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Depth and performance evaluation of a laboratory scale sand filtration system for wastewater treatment

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Abstract: Intermittent sand filtration (ISF) was adopted in the treatment of synthetic wastewater having septic tank effluent's properties in the laboratory. Over a period of 84 days synthetic wastewater was intermittently dosed onto two sand filters of 50 cm and 100 cm depths at an interval of 4 h. The filter material has an effective size d_{10} of 0.42 mm, d_{60} of 0.92 mm, coefficient of uniformity, Cu, of 2.2, and hydraulic conductivity of 4.632×10^{-3} ms^{-1} with an effective pore diameter of 0.094 mm. The hydraulic loading was 0.144 m/day and the BOD_5 of the wastewater was 172.3 mg/L. The removal of suspended solids, ammonium-nitrogen (NH_4-N), and BOD_5 in 100- and 50-cm columns was 91.4% and 88.6%, 98.7% and 99.8%, and 92% and 90%, respectively, while PO_4-P removal was about 45% in both columns. Unlike other parameters, NO_3-N was increasing, which signifies that denitrification did not take place in the filter columns. Based on the results, the filter column of 50 cm is economically preferable due to the insignificant difference when compared with the 100-cm filter column. The bacteria removal was slightly higher in 100 cm depth (99.88%) than in 50 cm depth (99.68%).

Key words: Intermittent filtration, synthetic wastewater, depth variation

1. Introduction

In Lagos State, Nigeria, there are over 14 million people (National Population Census, 2006). Lagos city can be divided into two, namely Island and Mainland. In the Island part the water table is high, leading to a threat to groundwater by pollutants that emanate from the wastes that are dumped or discharged into the environment.

Domestic wastewater is traditionally managed by septic tank-soak away system by most homes in Lagos. This system can be a treatment option where suitable soil conditions exist to remove organic carbon, phosphorous, ammonia-nitrogen, total suspended solids, and microorganisms [1]. In the Island part of Lagos where the water table and soil porosity are high, septic tank systems may not function satisfactorily. Installation of a septic tank percolation system can lead to potential health and environmental problems.

Filtration of wastewater is most commonly used for achieving supplemental removal of suspended solids (including particulate BOD) from wastewater that has undergone some biological and chemical treatment processes [2]. Although filtration is one of the principal unit operations used in the treatment of potable water, it has also been employed in filtration of effluents from the wastewater treatment process [3]. Intermittent sand filtration has been used to treat septic tank effluent [4] but in Nigeria it has not been adopted as a tertiary treatment of effluent from septic tanks.

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The process of passing the effluents from septic tanks to a sand column gives room for interaction between the percolate constituents (microbial, organic, and inorganic) and the media, thus leading to some removal of the pollutants. The processes that take place within the filter include nitrification, denitrification, and abiotic processes. The removal of P in the leach field can take place via abiotic processes through the sorption and binding of PO_4 to oxides of aluminum and iron in acidic soils and the formation of insoluble precipitates in alkaline soils [5–7]. The removal of nitrogen is through bacteria that mineralize organic nitrogen to ammonium, oxidize it to nitrate, and further reduce it to N_2 and N_2O gases, which are readily lost to the atmosphere [8]. The removal of microbes is through straining, adsorption, predation, and competition with resident microflora [9,10].

The performance of an intermittent sand filter system will vary with the media used, temperature, hydraulic loading rate (HLR), organic loading rate (OLR), and method of application [11]. Design specifications recommend that the sizing of the filter media should be in accordance with its use [12,13]. For single-pass operation, an effective grain size (d_{10}) of 0.35–1 mm and a uniformity coefficient (CU) of less than 3.5 are recommended.

In a study of four sets of three identical sand filters, 0.38 m deep; effective grain sizes of 0.33, 0.54, and 0.93 mm; uniformity coefficients of less than 1.42; and a hydraulic loading rate of 163 L/m^2-day, no discernible difference in performance results was noted [14].

The effectiveness of intermittent filters that comprise sand, soil, and glass media in the treatment of low-strength wastewater was studied, and it was found that an organic loading rate of 9.8 g COD/m^2-day and 0.65 m-deep soil performed best in the removal of organic carbon, ammonium-N, and bacteria [1].

This study entails the construction and operation of two sand filters with 50 and 100 cm depth to treat a synthetic wastewater of septic tank effluent strength for a period of 14 weeks. The aim is to examine the performance of intermittently loaded filters comprising sand medium with a gravel underlay to treat synthetic septic tank effluent in the laboratory.

2. Materials and methods

The study was carried out in the Granulometric Laboratory, Hydraulic Research Unit of Civil and Environmental Engineering Department, University of Lagos, Nigeria. The laboratory set up consisted of two filter columns of Perspex material. The columns were 100 mm in diameter and 5 mm thick. The bases of the columns were sealed with flat Perspex of 10 mm thickness. The filter sand was from Ilaje, a suburb of Lagos. The particle size distribution curve of the filter is shown in Figure 1. The characteristics of the filter material are shown in Table 1. The columns were preconditioned and saturated by pumping water into them followed by draining prior to performing the test.

The filter material has an effective size d_{10} of 0.42 mm, d_{60} of 0.92 mm, d_{15} of 0.47 mm, coefficient of uniformity, Cu, of 2.2, and effective pore diameter of 0.094 mm. These values fall within those recommended by USEPA [12].

Synthetic wastewater is commonly used in laboratory scale treatment systems [15]. For this experiment, synthetic wastewater with concentration close to measured septic tank values was prepared. The composition of the synthetic wastewater is shown in Table 2 [16]. The schematic of the experimental set up is presented in Figure 2. The influent was applied to the filter from the top through a peristaltic pump. The pump operation was for 15 min duration on each batch at a hydraulic loading rate of 0.144 m/day. The batching is 6 times a day for 84 days as shown in Figure 3. An effluent sample was collected at the end of each batch from the columns through a hole located 75 mm above the base of the column into a 1-L beaker for quality analysis.

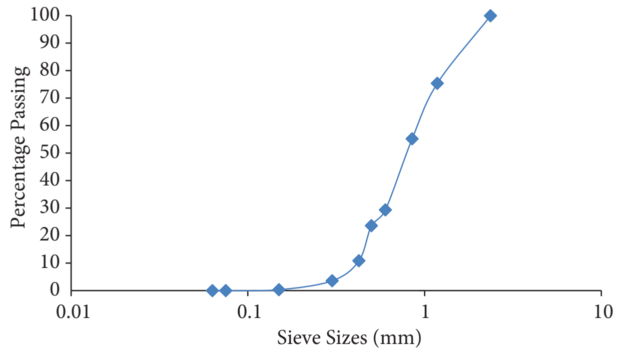

Figure 1. Particle size distribution curve of the filter sand materials.

Table 1. Granulometric and hydraulic characteristics of filter materials.

Parameter	Value
	0.42 mm
d_{10}	0.47 mm
d_{15}	0.92 mm
d_{60}	1.3 mm
d_{75}	2.2
Cu	0.094 mm
Effective pore diameter $\left(\frac{d_{15}}{s}\right)\left(\frac{d_{15}}{s}\right)$	0.004632 m/s
Hydraulic conductivity, K Bulk density	1701 kg/m^3

Table 2. Composition of domestic – strength synthetic wastewater used.

Component	Unit	Quantity
Milk	mg	265
$NaHCO_3$	mg	250
Meat extract	mg	260
Semo flour	mg	100
Saline water (mL)	ml	50
Saline water in 1000 mL of water		
Urea	mg	520
NaCl	mg	120
$CaCl_2$	mg	60
$MgSO_4 - 7H_2O$	mg	40

Source: Longe et al., 1989.

The influent was sampled daily, while the effluent was sampled every 4 h, thus totaling 6 effluent samples for testing every day. The water quality parameters tested were: BOD_5, NH_4-N, NO_3-N, and PO_4-P, and microbial. The BOD_5 was measured in accordance with the 5 day BOD test method. The NH_4-N, NO_3, and PO_4-P were measured using HI 83099 COD and a multiparameter bench photometer. All water parameters were analyzed using standard methods [17].

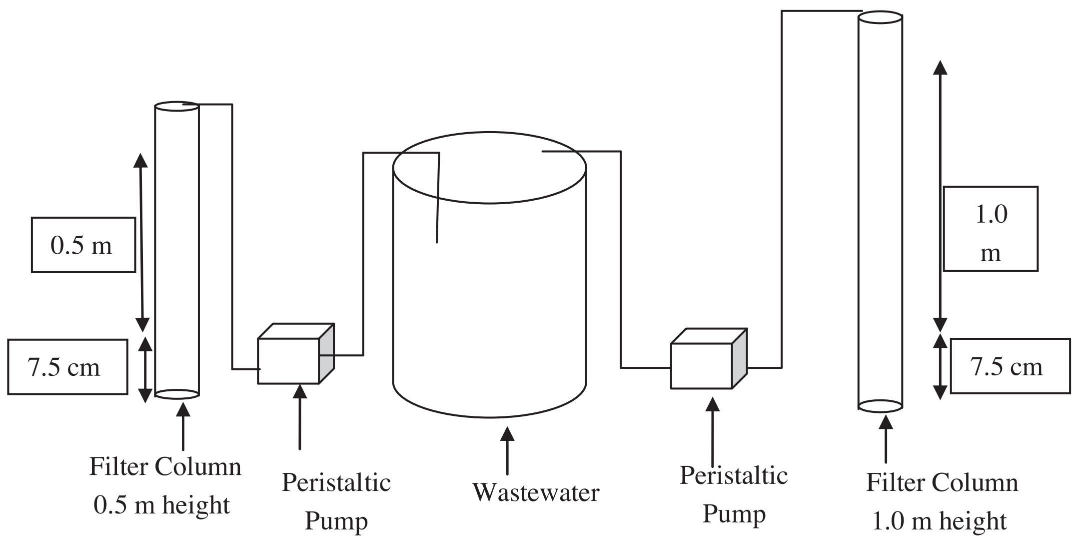

Figure 2. Schematic of experimental set up.

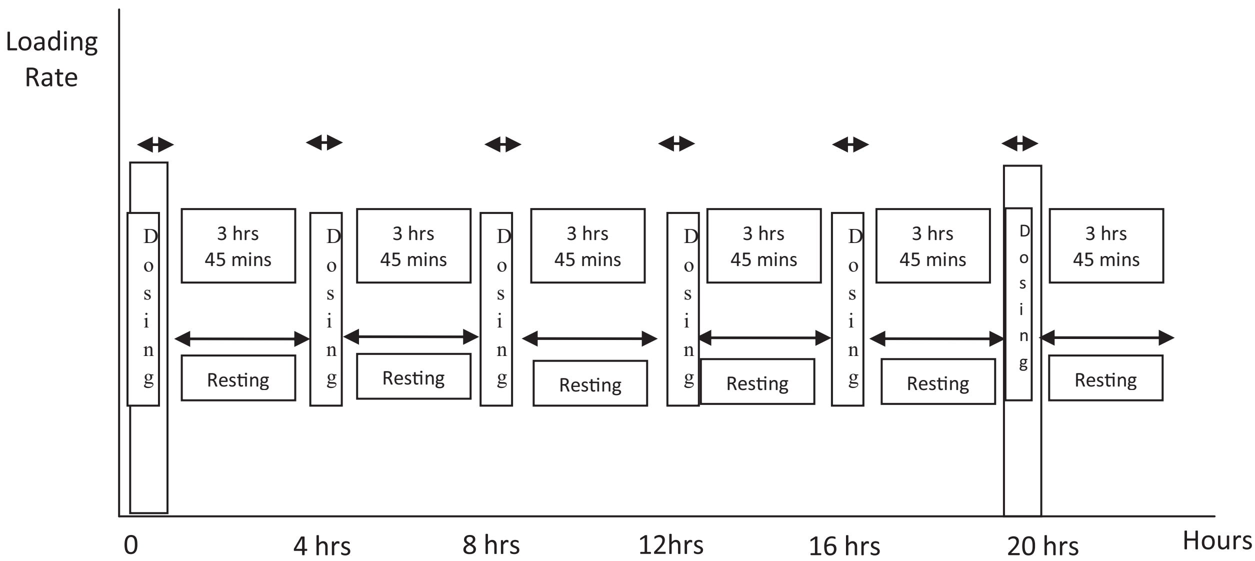

Figure 3. Batching operation of filtration system.

3. Results and discussion

The average pH of the influents was 7.8. The pH ranges between 7.9 and 8.5 for the effluents for the 100-cm column and between 8.0 and 8.4 for the 50-cm column. The pH slightly increased on average by 0.3 in the column of 100 cm height due to biological activity and gas exchange as reported by Kim et al. [18]. The range of pH values indicates that the system can operate optimally for biological activities.

A summary of the results is shown in Table 3. The average BOD_5 of the influents into the columns is 172.3 mg/L. In the two columns, the rate of BOD_5 removal increased over the course of the experiments. There is no significance difference in the rate of organic removal at the end of the experiment with BOD_5 removal of 92% and 90% in the 100-cm and 50-cm columns, respectively. This indicates that the organic loading removal is slightly higher in the 100-cm filter column. The values are close, thus indicating that organic removal by the filter is not dependent on depth, as earlier observed by Amador et al. [7]. The rate of removal of BOD_5 increased over the duration of the experiment as shown in Figures 4 and 5.

Table 3. Efficiency of the sand filter.

Parameters	Influent	Effluent		Percentage removal (%)	
		100-cm height	50-cm height	100-cm height	50-cm height
BOD (mg/L)	172.3	15	18.6	92	89.7
TSS (mg/L)	14	1.2	1.6	91.4	88.6
NH_4-N (mg/L)	7.54	0.1	0.07	98.7	99.8
NO_3-N (mg/L)	1.8	21	19	N.A	N.A
PO_4-P (mg/L)	4.25	2.84	2.26	41.6	47
DO (mg/L)	1.5	4.07	4.59	N.A	N.A
E. coli (CFU)	7.6 E+08	9.0E+06	2.4 E+06	99.88	99.68

N.A – Not applicable

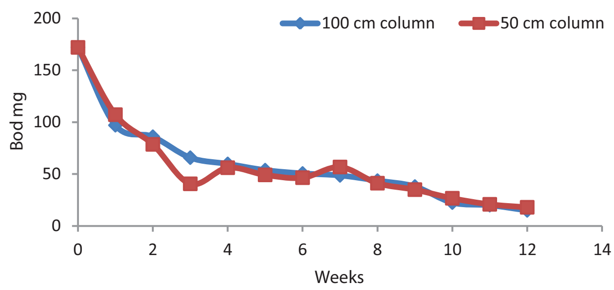

Figure 4. BOD_5 values as a function of time.

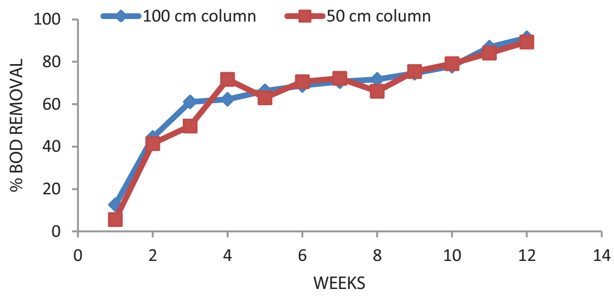

Figure 5. Removal efficiency of BOD_5 as a function of time.

The DO was measured every 4 h and the values of the effluent range between 4.07 and 4.59 mg/L, while those of the influent were between 1.4 and 1.65 mg/L. The influent is slightly lower than the effluent, indicating that organic decomposition by microbes is highly supported in the filter column.

The biological removal of nitrogen is a two-step process of nitrification and denitrification. During nitrification, a decrease in NH_4-N levels is noticed, followed by an increase in NO_3-N concentration. Nitrification occurs at optimum pH values of 7 and 8 [19]. Throughout the period of the laboratory experiment, the pH values were optimal for the nitrification process. From the 8th week, the nitrification process was almost complete. During this period, the removal rate of NH_4-N was 98.67% and 99.06%, respectively, for the 100- and 50-cm columns and values were less than 1 mg/L.

The average NO_3-N for the influent was 1.8 mg/L. NO_3-N was the dominant form of Total-N in the effluents. The nitrate concentration that percolates to filter depth increased initially for the first 3 weeks as shown in Figure 6. The average NO_3-N concentration of the effluent was 20.7 and 19.0 mg/L for the 100- and 50-cm columns, respectively, after the 14th week.

The observed reductions in NH_4-N from the column experiment agree with results obtained in a similar experiment by Rodger et al. [11]. There is no significant difference in NO_3-N levels between the depths as shown in Figure 5. This agrees with Amador et al. [7]. The effluent's nitrate value was higher than that of the influent due to the nonpresence of anoxic conditions in the filter that will denitrify the nitrate to nitrogen gas.

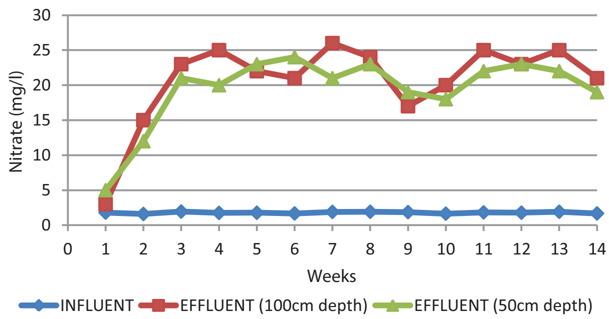

Figure 6. Nitrate values in filter effluents as a function of time.

The mechanism of phosphorus removal is abiotic and involves sorption and binding of PO_4-P with iron and aluminum oxides and oxyhydroxides on the surface of soil particles [5–7]. The average influent value of PO_4-P was 4.15 ($\pm$0.8) mg/L while the average value of the effluent was 2.26 ($\pm$0.81) mg/L. The percentage removal of PO_4-P was 45%; this is due to adsorption to the filter material and microbial assimilation of phosphate in the growing biofilm. Since anoxic conditions that can lead to desorption of the PO_4-P do not occur, removal efficiency is high but lower than the 95% reported by Hu et al. [20] and the 99% removal achieved by Achak et al. [21] after passing olive mill wastewater through sand.

The average *E. coli* concentration of 7.6×10^8 (cfu/100 mL) was loaded into each column for each dose. The 100-cm filter depth performed better than the 50-cm depth. The percentage removal of the bacteria was 99.88% and 99.68%, respectively, for 100-cm and 50-cm depth, respectively. The slight increase in percentage removal in 100 cm is not unconnected to the attachment of the bacteria to the surface of the filter materials at the lower depth. For a slight appreciable difference in the percentage removal of bacteria, a filter of 50-cm depth is adequate as a means of reducing the cost of filter material.

4. Conclusion

The present study examined the effect of sand filter depth on the treatment of synthetic wastewater in two intermittently dosed columns. The filter had the ability to polish the effluent from septic tanks with 100- and 50-cm depths. Based on the results of organic and ammonium removal, the usage of a 50-cm filter column is preferable since there is no significant difference when compared with the 100-cm filter column.

The percentage removal of BOD in this study was greater than 90% in both 100-cm and 50-cm depths. This is evidence of the high oxidation capacity and aerobic condition of the sand filtration system. The suspended solids were completely removed and ammonium value from the effluent was less than 1 mg/L.

The growth of bacteria within the filter grains enhances the removal of organic matter and SS. This may eventually lead to clogging of the filter. The rate of clogging is dependent on SS in the wastewater. Since the septic tank serves as the settling chamber for the wastewater from households, the SS from the effluent is expected to be low. This shall reduce the rate of earlier clogging. Moreover, in intermittent dosing, resting times allow diffusion of oxygen into the filter [22], hence allowing bacteria to mineralize organic matter within the pores and to nitrify ammonium. Furthermore, intermittent loading controls the growth of biomass, decreases the risk of clogging, and hence extends the service life of the filter [23]. Skimming sand when heavy incrustations occur and sand replacement to maintain filter design depth shall increase the life span of the system.

The results confirm the use of a sand filtration system as a viable treatment option for pretreated septic tank effluent for the removal of suspended solids, organic matter, and ammonium and bacteria. It is slightly less efficient in the removal of phosphorus. This will consequently reduce the threat to the water body that the effluent can cause. In addition, the treated water can be reused for gardening and in toilets.

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