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Performance Evaluation of Two Series Vertical Flow Filters for Wastewater Treatment: A Case Study of the Prototype Installed at Gaston Berger University, Saint-Louis, Senegal

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Abstract

This paper evaluates the efficacy of two sequential vertical flow filters (VFF), FV1 and FV2, implanted with Typha, in a pilot-scale wastewater treatment system. FV1 comprises three cells (FV1a, FV1b, and FV1c), while FV2 consists of two cells (FV2a and FV2b), each designed to reduce various physico-chemical and microbiological pollutants from wastewater. Quantitative analyses show significant reductions in electrical conductivity (from 1331 to 1061 μS/cm), biochemical oxygen demand (BOD5 from 655.6 to 2.3 mg/L), chemical oxygen demand (COD from 1240 to 82.2 mg/L), total nitrogen (from 188 to 37.3 mg/L), and phosphates (from 70.9 to 14.6 mg/L). Notably, FV2 outperforms FV1, particularly in decreasing dissolved salts and BOD5 to remarkably low levels. Microbiological assessments reveal a substantial reduction in fecal coliforms, from an initial concentration of 7.5 log CFU/100mL to 3.7 log CFU/100mL, and a complete elimination of helminth eggs, achieving a 100% reduction rate in FV2. The study highlights the impact of design parameters, such as filter material, media depth, and plant species selection, on treatment outcomes. The findings suggest that the judicious choice of these components is critical for optimizing pollutant removal. For instance, different filtration materials show varying efficacies, with silex plus river gravel in FV1c achieving superior pollutant reduction rates. In conclusion, VFFs emerge as a promising solution for wastewater treatment, underscoring the importance of design optimization to enhance system efficiency. Continuous monitoring and adaptation of treatment practices are imperative to ensure water quality, allowing for safe environmental discharge or water reuse. The research advocates for ongoing improvements in wastewater treatment technologies, considering the environmental challenges of the current era. The study concludes with a call for further research to maximize the effectiveness of VFFs in water management.

Keywords

Phytoremediation, Phytopurification, Plant-Based Purifier, Wastewater Treatment, Vertical Flow Filters, Pollutant Reduction, Typha, Physicochemical Analysis, Microbial Removal

1. Introduction

Access to clean and safe drinking water is a fundamental issue for public health and the well-being of populations worldwide. However, in many regions, particularly in developing countries, the supply of fresh water is increasingly threatened by the escalating pollution of wastewater from industrial, agricultural, and domestic activities [1]. Proper wastewater management is imperative to prevent the spread of waterborne diseases and to minimize adverse effects on the environment [2]. In this context, wastewater treatment systems play a pivotal role in purifying contaminated water before it is discharged into the environment or reused. Among the various treatment technologies available, vertical flow filters have emerged as promising solutions for effectively removing contaminants from wastewater [3]. These systems offer several advantages, including their simple design, low operational costs, and adaptability to diverse environmental conditions [4]. The aim of this study is to evaluate the performance of two vertical flow filters designed for wastewater treatment, based on a case study conducted at Gaston Berger University in Saint-Louis, Senegal. This West African region faces significant challenges in wastewater management due to rapid population growth and increased urbanization [5]. The wastewater treatment prototype installed at Gaston Berger University provides a unique opportunity to examine the efficacy and sustainability of these vertical flow filters under local environmental conditions. This study aims to contribute to the existing knowledge on wastewater treatment technologies by providing empirical data on the performance of these systems in a real-world context [6]. The primary aim of this research is to evaluate the efficacy of continuous vertical flow filters in wastewater treatment. Specifically, we seek to 1) ascertain the reduction rates of physicochemical and microbiological contaminants through these systems, 2) examine the influence of design and operational parameters on filter performance, and 3) assess the suitability of treated water for agricultural reuse, ensuring compliance with Senegalese reuse standards. Additionally, this study intends to compare the effectiveness of these filters with conventional wastewater treatment methodologies, addressing the unique environmental challenges in the northern region of Senegal. In the sections to follow, we will detail the methodology of our study, present the technical characteristics of the evaluated vertical flow filters, analyze the results obtained, and discuss the implications of our findings for sustainable wastewater management in the Saint-Louis region of Senegal, as well as for other regions facing similar challenges.

2. Materials and Methods

2.1. Description of the Study Area

The study area is located in the northern region of Senegal, more precisely within the precincts of Gaston Berger University, which is situated approximately 12 km from the city of Saint-Louis on the national road N2 leading to Richard-Toll or the Mauritanian border. It falls within the rural community of Gandon and is positioned between the two villages of SanarPeulh and Sanar Wolof. The purification system, constructed in recent years, comprises: 1) a manually cleaned coarse screen along with a sand cleaner; 2) a first French-type reed-planted filter (FPR) consisting of three cells of 24 m^2 each, totaling 72 m^2 for pretreatment and primary treatment; 3) a second French-type FPR consisting of two cells of 24 m^2 each, totaling 48 m^2 for secondary treatment; 4) a third refinement filter of horizontal FPR type, consisting of two cells of 36 m^2 each, totaling 72 m^2.

2.2. Description of the Pilot Station

The layout of the treatment prototype is depicted in **Figure 1**. It is composed of the following elements:

Pretreatment: Raw wastewater passes through a pretreatment system for the removal of large solids and sands. Given the area's frequent sandstorms, emphasis has been placed on sand separation. French-style vertical wetlands or vertical flow (VF) filters allow for the treatment of raw wastewater with a very simple

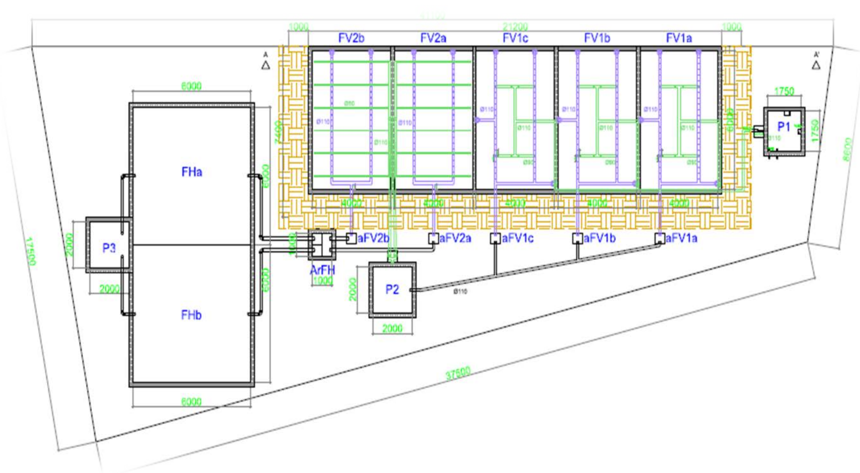


Figure 1. Schematic of the wastewater treatment prototype.

pretreatment for the separation of large solids [7]. For this particular project, a sand classifier is installed due to the high quantity of sand in the wastewater, to delay or prevent clogging in the downstream filters.

First pumping (P1): After passing through the pretreatment filter, the wastewater is channeled by gravity to a pumping well P1, equipped with two grinder pumps as a precaution. There are two level floats in this well: one for the minimum or stop, one for the start, and the other for safety, with the aim that both pumps start in case of a hydraulic overload or a failure of one of them. There is also an overflow weir as a precaution against power supply failure, to prevent the well from overflowing. These pumps operate alternately, which improves the efficiency of the motors. The pump lines include a non-return valve and manual keys. Besides the well, there is a manual distribution sump, which directs the wastewater to the different treatment cells FV1a, FV1b, and FV1c.

First vertical filter (FV1): Pump P1 directs the wastewater to the first filter FV1 consisting of vertical subsurface flow wetlands (FV1a, FV1b, and FV1c) with a surface area of 32 m^2 each. These wetlands are fed in an alternating manner, for periods of 3.5 days of feeding and 3.5 days of rest using manual ball valves. The protocol is as follows: on the first day, open the valve leading to the cell FV1a, and the other two valves are closed. After 3.5 days, open the valve leading to cell FV1b, and close the valve of cell FV1a. After another 3.5 days, open the valve of cell FV1c and close the valve of cell FV1b. It is important to always open and close the corresponding valves first to prevent a moment when all valves are closed while the pumps are operating, to lessen the risks of pump and pipe rupture. At the exit of the wetland, the partially treated effluent goes into the sumps aFV1a, aFV1b, and aFV1c by gravity flow. These serve for sampling and measuring flow profiles. From these sumps, the water flows by gravity to the pumping well P2.

Pumping well (P2): After the first filter FV1, the wastewater arrives by gravity at the pumping well P2, equipped with two pumps of 0.3 kW. In this well, as in well P1, there are two level floats assembled with the pumps whose operation is similar to the pump-float pairs of well P1. They are also equipped with non-return valves, manual ball keys.

Second vertical filter (FV2): The second filter FV2 consists of two cells with dimensions of 8 × 4 m. The water pumped from well P2 enters these wetlands through 50 mm diameter perforated PVC pipes in a "comb" shape, ensuring homogeneous distribution of water over the entire surface. These wetlands have feeding and resting regimes of 3.5 days each, just like in the first filter FV1, through opening and closing by manual ball keys. Once drained in the wetland, the water flows by gravity to the exit sumps aFV2a and aFV2b. These sumps have been designed for sampling and performing flow profiles in the wetlands.

Distribution sump (ArFH): At the exit of sumps aFV2a and aFV2b, there is a distribution sump where the wastewater will arrive by gravity. The function of this sump is the equitable distribution of wastewater to the two cells of the horizontal flow wetland FH.

Horizontal filter (FH): From the distribution sump ArFH, the water arrives by gravity to the influent piping of the horizontal flow wetland called horizontal filter (FH) composed of two cells FHa and FHb, through some perforations in the piping that connects it to the distribution sump ArFH. Thanks to the slope of the wetland's bottom, the water traverses the filter medium in a horizontal direction. At the end of the course, the water is ollectedvia a perforated "L"-shaped piping located at the bottom of the filter and conveyed to well P3.

2.3. Filterfeeding Period

The details of the operational parameters of the pilot station are recorded in Table 1. The pilot station has an average treatment capacity of 4.5 m^3 per day. The Reed Planted Filtering Beds with Vertical Flow (LFPR) were used intermittently, with flooding phases alternating with drainage periods. The number of flooding-drainage cycles was set to 10 per day for both types of vertical filters, with each cycle lasting 2 minutes. To test the effect of rest phases on the filter's efficiency, two flooding regimes were established for the same flow rate, with different feeding sequences. Consequently, two distinct operational periods were established: the first with no rest period, feeding all filters continuously, and the second following a conventional feeding approach with rest periods, where the V1 filters were alternately fed for 3 to 4 days, then left to rest for 7 days; similarly, the V2 filters were intermittently fed for 3 to 4 days, followed by a rest period of 7 days. In the context of this study, we focus exclusively on the vertical wetland zones in the operational mode corresponding to period 2 (feeding-rest). The design parameters of the two vertical filters are described in Table 2. All filter cells are planted with Typha and have the same dimensions (8 × 4 m) and area (32 m^2). There are differences regarding the depth and the nature of the filtering bed.

2.4. 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.

Table 1. Operational modes of the vertical filters.

Period		Vertical filter 1 (FV1)			Vertical filter 2 (FV2)		
	Duration (months)	Feeding/rest (days)	Filters in operation (m^3/days)	Number of cycles per day	Feeding/rest (days)	Filters in operation (m^3/days)	Number of cycles 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

Table 2. Design parameters of vertical filters FV1 and FV2. CU refers to the coefficient of uniformity, and d10 is the diameter at which 10% of the sample's mass is finer.

Filters	Cells	Depth (cm)	Material	Granulometry	Plant
FV1	FV1a	70	Flint	3 - 8 mm	Typha (Phragmites)
	FV1b	70	Granite	3 - 8 mm	Typha (Phragmites)
	FV1c	15	River gravel	3 - 8 mm	Typha (Phragmites)
FV2	FV2a	90	River sand	d10 = 0.27 CU = 3.6	Phragmites
	FV2b	70	River sand	d10 = 0.27 CU = 3.7	Phragmites

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 [8]. 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 [9] at the Wastewater Treatment and Water Pollution Laboratory of Cheikh Anta Diop University, in Dakar, Senegal [10]. 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 [8]. In the remainder of this study, we will focus exclusively on the water quality at the output of the vertical filters.

2.5. Data Analysis

Statistical analyses were performed on the raw data using Excel 2016 and IBM-SPSS Statistics [11]. 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. Physicochemical Quality of Treated Wastewater

Table 3 presents the values of parameters measured at different stages of the water treatment process. Data are distributed across columns corresponding to various filters of the treatment (Influent of the pilot installation, pretreatment effluent, first filter FV1 consisting of cells FV1a, FV1b, and FV1c, second filter

FV2 consisting of cells FV2a and FV2b) and rows representing the measured parameters T, EC, pH, SS, BOD5, COD, N-TN, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, and $P\text{-}PO_4^{3-}$. Based on the analysis results obtained and presented in Table 3, pollutant removal rates are calculated relative to the average values and presented in Table 4. The removal rates for pretreatment, the first filter FV1, and the second filter FV2 are calculated relative to the parameter values in the influent, after pretreatment, and the average of the first filter FV1, respectively.

Table 3. Average water quality and standard deviation.

Parameters	Influent	Pretreatment	First filter (FV1)			Second filter (FV2)	
			FV1a	FV1b	FV1c	FV2a	FV2b
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
EC (mS/cm)	1331 ± 170	1420 ± 129	1179 ± 91	1314 ± 132	1191 ± 94	888.0 ± 301	1061 ± 122
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
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
BOD5 (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
COD (mg/L)	1240 ± 589	1063 ± 293	239.2 ± 58	268,7 ± 83	188.5 ± 31	94.0 ± 36	82.2 ± 39
N-TN (mg/L)	188 ± 82	138.2 ± 29	68.2 ± 17	73.0 ± 19	79.8 ± 8	38.6 ± 21	37.3 ± 17
$N\text{-}NH_4^+$ (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
$N\text{-}NO_3^-$ (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
$P\text{-}PO_4^{3-}$ (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

Table 4. Removal rates of parameters.

Parameters	Pretreatment removal rate (%)	FV1 removal rate (%)			FV2 removal rate (%)	
		FV1a	FV1b	FV1c	FV2a	FV2b
EC (mS/cm)	**−6.7**	16.9	7.5	16.1	27.7	13.6
SS (mg/L)	45.9	84.7	83.5	87.3	96.9	76.3
BOD5 (mg/L)	24.4	78.2	77.1	83.6	99.5	97.7
COD (mg/L)	14.2	77.5	74.7	82.3	91.2	64.6
N-TN (mg/L)	26.5	50.6	47.2	47.2	72.1	49.4
$N\text{-}NH_4^+$ (mg/L)	23.8	58.0	57.1	57.4	95.2	91.7
$N\text{-}NO_3^-$ (mg/L)	37.2	**−692**	**−588**	**−690**	**−1063.0**	**−45.8**
$P\text{-}PO_4^{3-}$ (mg/L)	3.1	30.1	22.2	35.7	81.1	69.9

Table 3 demonstrates the efficiency of the water treatment process, with data showing significant reductions of various contaminants. The temperature remains stable around 26˚C. Electrical conductivity decreases from 1331 to 1061 mS/cm, and pH drops from 7.7 to 5.8, indicating chemical changes. Suspended solids are drastically reduced from 718.9 to 13.7 mg/L. Biochemical oxygen demand (BOD5) and chemical oxygen demand (COD) respectively decrease from 655.6 to 2.3 mg/L and from 1240 to 82.2 mg/L, reflecting the elimination of organic matter. Total nitrogen (N-TN) and ammonia nitrogen ($N\text{-}NH_4^+$) also decrease, from 188 to 37.3 mg/L and from 130.9 to 3.5 mg/L, respectively. Nitrate nitrogen ($N\text{-}NO_3^-$) slightly increases before decreasing, from 4.3 to 29.8 mg/L, while phosphorus ($P\text{-}PO_4^{3-}$) drops from 70.9 to 14.6 mg/L. These results indicate an overall improvement in water quality throughout the treatment.

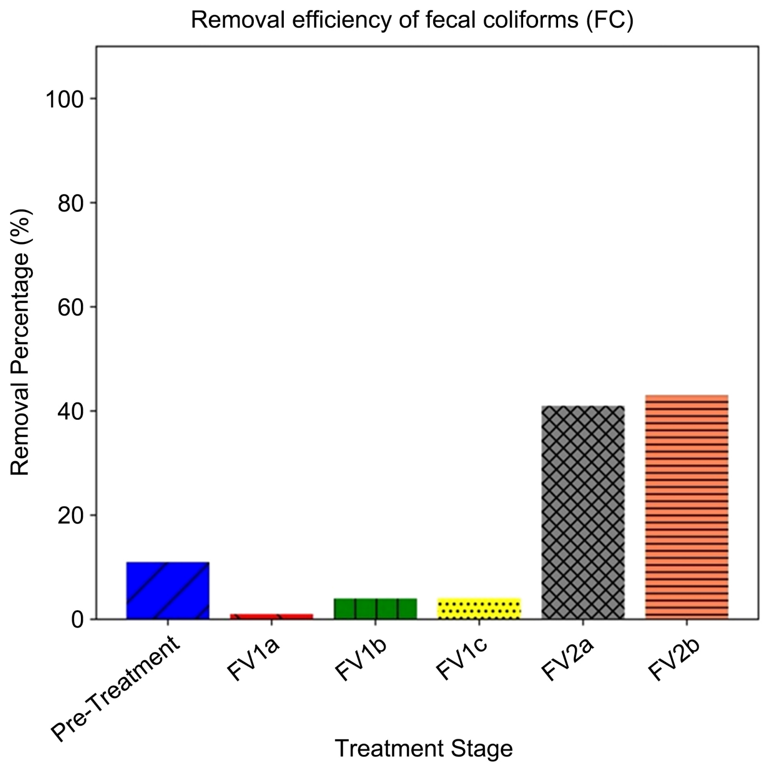
Table 4 shows that during pretreatment, there is a slight increase in electrical conductivity (−6.7%) and a moderate elimination of other pollutants, with reductions of 24.4% for BOD5, 14.2% for COD, and 26.5% for total nitrogen. In the FV1 filters, pollutant removal improves considerably, reaching up to 87.3% for suspended solids, 97.7% for BOD5, and 77.5% for COD. The FV2 filters continue this trend, especially for ammonia nitrogen with a removal reaching up to 95.2%. However, the treatment initially increases nitrate levels (negative values in FV1 and FV2 filters) before slightly reducing them in the FV2 filters. Phosphorus is also better removed in the later stages, with a reduction of up to 73.3% in the FV2 filters.

3.2. Microbiological Quality of Treated Water

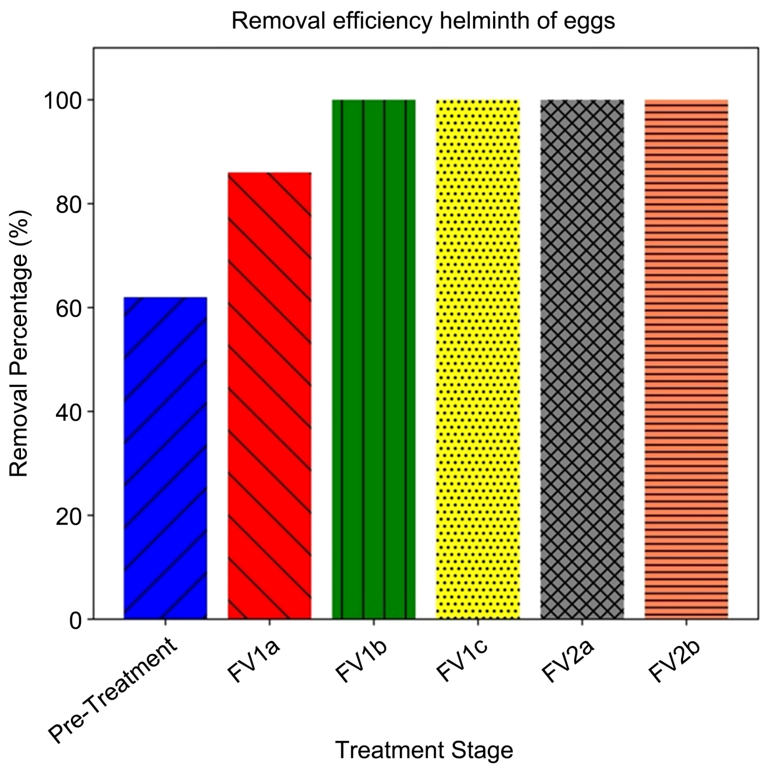
Table 5 presents the concentrations and removal rates of microbiological indicators, namely fecal coliforms and helminth eggs, by the treatment system. The changes in the removal rates of fecal coliforms (FC) (a) and helminth eggs (HE) (b) according to the different stages of treatment are presented in Figure 2.

Table 5. Concentration and removal rate of microbiological indicators (fecal coliforms and helminth eggs).

Indicator		Influent	Pretreatment	Filter FV1			Filter FV2	
				FV1a	FV1b	FV1c	FV2a	FV2b
Fecal Coliforms (Ulog/100 mL)	Average	7.5	6.7	6.6	6.4	6.4	3.8	3.7
	Max	8.1	7.1	7.1	6.7	6.7	4.5	3.8
	Min	7.2	6.4	6.4	6.0	6.0	3.5	3.5
	Ulog reduction		0.8	0.1	0.1	0.3	2.9	3.0
	Removal rate (%)	-	11%	1%	4%	4%	41%	43%
Helminth Eggs (Eggs/L)	Average	13	5	0.7	0	0	0	0
	Removal rate (%)	-	62%	86%	100%	100%	100%	100%



(a)



(b)

Figure 2. (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.

Regarding fecal coliforms, the average influent concentration is 7.5 Ulog/100mL, varying from a minimum of 7.2 to a maximum of 8.1. After pretreatment, the average concentration is reduced to 6.7 Ulog/100mL, with a minimum of 6.4 and a maximum of 7.1. At FV1a, the concentration remains relatively stable at 6.6 Ulog/100mL, while FV1b and FV1c maintain similar values. The greatest reduction in fecal coliform concentration occurs at FV2a and FV2b, with values of 6.4 and 3.8 Ulog/100mL, respectively. The Ulog results show a significant decrease in concentration after pretreatment, with a maximum reduction of 3.0 Ulog in FV2b. Concerning Helminth Eggs, the influent concentration is 13.0E2 Eggs/L, equating to 169 Eggs/L. Pretreatment has reduced this concentration to 5.0E3 Eggs/L, or 125 Eggs/L. The first vertical flow filter (FV1a, FV1b, and FV1c) continues to reduce the concentration, reaching a concentration of 0.7E3 Eggs/L, or 0.343 Eggs/L, in FV1c. The second vertical flow filter (FV2a and FV2b) has succeeded in completely eliminating helminth eggs, achieving a reduction rate of 100%. The results indicate a significant improvement in water quality throughout the treatment process. Fecal coliforms have been notably reduced from the pretreatment stage, with the minimum concentration observed in FV2b. This suggests that the treatment system was effective in eliminating these microbiological contaminants [12]. Regarding helminth eggs, the treatment has also been highly effective, with a reduction in concentration from 169 Eggs/L to a negligible concentration in FV2b. This indicates that the vertical flow filtration system was capable of retaining and eliminating these contaminants at a rate of 100% [13]. These results demonstrate the efficacy of the water treatment process in reducing the microbial load in water, thus ensuring better water quality for discharge into the environment or reuse. However, it is essential to maintain and regularly monitor the treatment system to ensure its long-term performance [14].

3.3. Operating and Design Parameters

We will examine the effect of different manipulated variables ($p \geq 0.05$) of design and operation on the removal of several parameters in our filtration system. The analyzed parameters include the concentration of SS, BOD5, COD, $N\text{-}NH_4^+$, $P\text{-}PO_4^{3-}$, and fecal coliforms. The variables examined are the filter material, the depth of the filter media, the plant species, and the operating modes of the vertical filters. The design and operation variables on parameter removal are represented in **Table 6**. Regarding the gravel material used in the first phase of the filters, significant variations were observed for the FV1c filter (flint gravel + 15 cm of 3 - 8 mm river gravel). This filter showed higher removal rates for most parameters. However, no significant difference was observed between FV1a (flint gravel) and FV1b (granite). For the second phase of vertical filters, the depth of the sand filters did not show significant differences in parameters. Both filters showed similar removal rates, likely due to the minor differences in sand height (20 cm), which were not sufficient to have a notable impact. The effect of the filter material on parameter removal is significant (S) for all parameters

Table 6. Effect of design and operation variables on parameter removal (S = Significant Effect).

Variable	Parameters					
	SS	BOD5	COD	$N\text{-}NH_4^+$	$P\text{-}PO_4^{3-}$	FC
Matériau filtrant (FV1a, FV1b, FV1c) (flint, granite, flint + river gravel)	S	S	S		S	S
Depth of Filter Media (FV2a, FV2b) (70 cm, 90 cm off sand)						
Plant Species	S	S	S	S	S	

except for the depth of the filter media (FV2a, FV2b). The three types of filter materials (flint, granite, and flint + river gravel) appear to have a significant impact on the removal of these parameters. This indicates that the choice of filter material is crucial for the efficient operation of the filtration system. Unlike the filter material, the depth of the filter media does not have a significant effect on parameter removal. This means that, in the context of this study, the variation in filter media depth between 70 cm and 90 cm of sand did not have a statistically significant impact on filtration performance. However, it should be noted that filters with greater depth generally provide better nitrogen removal [15]. Plant species have shown a significant effect on the removal of all parameter [16]. This suggests that the choice of plant species in the filtration system plays an essential role in the system's ability to effectively remove parameters such as SS, BOD5, COD, $N\text{-}NH_4^+$, $P\text{-}PO_4^{3-}$, and fecal coliforms. The operating modes of the vertical filters, according to [17], also have a significant impact on parameter removal. The "rest" and "sequential feeding" have variable effects on different parameters, indicating that the choice of operating mode can be important depending on the specific goals of pollutant removal.

3.4. Prospects for Reuse of Treated Water

Before their discharge or reuse, wastewater must be rid of its polluting elements, whether organic or chemical. This step is crucial for the preservation of natural environments and public health [18]. In **Table 7**, we present the analysis results obtained at the two vertical filters and compare them to the more stringent Senegalese standard [19] which is more demanding than international standards [20] [21]. From the analysis of **Table 7** we can draw the following conclusions. The temperature (T) is below the standard limit in all cases. The values of electrical conductivity (EC) are below the standard limit in all cases. The pH values are compliant with the standard for FV1a, FV1b, and FV1c. However, the pH values for FV2a and FV2b are significantly below the standard limit. The SS values exceed the standard limit for FV1a, FV1b, and FV1c. FV2a and FV2b are compliant with the standard regarding SS. The BOD5 values for FV1a, FV1b, and FV1c greatly exceed the standard limit. FV2a and FV2b comply with the

Table 7. Comparison of treated water analysis results to Senegalese discharge standards.

Parameters	Senegalese Discharge Standard Limit [19]	FV1			FV2	
		FV1a	FV1b	FV1c	FV2a	FV2b
T (˚C)	30	27.8 ± 0.9	27.2 ± 1.1	27.1 ± 1.4	26.1 ± 0.6	26.2 ± 0.5
EC (mS/cm)	2000	1179 ± 91	1314 ± 132	1191 ± 94	888.0 ± 301	1061 ± 122
pH	9.5	7.8 ± 0.2	8.3 ± 0.1	8.1 ± 0.1	5.7 ± 0.4	5.8 ± 0.4
SS (mg/L)	40	**59.7** ± 31	**64.0** ± 14	**49.5** ± 11	11.9 ± 4.2	13.7 ± 4.3
BOD5 (mg/L)	50	**107.9** ± 68	**113.4** ± 57	**81.0** ± 32	2.4 ± 1.6	2.3 ± 1.7
COD (mg/L)	200	**239.2** ± 58	**268.7** ± 83	188.5 ± 31	94.0 ± 36	82.2 ± 39
N-TN (mg/L)	30	**68.2** ± 17	**73.0** ± 19	**79.8** ± 8	**38.6** ± 21	**37.3** ± 17
$N\text{-}NH_4^+$ (mg/L)	30	**41.9** ± 11	**42.8** ± 13	**42.5** ± 14	4.8 ± 2.4	3.5 ± 2.1
$N\text{-}NO_3^-$ (mg/L)	30	21.4 ± 9.7	18.6 ± 8.6	21.3 ± 11	31.4 ± 12	29.8 ± 11
$P\text{-}PO_4^{3-}$ (mg/L)	10	**48.1** ± 25	**53.5** ± 21	**44.2** ± 23	**13.0** ± 5.2	**14.6** ± 4.8

standard limit for BOD5. The COD values for FV1a, FV1b, and FV1c are all above the standard limit. FV2a and FV2b are compliant with the standard regarding COD. The N-TN values for FV1a, FV1b, and FV1c exceed the standard limit. FV2a and FV2b are compliant with the standard for N-TN. The ammonium ($N\text{-}NH_4^+$) values for FV1a, FV1b, and FV1c are within the standard. FV2a and FV2b are also compliant with the standard regarding ammonium. The nitrate ($N\text{-}NO_3^-$) values are within the standard for FV1a, FV1b, FV1c, and FV2a. FV2b slightly exceeds the standard limit for nitrates. The phosphorus ($P\text{-}PO_4^{3-}$) values for FV1a, FV1b, and FV1c greatly exceed the standard limit. FV2a and FV2b comply with the standard limit for phosphorus considering the variance of intrinsic concentrations. The results indicate that FV2a and FV2b generally conform better to the Senegalese standards for wastewater discharge and reuse (NS 05-061) than FV1a, FV1b, and FV1c (first filter), which is explained by the serial operation of the FV1 and FV2 filters.

4. Discussion

4.1. Removal of Physicochemical Parameters

The results presented in Table 3 and Table 4 show that the system is generally effective in reducing temperature, electrical conductivity, suspended solids, biochemical oxygen demand, chemical oxygen demand, and the concentrations of total nitrogen as well as phosphorus. Figure 3 show the evolution of various water quality parameters through the different treatment stages, complete with error bars that represent the standard deviation. This visualization helps to observe the changes in each parameter and understand the efficiency and effectiveness of

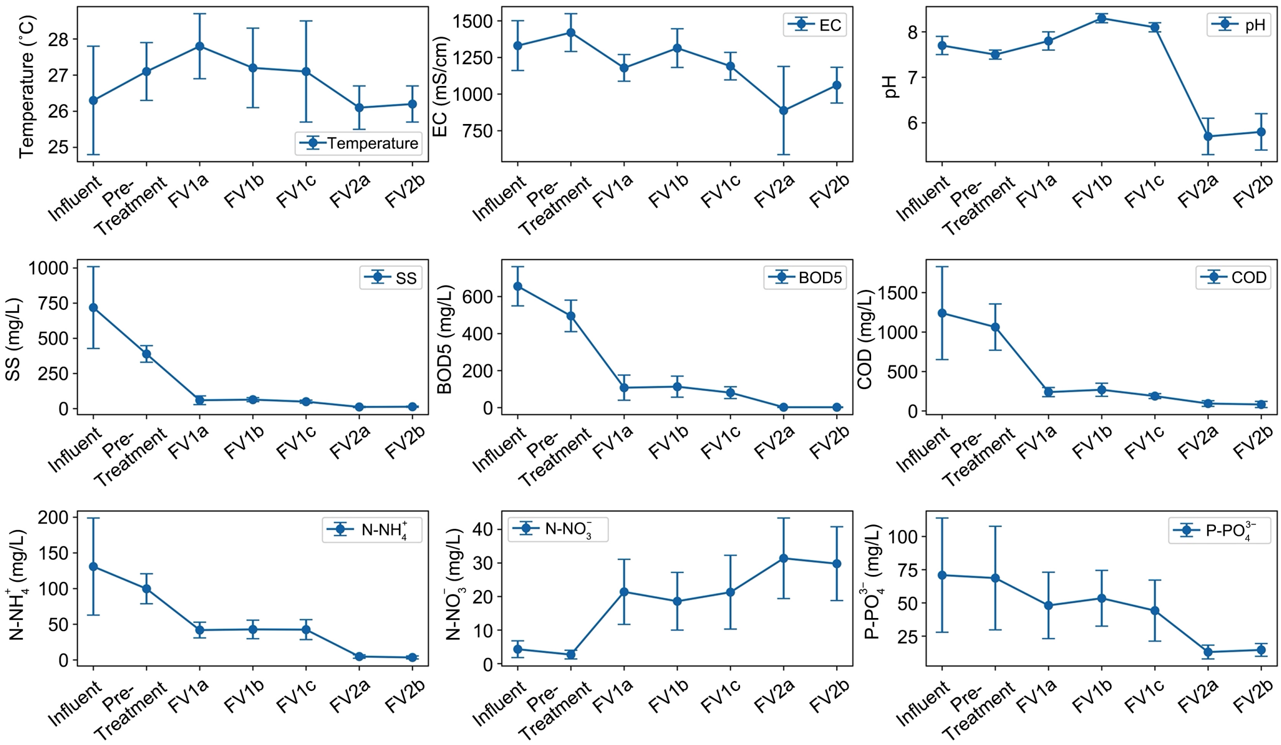


Figure 3. The evolution of various water quality parameters through the different treatment stages, complete with error bars that represent the standard deviation.

each treatment stage. These substantial reductions indicate a promising ability to remove organic matter, dissolved ions, suspended solids, and nutrients [22]. The stability of temperature suggests an isothermal treatment process, which is important for the biological performance of the filters [23]. The progressive reduction of electrical conductivity (EC) indicates the treatment's effectiveness in removing dissolved salts [24]. However, a significant observation is the substantial variation in pH throughout the treatment process. This trend from slight alkalinity in the pretreatment effluent to notable acidity in the second vertical flow filter can affect the biodegradability of organic compounds and the solubility of ions [25]. Adjustments to pH or appropriate control mechanisms should be considered to maintain optimal conditions throughout the process. The variation in pH may also be attributed to bioactivity in the filters, particularly nitrification and denitrification, which affect the acid-base balance [26]. The notable decrease in SS is a classic indicator of the effectiveness of mechanical and biological treatment in particle reduction [27]. The decrease in BOD5 and COD values demonstrates efficient removal of organic matter, a key indicator in the performance of wastewater treatments [28]. Data on nitrogen forms (ammoniacal - $N\text{-}NH_4^+$ and nitric - $N\text{-}NO_3^-$) reveal significant reductions throughout the treatment, indicating good performance in the removal of these critical components. The evolution of different nitrogen forms indicates the biological processes of nitrification and denitrification at play [29]. The reduction of phosphorus can be attributed to adsorption, precipitation, or biological assimilation [30]. The two-filter treatment system studied demonstrates notable efficiency in eliminating various pollutants from wastewater. It offers significant prospects for improving wastewater treatment systems to reduce the environmental impact of discharges. Further research can focus on optimizing operational parameters to ensure maximum system efficiency.

4.2. Elimination of Microbiological Indicators

Our study's results on the concentration and elimination of microbiological indicators, namely fecal coliforms and helminth eggs, presented in **Table 5**, within our treatment system, are significant and indicative of the treatment process's efficacy. This discussion will highlight the implications of these findings and the important considerations for water quality and public health. Fecal coliforms are bacteria indicative of fecal contamination of water [31]. Our results clearly show that the treatment process has significantly reduced the concentration of these bacteria at each stage. Pretreatment led to a notable reduction in fecal coliform concentration, indicating that the initial stages of treatment were effective in removing a significant portion of these bacteria. The vertical flow filters (FV1a, FV1b, FV1c, FV2a, and FV2b) played a crucial role in further reducing the concentration. The minimum concentration observed in FV2b, at 3.8 Ulog/100mL, attests to their efficiency in effectively eliminating fecal coliforms. The results also show that the fecal coliform concentration continues to decrease as the water moves through the treatment system. This progressive reduction suggests that the treatment process is robust and capable of maintaining high water quality. These results are extremely encouraging from a water safety perspective. Reducing fecal coliforms is essential to prevent waterborne diseases and ensure the quality of drinking water [32]. Helminth eggs are intestinal parasites that can be dangerous to human health [33]. Our results show that the treatment system has succeeded in completely eliminating these parasites, which is a remarkable outcome with significant reduction evident from pretreatment followed by complete elimination in the vertical filters. Helminth eggs were reduced from 169 Eggs/L to 125 Eggs/L in the pretreatment stage, indicating that this first step also played a crucial role. The vertical flow filters (FV2a and FV2b) achieved total elimination of helminth eggs, with a reduction rate of 100%. This means that the treated water no longer contains dangerous parasites. This complete removal of helminth eggs is of paramount importance for public health, as it ensures that the treated water does not pose a threat for the transmission of these parasites. The remarkable efficiency of the FV2 filters in eliminating fecal coliforms and helminth eggs can be explained by the treatment principles of constructed wetland systems, as detailed in [34], which highlight the importance of physical filtration, adsorption, and natural disinfection. These systems also utilize mechanisms of predation and microbial competition, described in [34]. The works of [23] provide a theoretical basis to understand how alternating anoxic/oxic conditions improve pathogen removal. Finally, WHO guidelines [35] establish standards for pathogen reduction in treated waters, which is consistent with the high elimination rates observed in the filters FV2. All these academic references support the results obtained and shed light on the mechanisms by which the filters achieve such efficacy in improving the microbiological quality of water.

4.3. Influence of Design Parameters

The results of the analysis of the effects of design and operation variables on the removal of parameters in the filtration system, presented in **Table 6** are rich in information and offer significant insights for the design and optimization of such systems. This discussion focuses on the main conclusions and implications of the results.

4.3.1. Filter Material

One of the highlights of this study is the significant effect of the filter material on the removal of parameters. It is clear that the choice of filter material (see **Table 2**) plays a crucial role in the overall efficiency of the filtration system. The three types of filter materials tested (flint, granite, and flint + river gravel) have shown significant differences in their ability to remove pollutants. Further studies would be interesting to understand in detail why certain materials proved to be more effective than others. This could involve specific physical and chemical properties of the materials, such as porosity, grain size, adsorption capacity, etc., as highlighted by [25] [36]. Therefore, the choice of filter material must be carefully considered based on the water treatment objectives.

4.3.2. Depth of Filter Material

Unlike the filter material, the depth of the filter media did not show a significant effect on the removal of parameters in this study. This suggests that, at least in the context of this experiment, the variation in filter media depth between 70 cm and 90 cm of sand did not have a major impact on filtration performance. However, it is important to note that other studies reveal significant effects at different filter media depths or in other types of media, such as [37] which focuses on the long-term performance of stormwater management biofilters. Therefore, the depth of the filter media remains a variable to monitor, especially for larger-scale filtration systems.

4.3.3. Plant Species

In our study, a choice was made for an invasive local plant, Typha [38]. Generally, many studies have shown that the type of plant species has a significant impact on the removal of all studied parameters [39] [40]. Different plant species may have specific phytoremediation mechanisms, such as nutrient uptake or degradation of organic pollutants. Consequently, the choice of plant species should be tailored to the target contaminants. Further research would be useful to identify the most appropriate plant species for specific water treatment conditions. Additionally, implementing proper landscaping techniques and managing plant species could further optimize the system's effectiveness. In summary, this study highlights the importance of considering design and operation variables in planning and managing filtration systems for pollutant removal. The choice of filter material, plant species, and operating mode must be based on specific treatment objectives and the characteristics of the contaminants to be removed.

4.4. Prospects for Reuse of Treated Water

The results presented in **Table 7** provide a thorough assessment of the water quality treated by the two vertical filters, highlighting compliance with discharge standards and possibilities for wastewater reuse according to Senegalese [19] or international standards [20] [21]. The findings highlighted several key points. Overall, the water treated by the two vertical filters demonstrated satisfactory quality across a wide range of parameters. Temperature (T), electrical conductivity (EC), pH, suspended solids (SS), biochemical oxygen demand (BOD5), chemical oxygen demand (COD), total nitrogen (N-TN), ammonium ($N\text{-}NH_4^+$), nitrate ($N\text{-}NO_3^-$), and phosphate ($P\text{-}PO_4^{3-}$) mostly remained in compliance with the discharge limits specified by the Senegalese standard. These results open promising perspectives for the reuse of treated water in various application fields, thus contributing to the sustainable management of water resources and environmental conservation. However, it is important to note that some variations were observed, particularly regarding the concentrations of nitrate and phosphate, underscoring the need to implement a horizontal filter at the exit of a vertical filter to ensure the appropriate use of treated water. Water quality standards may vary depending on specific uses, such as agricultural irrigation, vehicle washing, or discharge into the receiving environment, and it is therefore crucial to adjust treatment protocols accordingly. Ultimately, the results reinforce the importance of using vertical filters as an effective method of wastewater treatment, while highlighting the importance of monitoring, the necessity of adding a horizontal filter, and appropriate regulation to ensure water quality and environmental protection. For the future, it is essential to continue studies and efforts to further improve wastewater treatment methods and ensure the availability of quality water to meet the growing needs of society.

5. Conclusion

In conclusion, our study aimed at evaluating the performance of two types of vertical filters operating in series, designated as FV1 (FV1a, FV1b, FV1c) and FV2 (FV2a, FV2b), in wastewater treatment, has revealed significant results and marked differences between these two systems. Data gathered from several key parameters provided a comprehensive overview of the efficacy of each filter, as well as the factors influencing their performance. Overall, the two vertical filters proved to be effective water treatment solutions, capable of satisfactorily removing various pollutants. However, substantial differences were observed. The second filter (FV2a, FV2b) demonstrated a significantly higher reduction in electrical conductivity, indicating better removal of dissolved salts compared to the first filter (FV1a, FV1b, FV1c). For biochemical oxygen demand (BOD5), the second filter showed an even more considerable reduction, reaching very low levels, while the first filter also achieved significant reduction. Notable differences were also observed in the performance of ammoniacal nitrogen ($N\text{-}NH_4^+$) and nitric nitrogen ($N\text{-}NO_3^-$), with a higher removal of ammoniacal nitrogen in the first filter and a significant reduction of nitric nitrogen in the second filter. The first filter yielded better results regarding the removal of total nitrogen (N-TN) and phosphorus ($P\text{-}PO_4^{3-}$). It is crucial to emphasize that these differences can be attributed to design factors such as filter material, depth of filter media, plant species, and modes of operation of the vertical filters. These elements have a significant impact on filter performance, thus offering opportunities for optimization to meet specific treatment needs. Vertical filters emerge as a promising technology for wastewater treatment. However, their continuous optimization, exploration of new applications, and collaboration among water stakeholders are essential to meet the challenges of water management in the era of climate change and increasing environmental pressures. Ultimately, the choice between the two vertical filters will depend on treatment objectives, local constraints, and priorities for the removal of specific pollutants. Our study highlights the importance of optimizing design and operation variables to maximize the effectiveness of wastewater treatment systems. These results contribute to our understanding of the performance of vertical filters in water treatment and pave the way for ongoing improvements in this crucial technology for water management.

Conflicts of Interest

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

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