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Removal of Residual Phosphorus and Nitrates from Sewage Treatment Plants by a Fine Sand Filter

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Authors' contributions

This work was carried out in collaboration among all authors. Authors KBA and YYA designed the work and the experiment. Authors KBA and ZVES prepared the materials. Authors ZVES and MDEJC wrote the manuscript. Author TA revised the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Studies on eutrophication affirm that phosphorus is the limiting factor on which action must be taken to avoid the production of algal biomass and the appearance of green tides in waterways. A concentration of 1 mg/L of phosphorus in a body of water is sufficient to trigger eutrophication.

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However, according to the wastewater discharge standards in force in Côte d'Ivoire, the secondary water of a WWTP must have a phosphorus concentration of less than 2 mg/L. With the exception of lagooning, conventional biological purification processes, such as activated sludge, eliminate in the best case 50 % of the initial phosphorus contained in the raw wastewater. As a result, refining processes, called tertiary treatment, are implemented at these stations. Since the WWTP subject to our study does not have a refining system, it often turns out that the water leaving this station does not meet the standards. In addition, in some cases, when work is carried out on this station, it is shut down. In this case, the water is collected and discharged directly. Since eutrophication has harmful impacts on the receiving environment, it is important to conduct studies to minimize it. Thus, we were asked to set up a refining process for the elimination of phosphates. To refine this water, we opted for direct filtration on a sand bed. Having four types of sand, we carried out filtration tests, according to an experimental plan, in the laboratory by playing on the parameters: the type of treatment, the height of the sand, the volume of water poured and the grain size of the sand and measured the phosphorus and nitrate contained in the filtrates in order to determine optimal refining conditions. Thus, this study has shown that it is possible to refine the secondary waters of this WWTP by carrying out direct filtration on a bed of sand with a grain size of 0.5 mm < ∅ < 1 mm treated with acid, which can then serve as a basis for other future additional studies to determine the sizing parameters of this sand filter. We have also been able to see that the parameters that are: the type, grain size and height of the sand, and the volume of effluent passing over the filter are parameters that influence the efficiency of said filter on the retention of phosphorus and nitrate in discharge water.

Keywords: Removal; experimental design; phosphorus; nitrate; station.

1. INTRODUCTION

The presence of phosphates and nitrates in surface waters creates a significant ecological imbalance in aquatic ecosystems, leading to their eutrophication [1,2]. The development of algal production and higher plants constitutes a real pollution that depletes the environment in dissolved oxygen and compromises the use of the waters concerned. Certain algae (cyanophyceae) excrete toxins that make aquatic life difficult, particularly in stagnant waters (lakes and ponds) or with low flow speeds [3]. A concentration of 1 mg/L of phosphorus in a body of water is sufficient to trigger eutrophication [4]. The phosphorus content of industrial wastewater is of the order of 10 to 100 mg PT/L and 10 to 25 mg P_T/L for urban wastewater [5]. Total phosphorus discharges per inhabitant per day are estimated at between 3.5 and 4 g. Phosphorus is the limiting factor on which action must be taken to prevent the production of algal biomass and the appearance of green tides in watercourses. Phosphorus discharge standards according to the size of the treatment plants (< 1 mg P_T/L or 80 % elimination for plants with a capacity > 106 Eq.hab. and < 2 mg PT/L for plants < 106 Eq.hab.). There are many specific biological dephosphatement processes and their removal efficiency can reach 90 % [6,7]. The presence of nitrates inhibits the dephosphatement process and their removal requires a denitrification station, which leads to the multiplication of structures in anaerobic and aerobic zones. The configuration of the station then becomes important and its operation more difficult. In order to reduce the level of nutrients in the discharge water, it is necessary to set up a system for refining this water before releasing it into nature [8-10]. It is in this context that we undertook this study which consists of setting up a process for the elimination of nutrients responsible for eutrophication (phosphorus and nitrates) of bodies of water contained in the secondary waters of an activated sludge plant.

2. EXPERIMENTAL PROCEDURE

2.1 Setting up an Experimental Plan

The filtration tests were carried out according to an experimental design. A first-degree model, namely a 2^k complete factorial design (CFD), was chosen. The phenomenon studied is the filtration of water on a sand bed and the response is the rate of reduction of phosphate and nitrate ions. The type of sand (U_1), the granulometry (U_2) and the height of sand (U_3), and the volume of treated water (U_4) are the factors chosen to study the phenomenon. These four (4) factors led to the experimental field shown in Table 1. Two factors are qualitative (U_1 and U_2) while factors U_3 and U_4 have a quantitative character. In order to scan a certain amount of data, the levels of the factors likely to influence the response according to the literature are coded by (-1) and (+1) representing respectively the low level and the high level.

SH and SO (Table 1) sands are obtained after treatment of sea sand with an acid and an oxidant respectively. The phenomena studied in this work are removal of phosphorus and nitrates residual present in treatment plants. These phenomena thus give rise to the study of two responses (Y_1 and Y_2) according to the methodology of experimental designs. These answers which are, within the framework of this study removal rate (Y) of phosphates and nitrates ions is a linear function (eq.1) of all the coded variables X_1, X_2, X_3 and X_4 corresponding respectively to the variables real values U_1, U_2, U_3 and U_4.

$$Y = a_0 + a_1X_1 + a_2X_2 + \ldots a_kX_k + a_{12}X_1X_2 + \ldots +_{ak\text{-}1}kX_{k-1}X_k + \ldots + a_{1}\ldots kX_1X_2\ldots X_k \quad (1)$$

With ai the effect of the factor (Xi) and aij that of the interactions between factors i and j.

The different coefficients are calculated using the NEMROD-W software version 9901 as well as the standard deviations and the calculated responses (Ycalc.). The significance tests of each coefficient were established by considering that a coefficient is statistically significant if its absolute value is greater than 2σ (σ being the standard deviation).

2.2 Filtration Tests

The treatment of the waste water was carried out in a column with a diameter of 4.6 cm according to the predefined experimental plan. A certain volume of waste water is poured onto a layer of sand of well-defined height forming a filter, the percolate is collected and the nitrate and phosphate ion contents are determined using a UV/visible spectrophotometer of the Jasco 530 type.

2.3 Dosage of Phosphates and Nitrates

Concerning the dosage of phosphate ions; the method of the NF T90-023 standard of September 1982 [11] was used to determine the content of orthophosphate ions because the total phosphate load includes orthophosphates, polyphosphates, organic phosphorus compounds. It must be said that orthophosphate (PO_4^{3-}) is generally the most important form, this will be measured in this present work. As for the dosage of nitrates, the analysis method uses the NF T90-045 standard of June 1989 [12] was used in this work. Furthermore, it is important that the nitrate ion NO_2^- is the main form of combined nitrogen found in wastewater. It constitutes the final stage of nitrogen oxidation. Thus, the nitrite ion NO_2^- is easily oxidized into nitrate ion and, for this reason, it is rarely present in significant concentration in wastewater.'

2.4 Calculation of the Removal Rate

The removal rate (R) in PO_4^{3-} and NO_3^- ions is calculated from eq.2:

$$R\,(\%) = \frac{C_B - C_T}{C_B}\; x\; 100 \quad (2)$$

With C_B being the content of the ion in the raw water and C_T that in the treated water.

2.5 Weight of Main Effects and Interactions on the Response

The importance of factors and interactions on phosphate removal will be highlighted using eq.3. Indeed, it is possible to give more significant information by calculating the contribution of each factor on the response.

$$P_i = \left(\frac{b_i^2}{\sum b_i^2}\right) * 100 \;(i \neq 0) \quad (3)$$

3. RESULTS AND DISCUSSION

3.1 Characterization of the Raw Sample

The results obtained during this work from the analyses on the raw water sample are recorded in Table 2.

The phosphate and nitrate contents show that the water discharged without tertiary treatment does not meet the standards.

3.2 Analysis of the Removal Rates Obtained from the Experimental Design

The removal rates obtained for the different experiments are reported in Table 3. The values vary from 22.13 to 67.79 % and from 25.77 to 67.69 % for phosphate and nitrate ions, respectively. These rates are relatively high, and indicate, a priori, the effectiveness of the treatment. The high nutrient removal rates are obtained with experiment 5 consisting of the treatment of a volume of wastewater of 200 mL of water on a bed of fine SH sand 10.5 cm high.

3.3 Statistical Analysis of the Data Obtained

3.3.1 Phosphate ions (phenomenon 1: Y1)

The statistical analysis of this model initially leads to the variance analysis table (Table 4). It mainly indicates that the first degree model used does not indicate a good fit of the model. Indeed, the error due to the residuals (the adjustment error) is very large. In addition, the sum of squares due to the error ($1.07x10^3$) is very large compared to the total sum of squares ($2.95x10^3$). The values of the additional more detailed analysis are summarized in Table 7. These show that the fit is not correct. Indeed, the value of the multiple linear correlation coefficient (R^2 = 0.636) obtained by the software is too low and indicates that the fit is not correct. This means that the first degree model explains 63.60 % of the phenomenon of the elimination of phosphate ions present in the treatment plants. This percentage is therefore very low. It is therefore important to specify that R^2 is not at all close to 1. Based on these observations, it is important to clearly conclude that the first-order model therefore does not allow the study of the elimination of phosphate ions under the given experimental conditions. This observation observed in this study is similar to that obtained by E. Zran and al., [13]. In addition, the average elimination rate is 43.89 %, which is lower than the rates obtained by Qili et al., in 2023 and Asmaa et al. in 2024 [14,15].

3.3.2 Nitrate ions (phenomenon 1:Y1)

3.3.2.1 ANOVA and correlation coefficient (R^2) and residuals analysis

The variance measures the dispersion around the mean. The variance analysis (Table 5) shows that this first-degree model correctly fits the data obtained. The sum of squares due to the residuals, i.e. the adjustment error (1.61×10^2), is less than one-fifteenth of the sum of squares due to the regression. This good adjustment is confirmed by the more detailed analysis given by the value of the multiple linear correlation coefficient (R^2 = 0.940, i.e. 94 %), given by the software. Thus, the adjustment made is satisfactory because it is very close to 1. In addition, the first degree explains 94.00 % of the phenomenon of elimination of nitrate ions present in the treatment plants. Table 6 of the residuals also makes it possible to judge the quality of the adjustment made. Comparing the values of the measured responses (Yexp.) to those of the responses predicted by the model (Ycalc) shows that the adjustment is of good quality. Indeed, all the values of the differences are less than 5.00 % [16] with the exception of experiment 11. It is therefore important to specify that any “studentized” residual greater than 2 (in absolute value) reflects a significant lack of adjustment. The results obtained indicate, apart from experiment 11, that the values of the studentized residuals are less than 2 (in absolute value). This clearly indicates that the first model better explains the phenomenon of elimination of nitrate ions in these human achievements. Experiment 11 being the most studentized with a Cook distance of 0.695, thus constitutes the test having the greatest influence on the study of the effects.

Table 1. Experimental field

Factors	Designation	Low level (-1)	High level (+1)
U_1	Type of sand	SH	SO
U_2	Granulometry	Fine	Coarse
U_3	Height of sand (cm)	7.00	10.50
U_4	Volume of watter (mL)	200.00	400.00

Table 2. Characterization of the raw sample

Paramètres	pH	TDS (ppm)	Conductivité (µS/cm)	Turbidité (NTU)	Nitrate (mg/L)	Phosphore (mg/L)
Valeurs	8.06	360	720	108	5.2	3.57
Normes OMS	6.5 – 8.5	-	-	-	< 1	< 2

Table 3. Experimental field of coded and real variables of the Full Factorial Design (FD) factors

	Factors											
		Coded	Var		Real	Variables			Conc.	PO_4^{3-}	Conc.	NO_3^-
No Exp	X_1	X_2	X_3	X_4	Type of Sand	Granulo-metry	Sand height	Water volume (mL)	PO_4^{3-}	Removal rate (%)	NO_3^-	Removal rate (%)
1	-1	-1	-1	-1	SH	Fine	7.00	200.00	2.78	22.13	1.84	64.62
2	1	-1	-1	-1	SO	Fine	7.00	200.00	2.14	40.06	2.93	43.65
3	-1	1	-1	-1	SH	Coarse	7.00	200.00	2.00	43.98	3.13	39.81
4	1	1	-1	-1	SO	Coarse	7.00	200.00	2.53	29.13	3.69	29.04
5	-1	-1	1	-1	SH	Fine	10.50	200.00	1.15	67.79	1.68	67.69
6	1	-1	1	-1	SO	Fine	10.50	200.00	2.03	43.14	3.13	39.81
7	-1	1	1	-1	SH	Coarse	10.50	200.00	1.88	47.34	2.74	47.31
8	-1	-1	-1	1	SO	Coarse	10.50	200.00	2.46	31.09	3.58	31.15
9	1	-1	-1	1	SH	Fine	7.00	400.00	1.27	64.43	1.80	65.38
10	-1	1	-1	1	SO	Fine	7.00	400.00	2.92	18.21	2.10	59.62
11	1	1	-1	1	SH	Coarse	7.00	400.00	1.90	46.78	3.86	25.77
12	-1	-1	1	1	SO	Coarse	7.00	400.00	2.11	40.90	3.07	40.96
13	1	-1	1	1	SH	Fine	10.50	400.00	1.38	61.34	2.01	61.35
14	-1	1	1	1	SO	Fine	10.50	400.00	1.84	48.46	2.98	42.69
15	1	1	1	1	SH	Coarse	10.50	400.00	1.70	52.38	2.46	52.69
16	-1	-1	-1	-1	SO	Coarse	10.50	400.00	1.96	45.10	2.85	45.19

Table 4. Analysis of variance

Source de variation	Sum of squares	Degrees of freedom	Medium square	Rapport	Signif
Régression	1870	10	1870	0.8732	60.1%
Résidus	1070	5	2140		
Total	2950	15			

Table 5. Analysis of variance (response Y2)

Source de variation	Sum of squares	Degrees of freedom	Medium square	Rapport	Signif
Régression	2500	10	250	7.7666	*
Résidus	161	5	32,2		
Total	2670	15			

Table 6. Analysis of residues on nitrate retention

N° Exp.	$Y_{exp.}$	$Y_{calc.}$	Différence	Standardized	dU	Student-R	R-Student	D-Cook
1	64,620	66.599	-1.979	-0.348	0.688	-0.623	-0.580	0.078
2	43,650	46.887	-3.237	-0.570	0.688	-1.019	-1.024	0.208
3	39,810	34.919	4.891	0.861	0.688	1.539	1.898	0.474
4	29,040	28.714	0.326	0.057	0.688	0.102	0.092	0.002
5	67,690	66.984	0.706	0.124	0.688	0.222	0.200	0.010
6	39,810	35.299	4.511	0.794	0.688	1.420	1.644	0.403
7	47,310	50.927	-3.617	-0.636	0.688	-1.138	-1.183	0.259
8	31,150	32.749	-1.599	-0.281	0.688	-0.503	0.462	0.051
9	65,380	62.367	3.013	0.530	0.688	0.948	0.937	0.180
10	59,620	57.417	2.203	0.388	0.688	0.693	0.652	0.096
11	25,770	31.694	-5.924	-1.042	0.688	-1.865	-3.022	0.695
12	40,960	40.252	0.708	0.125	0.688	0.223	0.200	0.010
13	61,350	63.089	-1.739	-0.306	0.688	-0.547	-0.505	0.060
14	42,690	46.167	-3.477	-0.612	0.688	-1.094	-1.122	0.240
15	52,690	48.039	4.651	0.818	0.688	1.464	1.732	0.429
16	45,190	44.624	0.566	0.100	0.688	0.178	0.160	0.006

3.3.2.2 Estimates and statistics of the coefficients

The estimates and statistics of the coefficients are presented in Table 7. The experimental error (standard deviation) obtained is 1.421. Then the significant factors (those whose absolute value of their coefficient is greater than 2*σ = 2.842) are the effects:

- significant main ones: a_1 (type of sand); a_2 (granulometry);
- significant interactions: a_{12} (interaction effect between the type of sand and the granulometry); a_{23} (interaction effect between the granulometry and the height of the bed) and a_{14} (interaction effect between the type of sand and the volume of water). The absolute value of the coefficient a_{13} (2.993) is greater than 2*σ.

However, its effect on the response being weak, it is therefore not significant. The mathematical equation that describes the phenomenon is given by:

$$Y_2 = 47{,}296 - 5{,}782\ X_1 - 8{,}306\ X_2 + 3{,}377\ X_1X_2 + 3{,}906\ X_2X_3 + 3{,}691\ X_1X_4$$

Fig. 2 presents the contribution of different factors on the retention of nitrate ions during filtration. The contributions of the sand type and the particle size are 21.32 % and 44.00 % respectively. The coefficient a_0 = 47.296 represents the average of the responses of the 16 tests. This response is low compared to the results obtained by Dong et al. [9], and Ali et al. [17]. When the SH sand is replaced by SO, the retention rate of nitrate ions decreases by 11.564 % (5.782 x 2). The most important contribution is that of the particle size. Indeed, when moving from the fine fraction to the coarse fraction, the retention rate decreases by 16.612 % (8.306 x 2). Concerning the interaction effects, their contributions are the lowest.

Table 7. Estimates and statistics of the coefficients of the response Y2

Nom	a_0	a_1	a_2	a_3	a_4	a_{12}	a_{13}	a_{14}	a_{23}	a_{24}	a_{34}
Coefficient	47,296	-5,782	-8,306	1,189	1,911	3,377	-2,993	3,691	3,906	0,252	0,084
Ecartype	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421	1,421

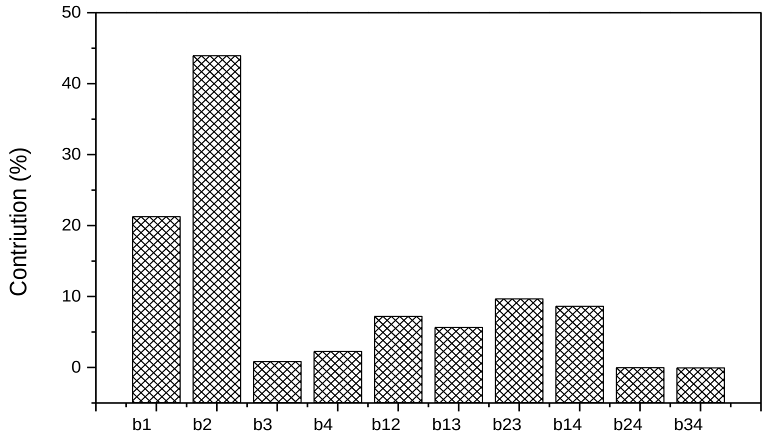

Fig. 1. Pareto analysis graph of the effects of different factors

3.3.2.3 Analysis of interaction coefficients

- **Sand-granulometry interaction coefficient**

Fig. 2 shows the effect of the sand type-granulometry interaction on the Y_2 response. Fine SH sand allows an average reduction of 64.76 % of nitrate ions. This rate constitutes the maximum capacity for removing nitrate ions for all the combinations carried out. Under the same conditions, the purification capacity of SO sand is 46.44 %. Regardless of the type of sand, fine granulometry has the greatest purification capacity.

- **Interaction coefficient Granulometry-sand height**

Fig. 3 shows that fine sands provide better removal of nitrate ions. However, the retention rate decreases with the height of the sand. However, in the chosen experimental range, the height has no effect on the retention of nitrate ions.

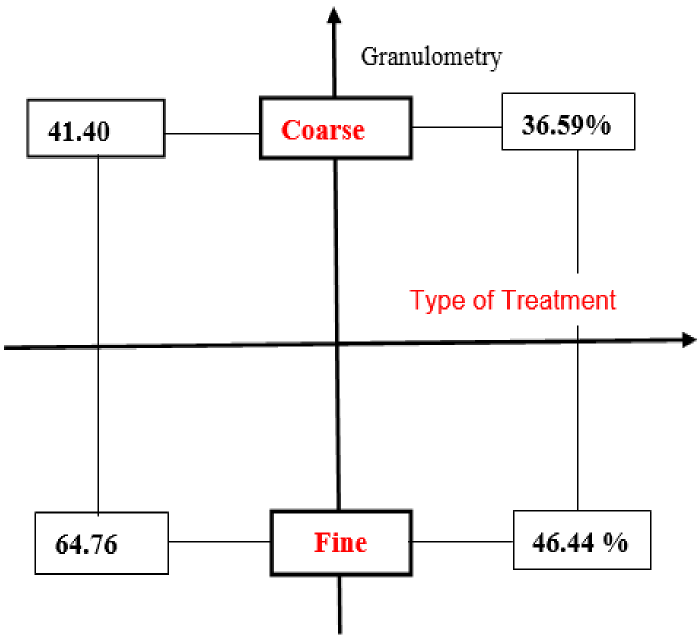

Fig. 2. Graph of sand type-granulometry interaction

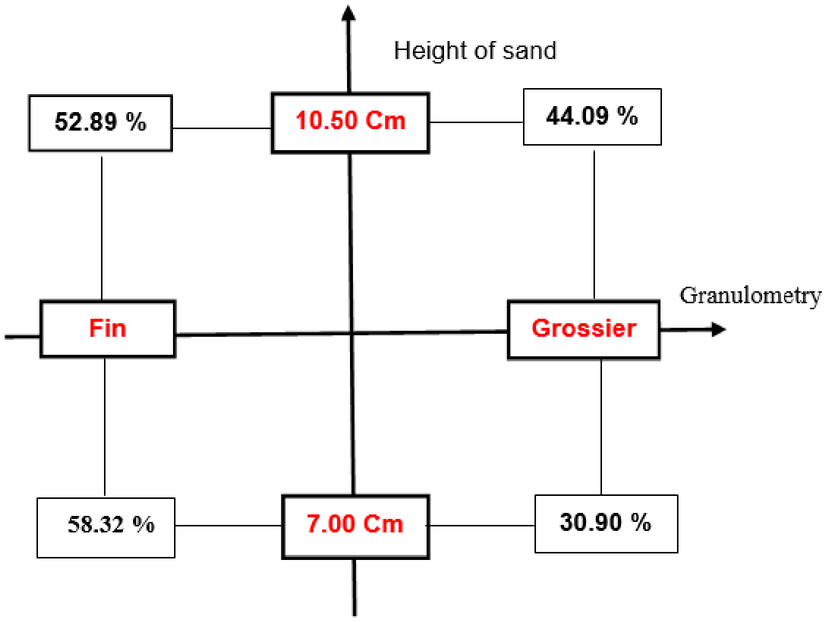

Fig. 3. Graph of the interaction between grain size and sand height

3.3.2.4 Choice of optimal conditions for response Y2

We have seen that the mathematical equation which describes the retention of nitrate ions by sand is in the form:

$$Y_2 = 47,296 – 5,782\ X_1 – 8,306\ X_2 + 3,377\ X_1X_2 + 3,906\ X_2X_3 + 3,691\ X_1X_4$$

The standard set by the WHO regarding the concentration of nitrate contained in wastewater before discharge into a natural environment is less than 1 mg.L^{-1}. The problem of this study is to find the values of the quantitative factors and the conditions allowing to retain the maximum of nitrate contained in the discharge water. In this part, we will call the optimal response the output: Y_2 = 100, which amounts to eliminating all the nitrate (100 %, ideal condition) in the effluent after its treatment by sands. Thus, finding the conditions allowing to satisfy this output amounts to solving the equation:

$$47,296 – 5,782\ X_1 – 8,306\ X_2 + 3,377\ X_1X_2 + 3,906\ X_2X_3 + 3,691\ X_1X_4 = 100$$

Factors X_1 (sand type) and X_2 (granulometry) are qualitative factors. However, we can quantify factor X_2 by considering the diameter ø of sand grains. And we associate factor X1 with the value 0. We set the following constraints for factors X_2 (granulometry), X_3 (sand height) and X_4 (water volume): 0.25mm ≤ X_2 ≤ 1mm, X_3 < 20 cm (taking into account the height of the test columns) and 100 mL ≤ X_4 ≤ 400 mL. Using the Excel Solver utility, we obtain the following results:

Y_2 =100.0001 for X_1 = 0; X_2 = 0.97 mm ; X_3 =16 cm and X_4 =100 mL

The optimal conditions for retention of nitrate ions would be:

X_1 = SH; X_2 = fin ($Ø_{grains}$= 0.97mm); X_3 = 16 cm and X_4= 100 mL.

4. CONCLUSION

The objective of our work is to address the possibility of refining secondary water from an activated sludge plant and to propose a more suitable treatment process. Thus, to address this issue, we opted for refining with a sand filter. The aim of this refining is to propose a less expensive treatment method capable of reducing phosphorus and therefore combating the phenomenon of eutrophication. Thus, we carried out filtration tests, following an experimental plan, in the laboratory, using two types of sand (fine sand and coarse sand) having received two types of treatment; which gives us four types of sand. We were able to see that it is possible to refine the discharge water from an activated sludge treatment plant by direct filtration on a sand bed. The parameters: the type of treatment, the particle size, the height of the sand and the volume of water poured, influence the efficiency of the filter formed. The acid-treated sand, with a grain size (Øgrains = 0.97mm) and height h=16 cm, and on which 100 mL of the sample is passed at a flow rate of approximately 0.208 mL/s, not only allows optimal retention of nitrate ions but also improves the retention of phosphates in the case of the chosen experimental domain. However, for the sizing of the refining system, it is important to carry out other studies in order to search for the sizing parameters.

5. RECOMMANDATIONS

We have just seen that SH sand allows a good satisfaction of the Y_1 and Y_2 responses than SO sand. Similarly, increasing the height of the sand improves its efficiency for the satisfaction of the Y_1 response. The evolution of the grain size is the weakest effect that influences the satisfaction of the Y_1 response (Table 7). Therefore, choosing SH sand with grain size (Øgrains = 0.97 mm) and height h = 16 cm, and passing 100 mL of the sample through it, not only allows an optimal retention of nitrate but also improves the retention of phosphates (35 % more). For the sizing of the structure, other studies must be done on this sand in order to determine the sizing parameters. Then an evaluation of the construction space of said structure should be carried out.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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