

Research Article

Performance Assessment of an Aerated Biofiltration Systems Based on Coconut Residues

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Abstract

This study investigates the effectiveness of an aerated biofiltration process employing coconut-based filter media for the treatment of domestic wastewater. To achieve this, a semi-industrial pilot system was constructed, consisting of five biofiltration columns packed with different proportions of coconut fibers and husks. The experimental design included an initial 30-day acclimation phase to allow biofilm establishment, followed by a 60-day monitoring period during which the system's performance was systematically evaluated. The influent wastewater, collected from a hotel, was first characterized and classified as urban wastewater with relatively low biodegradability, as indicated by a COD/BOD₅ ratio of 3.94. The results demonstrate that the biofiltration system provided high removal efficiencies for several key pollutants. Turbidity removal reached up to 88%, while ammonium and nitrites were reduced by more than 75%. Similarly, reductions exceeding 70% were observed for total phosphorus and total Kjeldahl nitrogen. COD removal, however, remained moderate at around 50%, highlighting limitations in the system's ability to eliminate carbonaceous compounds. Overall, the findings indicate that the coconut-based biofiltration process is particularly effective in nitrogen and turbidity removal, reflecting the suitability of coconut husk and fibers as sustainable filter media in decentralized wastewater treatment applications. Nevertheless, the study also reveals important constraints regarding carbon and phosphorus removal. These were attributed to the presence of refractory transphilic and hydrophobic organic fractions in the influent, as well as the limited availability of biodegradable carbon required to support complete phosphorus degradation. The outcomes of this research underscore both the potential and the limitations of coconut-based aerated biofiltration and provide insights for optimizing low-cost, nature-based treatment systems aimed at improving wastewater quality in resource-constrained settings.

Keywords

Aerated Biofiltration, Microorganisms, Biological Treatment, Coconut Husks and Fibers, Domestic Wastewater

1. Introduction

Wastewater management is a pressing global challenge and a key determinant of public health, environmental protection, and sustainable development [1-3]. The issue is even more critical for developing nations such as Benin, where rapid

urbanization, population growth, and industrial expansion are not yet matched by adequate sanitation infrastructure.

In the country, the majority of effluents are discharged directly into the environment, with serious consequences for

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ecosystems, drinking water resources, and human health.

Multiple factors contribute to this situation. These include limited financial resources for the construction and operation of treatment plants, inadequate technical capacity, and difficulties in accessing appropriate, affordable, and sustainable treatment technologies. In this context, it is crucial for countries like Benin to adopt alternative wastewater treatment processes that are both technically simple and cost-effective.

Biofiltration (BF) is one such process. Inspired by filtration systems traditionally used in drinking water production, biofiltration combines both physical and biological purification mechanisms. It uses an immersed filter medium—either aerated or non-aerated depending on the treatment objectives—on which microbial communities, known as biofilms, develop. These biofilms actively degrade organic and inorganic pollutants through natural biochemical processes [4-8]. One of the major strengths of biofiltration is its simplicity of implementation and its relatively low operating cost, as it requires little to no chemical reagents.

Moreover, biofiltration offers an additional environmental advantage: it can incorporate agricultural residues as filter media, thus creating a synergy between waste valorization and wastewater treatment [9-13]. In many African cities, the disposal of agricultural by-products such as coconut husks and fibers poses a significant waste management challenge. Utilizing these residues in biofiltration systems not only reduces the burden on waste disposal facilities but also provides an effective support for the growth of pollutant-degrading biomass.

Given these benefits, biofiltration stands out as a particularly suitable wastewater treatment technology for developing countries [14-16]. This study focuses on assessing the performance of an aerated biofiltration system using coconut residues as filter media. Special attention is given to understanding the influence of the filter material on pollutant removal efficiency from domestic wastewater. The ultimate aim is to explore how such an approach can be adapted and scaled up to improve sanitation services in Benin and similar contexts in sub-Saharan Africa.

2. Materials and Methods

2.1. Domestic Waste Water Sampling

The domestic wastewater used in this study was collected from a hotel in Cotonou, Republic of Benin, located on the shores of Lake Nokoué—the largest lake in the country—less than one kilometer from its outlet to the Atlantic Ocean. The hotel provides typical services of its category, generating wastewater from three main sources:

- 1) Guest rooms - wastewater from toilets and showers
- 2) Kitchen - wastewater from food preparation
- 3) Laundry - wastewater containing detergents

These sources produce an average daily flow of approximately 36.5 m³ (about 1.5 m³/h) with significant pollutant loads.

During the three-month experimental period, three sampling campaigns were conducted at monthly intervals.

2.2. Experimental Biofiltration Unit

2.2.1. Design

A pilot biofiltration system was constructed, consisting of five PVC columns (reactors A-E), each 63 mm in diameter and 2 m in height. The influent wastewater was fed into the top of the columns via a plexiglass connection (1 mm diameter). Treated effluent was collected at the bottom through outlet valves.

Two types of filter media were used:

- 1) Coconut shells (0.5-3 cm diameter)
- 2) Coconut fibers

These materials served as supports for biofilm growth. The columns were packed with different proportions of the two media to assess purification efficiency:

Table 1. Proportions of coconut shells and fibers used during the experiences.

Column	Coconut Shells (%)	Coconut Fibers (%)
A	100	0
B	70	30
C	50	50
D	30	70
E	0	100

2.2.2. Operation

The experiment was conducted over 90 days. The first 30 days served as an acclimatization phase, allowing microbial colonization of the filter media. This period was characterized by the initial release of materials from the media, followed by the natural development of purifying bacteria.

During the subsequent 60 days, the purification performance of each column was evaluated under continuous operation. A surface pump conveyed the influent from a reservoir to the column heads, maintaining a uniform hydraulic head. Wastewater percolated downward through the filter media under gravity, with a hydraulic retention time (HRT) of 24 h.

An air compressor supplied constant humidified air at the bottom of the columns, creating an upward airflow opposite to the downward water flow, resulting in counter-current biofiltration. Aerobic microorganisms in the media degraded the organic pollutants, and treated water was collected at an average flow rate of 1.19 L/day.

2.3. Analytical Methods

The following parameters were monitored: temperature, pH,

turbidity, conductivity, ammonium, nitrites, nitrates, chemical oxygen demand (COD), biochemical oxygen demand (BOD₅), total phosphorus (TP), color at 436 nm, and total Kjeldahl nitrogen (TKN).

Measurements were taken every 10 days at the reactor outlets. Table 2 summarizes the methodology used for each parameter.

Table 2. Analytical parameters and methods used in the study.

Parameter	Unit	Method / Standard Reference	Instrument / Technique
Temperature	°C	AFNOR NF T90-110	Calibrated digital thermometer
pH	-	AFNOR NF T90-008	pH meter (electrode method)
Turbidity	NTU	AFNOR NF EN ISO 7027	Turbidimeter
Conductivity	µS/cm	AFNOR NF EN 27888	Conductivity meter
Ammonium (NH ₄ ⁺)	mg/L	AFNOR NF T90-015	Spectrophotometry (indophenol blue)
Nitrites (NO ₂ ⁻)	mg/L	AFNOR NF T90-013	Spectrophotometry (sulfanilamide)
Nitrates (NO ₃ ⁻)	mg/L	AFNOR NF T90-012	Spectrophotometry (cadmium reduction)
Chemical Oxygen Demand (COD)	mg O ₂ /L	AFNOR NF T90-101	Closed reflux, colorimetric
Biochemical Oxygen Demand (BOD ₅)	mg O ₂ /L	AFNOR NF T90-103	5-day incubation at 20 °C
Total Phosphorus (TP)	mg/L	AFNOR NF EN ISO 6878	Spectrophotometry (ascorbic acid)
Color (436 nm)	m ⁻¹	AFNOR NF T90-033	Spectrophotometer
Total Kjeldahl Nitrogen (TKN)	mg N/L	AFNOR NF T90-110	Kjeldahl digestion & distillation

Table 3. Physicochemical characteristics of the domestic raw water compared to typical urban wastewater values.

Parameter	Units	Measurement Precision	Average Value	Maximum Value	Minimum Value	Usual Range in Urban Wastewater
pH	-	± 0.1	7.40	8.68	6.55	7.5 - 8.5
Temperature	°C	± 0.01	26.70	28.90	22.20	-
Conductivity	µS/cm	± 1	1320	2710	1345	1000
COD	mg O ₂ /L	± 20	268	512	64	300 - 1000
BOD ₅	mg O ₂ /L	± 20	68	155	35	150 - 500
Turbidity	NTU	± 0.01	176	370	71.6	-
Ammonium	mg NH ₄ /L	± 0.1	15.48	35.05	4.52	20 - 80
TKN	mg N/L	± 0.1	20.50	28.00	7.28	30 - 100
Ammonium (NH ₄ ⁺ as N)	mg N/L	± 0.1	0.24	0.63	0.01	< 1
Nitrite (NO ₂ ⁻ as N)	mg N/L	± 0.1	1.80	7.45	0.38	< 1

Parameter	Units	Measurement Precision	Average Value	Maximum Value	Minimum Value	Usual Range in Urban Wastewater
Total phosphorus (Pt)	mg P/L	± 0.01	17.59	24.47	9.02	10 - 25

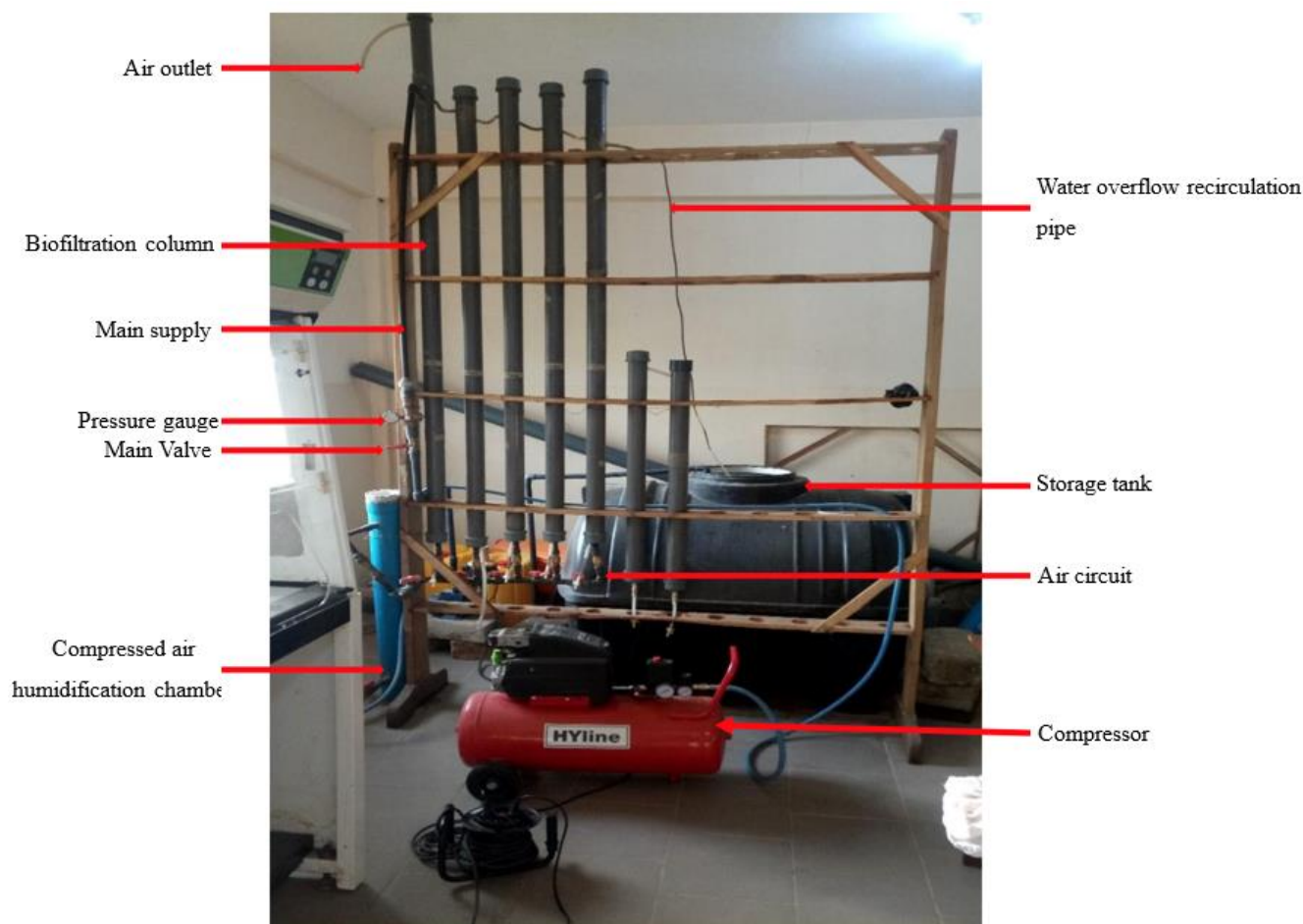


Figure 1. Biofiltration pilot.

3. Results and Discussion

3.1. Characteristics of Domestic Raw Water

Understanding the physicochemical profile of the influent is essential for assessing both the treatment challenges and the potential performance of biofiltration systems. The results obtained from the characterization of the domestic raw water are summarized in [Tables 3 and 4](#) and are discussed below. The conductivity of the influent was particularly high (1320 $\mu\text{S}/\text{cm}$), exceeding the typical values reported for household wastewater. This anomaly is likely attributable to the presence of laundry facilities within the hotel, as wastewater containing soap and detergent residues is known to display elevated

conductivity. The elevated phosphorus concentration, together with the substantial difference between COD and BOD₅ values, further supports this explanation. In general, wastewater from hospitality establishments is expected to be highly biodegradable. However, the COD/BOD₅ ratio observed in this study (3.94) suggests that the effluent exhibits characteristics more akin to industrial wastewater. This finding reinforces the relevance of employing biofiltration, a treatment process well-documented for its effectiveness not only with biodegradable domestic effluents but also with more complex industrial discharges. The N-NH₄/Total Kjeldahl Nitrogen (TKN) ratio was 0.75, indicating that the majority of nitrogen in the effluent was present in ammoniacal form. This suggests that nitrogenous compounds had undergone substantial degradation into forms readily assimilable by microorganisms for metabolic functions. The calculated

C/N/P ratio (100/30/25) was used to evaluate potential nutrient limitations during treatment. The values indicate a relative deficit in organic carbon, or conversely, an excess of nitrogen and phosphorus relative to the amounts typically required for effective organic matter removal. It is important to emphasize that pollutant removal in biofiltration units is

driven not only by biological processes but also by physico-chemical mechanisms, including adsorption. The combined influence of these mechanisms underscores the scientific and technological relevance of the biofiltration unit monitored in this study for the treatment of domestic raw water with atypical pollutant characteristics.

Table 4. Wastewater quality ratios and their interpretations.

Ratio	Value (s)	Interpretation
COD/BOD ₅	3.94	Indicates a poorly biodegradable effluent
N-NH ₄ /KTN	0.75	Most nitrogen is present in the form of ammonia
BOD ₅ /KTN/Pt	10/30/25	Indicates high nitrogen and phosphorus loads

Table 5. Biofiltration pilot removal efficiency.

Column	COD (mgO ₂ /l)	BOD ₅ (mgO ₂ /l)	Turbidity (NTU)	KTN (mgN/l)	Ammonium (mgNH ₄ /l)	Nitrite (mgN/l)	Nitrate (mgN/l)	Total Phosphorus (mgP/l)
A	32.25	0.73	58.86	55.23	76.36	81.22	75.23	77.62
B	27.07	27.94	85.51	60.20	69.90	66.60	76.19	76.22
C	49.39	19.60	83.67	73.55	60.89	12.99	46	74.41
D	24.28	69.36	81.21	60.20	12.29	1.03	69.23	72.59
E	23.9	20.83	88.66	64.47	73.57	5.57	49.90	73.32

3.2. Performance and Removal of Carbon Pollution

3.2.1. COD Removal Efficiency

Comparison of the results obtained for each filtration column (Table 5) shows that Column C, filled with a 50:50 mixture of coconut shells and coconut fiber, achieved the highest chemical oxygen demand (COD) removal efficiency. This column recorded a 49.39% reduction, with a residual COD concentration of 135.46 mg O₂/L in the treated effluent, compared to an initial concentration of 267.67 mg O₂/L in the raw water. The raw water contained a significant refractory fraction, which is resistant to biofiltration and therefore difficult to remove. In agreement with this observation, previous studies by Dia *et al.* [17] and Garzón-Zúñiga *et al.* [18] reported COD removal efficiencies below 20% in biofiltration units. Through fractionation analysis of OM before and after biofiltration, these authors demonstrated that the process performs well for hydrophilic fractions but is much less effective for hydrophobic and transphilic fractions. The rela-

tively modest COD removal observed in our study is likely attributable to the predominance of these less biodegradable hydrophobic and transphilic fractions in the effluent.

From a regulatory standpoint, the performance of the biofiltration unit (BFA) in our case does not meet the national discharge standard in the Republic of Benin, which sets the maximum allowable COD concentration in treated water at 125 mg O₂/L.

Figure 2 illustrates the evolution of COD concentrations before and after treatment in Column C. During the first days following the acclimatization period, the treated water exhibited relatively low residual COD values (approximately 128 mg O₂/L), corresponding to a 75% reduction. This stability persisted for about 20 days, indicating good microbial adaptation to the effluent and high OM degradation efficiency. However, after this period, a gradual increase in residual COD was observed, reaching 384 mg O₂/l on day 30, with removal efficiency dropping to 33.33%. This deterioration in performance may be explained by the leaching of non-biodegradable humic substances from the coconut shells and fibers into the treated effluent. This hypothesis is supported by the dark brown coloration of the effluent observed

from day 30 onward, consistent with the findings of Dia *et al.* [17] for biofiltration units treating leachate. Another plausible explanation is clogging, the progressive accumulation of suspended solids within the filter media. Clogging reduces the effective filtration surface area and promotes short-circuiting of the flow, whereby water bypasses the active biofilm zones, thus lowering the treatment efficiency.

From day 40 onwards, unexpected COD values were recorded across all columns. In Column C, the residual COD equaled that of the raw water (224 mg O₂/L), indicating 0% removal. In some cases, other columns even showed higher COD concentrations in the treated water than in the raw water,

likely due to the continuous leaching of humic substances from the coconut-based media.

These compounds are highly refractory and not readily degraded by microorganisms. Moreover, the pH of the effluent increased from 6.55 (raw water) to 6.90 after treatment, a trend observed in all pilot columns. This rise in pH may be linked to the presence of bicarbonates resulting from the mineralization of organic carbon in the filter media, which in turn may have enhanced the leaching of humic substances. The resulting coloration of the effluent contributed to the elevated COD levels in the final treated water.

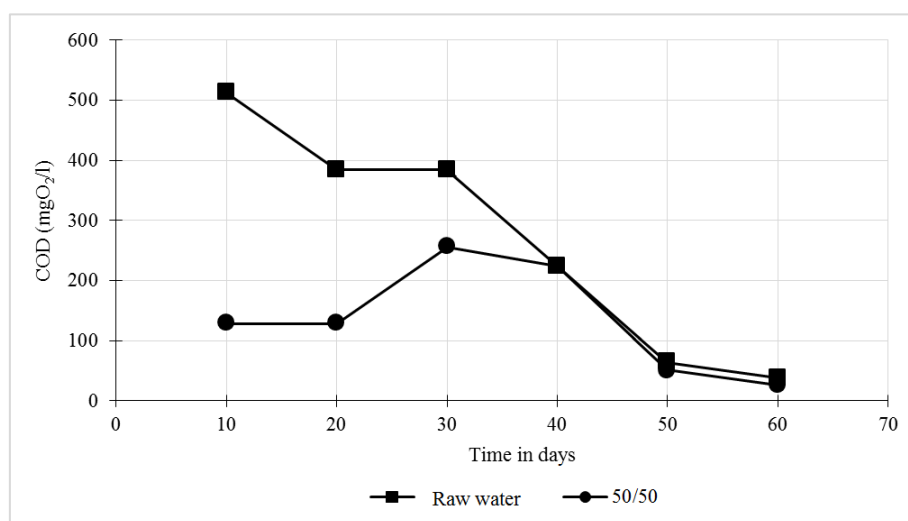


Figure 2. COD removal in column C.

3.2.2. BOD₅ Removal Efficiency

A comparative analysis of the BOD₅ removal efficiencies across the filtration columns (Table 5) revealed that Column D, containing 30% shell and 70% coconut fiber packing, achieved the highest removal efficiency. This column exhibited a BOD₅ reduction of 69.36%, with a residual concentration of 20.83 mg O₂/L in the treated effluent, compared to an initial raw water concentration of 68 mg O₂/L. Importantly, the residual BOD₅ concentration in Column D's effluent was below the regulatory discharge limit of 25 mg O₂/L, demonstrating compliance with environmental standards. These results suggest that the packing configuration in Column D effectively promotes the removal of biodegradable organic matter, likely through the metabolic activity of heterotrophic microorganisms. Comparable removal efficiencies have been reported in the literature where Chen *et al.* observed BOD₅ reductions of 60% and 61%, respectively, in their biofiltration systems, while Rasool *et al.* reported removal efficiencies as high as 86% [18, 19].

3.3. Nitrogen Removal Efficiency

In terms of nitrogen removal, Column C (50% shell and 50% coconut fiber packing) exhibited the highest performance for Kjeldahl Total Nitrogen (KTN) elimination. This column achieved a KTN reduction of 73.55%, with a residual concentration of 5.42 mgN/l in the treated effluent, compared to an initial raw water concentration of 20.5 mgN/l. Overall nitrogen removal efficiency for Column C reached 70.75%, with a residual nitrogen concentration of 6.57 mgN/l.

These results substantially exceed those reported by Rasool *et al.* [19], who obtained only a 34.4% KTN removal in a similar biofiltration setup. This high efficiency is particularly relevant given that the post-treatment discharge from the system flows into Lake Nokoué, a water body already experiencing eutrophication pressures.

Furthermore, the residual KTN concentration in Column C's effluent was markedly lower than the regulatory threshold of 15 mg N/l, further confirming the system's effectiveness in nitrogen removal.

3.4. Phosphorus Removal Efficiency

Column A, composed of 100% coconut shell packing, exhibited the highest total phosphorus (Pt) removal efficiency among all configurations tested. This column achieved a reduction of 77.62%, resulting in a residual Pt concentration of 3.84 mgP/l in the treated effluent, compared to an initial concentration of 20.5 mgP/l in the raw water.

This performance exceeds the 63.22% Pt removal reported by Rasool *et al.* [19] for a comparable biofiltration unit, indicating the strong potential of the system for phosphorus removal. However, despite the high removal efficiency, the residual Pt concentration in Column A's effluent remained above the regulatory limit of 2 mg P/L. Given the high ecological sensitivity of the receiving water body (an already stressed aquatic environment), compliance with phosphorus discharge standards would require coupling the biofiltration process with an additional polishing treatment step.

The temporal variation of Pt concentrations in raw and treated water is presented in Figure 3. A pronounced reduction in phosphorus was observed during the initial treatment phase (days 10-20), with an average removal efficiency of 91.02% and a residual Pt concentration of 1.54 mg P/L. This early-stage performance likely reflects the rapid development of biofilm and the activity of phosphorus-accumulating microorganisms, such as *Acinetobacter* spp., which assimilate phosphorus for metabolic needs.

Under conventional biological phosphorus removal, optimal elimination follows the 100/5/1 C/N/P ratio, and high

removal is typically associated with the “luxury uptake” mechanism. In the activated sludge process, biomass alternates between anaerobic and aerobic conditions. During the anaerobic phase, phosphorus-accumulating organisms (PAOs) hydrolyze intracellular polyphosphates, releasing phosphate into the surrounding medium, while synthesizing poly- β -hydroxyalkanoates (PHA) from easily biodegradable carbon. In the subsequent aerobic phase, these PHAs are oxidized, generating energy for cell growth and for the re-synthesis of intracellular polyphosphates, resulting in net phosphorus uptake.

In the present study, such anaerobic-aerobic cycling was not implemented. Therefore, the observed phosphorus removal is more plausibly attributed to adsorption phenomena associated with the coconut shell media. This interpretation is supported by Figure 4, which shows a positive correlation between the proportion of coconut shell in the reactor and phosphorus removal efficiency.

From approximately day 30 onwards, phosphorus removal efficiency decreased, with residual Pt concentrations stabilizing around 5 mg P/L, corresponding to an average removal of 70%. This decline can be explained primarily by the saturation of adsorption sites on the filter media, which reduced the contribution of adsorption to overall phosphorus removal. Additionally, the low carbon availability in the influent, as indicated by the C/N/P ratio, may have limited the activity of PAOs, thereby constraining biologically mediated phosphorus uptake.

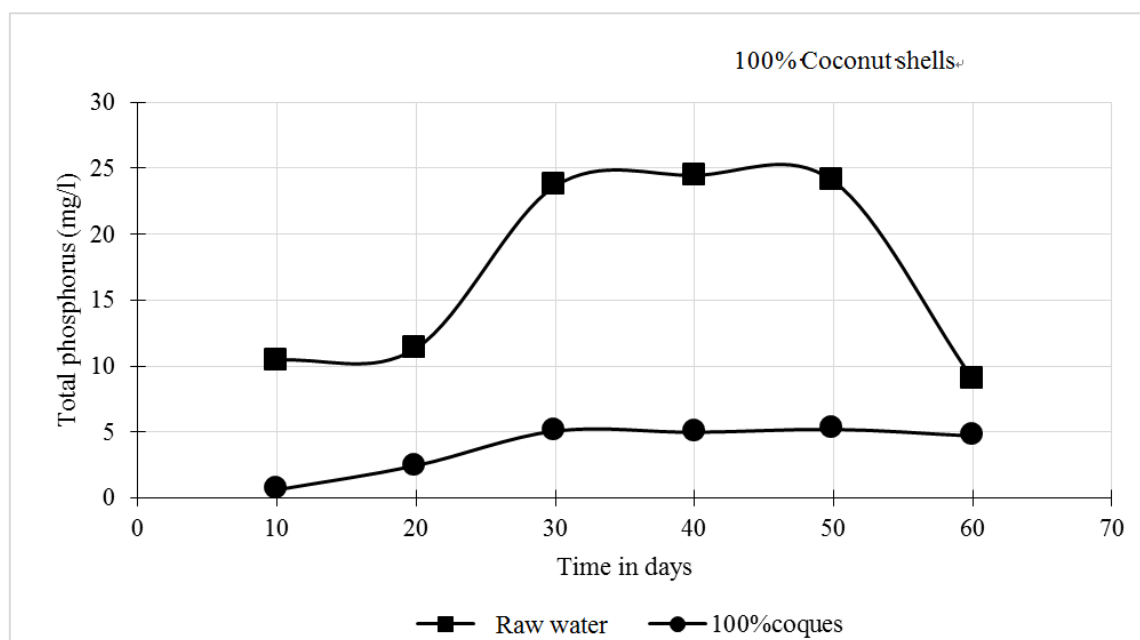


Figure 3. Total phosphorus removal in column A.

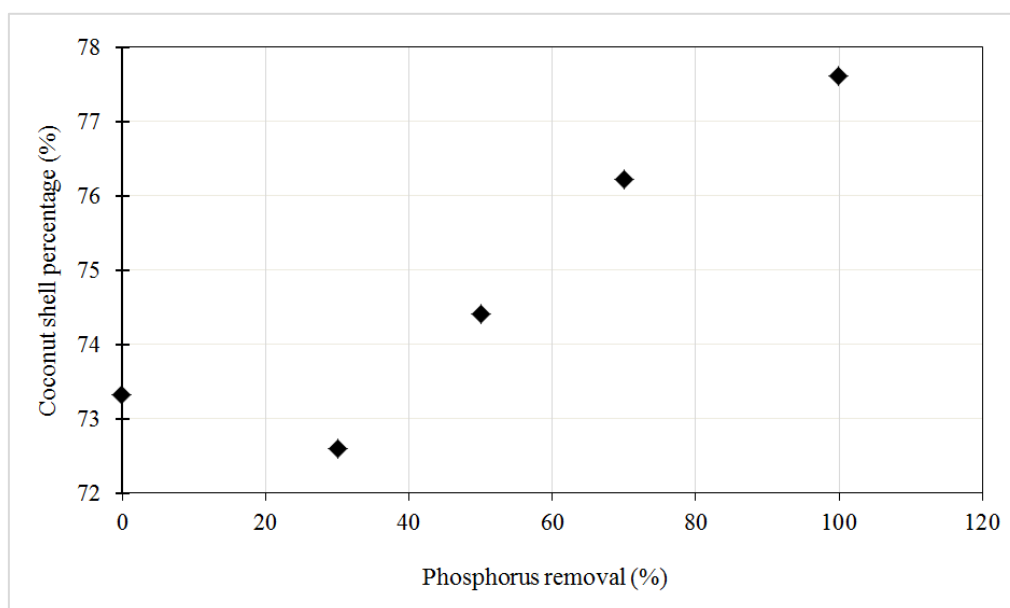


Figure 4. Correlation between the proportion of coconut shells in the reactors and the removal of phosphorus.

3.5. Turbidity Removal Efficiency

The coarse structure of the filter media generally resulted in high turbidity removal across all biofiltration columns, with an average reduction of 84.76%, except for Column A (100% coconut shell medium), which achieved only 58.86%.

The influent turbidity averaged 186 NTU, and Column E (composed entirely of coconut fibers) achieved the highest removal efficiency of 88.66%, yielding a residual turbidity of 26.16 NTU in the effluent.

There is a probable relationship between the proportion of coconut fiber in the reactor media and turbidity removal efficiency. The results indicate a positive correlation, the

higher the proportion of coconut fibers, the greater the turbidity reduction achieved. This trend suggests that coconut fibers are more effective for turbidity removal than coconut shells, likely due to their finer interstitial structure, which enhances particle retention [20-22].

3.6. Optimal Filtration Column

Based on the performance of each column for the parameters evaluated, it is difficult to designate a single “optimal” column capable of meeting all treatment requirements simultaneously. Therefore, the determination of the optimal column was carried out according to specific scenarios, as summarized in Table 6.

Table 6. Optimal Filter Media Configurations for Targeted Pollutant Removal in Biofiltration.

Pollutant removal objective (scenario)	Optimal filter media composition	Remarks
Standard configuration targeting simultaneous removal of carbonaceous and nitrogen pollution	50% coconut shells + 50% coconut fibers (Column C)	This configuration is ideal for nitrogen and phosphorus removal when phosphorus is not a limiting parameter, or when a complementary process is available for further phosphorus reduction.
Optimization for phosphorus removal	100% coconut shells	Phosphorus removal is enhanced by adsorption phenomena occurring on the surface of the coconut shells.

4. Conclusion

This study demonstrated the feasibility of applying the aerated biofiltration process for the treatment of domestic

wastewater. Characterization of raw effluent from the Hôtel du Lac revealed that it can be classified as urban wastewater, with low biodegradability and a C/N/P ratio indicating a deficit in carbonaceous matter.

Despite these limitations, the pilot-scale biofiltration

unit—comprising five columns with distinct filter media compositions—achieved promising treatment efficiencies: 49.39% COD removal with Column C, 69.36% BOD₅ removal with Column D, 73.55% total Kjeldahl nitrogen removal with Column C, 77.62% total phosphorus removal with Column A, and 88.66% turbidity removal with Column E. Based on these performances and the identified pollutant removal mechanisms, two optimal configurations were identified. For simultaneous removal of carbonaceous and nitrogenous pollution, Column C (50% coconut shells and 50% coconut fibers) provided the most balanced performance. For enhanced phosphorus removal, Column A (100% coconut shells) proved optimal, benefiting from the high specific surface area of the shells, which enhances phosphorus adsorption—a property also exploited in activated carbon production.

These results underscore the potential of tailored aerated biofiltration configurations to address specific treatment goals. Future research should evaluate the long-term operational stability of these systems and explore their integration with complementary processes to achieve stricter discharge standards, particularly in phosphorus-sensitive aquatic environments.

Abbreviations

BOD ₅	Biochemical Oxygen Demand over 5 days
COD	Chemical Oxygen Demand
HRT	Hydraulic Retention Time
TKN	Kjeldhal Nitrogen
TP	Total Phosphorus

Conflicts of Interest

The authors declare no conflicts of interest.

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