the removal of suspended solids (SS), 5-day biochemical oxygen demand (BOD5), chemical oxygen demand (COD), ammonium ($N\text{-}NH_4^+$) and phosphate ($P\text{-}PO_4^{3-}$) but not fecal coliforms. The lack of a significant notation for fecal coliforms indicates that this variable does not have a significant effect in this specific context. The significant effect (S) of plant species suggests their role in reducing suspended solids, with plant roots potentially playing a crucial role in trapping these particles and removing organic matter, thereby improving the quality of the treated water. Regarding the gravel material in the first stage of the horizontal filters, significant differences were observed for FHb (flint + 15 cm of 3 - 8 mm river gravel), which showed better elimination rates for almost all parameters. However, no significant difference was noted between FHa (flint) and FHb (granite), aligning with other studies [23] that showed poorer performance in horizontal filters with crushed gravel or sand. Specific studies might be needed to interpret these results in detail. The depth of the sand filters showed no significant differences in any parameter, likely due to the small differences in sand height (20 cm) not being sufficient to cause a significant effect. Horizontal filters planted with Typha (FHb) outperformed those planted with Phragmites for all physicochemical parameters. While the literature is not clear on which plant offers better performance in horizontal filters [24], our results show clear differences that could be attributed to

Table 5. Effect of design and operational variables on parameter removal.

Variable	SS	BOD5	COD	$N\text{-}NH_4^+$	$P\text{-}PO_4^{3-}$	FC
Plant species (FHa, FHb) (Phragmites, Typha)	S	S	S	S	S	-

the more substantial and faster development of Typha. Additionally, Typha colonized the entire bed in about a month, while the growth and spread on the Phragmites bed were much less significant. Clearly, the hydraulic load plays an important role in the elimination of certain pollutants in horizontal filters [25]. The UGB's horizontal filters did not show clogging or oxygenation problems during the study, even without resting periods. This was demonstrated by the good water infiltration capacity of the filters, the quality provided, and the nitrification capacity. Therefore, for the Senegalese conditions studied in a dry and hot climate, preliminary results indicate that no resting period is necessary. High temperatures and a dry climate would favor mineralization and the drying of solids and organic matter, leading to a significant reduction in construction and operational costs, as there would be no need to build/operate multiple beds in parallel. Despite these trends, further studies must be conducted to confirm these hypotheses. The results suggest that the choice of plant species, Phragmites and Typha, in horizontal filters (FHa, FHb), has a considerable impact on treatment efficacy. These plants are known for their ability to promote beneficial ecological processes in wastewater treatment systems. The significant effect observed for several parameters confirms the importance of horizontal filters in improving water quality, particularly regarding the reduction of organic pollutants and nutrients. In conclusion, integrating Phragmites and Typha into horizontal filters appears to be an effective strategy to enhance the overall performance of the wastewater treatment system. However, more in-depth investigations are necessary to fully understand the underlying mechanisms and further optimize these systems based on the specific characteristics of the site.

4.4. Prospects for the Reuse of Treated Water for Agricultural Irrigation

Table 6 offers a detailed comparison of water quality parameters from filters

Table 6. Comparison of the quality of treated water effluents with the quality requirements of Senegal, the EU, and the WHO, or recommendations for the elimination and reuse of water in irrigation.

Parameters	FHa	FHb	Senegalese Norms for Disposal Media (NS 05-061, 2001	WHO Recommendations for Water Reuse in Unrestricted Irrigation	European Legislation for Water Reuse in irrigation
SS (mg/L)	9.6	5.7	40	-	$10^a - 35^{b,c,d}$
BOD5 (mg/L)	3.8	2.3	50	-	$10^a - 25^{b,c,d}$
COD (mg/L)	79.8	71.3	200	-	-
N-TN (mg/L)	24.4	23.0	30	-	-
$N\text{-}NH_4^+$ (mg/L)	4.1	3.4	N/A	-	-
$N\text{-}NO_3^-$ (mg/L)	11.1	12.5	N/A	-	-
$P\text{-}PO_4^{3-}$ (mg/L)	5.5	2.1	10	-	-
FC (UFC/100ml)	**180**	**200**	2000	1000	**10^a-100^b-1000^c-10.000^d**
HE (Eggs/L)	0	0	-	<1	-

FHa and FHb against the target values of Senegalese discharge standards [26], the World Health Organization (WHO) guidelines for unrestricted water reuse in irrigation [27], and European legislation for water reuse in irrigation [28]. The analysis of **Table 6** shows that the treated effluents comply with Senegalese standards for discharge into the natural environment [26], the legislation of the European Union for the reuse of water in irrigation [28] and the recommendations of the World Health Organization (WHO) for the reuse of water in unrestricted irrigation [27]. According to the Senegalese standards, the constructed wetland system meets the quality requirements for discharge into natural environments for all the parameters studied. This compliance underlines the effectiveness of the station in treating municipal wastewater effluents, thus adhering to local norms and contributing to environmental preservation.

The classifications a, b, c, and d refer to categories of recycled water quality and permitted agricultural use and irrigation methods. Class A: All food crops including those eaten raw and food crops where the edible part is in direct contact with the recycled water. All irrigation methods are allowed. Class B: Food crops consumed raw when the edible part is produced above ground and not in direct contact with the recycled water, processed food crops, and non-food crops including those for feeding dairy or meat animals. All irrigation methods are permitted. Class C: The same category of crops as Class B, irrigable with Class B water quality. Only drip irrigation is allowed. Class D: Industrial, energy crops, and seeds. All irrigation methods are permitted.

Concerning the European Union requirements for wastewater reuse, the system reaches the required quality for all uses related to COD and SS. For fecal coliforms, the effluent could be reused for Classes C and D (1000 CFU/100mL - 10,000 CFU/100mL). The Class A of European legislation imposes more stringent standards for FC compared to the results from FHa and FHb. This extended reusability highlights the system's versatility in the context of European norms, opening up possibilities for various agricultural applications. In relation to the WHO recommendations, **Table 6** emphasizes that the multi-stage constructed wetland provides water suitable for unrestricted reuse in irrigation for all parameters, including fecal coliforms and helminth eggs. These results demonstrate that the multi-stage constructed wetland enables the safe reuse of water in agriculture, a crucial consideration in areas facing severe water scarcity like Senegal. Ultimately, horizontal filters emerge as a viable solution for the safe reuse of treated water, offering significant opportunities in regions confronted with water scarcity. Future planning of innovative irrigation based on drip and deficit irrigation demonstrates the practical feasibility of this approach in real-world applications. The positive results of **Table 6** underscore the necessity of ongoing research on horizontal filters, focusing on optimizing treatment parameters to meet the increasing needs for sustainable water management. In conclusion, horizontal filters present notable performances, paving the way for more efficient and sustainable use of water resources in contexts such as Senegal.

5. Conclusion

The detailed study of the wastewater treatment system through horizontal flow reed bed filters yields promising results regarding the process's effectiveness. The horizontal filters, FHa and FHb, have shown significant performance in eliminating contaminants both physico-chemically and microbiologically. Monitoring water quality throughout the treatment process has indicated substantial improvements, evidencing the horizontal filters' efficacy in pollutant removal. Significant reductions have been observed across various parameters, including temperature, electrical conductivity, suspended solids, biochemical oxygen demand, chemical oxygen demand, total nitrogen, ammonium, nitrate, and phosphate. These findings demonstrate the system's ability to effectively treat a range of contaminants present in wastewater. The enumeration and elimination of microbiological indicators, such as fecal coliforms and helminth eggs, are also encouraging. Horizontal filters have shown a significant reduction in fecal coliforms and complete elimination of helminth eggs, underscoring the system's effectiveness in treating microbiological contaminants. The analysis of design and operational variables revealed significant outcomes, particularly regarding the plant species used in the horizontal filters. Phragmites and Typha plants have shown a significant impact on the removal of suspended solids, organic matter, ammonium, phosphate, and fecal coliforms. These results highlight the importance of plant species selection in designing horizontal filters. Finally, the comparison of results with Senegalese standards, WHO recommendations, and European legislation for water reuse in irrigation highlights the system's compliance with water quality requirements. The treated effluents meet national and international standards, thus offering favorable prospects for reusing treated water in irrigation. In conclusion, this study provides encouraging results on the effectiveness of the wastewater treatment system based on horizontal flow reed bed filters. The physicochemical and microbiological performance, compliance with standards, and potential for reusing treated water in irrigation make it a promising solution for sustainable wastewater management in the Saint-Louis region of Senegal. However, further research could focus on the continuous optimization of the system and a deeper understanding of the underlying mechanisms to ensure consistent and reliable performance.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Hussain, M.I. (2019) Sustainable Use and Management of Non-Conventional Water Resources for Rehabilitation of Marginal Lands in Arid and Semiarid Environments. *Agricultural Water Management*, **221**, 462-476. https://doi.org/10.1016/j.agwat.2019.04.014

[2] Al-Hazmi, H.E. (2023) Wastewater Treatment for Reuse in Agriculture: Prospects and Challenges. *Environmental Research*, **236**, Article ID: 116711. https://doi.org/10.1016/j.envres.2023.116711

[3] Thalla, A.K. (2019) Performance Evaluation of Horizontal and Vertical Flow Constructed Wetlands as Tertiary Treatment Option for Secondary Effluents. *Applied Water Science*, **9**, Article No. 147. https://doi.org/10.1007/s13201-019-1014-9

[4] Street, R.M. (2020) Wastewater Surveillance for Covid-19: An African Perspective. *Science of the Total Environment*, **743**, Article ID: 140719. https://doi.org/10.1016/j.scitotenv.2020.140719

[5] Vymazal, J. (2007) Removal of Nutrients in Various Types of Constructed Wetlands. *Science of the Total Environment*, **380**, 48-65. https://doi.org/10.1016/j.scitotenv.2006.09.014

[6] Ndiaye, A.D. (2020) Eduquer aux changements climatiques au Sénégal, une initiation au modèle REDOC via les représentations sociales. *Hors-Serie*, **8**, 51-80.

[7] Public Health Association (APHA), American Water-Works Association (AWWA) and American Environment (2005) Standard Methods for the Examination of Water and Wastewater. Baltimore.

[8] Association Française de Normalisation (1999) Qualité de l'eau: Recueil, Environnement, 4 Vols. AFNOR, Paris.

[9] LATEU. Présentation|LATEU|Laboratoire de Traitement des Eaux Usées. https://lateu.ucad.sn/article/pr%C3%A9sentation

[10] IBM SPSS Statistics. https://www.ibm.com/products/spss-statistics

[11] Crouch, M.L. (2021) Defining Domestic Water Consumption Based on Personal Water Use Activities. *AQUA—Water Infrastructure, Ecosystems and Society*, **70**, 1002-1011. https://doi.org/10.2166/aqua.2021.056

[12] Kumar, J.E. (2019) Changes in Physico-Chemical Characteristics of the Sewage Effluent under Constructed Wetland Technology Treatment. *Madras Agricultural Journal*, **106**, 58-62. https://doi.org/10.29321/MAJ.2019.000222

[13] Tchobanoglous, G., Burton, F.L. and Stensel, H.D. (2003) Wastewater Engineering Treatment and Reuse (No. 628.3 T252s). McGraw-Hill, Boston.

[14] M. & Eddy, *et al.* (2014) Wastewater Engineering: Treatment and Resource Recovery. McGraw Hill Education, New York.

[15] Bridgewater, L.L., *et al.* (2017) Standard Methods for the Examination of Water and Wastewater. 23rd Edition, American Public Health Association, Washington DC.

[16] Sawyer, C.N., McCarty, P.L. and Parkin, G.F. (2003) Chemistry for Environmental Engineering and Science. 5th Edition, McGraw-Hill, New York. http://repository.vnu.edu.vn/handle/VNU_123/90733

[17] Henze, M., Harremoes, P., Jansen, J.L. and Arvin, E. (2002) Wastewater Treatment: Biological and Chemical Process. Springer, Berlin. https://doi.org/10.1007/978-3-662-04806-1

[18] Grady Jr., C.L., Daigger, G.T., Love, N.G. and Filipe, C.D. (2011) Biological Wastewater Treatment. CRC Press, Boca Raton. https://doi.org/10.1201/b13775

[19] Correll, D. (1999) Phosphorus: A Rate Limiting Nutrient in Surface Waters. *Poultry Science*, **78**, 674-682. https://doi.org/10.1093/ps/78.5.674

[20] Morvannou, A., Forquet, N., Michel, S., Troesch, S. and Molle, P. (2015) Treatment Performances of French Constructed Wetlands: Results from a Database Collected over the Last 30 Years. *Water Science & Technology*, **71**, 1333-1339. https://doi.org/10.2166/wst.2015.089

[21] Amoah, I.D., Reddy, P., Seidu, R. and Stenström, T.A. (2018) Removal of Helminth Eggs by Centralized and Decentralized Wastewater Treatment Plants in South Africa and Lesotho: Health Implications for Direct and Indirect Exposure to the Effluents. *Environmental Science and Pollution Research*, **25**, 12883-12895. https://doi.org/10.1007/s11356-018-1503-7

[22] Normes de l'OMS sur l'eau potable. https://www.lenntech.fr/applications/potable/normes/normes-oms-eau-potable.htm

[23] Varma, M.G. (2021) A Review on Performance of Constructed Wetlands in Tropical and Cold Climate: Insights of Mechanism, Role of Influencing Factors, and System Modification in Low Temperature. *Science of the Total Environment*, **755**, Article ID: 142540. https://doi.org/10.1016/j.scitotenv.2020.142540

[24] Sandoval, L., *et al.* (2019) Role of Wetland Plants and Use of Ornamental Flowering Plants in Constructed Wetlands for Wastewater Treatment: A Review. *Applied Sciences*, **9**, Article No. 685. https://doi.org/10.3390/app9040685

[25] Lavrnić, S.A. (2020) Hydrological and Hydraulic Behaviour of a Surface Flow Constructed Wetland Treating Agricultural Drainage Water in Northern Italy. *Science of the Total Environment*, **702**, Article ID: 134795. https://doi.org/10.1016/j.scitotenv.2019.134795

[26] Sénégalaise, N. (2001) NS 05-061. 2001. Eaux Usées Eaux Surf. Souterr. Mar. Pollut. Eaux Charge Polluante Épandage Valeur Lte. Paramètres Milieux Récepteurs Caractér. Générales Effl. Voies D'évacuation Stn. D'épuration.

[27] World Health Organization (2006) WHO Guidelines for the Safe Use of Wastewater Excreta and Greywater, Vol. 1. https://www.who.int/publications/i/item/9241546859

[28] (2018) Proposal for a Regulation of the European Parliament and on the Council on Minimum Requirements for Water Reuse. Brussels.