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Aerated Blast-Furnace-Slag Filters for the Simultaneous Removal of Nitrogen and Phosphorus from Primary Facultative Pond Effluents

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Abstract: Rock filters (RF) are a promising alternative natural wastewater treatment technology for upgrading waste stabilization pond (WSP) 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, a horizontal-flow ARF and a vertical upflow ARF, was compared: for N and P removals. A further aim of the study was to determine if either or both of these BFS-ARF 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 BFS-ARF are suitable unit processes for removing N and P from primary facultative pond effluents. The vertical-upflow BFS-ARF 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 BFS-ARF is warranted, and their performance in warm-climate countries requires to be investigated.

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

1. Introduction

In 1970's, the idea of using Rock filters (RF) as one of the alternative methods for removing BOD_5 and suspended solids from wastewater has been initiated at the University of Kansas, USA [1,2,3]. 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 the 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 TSS removals [7,8,9]. Therefore, the present study was carried out to investigate the performance of aerated RF (ARF) systems for enhancing the removal 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, 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 effluent in an economical way.

2. Materials and Methods

2.1 Pilot-scale units

The primary facultative pond (PFP) was loaded at 80 kg BOD/ha day using a variable-speed peristaltic pump (Watson Marlow model 505S pump fitted with a model 501RL pump head). A vertical-upflow ARF (1.5-

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m high, 0.30-m diameter) and a horizontal-flow ARF (4 × 0.5 × 0.5 m) as shown in Fig. 1 and Fig. 2 were operated in parallel at our experimental station at Yorkshire Water's Wastewater Treatment Works at Esholt, Bradford. The ARF were filled with 25−30 mm blast furnace slag and aerated using an oil-free Jun-air compressor (model OF302-25B) at an air flow rate of 20 L/min. The 12-mm reinforced plastic pipework, used to convey the facultative pond effluent to the ARF, was heated during winter using a T-type thermocouple (model DTC 410 with temperature control) and a heating cable (Flexelec model FTP). A flow meter was installed at the inlet of the vertical-upflow ARF to monitor the flow to it and airflow meters were installed for both ARF. The flow rates were 0.072 m^3/d to the vertical-upflow ARF and 0.605 m^3/d to the horizontal-flow ARF. The ARF effluents were discharged by gravity to the nearest drain. The pilot-scale ARF were operated during January−July 2010, during which time the mean monthly temperature was in the range 1-12°C.

Fig. 1 The vertical-upflow BFS ARF

Fig. 2 The the horizontal-flow BFS ARF

2.2 Wastewater sampling and analysis

Grab samples of the influent and effluent of the two ARF were collected and analysed weekly, following *Standard Methods for Water and Wastewater Examination* [10], for BOD (method no. 5210-B), COD (5220-C), ammonia (4500-NH_3 D), TKN (4500-N_{org}C) TSS (2540-D), and total phosphorus (4500-PE). Dissolved oxygen, pH, and temperature were measured in situ using a YSI sonde probe (model 610-DM), and nitrate was analysed weekly in an DIONEX ion analyser (model DX500). All laboratory analyses were conducted in the Public Health Engineering Laboratories, School of Civil Engineering, University of Leeds (16 km from Esholt).

2.3 Statistical analyses

Statistical analyses for all the wastewater quality parameters in the effluents of both ARF and their removal efficiencies were determined using the independent Student's *t*-test (2-tailed test).

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 Tables 1 and Table 2. Both the horizontal-flow and vertical-upflow BFS-ARF 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 BFS-ARF 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.

Table 1 Results from the vertical-upflow BFS-ARF

Parameter	Removal efficiency (%)	Final effluent concentration (mg/L ± s.d)
BOD_5	96	7.34 ± 4.01
Total N	20	16.32 ± 0.78
Ammonium-N	97	0.75 ± 0.14
Nitrate-N	−	13.88 ± 0.71
Total P	88	0.38 ± 0.09
Total reactive P	84	0.28 ± 0.14

Table 2 Results from the horizontal-flow BFS-ARF

Parameter	Removal efficiency (%)	Final effluent concentration (mg/L ± s.d.)
BOD_5	99	3.24 ± 1.35
Total N	41[a]	11.57 ± 0.78
Ammonium-N	86[a]	3.86 ± 1.19
Nitrate-N	–	7.11 ± 0.95
Total P	89	0.36 ± 0.06
Total reactive P	84	0.26 ± 0.01

[a]Significantly different from corresponding value in Table 1 ($p < 0.05$).

3.1 Biochemical oxygen demand (BOD_5) removal

BOD_5 removals in both of the aerated BFS filters remained high (>90%), which was expected and concurrent with data collected from the previous experiment. The BOD_5 was removed at an average of 60% in the PFP system, with an average influent concentration of 225 mg/L BOD_5. After 77 days of the monitoring period, the BOD_5 removal efficiencies were found to be fluctuating between 8% and 67%. As a result, BOD_5 concentrations in the effluent were found to be above 100 mg/L, which significantly influenced the nitrification rate, particularly in the HFARF system. The pond effluent BOD_5 concentration of 77 mg/L was then further reduced to an average of 7.34 mg/L and 3.24 mg/L by the vertical upward-flow system and horizontal-flow system, respectively. The average removal efficiency for the aerated vertical upward-flow filter was 96%, whilst the average removal of the aerated horizontal-flow filter was 99%. These are shown in Fig.3.

Furthermore, the fluctuations in wastewater PFP influent quality, in particular BOD_5, did not result in unsatisfactory biodegradable organic matter removal in either of the aerated BFS filters (Fig. 3). The highly oxygenated system, such as the aerated BFS filter, was expected to efficiently remove the biodegradable organic matter from wastewater, regardless of the incoming flow direction. Moreover, there was the notable presence of more aerobic conditions—presumably promoting further aerobic breakdown of biodegradable organic matter from wastewater in this biological filter system. Lee et al. [11] also stated that slag filters effectively removed BOD_5 from highly loading diary wastewater with an average BOD_5 influent concentration of 2,500 ± 33% mg/L: their slag filters, both vertical and horizontal flow systems, achieved high treatment efficiencies of 89% and 86%, respectively. Furthermore, the integrated system (CW—vertical-flow slag filter) achieved a 90% BOD_5 removal efficiency in comparison to horizontal-flow slag filter and hybrid system.

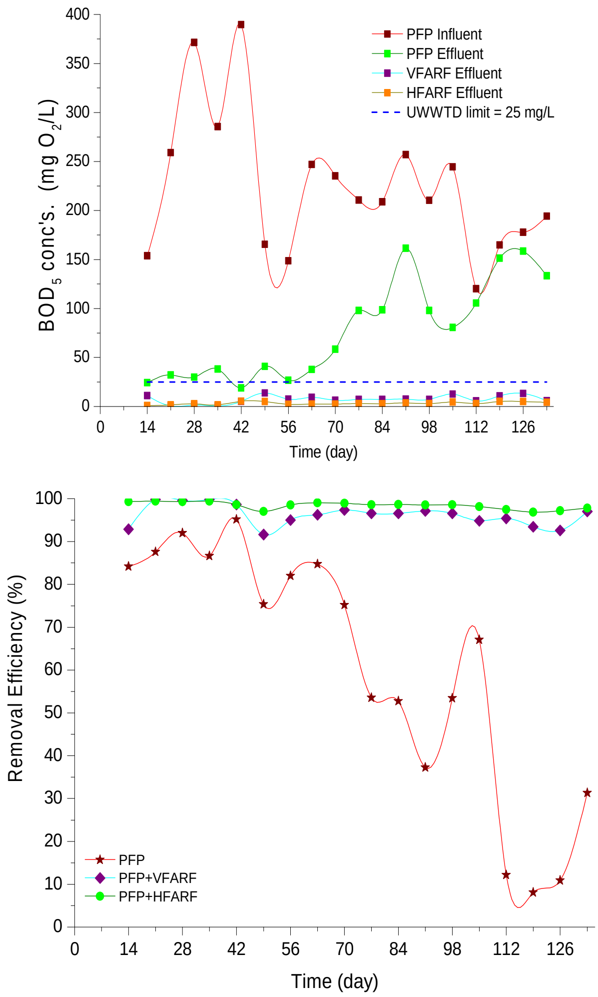

Fig. 3 BOD_5 concentrations in the influents and effluents and their removal efficiencies of the PFP and the BFS filters

3.2 Total Nitrogen (N_{Tot}) removal

In general, the removal of total nitrogen (N_{Tot}) was relatively low in both BFS filter 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 mg N/L and 12 mg N/L, respectively. Fig. 4 shows the influent and effluent treatment systems and their removal efficiencies respectively.

The removal of N_{Tot} in the aerated BFS filter varied according to the organic matter concentrations in the PFP effluent (ARF 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.

3.3 Total Phosphorus (TP) removal

Total phosphorus (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 accordingly able to produce averages in the final effluent of 0.38 mg P/L and 0.36 mg P/L. Fig. 5 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.

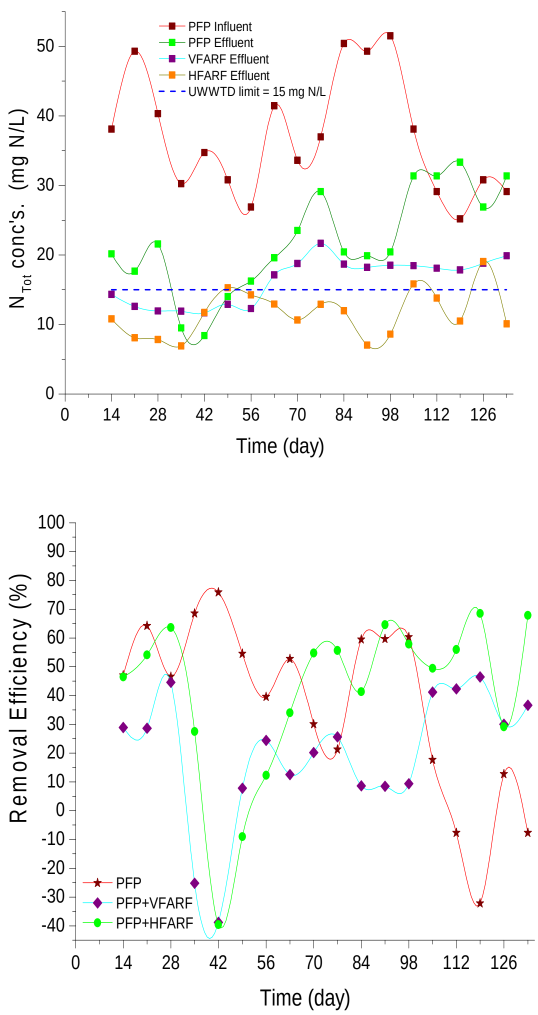

Fig. 4. N_{Tot} concentrations in the influents and effluents and their removal efficiencies of the PFP and the BFS filters

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 behaviour, resulting in significantly lower effluent levels of TP. On the other hand, Farahbakhshazad and Morrison [16] report that a CW vertical upward-flow system was expected to be more effective than horizontal flow, simply because the water-root contact can be optimised 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 differ 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 the wastewater flow direction does not affect phosphorus removal within the ARF system.

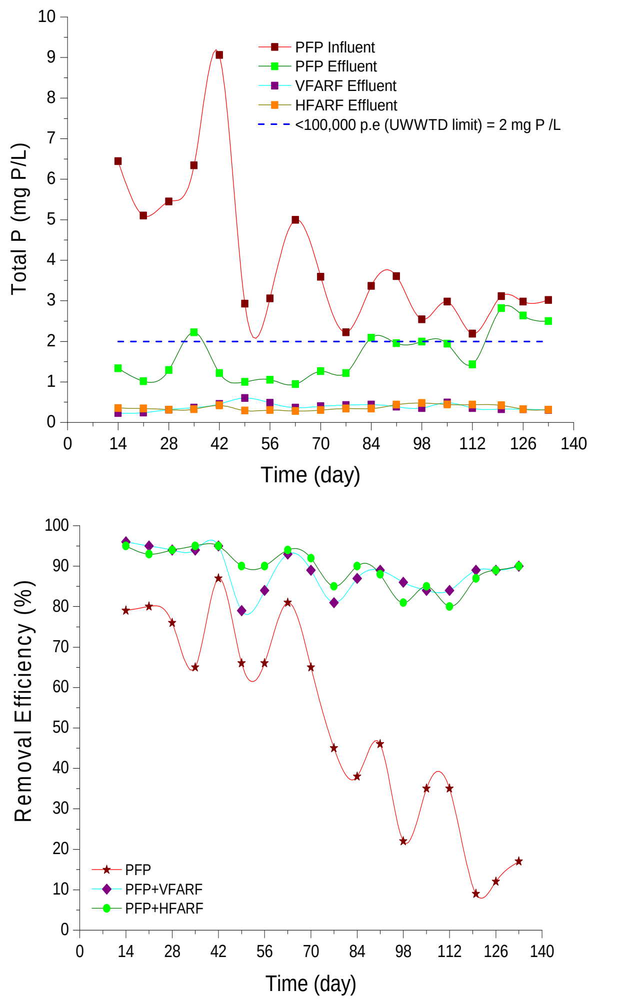

Fig. 5 TP concentrations in the influents and effluents and their removal efficiencies of the PFP and the BFS filters

4. Conclusions

From the results of the present study it can be concluded that the both BFS-ARF are suitable unit processes for removing N and P from primary facultative pond effluents. The vertical-upflow BFS-ARF 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 BFS-ARF is warranted, and their performance in warm-climate countries requires to be investigated.

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