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The use of laboratory sand, soil and crushed-glass filter columns for polishing synthetic wastewater that has undergone secondary treatment

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ABSTRACT

The aim of this study was to examine the performance of intermittently loaded, 150 mm-diameter stratified filter columns of two depths (0.65 and 0.375 m) - comprising different media – sand, crushed glass and soil – in polishing the effluent from a laboratory horizontal flow biofilm reactor (HFBR) treating synthetic domestic-strength wastewater. The HFBR has been successfully used to remove organic carbon and ammonium-nitrogen (NH₄-N) from domestic wastewater. In this treatment method, wastewater is allowed to

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flow over and back along a stack of polyvinyl chloride (PVC) sheets. Biofilms on the sheets reduce organic carbon, suspended matter, and nutrients in the wastewater, but to achieve the quality of a septic tank system, additional treatment is required. In all filters, at a hydraulic loading rate of $100 \text{ L m}^{-2} \text{ d}^{-1}$, 40-65 % of chemical oxygen demand (COD) and practically 100% of total suspended solids (TSS) were removed, nitrification was complete, and bacterial numbers were reduced by over 80%, with best removals achieved in the soil filters (93%). Soil polishing filters with the depth of 0.65 m performed best in terms of organic carbon, total nitrogen (Tot-N) and bacterial removal. Data from this preliminary study are useful in the design of treatment systems to polish secondary wastewaters with similar water quality characteristics.

Keywords: Wastewater treatment, horizontal flow biofilm reactor (HFBR), intermittent filtration, soil, sand, glass.

INTRODUCTION

Domestic wastewater treatment by septic tanks and percolation areas is common in Ireland and, where suitable soil conditions exist, these systems are excellent at removing organic carbon (C), phosphorus (P), ammonium-nitrogen ($\text{NH}_4\text{-N}$), total suspended solids (TSS) and microorganisms. A septic tank is a primary sedimentation tank used for the settlement of suspended matter from the wastewater. ^[1] Following primary treatment in the septic tank, the wastewater enters a percolation area where further removal of organic C, pathogenic bacteria, nutrients and TSS occurs. In 2002, there were approximately

400,000 septic tank systems operating in Ireland, serving approximately 1.28 million dwellings. ^[2] However, a significant proportion of septic tank systems may not function satisfactorily due to unsuitable site conditions such as poor drainage, surface slope and depth to bedrock. Installation of these systems on these unsuitable sites may give rise to potential health and environmental pollution problems.

European legislation such as the Water Framework Directive (WFD), 2000/60/EC ^[3], Surface Water Directive, 75/440/EEC ^[4], the Groundwater Directive, 80/68/EEC ^[5], the Drinking Water Directive, 98/83/EC ^[6], the Nitrates Directive, 91/676/EEC ^[7] and the Urban Wastewater Directive, 91/271/EEC ^[8] has focused attention on the inadequate treatment of domestic wastewater, and has forced researchers and practitioners to develop alternative methods for the treatment of domestic wastewater.

In Ireland, wastewater treatment systems, such as peat filters, are gaining in popularity as low-cost alternatives to conventional septic tank/percolation systems. Constructed wetlands (CWs) have good organic C, TSS, nutrient and bacteria removal but have a large areal requirement. ^[9] Potential danger to children may also make them undesirable for the treatment of domestic wastewater from single houses. Recently, an intermittently loaded filter containing peat (PurafloTM, Bord na Mona, Ireland) has been gaining in popularity. Gill et al. ^[10] examined the performance of a PurafloTM system for domestic wastewater treatment. At an organic loading rate (OLR) of 53 g chemical oxygen demand (COD) m⁻² d⁻¹ - based on footprint area - an average COD removal of 75% was achieved

and nitrification was almost complete. Intermittently loaded sand filters have also been successfully used to treat high-strength wastewater. [11, 12]

A novel horizontal flow biofilm reactor (HFBR) for treating wastewater, comprising a stack of about 40 horizontal polyvinyl chloride sheets, positioned over one another, has been developed by researchers at the National University of Ireland, Galway. [13] In this system, wastewater is intermittently pumped onto the top of the stack. Wastewater flows along each sheet from one end to the other and back again on the next underneath sheet, down through the stack. As the wastewater flows through the sheets of the stack, a biofilm forms and organic C, TSS, nutrients and bacteria are removed. Denitrification may be enhanced by incorporating a ‘step feed’ into the system at about the 25th – 30th sheet. This system has been successfully used in other studies to treat domestic-strength wastewater and has achieved COD and total nitrogen (Tot-N) removals of over 90%. [14, 15]

The aim of this present study was to examine the performance of intermittently loaded filters, comprising three different media – sand, crushed glass and soil – at two depths, 0.65 m and 0.35 m, when used to polish final effluent from a laboratory HFBR treating domestic-strength, synthetic wastewater. The data generated from this study will be used to inform the design of full-scale tertiary systems for the treatment of wastewaters with similar water quality characteristics.

MATERIALS AND METHODS

Fourteen 0.65 m and 0.375 m-deep laboratory filter columns containing sand, crushed glass and soil were built under a water suction of approximately 0.1 m (Fig. 1). Each of the columns had an internal diameter of 0.15 m. Six columns contained glass, five contained sand and three contained soil. Three glass columns were 0.65 m deep and three were 0.375 m deep. Two sand columns were 0.65 m deep and three were 0.375 m deep. The three soil columns were 0.65 m deep. The bottom layer of each medium was underlain by a 0.075 m layer of distribution gravel (10-20 mm in diameter). In the 0.65 m-deep glass and sand columns this bottom layer was overlain by a 0.2 m layer of fine glass (0.5 to 1.1 mm in particle size) or sand (effective size, $d_{10} = 0.15\text{mm}$) under a 0.075 m-deep distribution gravel and a 0.2 m-deep layer of fine glass or sand. The top layer was 0.1 m deep and comprised distribution gravel (10-20 mm in diameter). In the 0.375 m-deep glass/sand columns, a 0.1 m layer of distribution gravel (10-20 mm in diameter) overlay a 0.2 m layer of fine glass/sand. In the 0.65 m-deep soil columns, a 0.1 m layer of distribution gravel (10-20 mm in diameter) overlay a 0.475 m layer of top soil (a shallow podzolized soil sieved to less than 5 mm; $d_{10} = 0.02\text{ mm}$). The glass, sand and soil filters were packed to average bulk densities of 1.7, 1.5 and 1.2 g cm^{-3} , respectively. The base of each filter comprised perforated plastic stop-ends.

The influent wastewater used in this experiment was the final effluent from a laboratory HFBR treating synthetic domestic wastewater. Prior to operation, the HFBR was seeded with sludge from the return flow of an activated sludge plant used for biochemical oxygen demand (BOD) removal and nitrification of municipal wastewaters. The synthetic

wastewater was made up daily (after Odegaard and Rusten ^[16] and with composition as in Table 1) and pumped onto the top sheet of the HFBR. Synthetic wastewater is commonly used in laboratory-scale treatment systems. ^[17-20] The final effluent from the HFBR was collected daily in a sump and was intermittently loaded, via spiral distribution manifolds, onto the surfaces of the filters. The pump was operational for 5-minute durations each hour and, throughout the study period, a hydraulic loading rate (HLR) of $100 \text{ L m}^{-2} \text{ d}^{-1}$ was applied to all filter columns. The sand and glass filters were operated for a period of 525 days. The soil filters were commissioned after the sand and glass filters were operational, and were operated for 264 days.

During the study period, influent and effluent water samples were tested at least twice per week. The water quality parameters measured were: COD (closed reflux, titrimetric method), Tot-N (persulfate method), $\text{NH}_4\text{-N}$ (ammonia-selective electrode method), nitrate-N ($\text{NO}_3\text{-N}$) (nitrate electrode method), ortho-phosphate ($\text{PO}_4\text{-P}$) (ascorbic acid method), TSS (total suspended solids dried at $103\text{-}105^\circ\text{C}$) and heterotrophic plate counts (R2A agar spread plate method). All water quality parameters were tested in accordance with the Standard Methods. ^[21]

Adsorption is the main mechanism for $\text{PO}_4\text{-P}$ removal in intermittently loaded filters. ^[11] Dependent on the redox potential, pH, native iron (Fe), calcium (Ca) and aluminum (Al) minerals, and the iron to P ratio, various media have varying abilities to adsorb P. In addition to these factors, the ongoing ability of filters to adsorb P will depend on the rate at which they are loaded. Over a filter's lifetime, the adsorption capacity decreases as the

P-sorption sites become saturated. Freundlich and Langmuir adsorption isotherms may be used to assess the P-sorption capacity of the media. ^[22, 23] Using 10% hydrochloric acid and distilled water, the P content was stripped from the sand, crushed glass and soil media. PO₄-P solutions were made up to known concentrations using potassium dihydrogen phosphate (K₂HPO₄) and poured into separate containers containing the media. Each container was shaken in an end-over-end shaker for 24 hr, allowed to settle, and the supernatant liquid was filtered through 0.45 µm filter paper and analyzed for PO₄-P. The data were then analysed using a suitable adsorption isotherm.

Total phosphorus (Tot-P) on the column media was tested (after Byrne ^[24]) at the following depth increments below the distribution gravel layer: 0-0.01, 0.02 – 0.03, 0.05 – 0.06, and 0.09 – 0.12 m.

Pore-water pressures (pwps) in the filter media at the top and bottom of the 0.65 m-deep columns and mid-point of the 0.35 m-deep columns were measured using small-scale tensimeters (Soil Measurement Systems, Tucson, AZ). The accuracy of the tensimeter was ±1mbar (± 1cm water).

A conservative tracer (NaBr) was used to estimate the average hydraulic retention time (HRT) and the rate of tracer wash-out during the operation, after Levenspiel. ^[25] The tracer was made up to a 10g L⁻¹ concentration and applied as a pulse in one hydraulic loading interval to all the columns using a peristaltic pump. A fraction collector (REDIFRAC, Amersham Pharmacia Biotech, Bucks, UK), positioned under the column,

collected the drainage samples in timed increments. The sample volumes were subsequently measured and tested for bromide (Br) concentration using a Br ion selective electrode (Br 500, WTW, Weilheim, Germany) with a reference electrode (WD R502, WTW, Weilheim, Germany).

RESULTS AND DISCUSSION

Average Hydraulic Retention Time and Degree of Saturation

Significant differences were noted in the average HRT for the filters (Table 2). At 41.5 ± 6.6 hr, the average HRT was greatest in the soil columns. In comparison, the average HRTs for the sand and glass columns were 30.6 ± 1.5 hr and 11.8 ± 0.3 hr, respectively. The reduction of the filter depth from 0.65 m to 0.375 m reduced the average HRT in the sand and glass filter columns by 53% and 39%, respectively. The ‘breakthrough time’ – i.e., the time to first arrival of the chemical tracer – was shortest for the 0.375 m glass columns – 0.07 ± 0.02 hr. This may have had the effect of reducing its performance. All columns remained unsaturated over time. Pwp readings taken within all columns indicated that the pwps varied from -5 to -20 cm over a 1-hr loading cycle. Comparatively, Healy et al. ^[26] measured pwps of -7 cm in the uppermost layer of a sand filter column ($d_{10}=0.45$ mm) when it was loaded at a HLR of $26.7 \text{ L m}^{-2} \text{ d}^{-1}$.

Organic Carbon and TSS Removal

Over the study duration, the average COD concentration from the HFBR was 98.3 ± 13.4 mg COD L⁻¹ (Table 3). The OLR on the filters was 9.8 g COD m⁻² d⁻¹, based on the top plan area. Statistical analysis using a paired-samples T test proved that there was no significant difference in COD removal within each set of filters at the 95% confidence interval (P=0.05). The 0.65 m soil filter achieved the greatest COD reduction – 65% - and produced an average COD effluent concentration of 34.0 ± 10.5 mg COD L⁻¹. At the 95% confidence interval, there was a significant difference between the 0.65 m-deep soil, glass and sand columns. The 0.65 m and 0.35 m–deep sand filters had effluent COD concentrations of 53.8 ± 23.7 mg COD L⁻¹ and 54.5 ± 21.3 mg COD L⁻¹, respectively – a 45% and 44% reduction, respectively. This is consistent with other studies that used sand filters for tertiary treatment. For example, Rodgers et al. [15] used a 0.85-m-deep stratified sand filter to treat wastewater with an influent COD and TSS concentration of 230 mg L⁻¹ and 70 mg L⁻¹ and achieved respective removals of 40% and 64%. The 0.65 and 0.35 m–deep crushed glass filters had final effluent concentrations of 43.0 ± 14.3 mg COD L⁻¹ and 56.6 ± 19.5 mg COD L⁻¹, respectively, giving 56% and 42% reductions, respectively.

These effluent COD concentrations were much less than the Urban Waste Water Treatment Directive [8] value of 125 mg COD L⁻¹. Comparatively, Hu and Gagnon [27] measured organic C removals of 58 % and 69 %, respectively, for 0.6 m-deep, full-scale sand and glass filters, when loaded at an OLR of 61 g BOD₅ m⁻² d⁻¹, and Rodgers et al. [11] measured 99% COD removals when high-strength, synthetic wastewater was loaded at an OLR of 26 g COD m⁻² d⁻¹. In the present study, the OLR of 9.8 g COD m⁻² d⁻¹ was less than the recommended maximum loading rate on intermittent sand filters for the

secondary treatment of wastewaters (approximately $34 \text{ g COD m}^{-2} \text{ d}^{-1}$ for filters treating a comparable hydraulic load of $120 - 200 \text{ L m}^{-2} \text{ d}^{-1}$).^[28] Also, the influent in the polishing study – resulting from the secondary treatment of synthetic wastewater - was of low COD ($98.3 \text{ mg COD L}^{-1}$) strength and, probably, biodegradability in comparison with the high-strength influent wastewater used in many secondary treatment studies (Gill et al.^[10] – $1393 \text{ mg COD L}^{-1}$; Rodgers et al.^[11] – $1000 \text{ mg COD L}^{-1}$; Hu and Gagnon^[27] – $381 \text{ mg BOD L}^{-1}$). In addition, the average HRT within the columns – varying from 7.2 hr to 41.5 hr – was substantially lower than the other studies (discussed above). For example, Rodgers et al.^[11] achieved a high COD removal in intermittently loaded sand filters, operated at an average HRT of 6.4 – 8.8 days.

Over the study duration, the average TSS concentration from the HFBR was $22.4 \pm 13.5 \text{ mg L}^{-1}$, giving an influent TSS loading rate of $2.2 \text{ g m}^{-2} \text{ d}^{-1}$ on the filters (Table 3). Complete TSS removal occurred in all filter columns. Healy et al.^[12] found similar results when a laboratory sand filter was loaded with synthetic wastewater at TSS loading rates ranging from 5.2 to $12 \text{ g m}^{-2} \text{ d}^{-1}$. In filters loaded with medium- to high-strength wastewaters, a biofilm layer forms as a *schmutzedecke* on the filter surface.^[29] This layer strains the TSS from the influent wastewater. These results indicate that straining effects can still occur in relatively coarse ($d_{10} = 1.1 \text{ mm}$) filter media.

Nitrogen Conversion and Removal

The average effluent $\text{NH}_4\text{-N}$ concentration from the HFBR was $5.1 \pm 3.4 \text{ mg L}^{-1}$ (Table 3). The effluent $\text{NH}_4\text{-N}$ concentration from all filters was close to zero, indicating that practically complete nitrification had occurred in all filters, irrespective of their depth. Studies have indicated that when filters are intermittently loaded with frequent wastewater dosages, oxygen is allowed to diffuse further into the filter media, giving an oxygen-rich substrate. ^[10, 12] Hu and Gagnon ^[27] found that, when 0.6 m-deep, full-scale sand and glass filters were loaded with domestic wastewater at an OLR of $61 \text{ g BOD}_5 \text{ m}^{-2} \text{ d}^{-1}$, almost complete nitrification occurred in both filters. Average influent $\text{NO}_3\text{-N}$ concentrations were $22.3 \pm 12.6 \text{ mg L}^{-1}$ and effluent $\text{NO}_3\text{-N}$ concentrations ranged from $22.0 \pm 5.8 \text{ mg L}^{-1}$ (in the 0.65 m-deep soil filter) to $27.5 \pm 15.0 \text{ mg L}^{-1}$ (in the 0.65 m-deep sand filter).

Bacterial Removal

Over the study duration, the columns were loaded with bacteria with a concentration of $7.1 \times 10^6 \pm 1.4 \times 10^6$ colony forming units (CFU) per 100 ml (Table 3). The 0.65 m-deep soil columns performed best in bacteria removal and achieved an average effluent bacteria concentration of $0.5 \times 10^6 \pm 0.2 \times 10^6$ CFU per 100 ml. Depth appeared to be significant in bacteria removal, as both the 0.65 m-deep sand and glass columns outperformed their 0.35 m-deep counterparts ($P=0.05$). Average effluent bacteria concentration in the 0.65 m-deep and 0.35 m-deep sand columns were $1.0 \times 10^6 \pm 0.6 \times 10^6$ and $1.5 \times 10^6 \pm 0.5 \times 10^6$ CFU per 100 ml, respectively. Average effluent bacteria concentration in the 0.65 m-deep and 0.35 m-deep glass columns were $1.3 \times 10^6 \pm 0.6 \times 10^6$ and $1.4 \times 10^6 \pm 0.6 \times 10^6$, respectively.

Another study, using 0.6 m-deep, full-scale sand and glass filter media, achieved bacterial removals (measured in fecal coliforms) of 99 – 99.9%.^[27] Although the media was of a similar consistency ($d_{10}=1.5$ mm), the organic and TSS loadings were considerably higher – 61 g BOD₅ m⁻² d⁻¹ and 14 g TSS m⁻² d⁻¹. In the present study, a *schmutzdecke* was not visible on the uppermost filter layer and traditional indicators of biofilm build-up – elevated soil-water and nutrient content, reduced saturated hydraulic conductivity^[29] – indicated that the traditional bacterial removal mechanisms, such as straining, may not have occurred in any of the filters.

Phosphorus Removal

The P sorption capacities of the glass, sand and soil media – measured using a Langmuir isotherm - were 10.3, 85 and 1043 mg P kg⁻¹ media, respectively. These results were consistent with the measured PO₄-P removals from the filters. With the exception of the 0.65 m-deep soil filters, little PO₄-P removal occurred in the sand or glass filters (Table 3). Over the study duration, approximately 12 g P was applied to the sand and glass filters, whereas approximately 6 g P was applied to the soil filters. The Tot-P deposition was lowest in the glass filter and ranged from 31.8±2 mg kg⁻¹ near the filter surface to 19.2±2 mg kg⁻¹ at a depth of 0.12 m (Fig. 2). The Tot-P deposition in the upper 0.12 m layers of the sand and soil filters followed the same trend (i.e. higher concentrations at the filter surface versus lower concentrations with depth), but were more evenly distributed with depth below the filter surfaces. Tot-P deposition ranged from 50±5 mg kg⁻¹ to 30.2±4 mg kg⁻¹ for the sand filter, and from 50±3 mg kg⁻¹ to 45.6±4 mg kg⁻¹ for the soil

filter. The Tot-P adsorbed in the filters over the measured depth of 0.12 m (Fig. 2) was approximately 80 mg (glass), 120 mg (sand) and 173 mg (soil). The adsorption isotherm estimated maximum P retentions – over the same depth – of 37 mg (glass), 272 mg (sand) and 2608 mg (soil). Although the general trend is the same (i.e. soil has better P retention than, say, glass), the results echo the conclusions of other researchers^[30, 31], who found that the Langmuir adsorption isotherm was a poor estimator of P retention.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. Sand, glass or soil filters was used to effectively polish effluent from a HFBR treating synthetic wastewater. At a hydraulic loading rate of $100 \text{ L m}^{-2} \text{ d}^{-1}$, COD was removed by between 42 and 65%, and nitrification was complete.
2. TSS were removed in all filters when loaded with the HFBR effluent.
3. P removal only occurred in the soil filters. Adsorption isotherm testing indicated that the P adsorption capacity for the soil was $1043 \text{ mg P kg}^{-1}$ soil, in comparison with 10.3 and 85 mg P kg^{-1} media for the glass and sand, respectively.
4. Bacterial numbers were reduced by over 80%, with best removals achieved in the soil filters (93%).

In summary, it appears that soil columns perform best in polishing effluent from a HFBR that has been used for the secondary treatment of domestic-strength synthetic wastewater.

These results can be used in the design of experiments and systems for treating real wastewaters with similar water quality characteristics.

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FIGURE CAPTIONS

Figure 1. The experimental set-up.

Figure 2. Deposition of Tot-P (mg kg^{-1} of filter media) in the upper 0.12 m from the filter surface.

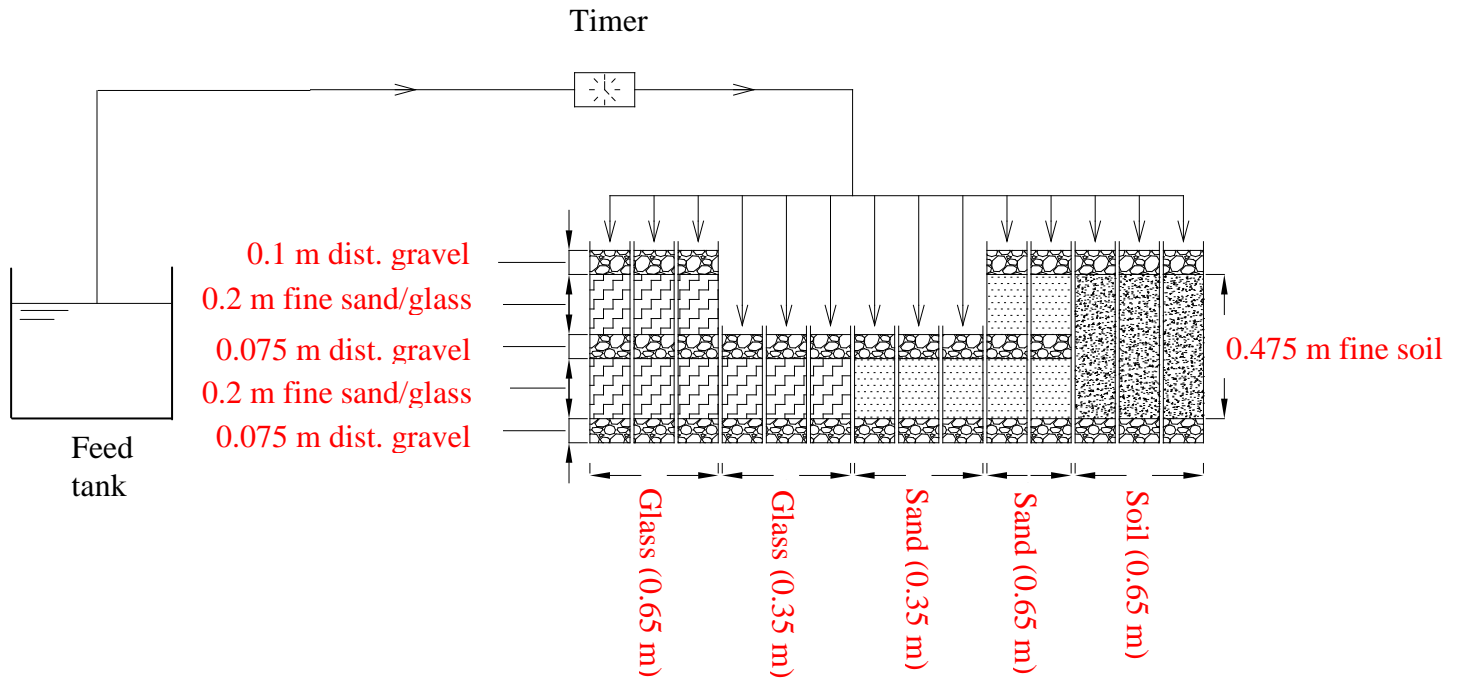


Fig. 1

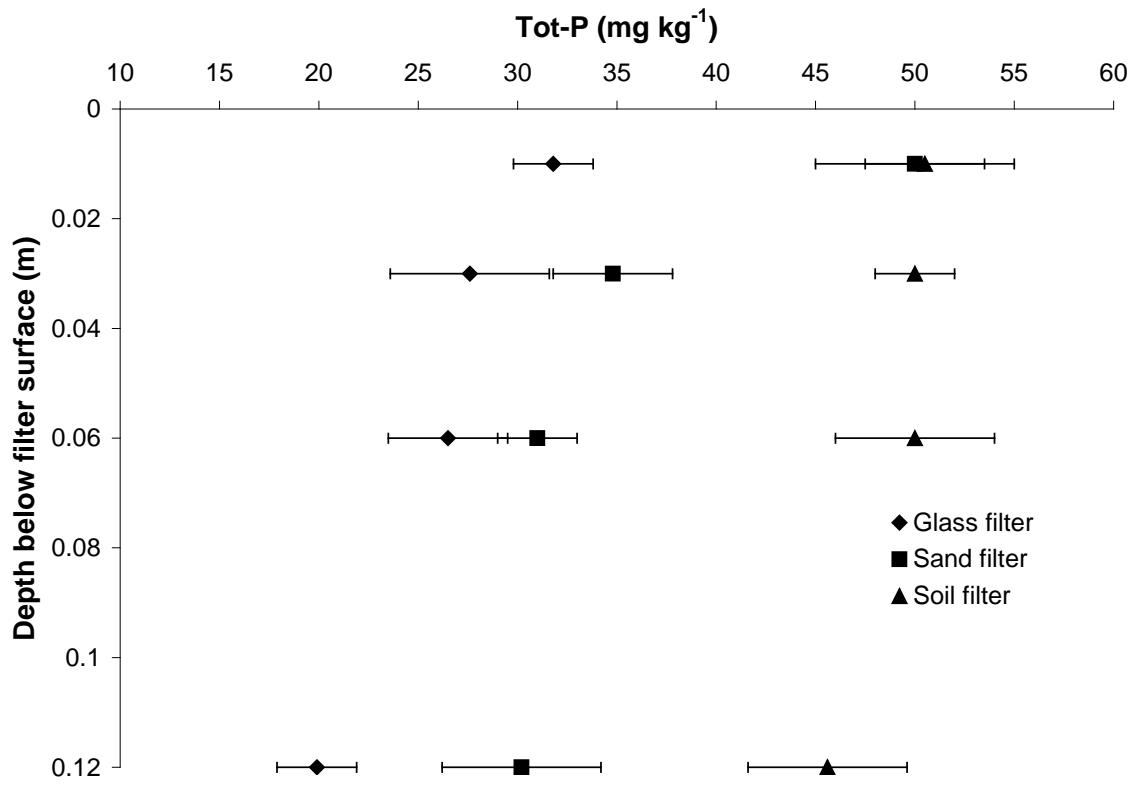


Fig. 2

Table 1. Composition of synthetic wastewater used to simulate domestic wastewater^{*}

Component	Amount (g)
Glucose	18
Yeast	2.7
Dried milk	10.8
Urea	2.7
NH ₄ Cl	5.4
Na ₂ PO ₄ ·12H ₂ O	9
KHCO ₃	4.5
NaHCO ₃	11.7
MgSO ₄ ·7H ₂ O	4.5
FeSO ₄ ·7H ₂ O	0.18
MnSO ₄ ·H ₂ O	0.18
CaCl ₂ ·6H ₂ O	0.27
Bentonite	3.6

^{*} Diluted to 90 liters.

Table 2. Average hydraulic retention time and breakthrough time \pm standard deviation of columns.

Filter media	Depth	Average hydraulic retention time	Breakthrough time*
	(m)	(hours)	(hours)
Glass	0.65	11.8 \pm 0.3	0.15 \pm 0.02
	0.375	7.2 \pm 0.8	0.07 \pm 0.02
Sand	0.65	30.6 \pm 1.5	0.72 \pm 0.04
	0.375	14.3 \pm 1.3	0.29 \pm 0.05
Soil	0.65	41.5 \pm 6.6	13.0 \pm 4.6

* Breakthrough time refers to time to first arrival of bromide.

Table 3. Influent and effluent wastewater characteristics \pm standard deviation for the filter columns.

	COD	Removal	Tot-N	Removal	NH ₄ -N	Removal	PO ₄ -P	Removal	TSS	Removal	NO ₃ -N	Heterotrophic plant count	Removal
	mg L ⁻¹	%	mg L ⁻¹	%	mg L ⁻¹	%	mg L ⁻¹	%	mg L ⁻¹	%	mg L ⁻¹	CFU/100ml	%
Influent	98.3 \pm 13.4	NA ¹	27.3 \pm 12.8	NA	5.1 \pm 3.4	NA	13.0 \pm 2.4	NA	22.4 \pm 13.5	NA	22.2 \pm 12.6	7.1x10 ⁶ \pm 1.4x10 ⁶	NA
Effluent													
Glass (0.65m)	43.0 \pm 14.3	56.2	26.9 \pm 14.6	3.9	0.1 \pm 0.1	99.0	12.7 \pm 2.6	2.4	ND ²	100	26.8 \pm 14.6	1.3x10 ⁶ \pm 6.4x10 ⁵	81.8
Glass (0.375m)	56.6 \pm 19.5	42.4	27.2 \pm 15.3	4.9	0.1 \pm 0.1	98.9	12.9 \pm 2.7	1.1	ND	100	27.1 \pm 15.3	1.4x10 ⁶ \pm 5.7x10 ⁵	79.7
Sand (0.65m)	53.8 \pm 23.7	45.3	27.5 \pm 15.0	3.5	0.03 \pm 0.1	99.3	12.5 \pm 2.8	4.3	ND	100	27.5 \pm 15.0	1.0x10 ⁶ \pm 6.2x10 ⁵	85.3
Sand (0.375m)	54.6 \pm 21.3	44.4	27.4 \pm 16.4	5.2	0.1 \pm 0.1	99.1	12.6 \pm 2.7	3.1	ND	100	27.3 \pm 16.4	1.5x10 ⁶ \pm 4.8x10 ⁵	79.6
Soil (0.65m)	34.0 \pm 10.5	65.4	22.0 \pm 5.8	6.6	0.01 \pm 0.01	99.8	0	100	ND	100	22.0 \pm 5.8	0.5x10 ⁶ \pm 2.3x10 ⁵	92.6

¹ NA – not applicable.

² ND – not detectable.