Different depth sand filters for laboratory treatment of synthetic wastewater with concentrations close to measured septic tank effluent

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Different depth intermittent sand filters for laboratory treatment of synthetic wastewater

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ABSTRACT

The objective of this study was to apply hydraulic and chemical oxygen demand (COD) loading rates at the upper limits of the design criteria for buried sand filters to test the sand filter depth design criteria. Over a 274 day study duration, synthetic effluent with a strength of domestic wastewater was intermittently dosed onto two sand filters of 200 mm diameter, with depths of 300 and 400 mm. Hydraulic and organic carbon loading rates of 105 L m^{-2} d^{-1} and 40 g COD m^{-2} d^{-1}, respectively, were applied to the filters. The filters did not clog and had good effluent removal capabilities for 274 and 190 days, respectively. However, the 300 mm-deep filter did experience a reduced performance towards the end of the study period. In the 300 and 400 mm-deep filters, the effluent COD and SS concentrations were less than 86 and 31 mg L^{-1}, respectively, and nitrification was nearly complete in both these columns.

Key Words: Intermittent sand filtration; domestic wastewater; sand depth; surface clogging.

INTRODUCTION

In Ireland, there are over 350,000 households connected to septic tank systems, comprising a septic tank and a percolation field. If constructed to standard design criteria [1], a septic tank will remove, on average, 40% of the influent biochemical oxygen demand (BOD) and 60% of the suspended solids (SS). [2] The septic tank-soil percolation system is one of the simplest and most effective methods used to treat domestic effluent. However, suitable soil for percolation areas is only available in about 50 % of the land of Ireland. Sand filters are an alternative to in-situ percolation areas.

Intermittent sand filters are aerobic, fixed-film biological reactors capable of producing high quality effluent. The treatment methodology involves the intermittent dosing of wastewater following primary sedimentation onto a single-layer [3] or stratified [4] sand filter. On a single pass through the sand filter, organic carbon removal, ammonification and nitrification of organic nitrogen can occur. Total nitrogen (Tot-N) may also be reduced on a single pass through the system, although further reduction will only take place if the nitrified effluent is recirculated through the anoxic zones of the septic tank. [5]

The performance of an intermittent sand filter will vary with the media used, temperature, hydraulic and organic loading rates, and method of application (Table 1). Design specifications recommend that the sizing of the filter media should be in accordance with its use. [6 - 8] 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 12 shallow sand filters (0.38 m deep), consisting of four sets of three identical sand filters with effective grain sizes of 0.33, 0.54 and 0.93 mm and uniformity coefficients of less than 1.42, Darby et al. [9] examined the effects of media size by applying a hydraulic loading rate (HLR) of 163 L m^{-2} d^{-1} (at 24 doses per day and based on a filter plan area) but noted no discernable difference in performance results.

The organic carbon and SS loading rates may have a significant effect on the clogging and performance of a filter. Darby et al. [9] found that an organic loading rate (OLR) in excess of 47 g COD m^{-2} d^{-1} (based on filter plan area) caused ponding on a sand filter with d_{10} of 0.29 mm. Results obtained by Nichols et al. [10] showed that when the OLR on a 3-layer stratified sand filter was 15 g COD m^{-2} d^{-1}, low rates of nitrification occurred. In a study of a single-layer intermittent sand filter (d_{10} = 0.45 mm, Cu = 3), Sauer et al. [11] demonstrated that, under a OLR of 58 g COD m^{-2} d^{-1}, the filter performed well, producing an effluent that was almost completely nitrified. However, when the loadings were doubled, very little nitrification of the septic tank effluent was accomplished. US EPA guidelines [6] recommend a buried filter HLR of less than 40 L m^{-2} d^{-1} and Anderson et al. [12] recommend that the OLR should not exceed 24 g BOD m^{-2} d^{-1}.

The objective of this study was to examine the effect of sand filter depth on the performance of two sand filters at hydraulic and organic loading rates at the upper limits of the USEPA design criteria for buried intermittently dosed sand filters. The phosphorus removal potential of fine sand and laterite were also examined in an ‘upflow’ filter, receiving effluent from the 300 mm-deep filter.

MATERIALS AND METHODS

Intermittent sand filters of different depths were set up and operated over a 10-month period and were designed to treat synthetic septic tank effluent. The units were constructed using clear acrylic tubing, 200 mm in diameter, with a wall thickness of 3 mm. The transparent material was used to allow observations of any clogging layer development and location in the sand filters. A flat acrylic base was cemented to each tube and a series of holes were bored in the base for discharge and sampling of the filter effluent. To prevent the growth of algae in the filters, removable black polythene sheeting was placed around the filters to block sunlight.

Sand filter depths of 300 and 400 mm of coarse sand (d_{10} = 1 mm; Cu=2.95) were used to examine the depth effects on the treatment of synthetic septic tank effluent. The sand was placed over a 75 mm-layer of pea gravel in the filter containers and was lightly compacted in 50 mm layers. The characteristics of the filter media are given in Table 2.

A 200 mm-diameter ‘upflow’ filter, containing 2 kg of fine sand (Table 2) and dosed by gravity, was used to polish the effluent from the 300 mm-deep sand filter and operated for a period of 66 days. After this period, the ‘upflow’ filter was filled with 2 kg of laterite soil (a red soil rich in oxides of iron, aluminium, manganese and titanium) and operated for a period of 58 days. The measured characteristics of the laterite are also given in Table 2.

Synthetic effluent [13] with concentrations close to measured septic tank values (Table 3), and with component concentrations as in Table 4, was made up and applied daily in four doses of 0.82 L/dose to the sand filters via a spiral distribution manifold using peristaltic pumps. The peristaltic pumps were operational for a period of 2 minutes per dose. For the study duration, the HLR onto each filter surface area was 105 L m^{-2} d^{-1}. On a daily basis, Monday to Friday, the HLR was calibrated and the influent and effluent water quality parameters were measured to establish when a near steady state performance occurred.

The water quality parameters measured were: BOD (5-day BOD test); chemical oxygen demand (COD) (closed reflux, titrimetric method); Tot-N (persulfate method); ammonia-N (NH_4-N) (ammonia-selective electrode method, NH 500/2, WTW, Weilheim, Germany); NO_3-N (nitrate electrode method; WTW, Weilheim, Germany); total and ortho-phosphate P (P_{tot} and PO_4-P, respectively) (ascorbic acid method); and suspended solids (SS) (total suspended solids dried at 103-105^{o}C). Influent and effluent PO_4-P, SS, colour and turbidity were measured in the ‘upflow’ filter. All water quality parameters were tested in accordance with the Standard Methods. [14]

The ability of the sand and laterite to adsorb phosphorus (P) was assessed using Freundlich (coarse sand) and Langmuir (fine sand and laterite) isotherms. [15, 16] The P adsorption isotherms were used to estimate the maximum mass of P adsorbed per mass of sand during the operation of the filters. To carry out the P adsorption isotherm test, a representative sand sample was washed with distilled water and 10% hydrochloric acid to ensure that its native P content was negligible. PO_4-P solutions were made up to known concentrations using potassium dihydrogen phosphate

(K_2HPO_4) and added to flasks containing 20 g of sand. Each mixture was shaken for 48 hours using an end-over-end shaker. The sample mixture was then filtered through 0.45 μm filter paper and tested for PO_4-P.

RESULTS AND DISCUSSION

Performance of the coarse sand filters.

Throughout the duration of the experiments, all coarse sand filters received the same organic and SS loading rate. The HLR was 105 L m^{-2} d^{-1}, which was over 2.5 times the maximum recommended HLR for covered single-pass sand filters. [6]

Steady-state conditions occurred in the filters after a period of approximately 2 months of operation. Throughout the period of analysis, the average influent organic and SS loading rates were 40 g COD m^{-2} d^{-1} (25.4 g BOD $m^{-2}d^{-1}$) and 12.1 g SS m^{-2} d^{-1}, respectively (Table 5). In the 300 and 400 mm-deep filters, steady-state effluent COD concentrations were about or below the EU Directive values for urban wastewaters (COD=125 mg L^{-1} [17]), having concentrations of 68±24 and 86±49 mg COD L^{-1}, respectively. Effluent SS concentrations in the 300 and 400 mm filters were 30±29 and 24±15 mg L^{-1}, respectively. The performance of the 300 mm-deep filter appeared to reduce over time; effluent COD and SS concentrations rose gradually as the study progressed (Figure 2); the 400 mm-deep filter did not exhibit the same effects.

Throughout the study, the Tot-N in the influent from the feed tank was 45 ± 6 mg L^{-1}. Although NO_3-N was the dominant form of Tot-N in the effluent, nitrification was not totally complete in all filters; the average measured sump pH values of between 6.7 and 7.0 were below the pH values at which the maximum rate of nitrification occurs (7.2 to 9.0). [18] The mean effluent NO_3-N concentrations from the 300 and 400 mm-deep filters were 28 and 28 mg L^{-1}, respectively (Table 5). NH_4-N was reduced from an influent concentration of 24±4 mg L^{-1} to average effluent concentrations of 2±1, and 6±5 mg L^{-1} for the 300, and 400 mm-deep filters, respectively.

The P adsorption capacity of the coarse sand (calculated by the Freundlich adsorption isotherm) was 47 mg PO_4-P kg^{-1} sand, which is within the range of values specified for sands by Foth and Ellis. [19] The effluent PO_4-P concentrations for the filters were approximately 10 mg L^{-1} (from an influent PO_4-P concentration of 16±2 mg L^{-1}).

'Upflow' filter performance.

Two 'upflow' filters were used as polishing filters in this study; both contained 2 kg of fine sand and laterite (Table 2) and were operated for periods of 66 and 58 days, respectively. After a period of 58 days, the laterite 'upflow' filter became clogged. This may have been due to the high SS loading rate applied to it thoughout its period of operation (3.6 g SS kg^{-1} laterite versus 1.2 g SS kg^{-1} sand for the fine sand 'upflow' filter). The variation in the SS loading rate was attributable to the gradual increase in the effluent SS concentration from the 300 mm-deep filter (Figure 2). Both filters received effluent (by gravity) from the 300 mm-deep sand filter at a HLR of 105 L m^{-2} d^{-1} (expressed in terms of sand filter plan area of the 300 mm-deep column). Influent and effluent PO_4-P, SS, turbidity and colour were measured throughout their operation (Table 6).

Before clogging, the laterite ‘upflow’ filter performed better in its removal of P than the fine sand ‘upflow’ filter. The measured P adsorption capacities of the fine sand and laterite of 122 and 359 mg PO_4-P kg^{-1} material, respectively, were reflected in their average PO_4-P removals of 10 % and 44 %, respectively. The final effluent PO_4-P concentrations were 9 and 6 mg L^{-1}, respectively, for the fine sand and laterite. The laterite produced an average effluent SS concentration of 4±2 mg L^{-1} from an influent SS concentration of 68±21 mg L^{-1} (a 94% reduction). An average effluent SS concentration of 2±2 mg L^{-1} from an influent SS concentration of 23±11 mg L^{-1} was measured for the fine sand. A similar trend in the data was recorded for the turbidity and colour (Table 6).

CONCLUSIONS

In this study, the effect of sand filter depth on treatment performance was examined in four intermittently dosed sand filters. The effective grain size of the filter media was 1 mm and the hydraulic and organic loading rates were 105 L m^{-2} d^{-1} and 40 g COD m^{-2} d^{-1}. Sand filters with depths of 300 mm and 400 mm had good effluent removal capabilities and were operational for 274 and 190 days, respectively, without clogging. However, the performance of the 300 mm-deep filter did appear to deteriorate towards the end of the study period. In the 300 and 400 mm filters, effluent COD concentrations were 68 and 86 mg L^{-1}, respectively, and SS effluent concentrations were less than 31 mg L^{-1}. Nitrification was almost complete in the 300 and 400 mm filters and the effluent NH_4-N concentrations were only 2 and 6 mg L^{-1}, respectively. The ‘upflow’ fine sand and laterite filters exhibited good SS, turbidity and colour removal capabilities. The percentage P removal in the upflow laterite filter, at 44%, was significantly higher than the fine sand filter before clogging occurred.

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List of Figures

Figure 1.

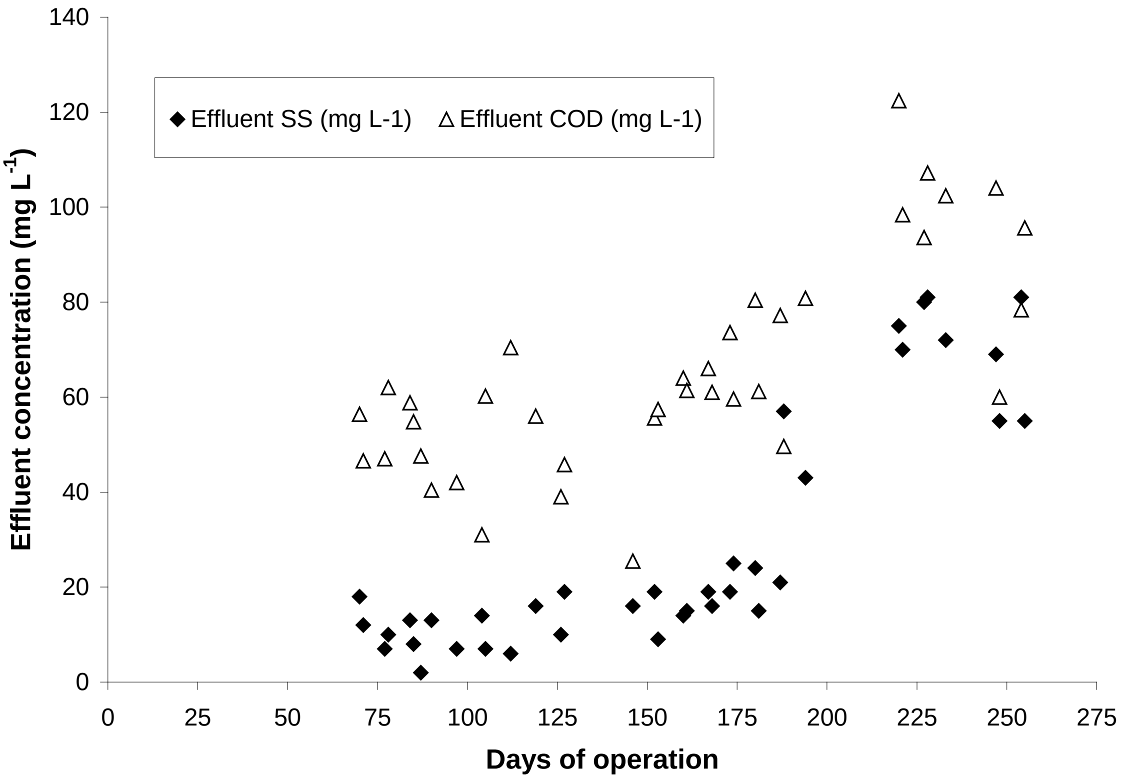
Effluent SS (mg L-1)
Effluent COD (mg L-1)
Effluent concentration (mg L-1)
Days of operation
0
20
40
60
80
100
120
140
0
25
50
75
100
125
150
175
200
225
250
275

Table 1. Filter design and loading rates from studies on single – pass sand filters.

Reference	Hydraulic loading rate	Frequency	Filter loading rates			Filter depth	Filter media	% removals				
			COD	SS	TKN			COD	Tot-N	NH_4-N	PO_4-P	SS
	(L m^{-2} d^{-1})	(times d^{-1})	_______ g m^{-2} d^{-1} _______			(m)						
Darby et al., (1996)	163	24	23	4.7	2.4	0.38	Single-layer filter d_{10} = 0.33 mm; UC=1.4	94.3	-	99.6	-	99
Boller et al., (1993)	30	6	8.0	1.7	~ 5.1	1.0	Single-layer filter Cu = 4.4	90.5	-	98.6	26.1	93.8
Nichols et al. ,	12.5	-	3.8	0.2	0.62	1.0	Stratified sand filter	-	-	99	37	89
(1997)	50	-	15	1.0	2.4		Top layer: d_{10} = 0.56 mm; Cu = 1.7	-	-	85	36	-
Sauer et al.,	203	4-13	58	9	6	1.77	Single-layer filter	82	-	96	39	87
(1976)	~400	8-25	116	18	~12		d_{10} = 0.45 mm; Cu=3	91	-	23	46	73
EPA guidelines†	<40	>2				0.61-0.91	Single-layer filter d_{10}=0.5-1 mm Cu < 3.5					
Anderson et al. (1985)‡	<61	>2	<24 (BOD)				As EPA (1980) guidelines					

† US EPA (1980). Design criteria for buried intermittently dosed sand filters.

‡ Design criteria for buried intermittently dosed sand filters.

Table 2. Characteristics of the intermittent filter media.

	Coarse sand	Fine sand	Laterite
d_{10} (mm)	1.0	0.12	-
Cu	2.95	3.17	-
Dry density (kg m^{-3})	1,700	1740	1,500
Void ratio	0.54	0.59	0.83
Porosity	0.37	0.35	0.45
Aluminium (mg L^{-1})	370	875	-
Magnesium (mg L^{-1})	1,575	515	-
Total iron (mg kg^{-1})	10,628	18,900	-
Organic content (%)	0.85	0.16	-
Alumina (Al_2O_3, mg kg^{-1})	-	-	272,000
Iron Oxide (Fe_2O_3, mg kg^{-1})	-	-	350,000
Titanium oxide (TiO_2, mg kg^{-1})	-	-	40,000

Table 3. Measured septic tank effluent concentrations[†].

Parameter	COD	BOD	SS	NH_4-N	Total Phosphorus
Average concentration	500	264	124	55	16.2

[†] Values obtained from Gray and Keenan (1993).

Table 4. Composition of synthetic wastewater

Component	Amount[†] (mg)
Glucose	4,500
Yeast extract	375
Dried milk	1,500
Urea	375
NH_4Cl	750
$Na_2HPO_4.12H_2O$	1,250
$KHCO_3$	625
$NaHCO_3$	1,625
$MgSO_4.7H_2O$	625
$FeSO_4.H_2O$	25
$CaCl.6H_2O$	5
Bentonite	560

[†] Dissolved in 10 L to make up synthetic effluent.

Table 5. Efficiency of sand filters at near steady-state conditions[†].

Hydraulic loading rate	105 L $m^{-2}d^{-1}$						
	BOD	COD	SS	Tot-N	NH_4-N	NO_3-N	PO_4-P
Influent (mg L^{-1})	241	380	115	45	24	1	16
± std deviation (mg L^{-1})	63	110	26	6	4	0.0	2
Influent (g m^{-2} d^{-1})	25.4	40.0	12.1	5	2.6	0.1	1.7
± std deviation (g m^{-2} d^{-1})	6.6	11.5	2.7	0.6	0.5	0.0	0.2
Effluent (±std dev.)							
	mg L^{-1}						
300 mm-deep filter	30	68	30	-	2	28	10
Period of operation=274 d	(12)	(24)	(29)	-	(1)	(6)	(1)
400 mm-deep filter	50	86	24	-	6	28	10
Period of operation=190 d	(31)	(49)	(15)	-	(5)	(6)	(1)

[†] Near steady-state assumed to occur after 70 days of operation for the 300 and 400 mm-deep filter columns.

Table 6. Summary of treatment performance of the upflow filters.

Upflow filter media	Fine sand				Laterite			
Hydraulic loading rate (L $m^{-2}d^{-1}$)[†]	105				105			
SS loading rate (g SS kg^{-1} mixture d^{-1})	1.2				3.6			
Period of operation (days)	0-66				67-124			
	PO_4-P mg L^{-1}	SS mg L^{-1}	Turbidity FTU	Colour PtCo	PO_4-P mg L^{-1}	SS mg L^{-1}	Turbidity FTU	Colour PtCo
Influent	10.3	23	18.3	103	11.3	68	32.8	182
± standard deviation	(0.6)	(11)	(5)	(24)	(1)	(21)	(15)	(80)
Effluent	9	2	5	31	6	4	5	31
± standard deviation	(0.5)	(2)	(2)	(11)	(0.5)	(2)	(3)	(14)
% removal	10	90	71	70	44	94	84	83

[†] The hydraulic loading rate is expressed in terms of the upflow filter plan area and was applied to the upflow filters by gravity from the base of the 300 mm-deep intermittent sand filter