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Evaluation of Woodchip and Synthetic Fiber as Biofilter Media for the Treatment of Livestock Stormwater

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가축사육단지 강우유출수 처리목적 바이오 필터 여재로서 우드칩과 합성섬유의 평가

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Abstract

Two vertical flow biofilters in series (BFS) employing synthetic fiber (FBF) followed by woodchip (WBF) was investigated in order to assess its potential as an alternative to the typical vertical-horizontal flow configuration in removing nonpoint source pollutants specifically nutrients and organics. These lab-scale column biofilters were operated for 176 days alongside three other columns that were added for control and sampling purposes. The biofilter columns were fed with either a semi-artificial piggery stormwater or artificial stormwater with specific ammonia and nitrate contents. Results reveal that the BFS was more effective than a single biofilter in removing pollutants especially nitrogen. FBF was found to remove up to 100% of ammonia from the stormwater with corresponding increase in nitrate in the outflow which shows evidence of active nitrification. Meanwhile, the succeeding vertical WBF was able to subsequently remove 77% of the nitrate. The effective reduction of nitrate in a vertical flow biofilter was believed to be due to the use of woodchip which can provide a carbon source that is required for denitrification. However, further investigation is needed to support this claim. Nonetheless, the study shows the potential of vertical flow BFS as a nitrogen removal mechanism especially in areas where enough land space for horizontal flow biofilters is limited.

Key words : Biofilter; stormwater; synthetic fiber; vertical flow wetland; woodchip

요 약

본 연구에서는 합성섬유로 충진된 바이오필터(FBF)와 우드칩으로 충진된 필터(WBF)로 구성된 수직흐름형 습지공정(BFS)의 처리성능을 평가하였다. BFS 시스템에서 단독 필터를 사용한 것보다 두개의 필터를 직렬로 결합한 경우 특히 질소제거에 탁월한 성능을 나타내었다. FBF 공정에서는 암모니아 질소 100%가 활발한 질산화 반응을 통하여 질산성 질소로 전환되었으며 후속 WBF에서 77%의 질산성 질소가 제거되어 우드칩이 제공하는 탄소가 탈질반응에 큰 영향을 끼치는 것으로 판명되었다. 바이오필터의 성능은 유입특성에 상관없이 독립적인 성능을 보였으며 인 제거에도 효과가 있었으나 종종 용출징후가 나타났으며 현장적용시에는 이와 같은 사항을 유념해야할 것으로 보인다. 한편 회귀식 분석결과 운전시간에 따른 바이오 필터내부의 미생물 증식상태를 간접적으로 암시해 주었다. 본 연구결과 질소제거 측면에서 본 연구에서 제안하고 있는 여재를 이용한 수직흐름형 직렬식 습지 공정은 전형적인 수직-수평흐름 습지와 비교하여 비용측면에서 많은 장점을 가지고 있다.

핵심용어 : 강우유출수, 바이오필터, 우드칩, 합성섬유, 수직흐름형습지

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1. Introduction

Piggery stormwater is produced when agricultural stormwater entrains piggery wastes that have accumulated on livestock farmlands since the preceding precipitation (KME, 2004). The removal of nutrients (e.g. nitrogen and phosphorus) and organics from piggery stormwater is enormously important due to the following reasons: (a) uncontrolled discharge of nitrogen and phosphorus into natural water channels fosters eutrophication, including excessive plant and algae growth, and possibly oxygen depletion of lakes and rivers (Chen et al., 2011, Taylor et al., 2004, Xinshan et al., 2010) and (b) untreated organic materials often deplete dissolved oxygen (DO) concentration in open water channels, leading to the death of aquatic organisms.

Biofiltration systems including VF (vertical flow) and HF (horizontal flow) biofilters are an effective and popular way to treat stormwater and have been employed in combination known as biofilters in series (Cooper, 1996). Such combinations often optimize nitrogen and organics removal, due to the presence of aerobic, anaerobic, and anoxic phases. In VF-HF biofiltration systems in series, organics are removed by heterotrophic bacteria via aerobic and anaerobic degradation (in both biofilters), while nitrogen is removed by autotrophic nitrifying bacteria reducing ammonia nitrogen in one biofilter (VF biofilter), in combination with heterotrophic denitrifying bacteria removing nitrate in another biofilter (HF biofilter) (Kadlec et al., 1995).

However, VF-HF biofilters in series are not sufficiently cost-effective, due to the requirement of a large area for construction of HF biofilters as the second stage, even though VF biofilters reduce the land requirement. HF biofilters are usually employed to achieve denitrification, which is usually limited in VF biofilters. VF biofilters were found to be unable to achieve active denitrification due to lack of carbon source and presence of excess dissolved oxygen, which is essential for nitrification (Sun, 1998). Considering this, VF-VF biofilters in series which requires less space may be a better alternative to VF-HF biofilters in series if proper environment for denitrification is provided.

Aside from the configuratrion of the biofilter, another major component is the selection of the packing material. Fiber media have been employed in VF biofilters as a physical filter substrate such as in the study of Ahammad et al. (2013) where two of the four 2-L trickling biofiolters investigated were packed with sponge media. They are light and can be constructed to greater depths, which increase hydraulic load capacity and improve mass transfer (Kim et al., 2005). Fiber media can also be utilized as a colonization medium for biofilm. Jurecska et al. (2013) studied the physico-chemical characteristics of four types of non-woven fibers and observed that if a polymer surface is hydrophilic, microorganisms can attach onto it. The greater the surface area of fiber media, the greater the ability of the biofilter to accomplish nitrification at higher volumetric loadings as compared to to rock media filters (Kim et al., 2005). Fiber filter media also provides better gas transfer due to the greater draft and higher void fraction as well as less plugging. In this study, synthetic fiber was employed in the first stage, while woodchip was employed in the second stage as the carbon supplier. The objective of this study is to investigate the functions of woodchip and fiber media in piggery stormwater treatment.

2. Materials and Methods

2.1 Description of the biofilters

A biofilter system (BFS) was set up composing of two biofilter columns in series: a fiber-packed biofilter (FBF) in column C followed by a woodchip-packed biofilter (WBF) in column D as shown in Fig. 1. In addition, two control biofilters, FBF-C in column A and WBF-C in column E were setup separately to observe the individual performance of each biofilter when they are not in series. An additional FBF in column B that is identical to column A and C was setup for sampling purposes without disrupting the recycling and transfer of flow between column C and D. All in all, five biofilters in column were operated during the experiments. Each cylindrical column is 100 cm in depth with a circumference of 10 cm and is made of black opaque acryl to prevent the growth of algae and provide a dark environment for biofilms during the operation. The columns are filled from bottom to top with quartz stones to facilitate proper drainage, either synthetic fiber or woodchip for the main media, followed by vermiculite to help distribute the inflow equally. The outlet is located at the bottom of the column and is controlled by a valve. To exclude the contribution of plants in the treatment, no vegetation was employed.

The configuration of the media in the control biofilters are exactly the same as the ones in the biofilters in series. FBF-C was used to observe the removal of NH_4-N while WBF-C was used to observe the removal of NO_3-N. All the biofilters were subjected to the same operational conditions except for the inflow type which will be discussed in the following section.

The properties of the filter materials are summarized in Table 1. The porosity of the woodchip is 66% while that of the synthetic fiber is 89%. Fiber is also the lightest at 120 kg/m^3 but has a really high specific surface area of 1.5 m^2/g as compared to woodchip and the other materials. The woodchip used was sourced from a local supplier and is made of hardwood.

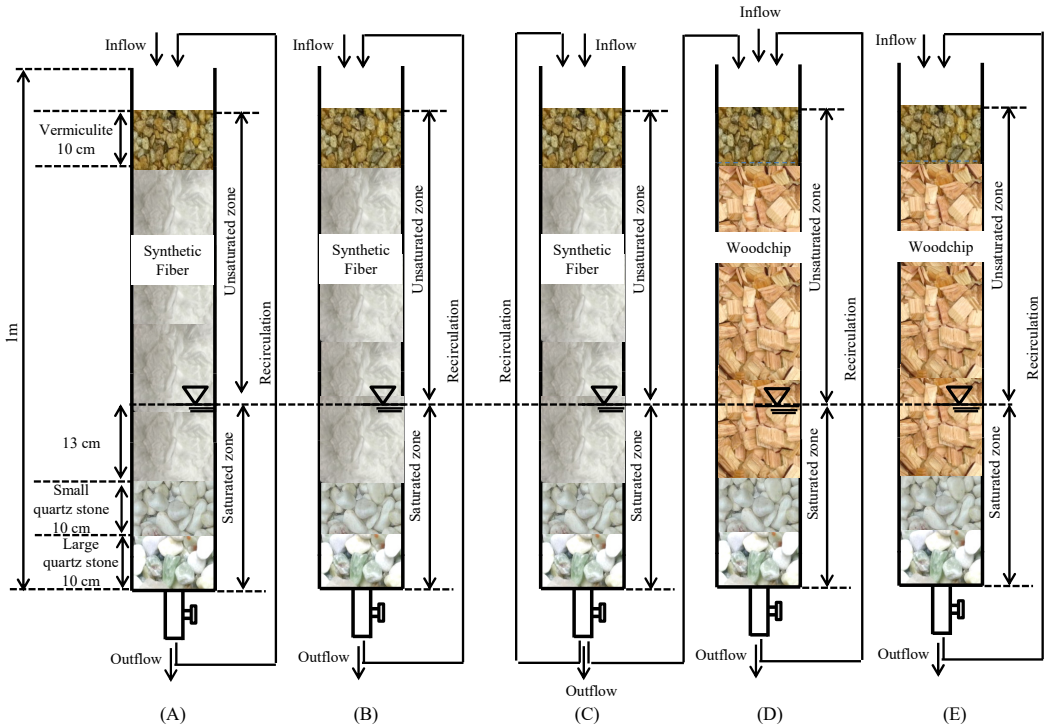


Fig. 1. Schematic diagram of the biofilter system in series.

Table 1. Characteristics of all the media employed in the biofilters

Media type	Diameter (cm)	d_{10} (cm)	d_{50} (cm)	d_{60} (cm)	U	Porosity (%)	BD ($kg \cdot m^{-3}$)	SSA ($m^2 \cdot g^{-1}$)
Vermiculite	0.48–0.55	–	–	–	–	55	482	–
Fiber*	4.5	–	–	–	≈1.0	89	120	1.5*
Woodchip	–	1.1	2.0	2.1	1.9	66	260	0.09
Quartz stone	2.2–3.2	2.28	2.51	2.60	1.13	40	1706	–

Note: U–uniformity coefficient; BD–bulk density; SSA–specific surface area;
*Fiber: synthetic fiber

2.2 Preparation of the synthetic stormwater

Stormwater from livestock farm regions may carry piggery wastes or mix with wastewater when stormwater runoff flows through farmlands, before entering natural water systems. Generally, this type of stormwater has varying concentrations of pollutants because the pollutant loading of stormwater varies. The variation depends on different rainfall characteristics and the composition of piggery wastes that have accumulated on the farmland preceding precipitation. Overall, it has a low C/N ratio with a typical value of 5 and a typical COD concentration of around 100 mg/L (Cheng et al., 2013). Based on this, a semi-artificial stormwater (SASW) was prepared by adding 60 mL of piggery wastewater from the same livestock farm to 20 L of tap water. This makes it easier to compare the performance of stormwater biofilters compared to that of the original piggery stormwater, with the use of varying concentrations of pollutants. Even though the piggery wastewater used in the experiment was from the same livestock farm and stored in a refrigerator, the concentrations of different pollutants differ between different feedings. However, this difference was unavoidable, due to the nature of its essential complex composition.

On the other hand, the artificial stormwater (ASW) was prepared by dissolving chemicals in distilled water, giving a fixed concentration of nitrogen species. ASW1 was prepared by adding 1.53 g of NH_4Cl to 20 L of distilled water. On the other hand, ASW2 was prepared by adding 2.89 g of KNO_3 to 20 L of distilled water. Therefore, ASW1 and ASW2 contain 20 mg/L NH_4-N and NO_3-N, respectively. In addition, to ensure normal growth of microorganisms, the same trace elements, including 0.44 g KH_2PO_4, 8.48 g $CaCl_2 \cdot 2H_2O$, 23.52 g $MgSO_4 \cdot 7H_2O$, 3.00 g $NaHCO_3$, 24.36 g NaCl, 0.042 g $FeSO_4 \cdot 7H_2O$, and 0.021 g $ZnSO_4 \cdot 7H_2O$, were also added to both ASW1 and ASW2 for each 20 L of distilled water (Saeed and Sun, 2011). Note that no microorganisms were introduced into the ASW. Table 2 shows the characteristics of the SASW and ASW.

Table 2. Characteristics of the inflows SASW, ASW1, and ASW2

Parameters	Unit	SASW	ASW1	ASW2
Temperature	℃	13.8 ± 3.0*	14.4 ± 3.4	14.6 ± 3.3
pH	-	7.47 ± 0.18	7.68 ± 0.24	7.7 ± 0.28
EC	μs/cm	331 ± 32	3143 ± 321	3040 ± 337
Alkalinity	mg/L as $CaCO_3$	114 ± 10	126 ± 17	130 ± 15
DO	mg/L	9.49 ± 2.13	11.29 ± 1.47	11.32 ± 1.46
Turbidity	NTU	27.1 ± 6.8	2.1 ± 1.9	2.2 ± 1.4
TSS	mg/L	40 ± 12	5 ± 3	5 ± 3
TN	mg/L	17.96 ± 2.82	22.2 ± 3.6	21.35 ± 3.55
TP	mg/L	1.06 ± 0.22	3.02 ± 0.81	3.12 ± 0.69
$TCOD_{Cr}$	mg/L	92 ± 28	0 ± 5	12 ± 10
NH_4	mg/L	8.54 ± 3.54	18.77 ± 3.53	0.23 ± 0.22
NO_3	mg/L	1.59 ± 0.68	1.77 ± 0.73	16.25 ± 2.89
BOD_5	mg/L	21.55 ± 9.93	2.03 ± 5.77	1.34 ± 1.85

* Mean ± standard deviation.

2.3 Experimental Procedure

2.1 L of inflow was fed to each column during one batch of feeding. Except for the fiber columns, the feeding time for all columns was 96 seconds, corresponding to an instant hydraulic loading rate of 240 m/day. Due to the unique properties of fiber, the initial feeding time for the fiber column was 192 seconds, corresponding to an initial instant hydraulic loading rate of 120 m/day.

The hydraulic retention time (HRT) is the same parameter as the number of ADD (antecedent dry days), because the inflow to the biofilter occurred only at the time of rainfall activity. The term HRT was used in this study to represent ADD. 2 days of HRT means that samples were taken from the effluent of the columns every 2 days and a new batch of inflow was immediately fed. The operation was designed based on the hypothetical occurrence of rainfall events. All single columns were operated with 2 days of HRT. Therefore, the BFS system was operated with 4 days of HRT.

For all the stormwater biofilter columns, internal recirculation was carried out at the same time once a day, until the next feeding of inflow was conducted. A typical recirculation ratio of 1:1 was applied, which means that all of the outflow was recirculated back to the biofilter. On the first day of operation, SASW was fed to column C (ADD = 0 day), and after 24 hours, the total outflow from C was recycled once (ADD = 1 day). After another 24 hours, the outflow from C was taken out and fed to column D, and newly mixed SASW was fed to column C at the same time (ADD = 2 days). After another 24 hours, the total outflow from D was recycled once, while total outflow from column C was also recycled once at the same time (ADD = 3 days). After another 24 hours, outflow D was sampled and discharged, total outflow C was taken out and fed to column D (ADD = 4 days), and a batch of newly mixed SASW was fed to column C at the same time. For the control columns A (FBF-C) and E (WBF-C), the total outflow was recycled as inflow every 2 days. Meanwhile, column B was operated the same way as column C but the outflows every 2 days were collected as a sample representing the outflow from column C that is fed to column D. This ensures that all the outflow from column C was fed to column D and the representative samples from column B could be subjected to water quality analysis. The operation was conducted continuously for 176 days. Table 3 summarizes the operating conditions.

Basic water quality parameters, including temperature, turbidity, pH, electric conductivity (EC), and dissolved oxygen (DO), were measured *in situ,* immediately after the samples were taken from the outflow. The water temperature, pH and electric conductivity (EC) were measured by a YSI 556MPS multi-probe system (www.ysi.com). Turbidity and DO were determined by HACH 2100H turbidimeter and TSI 5000 DO meter, respectively. The samples were stored in a cool box in darkness (with a temperature of around 4 ° C), and immediately transported to the laboratory. Other water quality parameters, including total suspended solids (TSS), total chemical oxygen demand ($TCOD_{Cr}$), soluble chemical oxygen demand ($SCOD_{Cr}$), total nitrogen (TN), dissolved total nitrogen (DTN), ammonia (NH_4^+-N), nitrate (NO_3^--N), dissolved phosphorus (DTP) and total phosphorus (TP), were analyzed in accordance with the Standard Methods for the Examination of Water and Wastewater, 21st Edition (APHA et al., 2005). Pollutant concentrations in the inflow and outflow were used to calculate the pollutant removal in the biofilters.

Table 3. Operating conditions of the stormwater biofilters

Biofilter	Inflow	ADD (day)	RF (times)	Remark
Synthetic Fiber (Column B and C)	SASW	2	1	For the BFS system (C–D), ADD = 4 and RF = 2
Woodchip (Column D)	Outflow from fiber biofilter	2	1	
Synthetif Fiber – Control, (Column A)	ASW1	2	1	No incubation or any microorganisms in the inflow
Woodchip – Control (Column E)	ASW2	2	1	

* ADD – antecedent dry days; RF – recirculation frequency; SASW – semi–artificial stormwater; ASW – artificial stormwater

3. Results and Discussion

3.1 Overall pollutant removal

Fig. 2 shows the inflow and outflow concentrations of the pollutants that were analyzez over the course of the study. This represents 88 inflow and outflow samples in 176 days. The figure clearly shows that the BFS system (columns C or B and D) was more efficient in removing TSS, TCOD, TN and TP, compared with single biofilters, such as the FBF–C system (column A) fed with ASW1, and the WBF–C system (column E) fed with ASW2. The results show that TSS and TCOD were largely reduced in the fiber packed stormwater biofilter (FBF) (column B), whereas their concentrations slightly increased in the woodchip packed stormwater biofilter (WBF) (column D). This was due to the release of organics from woodchip in the WBF unit. For nitrogen, the FBF unit removed a little TN, while the WBF unit was able to reduce TN, because the FBF unit mostly converted ammonia to nitrate, while the WBF unit completely removed nitrate from the system. For phosphorus, the FBF unit removed about 25% of TP, and the WBF unit removed another 50% of TP.

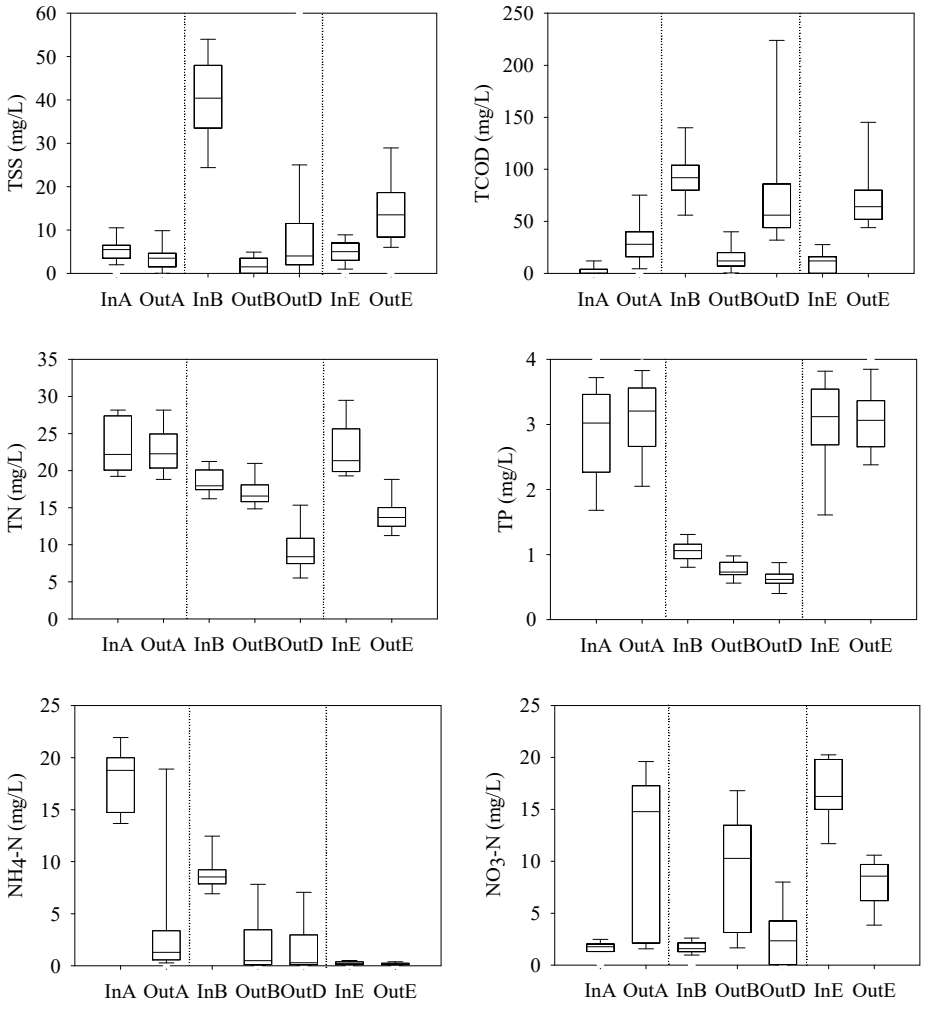


Fig. 2. Overall performance of the BFS system and control biofilters.

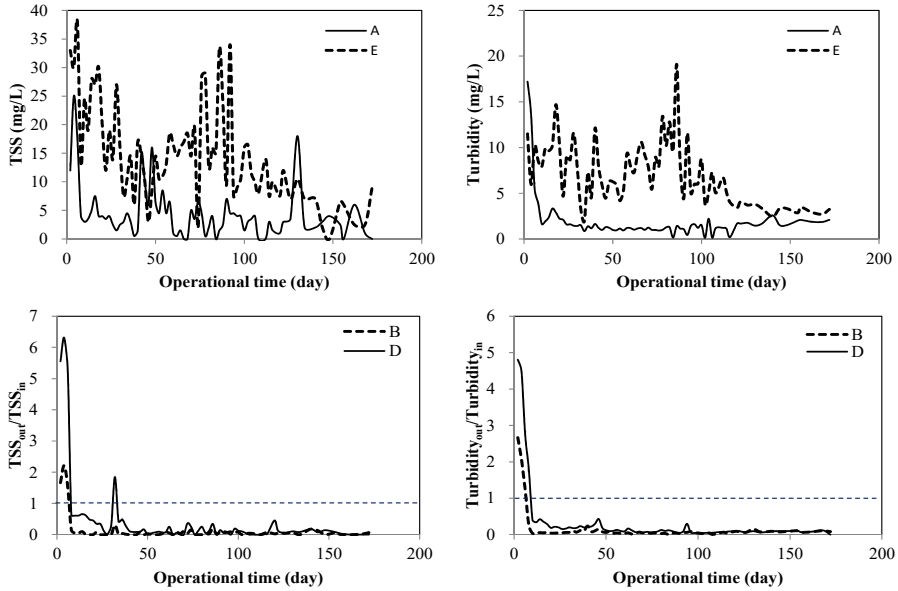


Fig. 3. Variation of the outflow concentrations and the outflow to inflow concentration ratio of turbidity and TSS with respect to operational time.

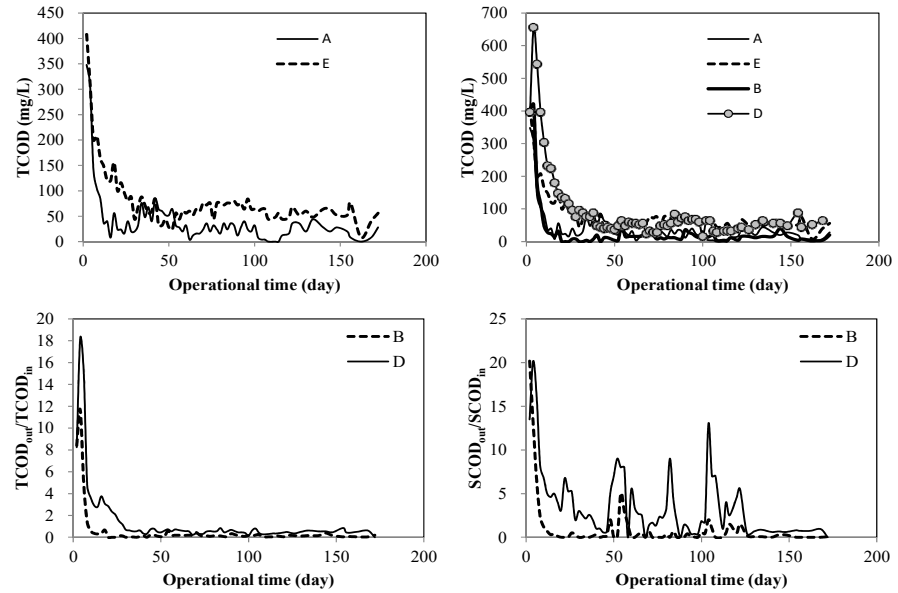


Fig. 4. Variation of the remaining percentages and outflow concentrations TCOD and SCOD with respect to operational time.

3.2 Removal of solids and organics

In FBF-C (column A) and WBF-C (column E), the turbidity and TSS concentrations of ASW1 and ASW2 were almost zero. The outflow turbidity and TSS concentrations thus indicate the release of substrates from the media inside the column. Fig. 3 shows that the release of solids occurred considerably during the start-up period for several days only. Continuous release was observed after that but it was insignificant and unstable. The release of solids was much more significant in the WBF-C system, compared to the FBF-C system. This release started from the beginning of the operation, and showed a decreasing trend with time. The turbidity shows that after 110 days of operation, the release in the WBF-C system became stable. When SASW was fed in column B, significant release was also observed at the start-up period as indicated by the high outflow to inflow concentration ratio. However, after 10 days of operation, solids started to be evidently removed up to the end of operation.

In the case of COD, a significant release occurred during the start-up period for both fiber and woodchip biofilters as shown in Fig. 4. This is probably due to the wash-out of impurities on the media surface. However, the outflow TCOD concentrations of both biofilters rapidly decreased with time, due to the removal of particulate organics through filtration, and significant aerobic biodegradation of soluble organics by

the attached biofilms on the media surface. The fiber biofilter showed better removal of TCOD than the woodchips, since the release of organics from fiber was less significant, and it ceased earlier. The SCOD showed similar results.

3.3 Removal of nutrients

The mean inflow and outflow concentrations of different nitrogen forms in different stormwater biofilters are shown in Fig. 5. It is apparent that the BFS system shows effective removal of TN (57%), with the FBF unit converting ammonia to nitrate, and the WBF unit subsequently removing nitrate from the system. The FBF unit converted 93% of NH_4–N and removed 38% of organic nitrogen, while it accumulated 8.62 mg/L of NO_3–N resulting in only 14% of TN removal. This conversion of ammonia to nitrate in the FBF unit was found to be independent of inflow types, since similar results were also obtained using the same biofilter (FBF–C), but fed with ASW1 containing 18.77 mg/L of ammonia. In the FBF–C unit, 17.45 mg/L of NH_4–N was reduced (93%), whereas 12.61 mg/L of NO_3–N accumulated, resulting in 20% of TN removal. Note that the organic nitrogen in ASW1 was mostly non–biodegradable (no organic nitrogen removed), so that the difference between TN removal by these two biofilters could be due to the disparity of inflow TN concentration.

On the other hand, in the WBF unit fed with outflow from the FBF unit, 40% of ammonia was further reduced and 7.84 mg/L of NO_3–N was removed (77%), resulting to 50% of TN removal by the WBF unit and a total of 57% TN removal in the BFS system. This removal of nitrate in woodchip biofilter was also found to be independent of inflow type, since similar results were obtained using the same biofilter, but fed with ASW2 containing 16.25 mg/L of nitrate (WBF–C). In the WBF–C system, 7.75 mg/L of NO_3–N was removed (48%), resulting to 36% of TN removal. Since the organic nitrogen in ASW2 was mostly non–biodegradable (no organic nitrogen removed) and the inflow ammonia was below 0.3 mg/L, the difference between the TN removals by these two biofilters was due to the disparity of inflow TN concentration. Note

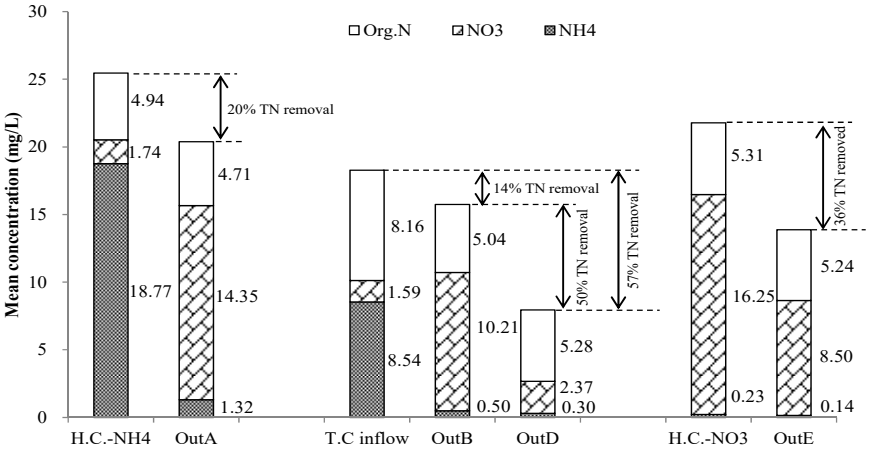


Fig. 5. Mean inflow and outflow concentrations of NH_4–N, NO_3–N, and TN.

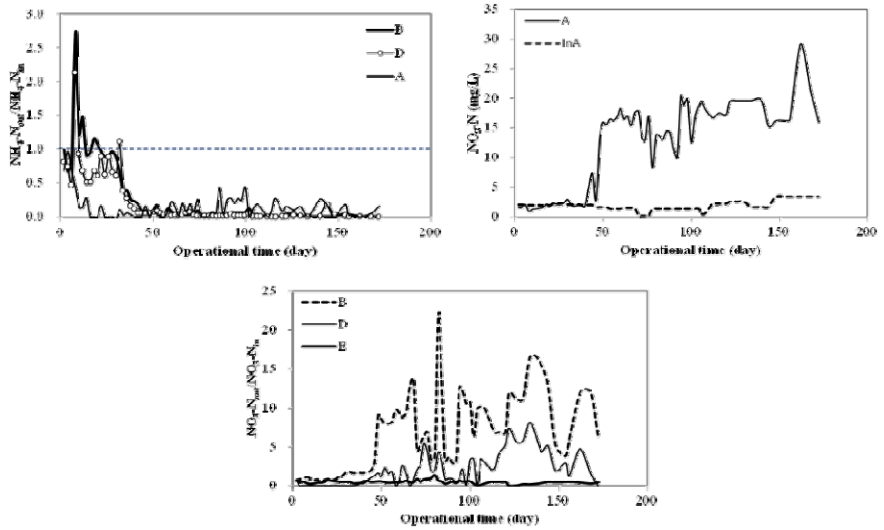


Fig. 6. Variations of the remaining NO_3–N percentage and outflow NO_3–N concentration with operational time.

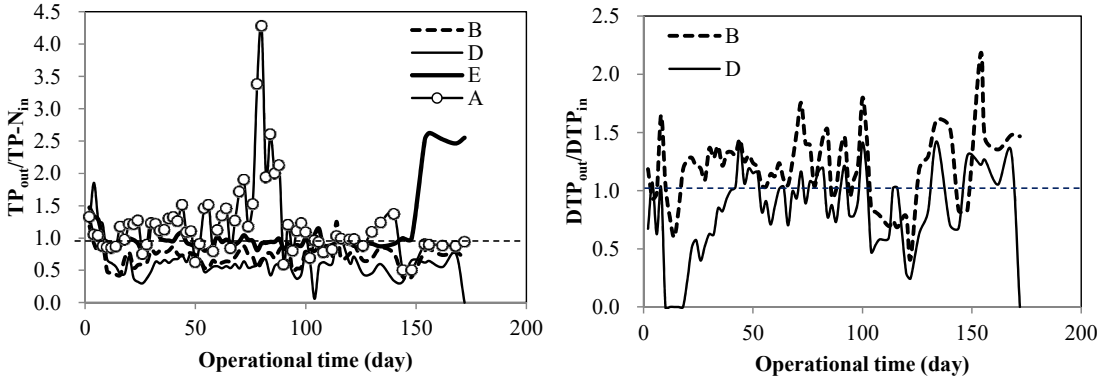


Fig. 7. Variation of the remaining TP and DTP percentages with respect to operational time.

that the amount of removed nitrate was the same (≈7.8 mg/L), although the percentage of nitrate removal was different (77% vs. 48%). This implies that the maximum removal capacity of the woodchip biofilter to remove nitrate could be about 7.8 mg/L.

In Fig. 6, it is evident that an initial release of ammonia occurred. However, significant removal was observed for both the FBF and FBF-C systems after 30 and 40 days, respectively, indicating active and stable nitrification. The FBF unit achieved significant accumulation of nitrate and the FBF-C unit performed similarly. Then, the WBF unit reduced the accumulated nitrate although it was not completely removed, indicating that the amount of organics released from woodchip might be insufficient for total nitrate removal.

Meanwhile, the FBF and WBF units removed 25% and 50% of TP, respectively, as shown in Fig. 7. However, in both systems, the removal of DTP was almost zero on average. This implies that fiber and woodchip biofilters removed only particulate phosphorus. Furthermore, the FBF-C system (column A) showed release of phosphorus while the WBF-C system (column E) did not remove TP at all, and a release was also observed at the end of the operation. This was due to little particulate phosphorus in ASW, compared to SASW.

3.4 Kinetic removal rate of organics and nitrogen

In Fig. 8, the variation of TCOD and NO_3-N concentrations with respect to operational time in woodchip biofilters, wherein (1), (2) and (3) correspond to the WBF, BFS and WBF-C systems, respectively was shown. C and C_0 indicate the outflow and inflow concentrations of the corresponding systems, respectively. Table 4 summarizes the kinetic removal rates of organics and nitrogen with respect to operational time. The term ln (C/C_0) is used to present the variation trend with time, since most of the removal or release processes in this study follow the first order reactions. The term ln (C) is used when the inflow concentration C_0 is zero.

For fiber biofilters including the FBF and FBF-C systems, during Phase 1 (start ~ 24th day), the outflow TCOD concentration was evidently higher than inflow TCOD concentration (ln (C/C_0) > 0), and it decreased with operational time at a constant rate, since both ln (C/C_0) for the FBF unit and ln(C) for the FBF-C system decreased linearly with time. From the start to the 16th day, the TCOD removal rate (indicated by − ln (C/C_0) with respect to time) followed the first order reaction. The removal rate was greater in the FBF than in the FBF-C system, probably due to the lesser significant amount of initial release in the FBF than in the FBF-C system. After that, the removal rate slightly declined in both biofilters, implying that most of the organics were released at the start-up period, and they were then removed until the end of the operation.

At the same time (start ~ 16th day), outflow concentrations of both ammonia and nitrate were not far from the inflow (ln (C/C_0) = 0), indicating that nitrification did not take place. This implies that high outflow TCOD concentration was unfavorable for the removal of ammonia, probably due to the inhibition effect that high concentration of organics may impose on nitrification. The FISH (fluorescence *in situ* hybridization) analysis by Nogueira et al. (2002) showed that this effect was caused by the unexpected formation of a heterotrophic microorganism layer on top of the nitrifying biofilm that limited the nitrifiers' oxygen supply.

During Phase 2 (25th ~ 44th day), outflow TCOD concentration decreased to almost zero. At the same time (18th ~ 44th day), outflow ammonia concentration decreased dramatically at a constant rate. The ammonia removal rate followed the first order reaction. Correspondingly, the outflow nitrate concentration increased at a constant rate. This indicates that the removal of organics imposed a positive effect on the removal of ammonia. This is consistent with the results that have been mentioned in the former paragraph, that high concentration of organics might have imposed a negative effect on nitrification. In addition, the ammonia removal rate was greater in the FBF

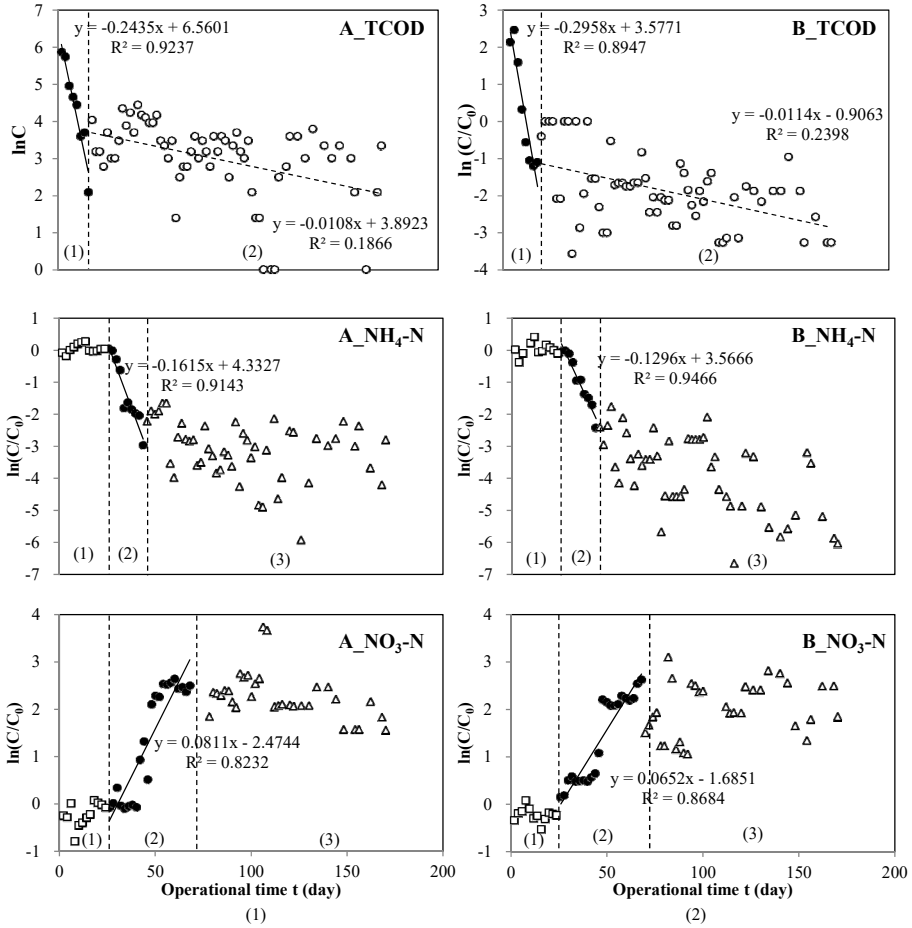


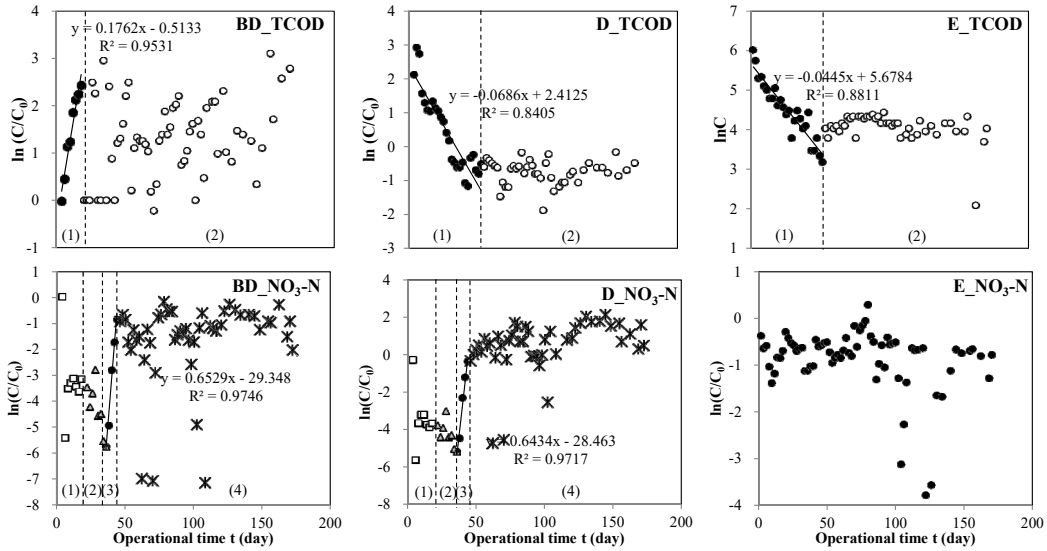
Fig. 8. Variation of remaining percentages or outflow concentrations of TCOD, NH_4-N, and NO_3-N of synthetic fiber biofilters with respect to operational time.

than in the FBF-C system, probably due to the higher ammonia input loading in ASW1 than in SASW. After that, the ammonia removal rates slightly decreased in both biofilters, implying that the nitrification rates tended to reach their maximum rates.

During Phase 3 (45^{th} day ~ end), the outflow TCOD concentration was constantly close to zero. At the same time (18^{th} ~ 66^{th} day), the outflow ammonia concentration decreased with a slightly smaller rate, and nitrate stably accumulated. The nitrate removal rate followed the first order reaction, and was greater in the FBF than in the FBF-C system, corresponding to the variations of the ammonia remaining in both systems. After that, the nitrate removal rate tended to be constant in both biofilters, corresponding to the result that the ammonia tended to be stably removed. In other words, ammonia was effectively removed by both fiber biofilters fed with different inflows, implying that fiber biofilter effectively removes ammonia, in spite of the inflow type. Note that ammonia removal was accompanied by nitrate accumulation, indicating that fiber biofilter only converted ammonia to nitrate.

For woodchip biofilter (Fig. 9), during Phase 1 (start ~ 24^{th} day), the outflow TCOD concentration was higher than the inflow TCOD concentration ($\ln (C/C_0) > 0$), and for both the WBF and WBF-C systems, it decreased with operational time at a constant rate. For the WBF unit (column D) fed with the outflow from C, the TCOD release rate followed the first order reaction from the start to the 16^{th} day, and it was greater in the WBF than in the WBF-C system. This release included both the release from woodchip within the WBF unit, and the continuous input of TCOD from outflow B, which also followed the first order reaction. After that, the removal rate of TCOD was highly variable, until the end of operation. At the same time (start ~ 16^{th} day), the BFS (C-D system) and WBF (column D) systems greatly removed nitrate, indicating that the high outflow TCOD concentration did not impose an adverse effect on the removal of nitrate. Note that during this period, there was no additional input of nitrate from the first step (fiber biofilter).

During Phase 2 (25^{th} ~44^{th} day), the outflow TCOD concentration deceased to a relatively stable level (50~80 mg/L). For the BFS and WBF-C, from the start to the 44^{th} day, the TCOD removal rates followed the first order reaction, and after that they were constant, until the end of operation.



(1) (2) (3)

Fig. 9. Variation of the remaining percentages or outflow concentrations of TCOD and NO_3-N of woodchip biofilters with respect to operational time.

Table 4. Summary of the variation of ln (C/C_0) and ln(C) with respect to operational time

Outflow ID	Pollutant	Operational period (days)				
		2 – 16	18 – 32	34 – 44	46 – 66	68 – 170
Synthetic Fiber	TCOD	$C=C_0e^{0.1762t-0.5133}$ R^2=0.9531	ln (C/C_0) highly variable			
	NO_3-N	ln (C/C_0) constant	slightly decreased	C= $C_0e^{0.6529t-29.348}$ R^2=0.9746		ln (C/C_0) constant
Woodchip	TCOD	C= $C_0e^{-0.0686t+2.4125}$ R^2=0.8405				ln (C/C_0) constant
	NO_3-N	ln (C/C_0) constant	slightly decreased	C= $C_0e^{0.6434t-28.463}$ R^2=0.9717		ln (C/C_0) constant
Synthetic Fiber (Control)	TCOD	$C=e^{-0.2435t+6.5601}$ R^2=0.9237	ln C slowly decreased			
	NH_4-N	ln (C/C_0) = 0	$C=C_0e^{-0.1615t+4.3327}$ R^2=0.9143			ln C slowly decreased
	NO_3-N	ln (C/C_0) = 0	C= $C_0e^{0.0811t-2.4744}$ R^2=0.8232			ln C: constant
Woodchip (Control)	TCOD	$C=e^{-0.0445t+5.6784}$ R^2=0.8405				ln C constant
	NO_3-N	ln C constant				

From the 18th to the 32nd day, the nitrate removal rate slightly decreased. From the 34th to the 44th day, the outflow nitrate concentration increased dramatically at a constant rate, which followed the first order reaction. The nitrate removal rate was slightly greater in the BFS than in the WBF system. After that, the nitrate removal rates were constant, until the end of operation. Note that during this period, there was continuously increasing input of nitrate from the first step. The system tended to be balanced, in terms of microorganism community, carbon source, oxygen concentration, and nitrate concentration. This also explains why the system could remove only limited amounts of nitrate. In the WBF-C system fed with ASW2 from start to end, the nitrate removal rate was constant.

During Phases 3 and 4 (45th ~170th day), the outflow TCOD concentrations of both the WBF and WBF-C systems were almost constant within the range (50~80 mg/L). This indicates that the release of organics turned insignificant but stable, corresponding to the results shown in Table 4, wherein ln(C/C_0) for the BFS system and ln(C) for the WBF-C system were constant. Although the input of nitrate from the first step (the FBF unit, thus column C) was much higher than the nitrate concentration in SASW, the nitrate removed in both the WBF

and WBF-C systems was almost the same, and significant. This indicates that woodchip biofilter effectively removes nitrate, in spite of inflow type. In addition, it took about 44 days for the system to reach maturity. After that, the biofilter was stable in reducing nitrate even though it continuously received an increasing amount of nitrate from the FBF unit. In other words, the BFS system successfully removed TN from the piggery stormwater, with the FBF unit converting ammonia to nitrate, and the WBF unit removing nitrate.

4. Conclusions and Recommendations

Based on the results of this study, the BFS system can effectively treat stormwater from livestock farm regions specifically piggery stormwater. Removal efficiencies based on pollutant concentrations of over 800 samples taken over a period of 176 days showed reductions of COD (98%), total N (50%), NH_4-N (100%), and nitrate (77%). The FBF unit in the BFS system was observed to decrease ammonia from the inflow with elevated amounts of nitrate in the outflow. This was considered as evidence of ammonia being converted to nitrate via active nitrification taking into account that a conducive environment for the process was provided throughout the study period. The succeeding WBF unit which received the nitrate from the FBF was able to reduce it signifying its potential for nitrate and total nitrogen removal via denitrification considering that the woodchip can provide the carbon source required for the process. While these results can still be further justified by additional support through measurements of DO and other factors that can affect the nitrification and denitrification processes, they showcase the potential of VF-VF biolfilter system as an alternative to the typical VF-HF which requires more land area as well as filter materials in comparison. Future studies can focus on the selection of media and a more detailed monitoring of the operational conditions to optimize the performance of the system.

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