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Ecological Wastewater Treatment System in a School Environment Using a Horizontal Flow Biological Reactor: The Case of Typha

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Abstract

The overarching goal of this study is to offer an effective and sustainable solution to the challenges of sanitation in rural and school settings in the northern region of Senegal. The study explores a wastewater treatment approach based on phytoremediation, with a particular focus on the use of horizontally-flowing reed bed filters. Furthermore, it aims to adapt and optimize these systems for the specific needs of Senegal, focusing on wastewater in school environments. Thus, we constructed a horizontally-flowing reed bed filter, planted with Typha, at the Ndiébène Gandiol school in Senegal. We will investigate the efficiency of wastewater treatment by this horizontally-flowing reed bed filter, emphasizing the role of the plant used: Typha. The filter is described in detail, specifying its dimensions, its composition of flint gravel, and the choice of plants, namely Typha. The experimental protocol is detailed, describing the sampling at the entrance and exit of the filter to evaluate water quality. The parameters analyzed include Chemical Oxygen Demand (COD), Biochemical Oxygen Demand over 5 days (BOD5), suspended solids, ammonium, nitrates, phosphates, pH, conductivity, and fecal coliforms. The results indicate a significant improvement in water quality after treatment. COD, BOD5, suspended solids, and fecal coliforms are greatly reduced, thus demonstrating the efficacy of the Typha filter. However, nitrate concentrations remain relatively stable, suggesting room for improvement in their elimination. A perspective of reuse of the treated water is considered, showing that the effluents from the planted filter meet Senegalese and international standards for irrigation. The findings suggest that these waters could be used for a variety of crops, thereby reducing the pressure on freshwater resources. In conclusion, the Typha-based filtration system shows promising results for improving water quality in this region of Senegal. However, adjustments are necessary for more effective nitrate removal. This study paves the way for sustainable use of treated wastewater for irrigation, thus contributing to food security and the preservation of water resources.

Keywords

Hydraulic Engineering, Wastewater Quality, Wastewater Treatment, Agricultural Irrigation, Sanitation, Engineering, Environment

1. Introduction

Senegal's latest sanitation policy (2016-2025) explicitly aims to contribute to the achievement of the Sustainable Development Goals (SDGs) by ensuring universal access to clean drinking water and sanitation by 2030 while guaranteeing integrated water resource management [1]. The policy emphasizes key elements of SDG 6, which include: (i) household access to sustainable sanitation, (ii) wastewater and rainwater management, and (iii) the eradication of open defecation. Confronting this ambition with the reality on the ground reveals a significant gap. According to data available up to 2021, approximately 56% of the Senegalese population had access to improved sanitation services, such as toilets connected to a sewage disposal system [2]. This indicates that a significant portion of the population still lacks access to adequate sanitation facilities. Sanitation networks, such as sewers, remain limited in many regions of the country, particularly in rural areas. Most sanitation systems are concentrated in urban areas, especially in the capital, Dakar. Wastewater treatment is still insufficient in Senegal. Most of the existing wastewater treatment facilities are located in large cities, while rural areas largely lack them. This leads to pollution of watercourses and groundwater from untreated wastewater. The Senegalese government has taken steps to improve sanitation and wastewater treatment. It launched the Millennium Sanitation Program (PAM) in 2009, which aims to extend access to sanitation across the country. Additionally, the National Sanitation Plan (PNA) was established to improve wastewater management and develop sanitation infrastructure. Senegal also benefits from the support of international bodies such as the World Bank, the African Development Bank, and NGOs, which work in collaboration with the government to strengthen capacities in the sanitation sector. Like many countries, Senegal has committed to achieving the Sustainable Development Goals (SDGs) set by the United Nations General Assembly in 2015 [3] These commitments cover various aspects related to water and sanitation. Despite ongoing efforts and national and international initiatives, challenges remain in sanitation, particularly in rural areas [4]. Alternative wastewater treatment methods, such as reed bed filters, have been studied in various contexts, including in developing countries [5]. These methods have proven effective, but their application requires specific local adaptation. Thus, faced with Senegal's unique challenges, how can phytoremediation-based systems be adapted and optimized for wastewater treatment? Our study addresses this question, seeking to identify gaps and opportunities for improvement. It also aims to formulate recommendations with a focus on sustainable solutions tailored to local needs, with particular attention to school wastewater. The main steps of our study are:

- Conducting field surveys to understand the specifics of the site.
- Analyzing wastewater samples in the laboratory to determine the pollutant load.
- Monitoring the quality of water treated by the filter.
- Conducting a comparative study of the quality of the effluents from the planted filters (average) with the quality requirements or recommendations of Senegal, the EU, and the WHO for the elimination and reuse of water in irrigation.

The structure of this article is as follows: Section 2 details our methodology, Section 3 presents our results, Section 4 discusses their implications, and Section 5 concludes by suggesting future recommendations.

2. Materials and Methods

2.1. Presentation of the Study Area

Ndiebene Gandiol is a commune in Senegal located 20 kilometers from the city of Saint-Louis, near the mouth of the Senegal River. Geographically, Ndiébène lies at the heart of the historic Gandiol region. Since 2014, with the adoption of Act 3 of decentralization, Ndiébène Gandiol has become the capital of the Gandiol commune. Within the Gandiol commune, several schools were explored. However, our study will primarily focus on the Gandiol School, which is considered for implementing an ecological wastewater treatment system. The location and size of the establishment are illustrated in **Figure 1**. The school accommodates 505 students, aged between 7 and 14 years, who are distributed across 12 classrooms. Despite this substantial number, the school has only 4 latrines for students and one reserved for teachers. Unfortunately, none of these latrines are operational. Moreover, the school lacks any water points, being devoid of taps. Its sanitation system is considered non-compliant. Finally, the condition of the toilets is concerning: they are in poor condition, frequently obstructed, and thus unusable for students and teachers most of the time.

2.2. Description of the Filter

The configuration of the horizontally flowing planted filter is presented in 3D in **Figure 2**. The filter consists of two filtering bed cells, each measuring 12 × 8.5 m, preceded by a septic tank. A tank collects the treated water. Both cells have the same depth; the difference lies in the choice of plants, as we aim to determine their influence on water treatment. Similarly, flint gravel is used throughout but at different diameters. At the entrance and exit, over a width of 0.5 m, large gravel covers the pipes for the distribution and recovery of wastewater. In the middle,

Figure 1. Location of the study site: Ndiebene Gandiol School. In yellow, the boundary of the study site.

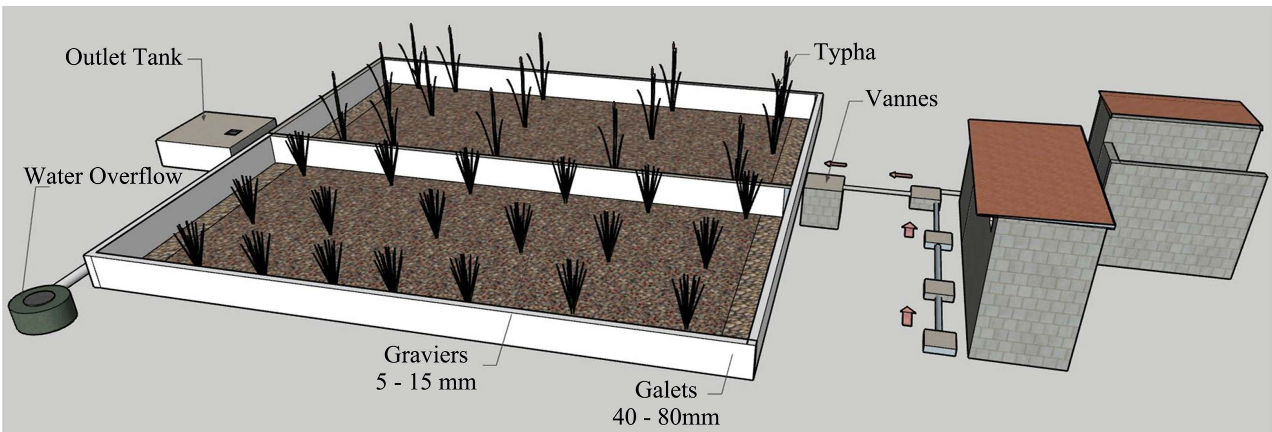

Figure 2. 3D plan of the filter.

between the two layers of large gravel, there are smaller 5 - 15 mm diameter gravels. The filter's characteristics are presented in Table 1. For this study, only the results concerning Typha are presented.

2.3. Experimental Protocol

2.3.1. Sampling Procedure

To assess the water quality at the input and output of the filter, a sampling schedule was established, detailed in Table 2. The parameters analyzed during each sampling campaign are presented in Table 3.

2.3.2. Sample Analysis

In line with the schedule from Table 2, a monitoring program was established as detailed in Table 3. This program involved the collection of samples, followed by their preservation and storage according to standard methods referenced in

Table 1. General characteristics of the filter.

Filter	Dimension	Height	Material	Input and output granulometry over 0.5 m	Middle granulometry	Plant
FHT	12 × 8.5 m	70	Silex	40 - 80 mm	5 - 15 mm	Typha
FHV	12 × 8.5 m	70	Silex	40 - 80 mm	5 - 15 mm	Vetiver

Table 2. Sampling periods.

Sampling campaign No.	Date	Sampling points	Location points
1	Mid-February	3	Septic tank entry, Septic tank exit, FHT exit
2	End of February	3	Septic tank entry, Septic tank exit, FH1 exit
3	Mid-March	2	Septic tank exit, FHT exit
4	Mid-April	2	Septic tank exit, FHT exit
5	Mid-May	2	Septic tank exit, FHT exit
6	Mid-June	3	Septic tank entry, Septic tank exit, FHT exit

Table 3. Parameters sought by sampling campaign.

Sampling campaign No.	SS	COD	BOD5	NH_4^+	NO_3^-	TP	PO_4^{3-}	Fecal coliforms	Helminth eggs	pH	EC
1	x	x	x	x	x	x	x	x	x	x	x
2	x		x	x	x		x	x		x	x
3	x	x	x	x				x			
4	x	x	x					x			
5	x	x	x	x				x	x		
6	x	x	x	x		x	x	x		x	x

[6]. *In situ* measurements of pH, electrical conductivity (EC), and temperature (T) were also performed using portable instruments. The analysis of water quality parameters, including Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD5), Suspended Solids (SS), Total Nitrogen (TN), Ammonia ($N\text{-}NH_4^+$), Nitrates ($N\text{-}NO_3^-$), Phosphates ($P\text{-}PO_4^{3-}$) and Total Phosphorus (TP), was conducted according to French standard methods, referenced in source [5]. These analyses were carried out at the Wastewater Treatment and Water Pollution Laboratory, affiliated with Cheikh Anta Diop University in Dakar, Senegal [7]. For the evaluation of fecal coliforms (FC), the standard method using violet red bile lactose (VRBL) agar was implemented, and the results were expressed in log10 colony-forming units (FCU) per volume unit. The quantification of helminth eggs was carried out in accordance with the standard methods mentioned in reference [6].

2.3.3. Data Processing

Statistical analyses were performed on the raw data using statistical software Excel 2016 and IBM-SPSS Statistics for Windows [8]. Excel 2016 was used for descriptive statistics (averages, maximums, minimums, and standard deviation). IBM-SPSS Statistics was utilized for an analysis of variance (ANOVA). The variance analysis was conducted to evaluate the influence of different design and operational variables on the elimination of pollutants. A statistical significance was established at $p \le 0.05$.

3. Results

3.1. Wastewater Quality

Le Table 4 details the changes in water quality at three specific stages: upon entry into the septic tank, at its exit, and after passing through the Typha filter. For each parameter, average, minimum, maximum, and standard deviation values are provided when available. At the entry, the average COD concentration is 1347 mg/L. After Typha filtration, it drops to 155 mg/L, ranging from 48 mg/L to 358 mg/L. For BOD5, it starts at 259 mg/L and is reduced to 8 mg/L after filtration, ranging from 6 mg/L to 11 mg/L. The suspended solids are reduced from an average of 76 mg/L to 1 mg/L, with a range from 1 to 3 mg/L. Ammonium, denoted as $N\text{-}NH_4^+$, decreases from an average of 248 mg/L to 8 mg/L, fluctuating from 0 to 2 mg/L. Nitrates, $N\text{-}NO_3^-$ maintain a stable average of 30 mg/L after the septic tank and filter. Phosphates, $P\text{-}PO_4^{3-}$ drop from 48 mg/L to 8.6 mg/L after filtration. Regarding pH, it starts at 8.2, slightly increases to 8.5, then falls to 7.9 after passing through the filter. The conductivity, noted as EC, starts at 2950, rises to 3400, then drops to 1710. Finally, fecal coliforms are measured at 830,000 FCU (100 mL) at the entry, drop to 38,000 FCU (100 mL), and settle

Table 4. Water quality results.

Parameter	Septic tank entry	Septic tank exit			Typha filter exit		
	Average	Average	Max	Min	Average	Max	Min
COD (mg/L)	1347	291	500	186	155	358	48
BOD5 (mg/L)	259	78	101	59	8	11	6
SS (mg/L)	76	35	40	33	1	3	1
$N\text{-}NH_4^+$ (mg/L)	248	53	146	15	8	2	0
$N\text{-}NO_3^-$ (mg/L)	30	30			15		
$P\text{-}PO_4^{3-}$ (mg/L)	48	47			8.6		
pH	8.2	8.5			7.9		
EC	2950	3400			1710		
Fecal coliforms FCU (100 mL)	8.30E+05	3.80E+04	5.40E+04	2.30E+04	170	300	0
Fecal coliforms (Log10)	5.9	4.6	4.7	4.4	2.2	2.5	0
Helminth eggs (Larvae eels)		0			0		

at 170 FCU (100 mL) after the filter, varying from 0 to 300 FCU. The Log10 of these coliforms decreases from 5.9 to 2.2 passing through 4.6. Helminth eggs are not observed after the filtration.

3.2. Filter Performance

Table 5 presents the percentages of pollutant elimination by the Typha filter after treatment in the septic tank. COD shows a reduction of 46.74%. BOD5 has been eliminated at a rate of 89.70%. Suspended Solids (SS) have experienced an elimination of 96.30%. Ammonium ($N\text{-}NH_4^+$) has been reduced by 85.20%. For Fecal Coliforms, the indicated logarithmic reduction is 2.4 units.

4. Discussion

4.1. Filter Performance: Quality of Treated Water and Pollutant Elimination

The analysis of the water quality treated by the Typha planted filter, based on the information from Table 4 and Table 5, provides a relevant overview of the treatment system's efficiency. According to the pollutant elimination percentages by the filter presented in Table 6, the system excels in the removal of BOD5, SS, and Fecal Coliforms, with respective elimination rates of 89.70%, 96.30%, and a logarithmic reduction of 2.4 for coliforms. This highlights the efficiency of Typha as a treatment agent, consistent with previous reports on its purification capabilities [7] [9]. Table 4 results show that, at the filter's output, the average BOD5 value is 8 mg/L. Compared to the target value according to [10] which is less than 25 mg/l, the obtained value is well below, indicating effective treatment. Regarding COD, the average concentration at the filter output is 155 mg/L, while the target value is less than 125 mg/l. This means that the concentration obtained slightly exceeds the target value, indicating the need for improvements to reach an acceptable discharge level. For SS, the value after filtration is 1 mg/L, significantly lower than the target value of 35 mg/l, suggesting very effective treatment. As for nitrates, they remain stable with an average value of 30 mg/L at the filter output, which is below the target value of 50 mg/l, thus illustrating satisfactory treatment. As for phosphates, at the filter output, their average value is 8.6 mg/L, significantly higher than the target value of 2 mg/l, highlighting a clear need to improve treatment for these elements. Finally, for Fecal Coliforms, the

Table 5. Percentages of major pollutant elimination by the typha filter.

Parameter	% Elimination by Typha
COD	46.74%
BOD5	89.70%
SS	96.30%
$N\text{-}NH_4^+$	85.20%
Fecal coliforms (ULog reduction)	2.4

Table 6. Comparison of the quality of effluents from planted filters (average) with quality requirements or recommendations from Senegal, the EU, and WHO for elimination and reuse of water in irrigation.

Parameter	Typha FH filters output	Senegalese standard discharge environment (NS 05-061, 2001)	Old WHO recommendations for unrestricted water reuse in irrigation	European legislation on water reuse in irrigation
SS (mg/L)	2	40		10^a - $35^{b,c,d}$
BOD5 (mg/L)	8	50		10^a - $25^{b,c,d}$
COD (mg/L)	125	200		
TN (mg/L)		30		
N-NH_4^+ (mg/L)	7,8			
PO_4^{3-} (mg/L)	5.5	10		
FC (FCU/100 mL)	166	2000	1000	10^a-100^b-1000^c-$10,000^d$
Helminth eggs (Eggs/L)	0		<1	

a, b, c, d Classes of recycled water quality and agricultural use and permitted irrigation method: Class a: All food crops, including raw-consumed roots and food crops where the edible part is in direct contact with the recycled water. All irrigation methods are allowed; Class b: Raw-consumed food crops when the edible part is produced above ground and is not in direct contact with the recycled water, processed food crops and non-food crops, including crops for feeding milk or meat-producing animals. All irrigation methods are permitted; Class c: The same category of crops irrigable with class b quality water. Only drip irrigation is allowed; Class d: Industrial, energy crops, and seeds. All irrigation methods are allowed.

value obtained at the filter output is 170 FCU (100 mL), well below the target value of 1000 FCU/100ml, indicating effective elimination. In conclusion, the majority of the parameters in Table 5 meet or exceed the target values for effective treatment or acceptable discharge. However, some elements, particularly COD and phosphates, require special attention to achieve the desired standards. Reviewing the results from Table 4 reveals several key elements concerning the treated water quality. By juxtaposing these results with existing data for the region [9], we can better understand the context. If the water in the region typically shows high concentrations of organic materials such as COD and BOD5, the post-filtration values by Typha show a notable treatment efficacy. Conversely, initial concentrations that are comparable or lower than other similar regions suggest that the upstream septic tank already plays a significant role in water treatment. The system's strengths lie in the reduction of organic materials. The significant decrease in COD and BOD5 values attests to the Typha filter's effectiveness in eliminating organic matter. The microbiological efficiency is also highlighted, notably with the significant reduction of Fecal Coliforms. This demonstrates the filter's potential to eradicate microbiological contaminants, thereby enhancing the sanitary quality of the water. Additionally, the reduction in SS indicates that the post-treatment water contains fewer solid particles. On the weakness side, nitrates do not appear to vary significantly after passing through the septic tank and filter. This could suggest that the current system is not optimized enough for their elimination. In certain regions, high nitrate concentrations in water can pose public health risks. Furthermore, the variability of the results is an aspect to consider. Standard deviations, if available, could provide insight into this variability. Wide variances could indicate fluctuating performance of the treatment system. To conclude, the treatment system combining septic tanks and Typha filters seems effective in improving water quality, especially regarding the reduction of organic matter and microbiological contaminants. However, certain components, such as nitrates, might require optimization. A more detailed analysis, compared to regional data, would provide a more complete picture of the situation. The ineffectiveness of nitrate treatment in the system based on Typha and river sand can be explained in several ways. Firstly, regarding Typha, it is known for its ability to absorb nutrients, including nitrates, from wastewater [11]. However, the absorption and transformation of nitrates by Typha depend on factors such as the age of the plant, seasonality, and environmental conditions, particularly substrate oxygenation. In conditions where substrate oxygenation is high, the denitrification process, which transforms nitrates into gaseous nitrogen, may be limited [12]. Regarding the filtering mass, river sand is a granular material with low nitrate adsorption capacity. Additionally, it tends to promote rapid water infiltration, which could limit contact time and consequently denitrification [13]. River sand is generally more aerated, which may favor aerobic conditions rather than the anaerobic conditions needed for denitrification [14]. To improve denitrification efficiency, some modifications could be considered. One option might be to mix river sand with organic material to increase its nitrate adsorption capacity and promote anaerobic conditions [13]. Additionally, creating specific anaerobic zones could enhance denitrification. Finally, research could be conducted to determine if specific variations in Typha cultivation, for example, planting density or moisture rate management, could optimize nitrate absorption [12]. It is important to note that the combination of Typha and river sand, while potentially improvable, could already offer good elimination rates for other contaminants. Thus, each system must be evaluated based on its strengths and weaknesses and adapted according to the specific needs of the site.

4.2. Prospects for Reuse of Treated Waters

Table 6 provides a comparison of the quality of effluents from planted filters with standards and recommendations from various entities: the Senegalese standard, the old WHO recommendations, and European legislation. This comparison focuses on the elimination and reuse of water in irrigation. Upon analyzing **Table 6**, an initial observation is clear: the output from the Typha planted filters shows parameters well below the Senegalese standards for discharge into the natural environment. This demonstrates the system's ability to produce quality effluents. A comparison with international recommendations offers an even broader perspective on the potential for reusing these waters for various applications. For Suspended Solids (SS), with a value of 2 mg/L, the effluent is well below the Senegalese, EU, and WHO norms. Thus, this water could be used for all the quality classes defined by the EU, ranging from irrigation of crops eaten raw to industrial crops. The BOD5, with a concentration of 8 mg/L, is also very promising. It is well below Senegalese standards and falls within the range set by European legislation for reuse in irrigation, opening the door to potential use for all food crops, including those consumed raw. As for COD, at 125 mg/L, it is significantly below the Senegalese standard, although neither the WHO nor the EU sets specific criteria for this. However, this low concentration confirms the Typha filter's ability to decompose organic matter. Regarding nitrates (TN), no value is indicated for the output from the filter, but with a concentration of $N\text{-}NH_4^+$ at 7.8 mg/L, one might deduce that the level is potentially acceptable for various uses, although a more in-depth analysis would be necessary. The phosphate ($P\text{-}PO_4^{3-}$), with a value of 5.5 mg/L, is below the Senegalese standard, indicating water that is relatively low in phosphorus, which can be advantageous for preventing eutrophication in certain aquatic systems. Microbiologically, the concentration of fecal coliforms is 166 FCU/100mL, which is significantly below the Senegalese standard and the old WHO recommendation for unrestricted irrigation. According to European legislation, this water would be suitable for classes A to C, offering a wide range of usage options, from crops eaten raw to industrial crops. The value for helminth eggs is zero, indicating water of excellent parasitological quality, compatible with the WHO recommendation for unrestricted irrigation. In conclusion, based on the data from **Table 6** and previous discussions, the waters treated by the FH Typha planted filter offer remarkable potential for reuse, particularly in irrigation. Whether following Senegalese [15], European [16], or WHO recommendations [17], these waters exhibit favorable characteristics for a wide range of agricultural applications. This could not only reduce the pressure on freshwater resources but also offer a sustainable solution for managing wastewater while supporting agricultural production.

5. Conclusion

The importance of proper wastewater management and its potential reuse in an agricultural context is undeniable, particularly in regions where water resources are limited or subject to constraints. This article has undertaken a methodical approach to address this issue within a specific context, thus meeting several operational objectives. Firstly, a field survey was conducted, allowing us to identify the specifics of the studied site. This field approach was essential to understand the characteristics unique to the study area, ensuring that the proposed interventions and obtained results were contextually relevant. Secondly, laboratory analyses were performed on wastewater samples to determine the pollutant load. This allowed for the quantification of the present pollution and an understanding of the challenges in water treatment. Monitoring the quality of the water treated by the filter highlighted the capabilities and limitations of the FH Typha planted filters in wastewater treatment. It appeared that these filters, while promising, require optimization to treat certain types of pollutants. Finally, a comparative study was undertaken, pitting the quality of the effluents from the planted filters against the quality requirements or recommendations issued by Senegal, the EU, and the WHO for the elimination and reuse of water in irrigation. It turns out that while the treated effluents largely satisfy Senegalese standards, they range between the recommendations of the WHO and the EU, depending on the parameters. In sum, this study offers a comprehensive and nuanced view of the possibilities for treatment and reuse of wastewater in a specific context, while laying the groundwork for future research and interventions. It highlights the need to continue efforts in innovation and adaptation to ensure sustainable management of water resources while meeting the growing agricultural needs.

Conflicts of Interest

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

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