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Ecological Wastewater Treatment System Using a Horizontal Flow Biological Reactor: The Case of Vetiver

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Abstract

Confronted with the challenge of wastewater management, particularly in the school environment of Senegal, our study set out to achieve multiple objectives. Following field surveys, laboratory analyses of wastewater samples were carried out, revealing a significant pollutant load. In the community of Gandiol, near Saint-Louis (Senegal), the school of Ndiebene Gandiol 1 faces significant sanitation challenges. Our study aimed to address this issue by using a constructed filter composed of two filtering bed cells measuring 12 × 8.5 m, preceded by a septic tank. We particularly focused on the influence of Vetiver; a plant chosen for its purification potential. Our analyses showed remarkable efficiency of the filter. Elimination rates reached 95% for 5-Day Biochemical Oxygen Demand (BOD5), 91% for Chemical Oxygen Demand (COD), and 92% for SS, far exceeding the Senegalese standards set at 50 mg/L, 200 mg/L, and 40 mg/L, respectively. Furthermore, the concentration of fecal coliforms was reduced to 176 FCU/100mL, well below the Senegalese threshold of 2000 FCU/100mL and close to the World Health Organization's (WHO) recommendation of 1000 FCU/100mL. However, despite these promising results, some parameters, particularly the concentration of certain pollutants, approached the thresholds defined by European legislation. For example, for Suspended Solids (SS), the post-treatment level of 3 mg/L was well below the Senegalese standard but edged close to the European minimum of 10 mg/L. In conclusion, the Vetiver filter demonstrated a remarkable ability to treat school wastewater, offering high pollutant elimination percentages. These results suggest significant opportunities for the reuse of treated water, potentially in areas such as irrigation, though some adjustments may be necessary to meet the strictest standards such as those of the European union (EU).

Keywords

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

1. Introduction

The latest sanitation policy in Senegal (2016-2025) explicitly aims to contribute to achieving the Sustainable Development Goals (SDGs) by ensuring universal access to safe drinking water and sanitation by 2030 while ensuring integrated water resource management. The policy emphasizes key elements of SDG 6, including: 1) household access to sustainable sanitation, 2) wastewater and stormwater management, and 3) the eradication of open defecation. When confronting this aspiration with the on-ground reality, a significant gap becomes apparent. According to available data until 2021, approximately 56% of the Senegalese population had access to improved sanitation services, such as toilets connected to a sewage system. This means that a large portion of the population still lacks access to adequate sanitation facilities. Sanitation networks, such as sewers, are still limited in many regions of the country, especially in rural areas. The majority of sanitation systems are concentrated in urban areas, particularly in the capital, Dakar. Wastewater treatment remains insufficient in Senegal. Most existing wastewater treatment facilities are located in large cities, while rural areas lack such infrastructure. This leads to watercourses and groundwater pollution due to untreated wastewater. The Senegalese government has taken measures to improve sanitation and wastewater treatment. It launched the Millennium Sanitation Program (PAM) in 2009, which aims to expand access to sanitation throughout the country. Additionally, the National Sanitation Plan (PNA) was put in place to improve wastewater management and develop sanitation infrastructure. Senegal also benefits from the support of international organizations 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. Senegal, like many countries, has committed to achieving the Sustainable Development Goals (SDGs) defined by the United Nations General Assembly in 2015 [1]. These commitments cover various aspects related to water and sanitation. Despite ongoing efforts and national and international initiatives, challenges persist in sanitation, particularly in rural areas [2]. Alternative wastewater treatment methods, such as reed bed planted filters, have been studied in various contexts, including in developing countries [3]. These methods have demonstrated their effectiveness, but their application requires specific local adaptation. Sustainable wastewater management is crucial, especially in regions with limited water resources. In this context, the experimentation of ecological systems for wastewater treatment is constantly evolving. Among these systems, the use of plants, such as Vetiver, is increasingly recognized for its efficiency. Vetiver

(*Chrysopogon zizanioides*) is a tropical grass with deep root systems that impart it with particular properties for erosion control, phytoremediation, and wastewater treatment [4] [5] [6]. This work presents a case study focusing on Ndiebene Gandiol 1 School, where a horizontal flow biological reactor using Vetiver has been implemented, an innovation in the domain of ecological wastewater treatment. Our inquiry delved into this issue to identify existing gaps and opportunities for enhancement. Our approach proposes sustainable solutions tailored to local needs, with a focus on agricultural reuse of treated water in compliance with EU and WHO water quality requirements. Through this work, we introduce a significant innovation: leveraging Vetiver not merely as a phytoremediation agent but as an integral component of a holistic treatment system that aligns with sustainable development goals and addresses specific wastewater management challenges in the rural Senegalese context. Herein, we outline the key steps of our research, from field survey to comparative effluent analysis, and sketch out recommendations for the future. Our study delves into this issue, seeking to identify gaps and improvement opportunities. It also aims to formulate recommendations with an emphasis on sustainable solutions tailored to local needs, particularly in the context of school wastewater. The main steps of our study include:

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

Figure 1. Location of the study site: Ndiebene Gandiol School.

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

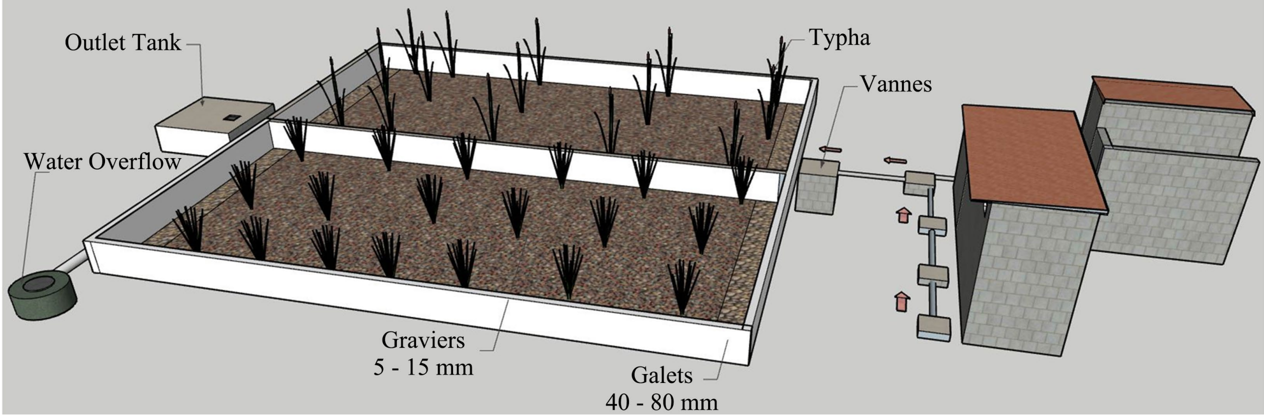

Figure 2. 3D plan of the filter.

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, FHV exit
2	End of February	3	Septic tank entry, Septic tank exit, FHV exit
3	Mid-March	2	Septic tank exit, FHV exit
4	Mid-April	2	Septic tank exit, FHV exit
5	Mid-May	2	Septic tank exit, FHV exit
6	Mid-June	3	Septic tank entry, Septic tank exit, FHV 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

[7] [8]. *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 [9]. 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 [7].

2.3.3. Data Processing

Statistical analyses were performed on the raw data using statistical software Excel 2016 and IBM-SPSS Statistics for Windows [10]. Excel 2016 was used for descriptive statistics (averages, maximums, minimums, and standard deviation). SPSS 24 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 $p \leq 0.05$.

3. Results

3.1. Water Quality

The analysis of the results in **Table 4** demonstrates a significant improvement in water quality after passing through the Vetiver filter. Initially, the values of COD and BOD5 at the entrance of the septic tank are 1347 mg/L and 259 mg/L, respectively. After treatment by the septic tank, these values decrease drastically to 291 mg/L and 78 mg/L, respectively. However, after passing through the Vetiver filter, an even more pronounced decrease is observed, with average values of 74 mg/L for COD and 11 mg/L for BOD5.

Table 4. Water quality results.

Parameter	Septic tank inlet	Septic tank outlet			Vetiver filter outlet		
	Average	Mean	Max	Min	Average	Max	Min
COD (mg/L)	1347	291	500	186	74	149	35
BOD5 (mg/L)	259	78	101	59	11	20	7
SS (mg/L)	76	35	40	33	3	6	0
$N\text{-}NH_4^+$ (mg/L)	248	53	146	15	7	20	0
$N\text{-}NO_3^-$ (mg/L)	30	30			27		
$P\text{-}PO_4^{3-}$ (mg/L)	48	47			4.5		
pH	8.2	8.5			7.9		
EC	2950	3400			1870		
Fecal Coliforms FCU (100 mL)	8.30E+05	3.80E+04	5.40E+04	2.30E+04	180	330	0
Fecal Coliforms (Log10)	5.9	4.6	4.7	4.4	2.2	2,5	0
Helminth Eggs (Anguillule Larvae)		0			0		

Regarding Total Suspended Solids (SS), a significant decrease is observed from 76 mg/L to 35 mg/L after the septic tank and a spectacular reduction to only 3 mg/L after the Vetiver filter. The concentrations of ammonium ($N\text{-}NH_4^+$) and nitrate ($N\text{-}NO_3^-$) also show a decreasing trend after each treatment step. In particular, the ammonium concentration decreases from 248 mg/L to 53 mg/L after the septic tank and reaches 7 mg/L after the Vetiver filter. The phosphate concentration ($P\text{-}PO_4^{3-}$) undergoes a marked decrease from 48 mg/L to 47 mg/L after the septic tank, but it is after passing through the Vetiver filter that its concentration drops drastically to 4.5 mg/L. Microbiologically, the concentration of fecal coliforms decreases significantly from 5.9 log10 FCU/100mL at the septic tank outlet to as low as 2.2 log10 after treatment by the Vetiver filter. It is also noteworthy that helminth eggs, especially anguillule larvae, are not detected at the filter outlet, indicating that the system effectively eliminates these pathogens. In summary, these results indicate that the Vetiver filter plays a crucial role in water purification, resulting in improved water quality in terms of physico-chemical and microbiological parameters.

3.2. Filter Performance

Table 5 presents the percentage removal of pollutants by the Vetiver filter after treatment in the septic tank. COD shows a reduction of 74.57%. BOD5 exhibits a reduction of 85.90% after passing through the Vetiver filter. For Total Suspended Solids (SS), the Vetiver filter successfully removed 91.40% of the particles present. The removal rate of ammonium ($N\text{-}NH_4^+$) by the filter is 86.70%. Finally, in terms of fecal coliforms, the filter achieved a reduction of 2.3 log units.

4. Discussion

4.1. Filter Performance: Treated Water Quality and Pollutant Removal

The analysis of water quality treated by the Vetiver planted filter, based on the information in Table 4 and Table 5, clearly demonstrates that the Vetiver filter offers a significant improvement in water quality, especially in terms of pollutant removal. Comparing these results with existing data can provide insight into the

Table 5. Percentage removal of major pollutants by the Vetiver filter.

Parameter	% Elimination by Vétiver
COD	74.57%
BOD5	85.90%
SS	91.40%
$N\text{-}NH_4^+$	86.70%
Fecal Coliforms (Log10)	2.3

effectiveness of the Vetiver filter in regional and similar contexts. [11] studied a constructed wetland wastewater treatment system for the treatment and reuse of municipal wastewater for agricultural purposes in Senegal. While their study does not specifically focus on Vetiver, it provides a solid basis for comparing the efficiencies of different treatment methods. Regarding COD, which is an indicator of the amount of oxygen required to oxidize organic matter, our study revealed a drastic reduction from 1347 mg/L to 74 mg/L thanks to the Vetiver filter. This performance appears to be more effective than those reported by [11] although precise values are needed for an accurate comparison. The reduction in BOD5 from 259 mg/L to 11 mg/L is also noteworthy, indicating a significant decrease in the amount of oxygen required for biochemical degradation over 5 days. These results seem to be in line with or even surpass those in the literature, highlighting the efficiency of the Vetiver filter for wastewater treatment. The substantial decrease in Total Suspended Solids (SS) from 76 mg/L to only 3 mg/L demonstrates the filter's efficiency in capturing and retaining solid particles. Compared to existing data for the region, this performance is impressive and may even outperform other wetland treatment systems. The reduction in concentrations of ammonium ($N\text{-}NH_4^+$) and phosphate ($P\text{-}PO_4^{3-}$) lso indicates effective nutrient removal, which is essential to prevent eutrophication when treated water is discharged into the environment. The values obtained in this study appear to be comparable to, if not better than, those reported by [11] for the same geographical area. Finally, from a microbiological perspective, the drastic reduction in fecal coliforms from 5.9 log10 FCU/100mL to 2.2 log10 demonstrates the filter's efficiency in eliminating pathogens. This performance is essential to ensure that treated water is safe for potential reuse, especially for agricultural purposes. In conclusion, the Vetiver filter stands out as a promising solution for wastewater treatment. However, like any study, it has limitations. A more in-depth analysis of operational conditions and specific constraints related to Vetiver would be beneficial for large-scale implementation. Based on target values for effective treatment or acceptable discharge established by [12], the performance of the Vetiver filter can be evaluated. Regarding 5-day Biochemical Oxygen Demand (BOD5), the post-treatment results show a concentration of 11 mg/L, well below the standard of 25 mg/L. This demonstrates the filter's effectiveness in removing biologically degradable organic matter. For Chemical Oxygen Demand (COD), the post-treatment concentrations are at 74 mg/L, lower than the target value of 125 mg/L, highlighting the efficient removal of the majority of organic matter. Post-treatment Total Suspended Solids (SS) displays a concentration of 3 mg/L, well below the standard of 35 mg/L, indicating effective particle removal. Nitrate concentrations after treatment are at 27 mg/L, meeting the limit of 50 mg/L. As for Total Kjeldahl Nitrogen (TKN), although it is not explicitly in our data, the concentration of ammonium nitrogen after treatment is 7 mg/L, thus meeting the standard of less than 30 mg/L. However, for phosphates, the post-treatment concentration of 4.5 mg/L exceeds the standard of 2 mg/L, which may require specific attention. Regarding fecal coliforms, they display a concentration of 180 FCU/100mL after treatment, significantly lower than the standard of 1000 FCU/100mL. In summary, the Vetiver filter demonstrates excellent performance for most of the analyzed parameters, meeting or even exceeding established standards. However, phosphate treatment may require optimization or additional measures to fully comply with standards. The strengths and weaknesses of water quality results and pollutant removal percentages by the Vetiver filter, which uses flint gravel as the filter medium, are evident. The Vetiver filter demonstrates a strong ability to reduce BOD5 and COD, indicating effective removal of biologically degradable organic matter. These findings align well with the standards established by [12], highlighting the optimal performance of the Vetiver filter in this situation. Additionally, post-treatment SS concentrations are remarkably low, indicating that flint gravel plays a crucial role in physically filtering suspended particles, as noted by [13]. The filter's efficiency in nitrogen treatment is also commendable, with significantly reduced levels of ammonium nitrogen after treatment, suggesting effective prevention of eutrophication risks. Furthermore, the low concentrations of fecal coliforms after treatment are a positive indicator of improved microbiological water quality, making it safer for applications like irrigation. However, despite these strengths, the Vetiver filter has limitations, especially in phosphate removal. Flint gravel, as a filter medium, may not have ideal surface chemistry for phosphate adsorption. Over time, the flint could potentially reach a saturation point, further reducing its effectiveness in phosphate removal [14] [15]. Other factors, such as the nature of phosphates, adsorption capacity, the presence of other ions, high initial concentration, and issues related to hydraulic residence time or excessive flow, can also contribute to this limitation [3] [16] [17] [18]. In particular, the specific adsorption capacity of flint or its granulometry can influence this efficiency [13] [15]. In summary, while the Vetiver filter with flint gravel has notable advantages for water treatment, especially for the removal of organic matter, suspended solids, and nitrogen, there are areas, such as phosphate removal, that require additional attention and optimization.

4.2. Prospects for Reuse of Treated Waters

Table 6 provides a comparison of the quality of effluents from Vetiver planted filters with standards and recommendations from various entities: the Senegalese standard [19], old WHO recommendations [20], and European legislation [21]. This comparison focuses on the elimination and reuse of water for irrigation. The analysis of **Table 6** reveals crucial information regarding the quality of effluents from Vetiver planted filters compared to the standards and recommendations in place in Senegal, the EU, and those from WHO. Overall, the water treated by the Vetiver filter appears to have a significantly higher quality than the requirements of the Senegalese standard for discharge into the environment, suggesting diverse opportunities for reuse. For the parameter of Total Suspended Solids (SS), the treated water shows a concentration of 3 mg/L, which is well below the Senegalese standard of 40 mg/L and also falls within the range

Table 6. Comparison of the quality of effluents from planted filters (average) with the quality requirements or recommendations of Senegal, the EU, and WHO for water elimination and reuse 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)	3	40		10^{a} - $35^{b,c,d}$
BOD5 (mg/L)	10	50		10^{a} - $25^{b,c,d}$
COD (mg/L)	98	200		
TN (mg/L)		30		
N-NH_4^+ (mg/L)	3			
PO_4^{3-} (mg/L)	2.1	10		
FC (FCU/100mL)	176	2000	1000	10^{a}-100^{b}-1000^{c}-10.000^{d}
Helminth Eggs (Eggs/L) SS (mg/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.

recommended by European legislation, ranging from 10a to 35 b, c, d, depending on the class and intended agricultural use. The levels of BOD5 and COD, which are 10 mg/L and 98 mg/L, respectively, are well below the thresholds set by the Senegalese standard and European legislation. This indicates the efficiency of the Vetiver filter in treating organic matter. The level of fecal coliforms (FC) at 176 FCU/100mL is significantly lower than the Senegalese standard of 2000 FCU/100mL and falls within the range of European legislation, allowing for water reuse in various crop classes. The absence of helminth eggs in the treated water is also a positive point, in line with WHO recommendations for unrestricted irrigation water reuse. The conclusions drawn from Table 6 suggest that water treated by the Vetiver filter is of a sufficiently high quality to be safely reused in agricultural applications, especially for irrigation. Taking into account the water quality classes established by European legislation, this treated water would be suitable for a wide range of crops, from raw food crops to industrial and energy crops. However, it is important to note that while water quality meets current standards, additional considerations, such as the long-term impact of reused treated wastewater on soil health and crop quality, should be taken into account. Furthermore, the implementation of such a system on a large scale would require a detailed study of technical and economic feasibility, as well as acceptance by local stakeholders. In summary, the Vetiver filter, with flint gravel as the filter medium, appears to offer a viable solution for treating wastewater to a level that allows for reuse in agriculture. The opportunities it presents could help meet growing water needs while ensuring sustainable water resource management.

5. Conclusion

The importance of proper wastewater management and its potential reuse in an agricultural context is undeniable, especially in regions where water resources are limited or constrained. This article has undertaken a systematic approach to address this issue in a specific context, thereby serving several operational objectives. At the end of this wastewater management study, with a primary focus on the school setting, profound insights and implications have been derived. Our field survey provided us with a precise perspective of site-specific characteristics, which influenced and directed our subsequent actions for an adapted approach. Laboratory analysis revealed significant pollutant loads in wastewater samples, highlighting the urgent need for intervention to ensure a healthy environment for students and school staff. Through regular monitoring of wastewater treated by the Vetiver filter, we observed a significant reduction in several pollutants. Specifically, the effluents from the planted filter exhibited levels of Suspended Solids (SS) at 3 mg/L, well below the 40 mg/L recommended by Senegalese standards. Similarly, Biochemical Oxygen Demand (BOD5) was reduced to 10 mg/L, and Chemical Oxygen Demand (COD) to 98 mg/L, both significantly lower than the thresholds set by national and international standards. However, our comparative study, referring to **Table 6**, highlighted that, despite the filter's overall performance, some standards, particularly those of the EU, remain stricter in terms of SS and BOD5. This underscores the importance of ongoing optimization of the treatment process to broaden the possibilities for the reuse of treated water. Comparison with EU, Senegalese, and WHO standards and recommendations shows real potential for the reuse of this water, especially in irrigation. This offers advantageous economic and environmental prospects for the region. In conclusion, our study has not only identified crucial challenges related to wastewater management in a school environment but has also highlighted the potential of solutions based on planted filters. Nevertheless, it is imperative to continue research and optimization efforts to better meet the strictest standards, thus enabling broader and safer reuse of treated water.

Conflicts of Interest

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

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