Removal of nitrogen and phosphorus from waste stabilization pond effluents using aerated blast-furnace-slag filters

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Abstract

Rock filter (RF) system emerged as one of the well established alternative methods for polishing lagoon and pond effluents. However, the use of RF to remove nutrients, such as nitrogen (N) and phosphorus (P), is very limited. Therefore, the present study was carried out to investigate the performance of aerated RF (ARF) systems for removing both nitrogen and phosphorus from domestic wastewater using blast furnace slag (BFS) as the filter medium. The performance of two aerated BFS filter systems, an aerated horizontal-flow BFS filter and an aerated vertical up-flow BFS filter, have been monitored and were compared: for N and P removals. A further aim of the study was to determine if either or both of these aerated BFS filter systems could produce effluents which complied with the nutrient removal requirements of the EU Urban Waste Water Treatment Directive (UWWTD) (91/271/EEC) for small communities. From the results of the present study it can be concluded that the both aerated BFS filter systems are suitable unit processes for removing ammonium-N and P from primary facultative pond effluents as the systems were able to produce high effluent quality to levels below the EU UWWTD maximum permissible limit. The aerated vertical-upflow BFS filter has the advantage of removing more ammonium-N (to below 1 mg N/L), but the disadvantage of removing less total-N. Further research on optimizing the design and performance of both aerated BFS filter systems are warranted, and their performance in warm-climate countries requires to be investigated.

Keywords: aerated rock filter, nitrogen, phosphorus, blast furnace slag.

1 Introduction

In 1970s, the idea of using Rock filters (RF) as one of the alternative methods for removing biochemical oxygen demand (BOD) and suspended solids from wastewater has been initiated in the University of Kansas, USA [1–3]. From these previous works, the researchers found that RF systems were able to remove BOD_5 and suspended solids efficiently. However, removal of ammonia nitrogen becomes negligible as the system rapidly becomes anoxic. Middlebrooks [4, 5] reported that high concentrations of ammonia nitrogen in the RF effluents could limit the application of the process. To remove ammonia nitrogen, the RF must be aerated and past works [6] has shown that it is better to treat facultative pond effluents (rather than maturation pond effluents) in aerated rock filter (ARF) so as to reduce the need for maturation ponds and thus save land. An added advantage is the important role of the aeration in its capacity for improving the BOD and total suspended solid (TSS) removals [7–9]. Therefore, the present study was carried out to investigate the performance of aerated RF (ARF) systems to enhance the removal of both nitrogen and phosphorus from domestic wastewater using blast furnace slag (BFS) as the filter medium. In the present study, a combination of natural wastewater treatment systems, waste stabilization pond (WSP) and ARF, has been shown to be a good low-cost technology for the purpose of treating municipal wastewater, particularly in simultaneously and effectively removing nitrogen and phosphorus. It is a viable alternative to conventional nutrient removal systems concerned with further polishing nutrients in an economic way, and can be of special interest in rural and remote areas with small populations. The present study considers the development of an RF using inexpensive yet effective—as well as reactive—filter media, mainly for the purpose of nutrient removal. Conventional wastewater nutrient-removal treatment requires advanced treatment systems, which are costly. Thus, the application of a WSP and an ARF can produce a high quality of final effluent with the use of a low-cost nutrient-removal technology; this is ultimately considered to be the best alternative for nutrient removal in the case of small communities seeking high final effluent qualities. Furthermore, the ARF system used in the present study was effectively shown to be able to upgrade the primary facultative pond (PFP) effluent in an economical way.

2 Material and methods

2.1 Pilot-scale set-up for nitrogen/phosphorus removal study

These experimental studies, located at Yorkshire Water's wastewater treatment plant at Esholt, Bradford, England, employed a primary treatment system (PFP) and a secondary treatment system (aerated vertical upward-flow BFS filter and aerated horizontal-flow BFS filter), operated in parallel. BFS has been used as the medium for both aerated filter systems. Photographs of both aerated BFS filter systems are shown in Figure 1.

The PFP was loaded with screened wastewater at a rate of 80 kg BOD/ha day [10] and with sufficient fresh water. The wastewater was passed to the pond using

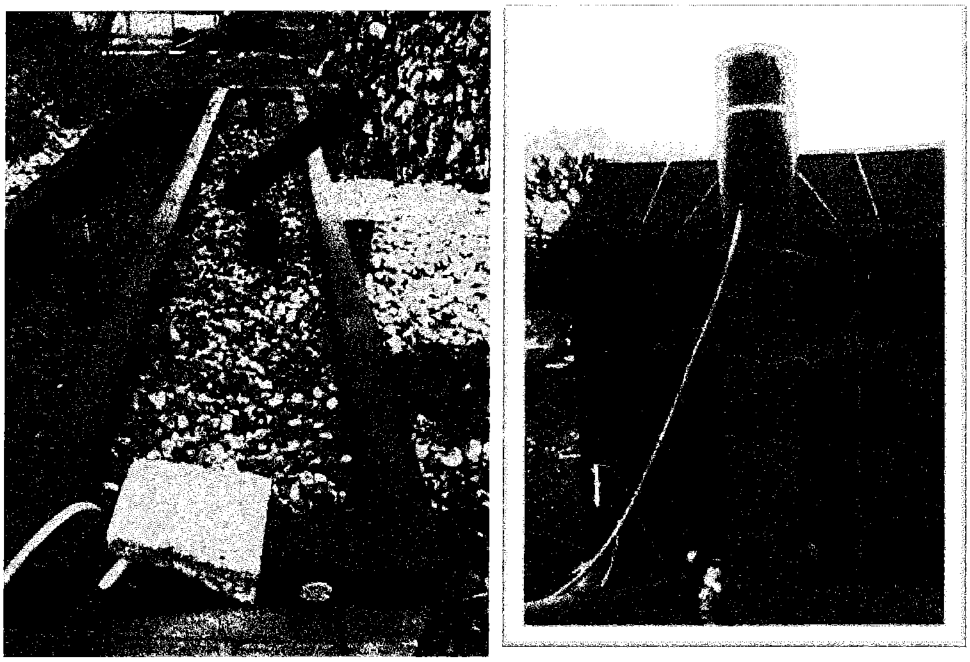

Figure 1: The aerated horizontal-flow BFS filter (left); the aerated vertical upward-flow BFS filter.

25.4-mm reinforced plastic pipework connected to a stainless-steel inlet strainer and variable-speed Watson Marlow Model 640 peristaltic pumps. The PFP effluent was fed into the secondary treatment systems using identical variable-speed Watson Marlow Model 505S peristaltic pumps fitted with Model 501RL pump heads, located at the base of the aerated BFS vertical upward-flow filter and the aerated BFS horizontal-flow filter using 12-mm reinforced plastic pipework. The pipework was heated during winter using a heating cable (Flexelec model FTP), controlled using a model DTC 410 controller with a T-type thermocouple. A float-and-tube flow meter was installed at the inlet of the VFARF to monitor the wastewater flow rate and air flow meters were installed for both the ARF. Both the filters were aerated using an oil-free compressor (OF302-25B; Jun-Air International, Nørresundby, Denmark) feeding a 250-mm fine bubble rubber disc aerator (Biwater Treatment, Heywood, England); the air flow was maintained at 20 L/min. The hydraulic loading rate of both ARF was maintained at 0.6 m^3/m^3 day at a retention time of 1.6 days. The filter effluent was discharged by gravity from the filter outlet back to the sewage channel.

2.2 Wastewater sampling and analysis

Grab samples of the influent and effluent of the two aerated BFS filter system were collected and analyzed at weekly intervals from January to May 2010, following *Standard Methods for the Examination of Water and Wastewater* [11], for BOD (using method 5210-B), ammonium-N (4500-NH_3 D), TKN (4500-N_{org}C), and total phosphorus (TP) (4500-PE). Nitrate was analyzed weekly in a

Table 1: Removal Efficiencies of the Both Aerated BFS Filter Systems.

Parameter	Removal Efficiency (%)	
	PFP + VFARF (mean± s.d.)	PFP + HFARF (mean± s.d.)
BOD_5	96 ± 2.5	99 ± 0.8
Total N	20 ± 22.9	41 ± 28.6
AN	97 ± 2.5	86 ± 17.6
TKN	94 ± 2.8	86 ± 17.7
TP	88 ± 5.2	89 ± 5.0

*s.d.= standard deviation (n=18).

DIONEX ion analyzer (model DX500). All laboratory analyses were conducted in the Public Health Engineering Laboratories, School of Civil Engineering, University of Leeds.

3 Results and discussion

The average removal efficiencies and final effluent concentrations of the parameters in both BFS-ARF treating the PFP effluent are shown in Table 1. Both the aerated BFS horizontal-flow and vertical-upflow systems achieved high removals of total and total reactive phosphorus. The former produced higher removals of BOD_5 and total N (although the removal of total N in both aerated BFS filters was poor), but the latter achieved a much higher removal of ammonium-N with a correspondingly higher production of nitrate-N. Both BFS–ARF produced effluents which complied with the EU UWWTD for BOD_5 and total P (i.e., ≤25 mg BOD_5/L and, for >100,000 p.e., ≤1 mg P/L), but only the horizontal-flow BFS-ARF produced an effluent with ≤15 mg total N/L (for 10,000–100,000 p.e.), although the effluent from the vertical-upflow BFS-ARF was close with just over 16 mg total N/L.

3.1 Total nitrogen (TN) removal

In general, the removal of total nitrogen (N_{Tot}) was relatively low in both BFS filters treatment systems in comparison to other parameters. However, TKN and ammonium nitrogen removal were found to be relatively high after the wastewater was further treated in both aerated BFS filter systems; this will be discussed later in this subsection. During the monitoring period, the average N_{Tot} concentration in the PFP system influent was 37 mg N/L, whilst in the effluent it was 22 mg N/L. The average PFP system removal efficiency was 37%. Furthermore, N_{Tot} removal was observed to be relatively poor in both the aerated BFS filters due to incomplete nitrification. In the aerated vertical upward-flow BFS filter, the average of N_{Tot} removal was 20%, whilst an average of 40% of N_{Tot} was removed in the aerated horizontal-flow BFS filter, which thereby produced average final effluent qualities of 16 and 12 mg N/L, respectively. Figure 2 shows the influent and effluent treatment systems and their removal efficiencies, respectively.

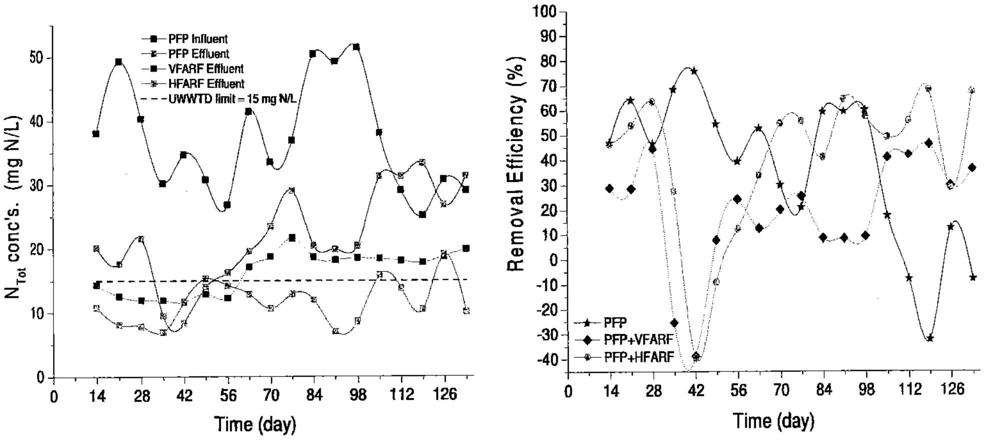

Figure 2: N_{Tot} concentrations in the influents and effluents and their removal efficiencies of the PFP and the aerated BFS filters.

The removal of N_{Tot} in the aerated BFS filter varied according to the organic matter concentrations in the PFP effluent (aerated BFS filters influent). The ratio of BOD_5: N was able to exert an impact on the fraction of nitrifiers in RF systems, which subsequently allowed nitrification to occur. In general, the fraction of nitrifiers increasing, with a decreasing BOD_5:N ratio would in turn enhance nitrification performance. Therefore, a higher nitrification rate could be achieved by lowering the BOD_5:N ratio [12]. This is due to the fact that higher biodegradable organic matter found in the ARF system leads to the competition of dissolved oxygen demand between heterotrophic bacteria, which are predominantly responsible for the aerobic degradation of biodegradable organic matter [13,14] and nitrification processes. Therefore, in order to maintain a high nitrification rate in the ARF system, carbon should be removed so that it is as low as possible in the facultative pond prior to entering both aerated BFS filters. In this experiment, the PFP was unable to produce a high quality of effluent with low BOD_5, most probably due to the influent wastewater quality found to be fluctuating after day 70 of the experiment. Therefore, the PFP effluent was not of a very good quality because it had already started to degrade in the holding pond. As a result, N_{Tot} removal was relatively low in this experiment.

3.2 Total phosphorus removal

TP removal in this experiment was very impressive in both aerated BFS systems, as the filters consistently achieved high phosphorus removal efficiencies throughout the present study. TP was removed at an average of 51% in the PFP. The average influent of TP to the PFP during this monitoring period was found to be 3.9 mg P/L, and the final effluent produced an average of 1.7 mg P/L. The PFP effluent was further treated efficiently in both aerated BFS, as the final effluent from both filters measured consistently below 0.5 mg P/L. The average removal efficiencies in the aerated vertical upward-flow BFS filter and in the aerated horizontal-flow BFS filter were 88% and 89%, respectively, which was

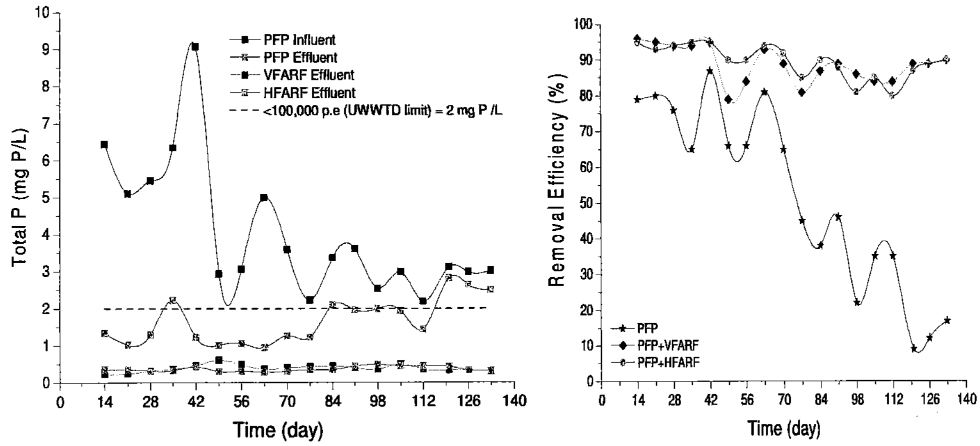

Figure 3: TP concentrations in the influents and effluents and their removal efficiencies of the PFP and the aerated BFS filters.

accordingly able to produce averages in the final effluent of 0.38 and 0.36 mg P/L. Figure 3 illustrates this data.

This result demonstrates that the aerated BFS filter appears to be a promising system for upgrading pond effluent, which would enable discharge to receiving water bodies. In terms of TP removal, the quality of final effluent produced by the aerated BFS filter was comparable to the study conducted in Canada by Cameron et al. [15]. In that study, the slag filters were able to upgrade the lagoon effluents to <0.03 mg P/L of TP, and TP removal efficiencies of up to 99% were recorded during the experiment with an average of 0.91 mg P/L. Although the aerated system has been used in this study, it was principally designed for nitrogen removal. Therefore, the systems presumably have no difference in removing phosphorus.

Furthermore, the removal of TP achieved from this set of experiments shows that the direction of wastewater flow into the filters did not influence the filter capacity in removing phosphorus from the PFP effluent. Both filters did not exhibit any significantly different behavior, resulting in significantly lower effluent levels of TP. On the other hand, Farahbakhshazad and Morrison [16] report that a constructed wetland (CW) vertical upward-flow system was expected to be more effective than horizontal flow, simply because the water-root contact can be optimized in vertical systems through an upward-flow, which thereby promotes plant uptake. Hence, the nutrients nitrogen and phosphorus were satisfactorily removed. However, in this experiment—the BFS used differs in contrast to CW systems, as plants were not used as part of the BFS design treatment process—no differences in terms of phosphorus removal were witnessed. Thus, it can be concluded that wastewater flow direction does not affect phosphorus removal within the ARF system.

4 Conclusions

From the results of the present study, it can be concluded that the both aerated BFS filter systems are suitable unit processes for removing N and P from PFP effluents. The aerated vertical upward-flow BFS filter efficiently produced a satisfactory final effluent to levels below the EU UWWTD maximum permissible limit for WWTP< 100,000 population equivalent required for direct discharge to nearby receiving waters. The average concentrations of parameters monitored were found to be consistently below the consent limits. The aerated horizontal-flow BFS filter also produced a higher quality of final effluent which can achieve a satisfactory effluent consent limit for EU UWWTD (91/271/EEC) maximum permissible limits for both large and small WWTP for direct discharge to nearby receiving waters. The average concentrations of parameters monitored were found to be constant below the consent limits.

The aerated vertical-upflow BFS filter has the advantage of removing more ammonium-N (to below 1 mg N/L), but the disadvantage of removing less total-N. Hence, the combination of highly efficient nitrogen removal—obtainable in the vertical upward-flow ARF and economical and effective phosphorus removal by BFS should be an ideal option for the total nutrient removal from wastewater at small WWTP. Further research on optimizing the design and performance of both aerated BFS filter systems is warranted, and their performance in warm-climate countries requires to be investigated.

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