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Lab-scale study on recirculated subsurface flow wetlands packed with pumice for the treatment of stormwater from animal feeding-lots

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ABSTRACT

Three lab-scale recirculated vertical subsurface flow (VSF) wetlands (VSF1, VSF2 and VSF3) packed with pumice were constructed to polish the artificial feeding-lots stormwater. VSF1, VSF2 and VSF3 operated with intermittent inflow had the hydraulic retention time (HRT) of 2, 4 and 8 dry d, respectively. The averaged removal efficiencies of total suspended solids (TSS), total chemical oxygen demand (TCOD), total nitrogen, ammonia (NH_4-N) and total phosphorus (TP) were 74%, 72%, 35%, 34% and 63% for VSF1; 78%, 84%, 54%, 70% and 83% for VSF2, and 69%, 88%, 58%, 95% and 91% for VSF3. The removal of TSS was not enhanced by the increase in filtering times. Moreover, the wetland system performed well in removing organic matters whose biodegradable forms were removed almost completely over 4 dry d resulting in the fact that the nitrogen was unable to be removed due to the lack of carbon sources after 4 d. This experiment confirmed that the recirculation had significant enhancement on nitrification. The particle-combined phosphorus was reduced to very low level during 4 dry d; and the removal of dissolved phosphorus was promoted by the increase in HRT. Overall, VSF wetlands achieved stable and attractive performance with HRT of 4 d.

***Keywords**:* Animal feeding-lots; Pumice; Recirculation; Stormwater; Vertical subsurface flow wetlands

1. Introduction

Nowadays, the collection and treatment of stormwater from animal feeding-lots is an important factor in reducing non-point pollution, because stormwater can lead to a series of negative effects on the catchment area, such as changing the environmental health status of water bodies, impacting on aquatic habitats, compromising recreation and esthetic values and stimulating algae to grow uncontrollably [1,2] by increasing the concentration of organic matters, nutrients, etc. [3,4].

Constructed wetlands (CWs) refer to the engineered water saturated areas where the natural pollutant removal processes occur [5]. As the alternatives to conventional treatment units, CWs have been widely used due to their moderate capital cost, easy operating management and effective removal performance [6,7]. As an important type of CWs, vertical subsurface flow (VSF) wetlands can transport more oxygen than the horizontal flow ones [8], resulting in more effective reduction in organic matters and NH_4-N [9]. At present, VSF wetlands have been employed to reduce the pollutants in stormwater runoff in many countries [10,11].

The treatment performance of VSF wetlands is governed by water depth, substrates, hydraulic retention time (HRT) and hydraulic loading rate (HLR). The substrate should not

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only be cheap but also have a high porosity to decrease the probability of clogging. Commonly, gravels, a kind of mineral aggregates, are the media of choice in wetland beds [8]. In addition, other available materials, such as woodchips and construction wastes, are being tested as wetland media. In this study, pumice, which are inorganic and porous, were used as a wetland substrate.

Recirculation is very common in water and wastewater treatment plants because it can significantly improve the effluent water quality. To improve the polishing performance of VSF wetlands, recirculation has been employed in some cases. Prost-Boucle and Molle [12] demonstrated that nitrification in VSF wetlands is controlled remarkably by the recirculation rate. Sun et al. [13] identified that the removal efficiency of NH_4-N was increased by about 50% as effluent recirculation was operated. However, the use of recirculation in the VSF wetlands treating stormwater is rare. In this study, internal recirculation was employed on dry days to enhance the removal of organic matters and NH_4-N both via increasing the contact time between stormwater and the media and providing more oxygen for the internal bed of wetlands [14].

This study is carried out to evaluate the feasibility of pumice as VSF wetlands substrate to control the stormwater pollution from animal feeding-lots. The specific aim was to understand the efficacy and stability of the system performance in terms of removing solids, organic carbon, nitrogen and phosphorus from the animal feeding-lots stormwater when internal recirculation was employed over dry days.

2. Materials and methods

2.1. Design of the VSF wetland system

A lab-scale VSF wetland rig comprising three identical column beds, namely VSF1, VSF2 and VSF3, which were packed with pumice, was constructed for the treatment of artificial feeding-lots stormwater. Pumice is widely used in horticulture and gardening. The column with a length of 100 cm and an internal diameter of 10 cm was made of opaque acryl. The configuration of wetland system is shown in Fig. 1 and the characteristics of media are summarized in Table 1. The wetland system is very small in comparison with the large-scale. However, the previous study based on the similar column wetlands has been fully accepted by the scientific community [15]. In order to avoid the clogging, the bottom part was not packed with any media, and plant support soil was not used in the top layer where *Acorus calamus* was planted. As to pumice, the D_{10}, D_{50} and D_{60} were 1.0, 1.2 and 1.3 cm, respectively, with a uniformity coefficient of 1.3, and a specific area of 29.55 $m^2 g^{-1}$.

2.2. Operation of the VSF wetlands

For a long-term experiment, the natural feeding-lot stormwater was usually unavailable. Therefore, the artificial feeding-lot stormwater, which was made by mixing the piggery slurry with tap water, with the concentrations of 19–68 mg/L for total suspended solids (TSS), 57–141 mg/L for total chemical oxygen demand (TCOD), 11.54–24.92 mg/L for TN and 0.45–2.82 mg/L for total phosphorus (TP) was employed. The water quality of feeding-lot stormwater varies greatly depending on the rainfall condition, the scale of the livestock farm, etc. Thus, there is no clear process to determine the correct range of concentrations to apply to such a test. Though the concentration of the stormwater in this study is not excessively high, it is appropriate, based on previously reported data [16,17].

Because the stormwater inflow takes place only during wet days and it may be stored in the wetland until the stormwater event occurs again, the batch operation for wetlands was employed. VSF1, VSF2 and VSF3 were operated with retention time as 2, 4 and 8 d to simulate the common dry

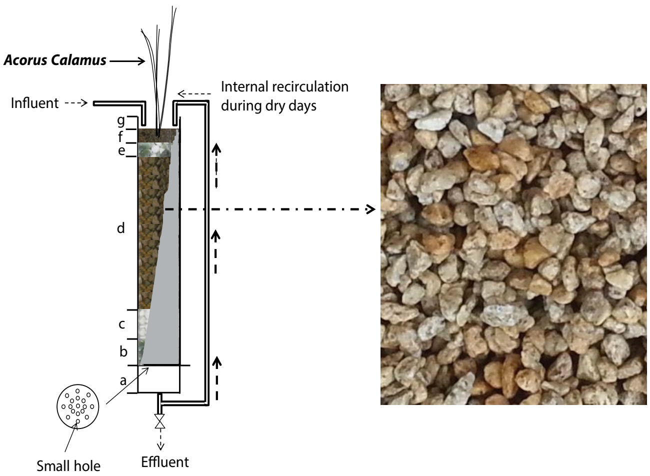

Fig. 1. Schematic diagram of VSF wetlands.

Table 1
Physical characteristics of the media used in the wetlands

Layer	Height (cm)	Substrate	Width (cm)	Height (cm)	Length (cm)	Volume (cm^3)	Porosity (%)
a	0–10 (bottom)	–	–	–	–	–	100
b	10–20	Quartz	1.9–3.1	2.0–5.0	0.8–1.9	5.8–15.6	41
c	20–30	Quartz	1.4–2.4	1.7–3.6	0.6–1.7	1.7–11.0	40
d	30–85	Pumice	0.7–1.8	1.0–2.3	0.5–1.3	0.5–4.9	51
e	85–90	Quartz	1.9–3.1	2.0–5.0	0.8–1.9	5.8–15.6	41
f	90–95	Vermiculite	4.8–5.5 mm in diameter				45
g	95–100 (top)	–	–	–	–	–	100

days in Korea, respectively. 2.1 L stormwater, determined based on the porosity of wetland bed, was fed into each wetland by the natural gravity within 1.5 min resulting in the instant HLR as ~257 m/d. And during dry days, the stormwater in wetlands was recirculated once per 24 h by employing a drain-and-fill mode. This operation provides aeration of the wetland substrates and exposes the internal biofilms to atmospheric oxygen [8]. During 136 operational d, VSF1, VSF2 and VSF3 were operated 68, 34 and 17 test runs, respectively.

2.3. Water quality analysis

Temperature, pH, electrical conductivity, TSS, TCOD, soluble chemical oxygen demand (SCOD), TN, total Kjeldahl nitrogen (TKN), dissolved total nitrogen (DTN), TP, dissolved total phosphorus (DTP), NH_4-N and NO_3-N were measured using the method from APHA et al. [18].

The removal efficiency (100%) was calculated as the difference between the influent and effluent concentrations divided by the influent concentration, and multiplied by 100. P_N (the percentage of specific N form occupying the TN) was calculated based on:

$$P_N(\%) = \frac{C_N}{C_{\mathrm{TN}}} \times 100$$

where C_N is the concentration of specific nitrogen form.

The removal rate was obtained by the difference between the influent and effluent concentrations multiplied by stormwater volume, and divided by the area of wetland and retention time.

2.4. Data evaluation

Statistical analysis on data was performed to estimate the treatment performance of the system by employing the analysis of variance (ANOVA) and the Pearson's correlation analysis with the help of SPSS (version 18.0 for windows).

3. Results and discussion

3.1. Particulate solids removal

The comparison of the TSS concentrations in the influent and effluent is shown in Fig. 2. As shown, the ripening stage occurred during the first several events; then the VSF wetlands performed well in intercepting TSS; thereafter, the effluent TSS concentrations increased a little due to the wash-out of some particles. The particles in the effluent of the wetlands comprised non-trapped solids in the influent, detached biofilms and plant litters [19].

The results show that the VSF wetland system was capable of removing solid particles, and the outlet concentration did not vary remarkably with the change in inlet concentration ($p > 0.05$). On average, the influent TSS was reduced to 11 mg/L by 74% for VSF1, to 9 mg/L by 78% for VSF2, and to 12 mg/L by 69% for VSF3 (Table 2). However, there was no significant difference for the effluent TSS concentrations between the three wetland systems ($p = 0.578$), suggesting that particle removal

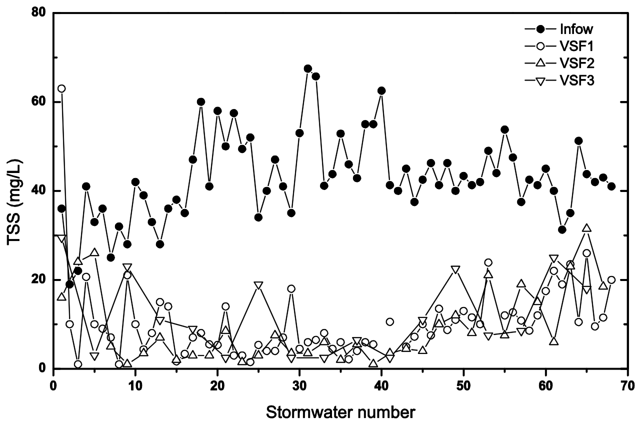

Fig. 2. Comparison of the TSS concentrations in the influent and effluent.

Table 2
Summary of the influent and the effluent water qualities

Item	VSF1			VSF2			VSF3		
	Influent (mg/L)	Effluent (mg/L)	Removal (%)	Influent (mg/L)	Effluent (mg/L)	Removal (%)	Influent (mg/L)	Effluent (mg/L)	Removal (%)
TSS	43 ± 9	11 ± 9	74	41 ± 9	9 ± 8	78	39 ± 6	12 ± 9	69
TCOD	97 ± 23	27 ± 10	72	110 ± 21	18 ± 8	84	123 ± 12	15 ± 6	88
SCOD	38 ± 19	18 ± 9	53	49 ± 18	13 ± 6	73	60 ± 5	11 ± 6	82
PCOD	59 ± 13	10 ± 7	83	60 ± 11	6 ± 8	90	64 ± 10	4 ± 3	94
TN	17.7 ± 3.1	11.5 ± 2.4	35	18.2 ± 2.9	8.3 ± 3.3	54	19.4 ± 2.5	8.2 ± 3.8	58
DTN	14.5 ± 2.8	10.2 ± 2.1	30	15.3 ± 2.8	7.6 ± 2.9	50	17.0 ± 2.5	7.5 ± 3.9	56
PTN	3.1 ± 1.5	1.3 ± 1.4	58	2.9 ± 1.4	0.71 ± 1.41	76	2.4 ± 0.7	0.7 ± 0.7	71
NH_4-N	9.40 ± 1.69	6.19 ± 1.60	34	9.46 ± 2.03	2.86 ± 1.29	70	9.82 ± 2.40	0.51 ± 1.04	95
NO_3-N	1.41 ± 1.05	0.62 ± 0.30	56	2.03 ± 1.14	0.86 ± 0.88	58	2.64 ± 1.07	3.20 ± 2.12	-21
TP	2.02 ± 0.57	0.74 ± 0.32	63	2.05 ± 0.61	0.34 ± 0.15	83	2.06 ± 0.65	0.19 ± 0.08	91
DTP	1.35 ± 0.50	0.53 ± 0.24	61	1.44 ± 0.52	0.28 ± 0.12	81	1.54 ± 0.49	0.14 ± 0.05	91
PTP	0.67 ± 0.26	0.21 ± 0.14	69	0.61 ± 0.23	0.06 ± 0.13	92	0.52 ± 0.18	0.05 ± 0.08	94

was not likely to be enhanced by recirculation. Hence, when the stormwater went through the filter twice (in VSF1), the bulk of the particles had been captured and recirculation had not contributed to an additional removal as was the case in VSF2 and VSF3. Usually, in VSF wetlands, deposition and filtration are the dominant mechanisms of TSS removal, especially in the place close to the surface of wetland bed [8]. And Hua et al. [20] demonstrated that 80%–90% removed solid particles appeared in the surficial 6 cm of the bed for VSF wetlands. As to our study, it was also observed that particle solids were mainly accumulated in the surface layer. Thus, the long-term operation might bring about clogging in wetland systems. However, clogging was not observed during the experimental stage.

3.2. Organic matters removal

In wetland systems, organic compounds are mainly removed via aerobic or anaerobic biodegradation, which is affected by factors influencing on the transmission of oxygen from the air to the wetland beds. And the particulate organic matters can also be physically removed with the deposition and filtration of particles [21].

As shown in Fig. 3(a), the effluent TCOD concentrations in the study period varied between 8 and 53 mg/L for VSF1, between 7 and 43 mg/L for VSF2 and between 7 and 29 mg/L for VSF3, wherein the corresponding average removal efficiencies were 72%, 84% and 88%, respectively. Though the performance increased with increasing retention time, no significant difference in effluent TCOD concentrations between VSF2 and VSF3 was observed ($p > 0.10$). Thus, it is believed that the biodegradable organic matters had been almost removed completely over 4 dry d. On average, the influent SCOD was reduced from 38 ± 19 mg/L to 18 ± 9 mg/L, 49 ± 18 mg/L to 13 ± 6 mg/L, and 60 ± 5 mg/L to 11 ± 6 mg/L in VSF1, VSF2 and VSF3, respectively. In this regard, the removal of SCOD contributed to the TCOD removal by 29% for VSF1, 39% for VSF2 and 45% for VSF3. Therefore, the removal of organic matters was also dependent on the filtration of the particulate forms, which occupied a major part of the TCOD. The proportion of the particle COD removed to the total COD removed was 70% for VSF1, 61% for VSF2 and 55% for VSF3.

The effect of the influent TCOD concentration on the performance of the wetland system in reducing organic matters is investigated and is shown in Fig. 4(a). The amount of removed COD was proportional to the influent concentration ($p < 0.001$). Also, the mass of removed organic matters significantly increased as dry days increased ($p < 0.001$), which indicates that wetland treatment systems constructed with pumice have the capacity of reducing organics as an increase in HRT.

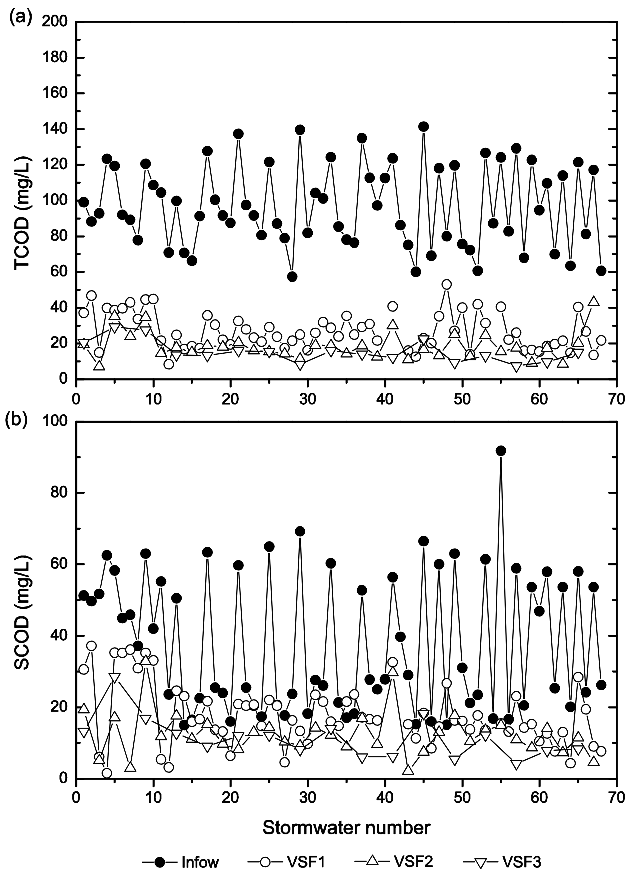

Fig. 3. Comparison of the COD concentrations in the influent and effluent (a) TCOD; (b) SCOD.

3.3. Nitrogen conversion

The influent nitrogen took place with NH_4-N (53%), followed by organic nitrogen (Org.-N [TKN deducted by NH_4-N], 39%) and a small proportion of NO_3-N. However, the effluent nitrogen composition varied obviously among wetlands.

The nitrogen in the effluent of VSF1 was still dominated by NH_4-N (54%) with less Org.-N (41%) and NO_3-N (5%). In the case of VSF2, nitrogen consisted of 34% NH_4-N, 55% Org.-N and 10% NO_3-N. While the effluent of VSF3 mainly comprised Org.-N (55%) and NO_3-N (39%). It is concluded that nitrogen species in the effluent was affected by the number of dry days, which was related to the treatment time in the wetland systems.

The elimination of TN is summarized in Fig. 5(a). It was observed that the effluent concentrations varied with the influent concentration, indicating that the performance was affected by the influent nitrogen strength. The averaged TN concentrations in the influent and effluent were 17.7 and 11.5 mg/L for VSF1, 18.2 and 8.3 mg/L for VSF2, and 19.4 and 8.2 mg/L for VSF3. Overall, the TN in the influent was reduced by 35% in VSF1, by 54% in VSF2 and by 58% in VSF3. The elimination of nitrogen was greatly dependent on the sink of soluble forms (DTN), which accounted for over 80% of TN. The removed DTN accounted for 69% of removed nitrogen in VSF1, 78% in VSF2 and 85% in VSF3, respectively.

There was no significant difference in the effluent TN concentrations between VSF2 and VSF3 ($p > 0.05$), thus it can be concluded that no additional TN was removed further as dry days were increased from 4 to 8 d, which was most likely attributed to the lack of available carbon sources for denitrification, since the effluent COD contents in VSF2 and VSF3 were similar.

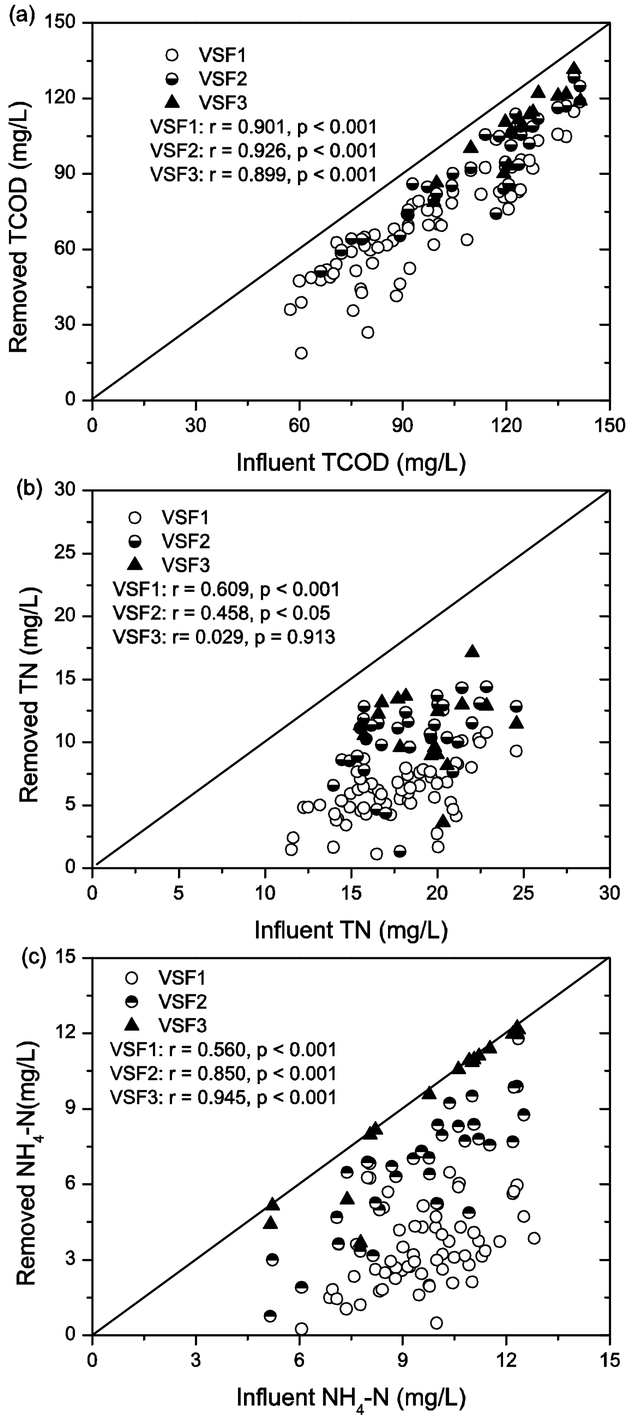

Fig. 4. Effect of influent concentrations on performance (a) TCOD; (b) TN; (c) NH_4-N.

The relationship between the removed TN concentration and the influent TN concentration was pursued. As shown in Fig. 4(b), in VSF1 and VSF2, the mass of removed TN was greatly affected by the influent TN concentration ($p < 0.05$); however, in VSF3 the removed TN concentration did not increase with the increase in the influent TN concentration ($p = 0.913$), also suggesting that denitrification was suppressed. Consistently, NO_3-N appeared to be accumulative in the effluent of VSF3 (Fig. 5(c)). In this study, it was due to the lack of carbon sources for denitrification after 4 dry d. The result demonstrates that the removal of organics affected the nitrogen reduction significantly ($r = 0.621$, $p < 0.001$).

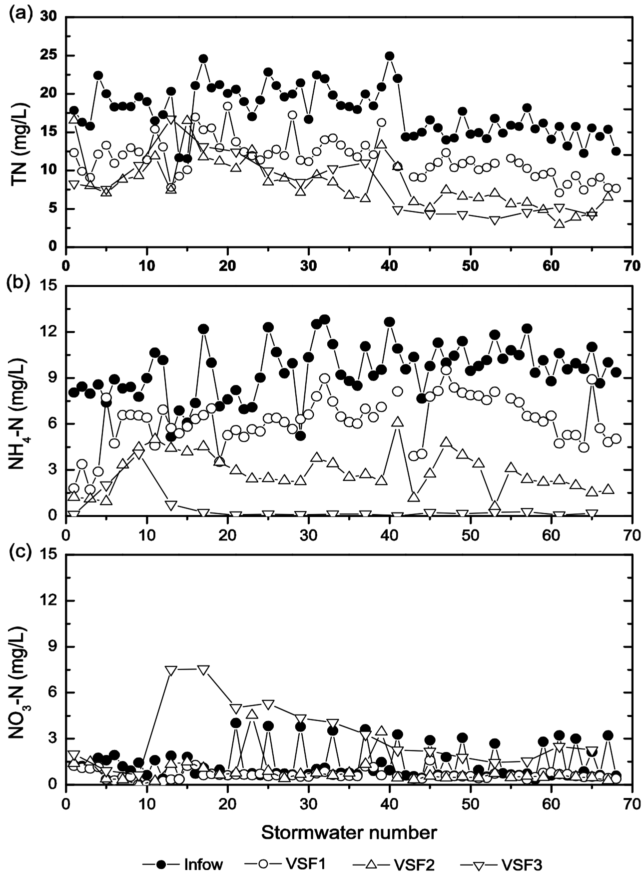

Fig. 5. Comparison of the TN, NH_4-N and NO_3-N concentrations in the influent and effluent (a) TN; (b) NH_4-N; (c) NO_3-N.

Fig. 5(b) shows the change of NH_4-N concentration in the wetland systems. On average, the influent NH_4-N was reduced by 34% (from 9.40 to 6.19 mg/L), by 70% (from 9.46 to 2.86 mg/L) and by 95% (from 9.82 to 0.51 mg/L) in VSF1, VSF2 and VSF3, respectively. Recirculation did not only increase the contact time between the contaminants and micro-organisms but also supply more oxygen which benefited the removal of organic matters and NH_4-N. In addition, the amount of removed NH_4-N was increased significantly as the influent NH_4-N concentration increased ($p < 0.001$), which means that the recirculated VSF wetland system had a favorable performance in nitrification.

Nitrogen removal can be achieved by denitrification, ammonia volatilization, substrate sorption, micro-immobilization, dissimilatory NO_3^- reduction to NH_4^+ (DNRA), anammox or plant uptake [8,22]. In the studied VSF wetland system, nitrogen was most likely eliminated by denitrification, because when the biodegradable organic matters were deficient, nitrogen could not be further reduced and NO_3-N started to accumulate in the effluent. Moreover, pH values were always below 8.0, and thus, the volatilization of NH_3 from wetlands to air happened impossibly. Nitrogen might be sorbed by the materials packed in wetlands. However, this mechanism should not be a significant sink for nitrogen. Immobilization might be another important pathway until the microbial population was stabilized; but this could not account for the long-term removal of nitrogen. It seemed unlikely that DNRA was a mechanism for NO_3^- as no accumulation of NH_4-N was observed. Anammox was also not a pathway for nitrogen removal because anammox microbes could not establish an active population in 136 d [23,24].

3.4. Phosphorus retention

In wetland system, phosphorus can be removed via adsorption, complexation and precipitation as well as plant uptake and microbial immobilization [25,26]. Generally, the removal of phosphorus varies greatly depending on the media [19,27]. A number of studies [28,29] have shown that phosphorus removal may be enhanced by the use of those materials which contain higher content of calcium, aluminum, and iron, such as limestone, wollastonite, gravel, etc.

As shown in Fig. 6, the studied wetlands appeared to have a high capability of eliminating phosphorus, including both dissolved and particulate forms. The TP in the influent was reduced by an average of 63% (to 0.74 mg/L) in VSF1, 83% (to 0.34 mg/L) in VSF2, and 91% (to 0.14 mg/L) in VSF3. The averaged effluent DTP was 0.53, 0.28 and 0.14 mg/L from VSF1, VSF2 and VSF3, respectively; and the effluent particulate total phosphorus (PTP) averaged at 0.21, 0.06 and 0.05 mg/L from VSF1, VSF2 and VSF3, respectively. This result shows that the increase in retention time benefited the removal of phosphorus. However, Vohla et al. [29] concluded that it was impossible to give any definite correlation between retention time and phosphorus retention based on the studies available.

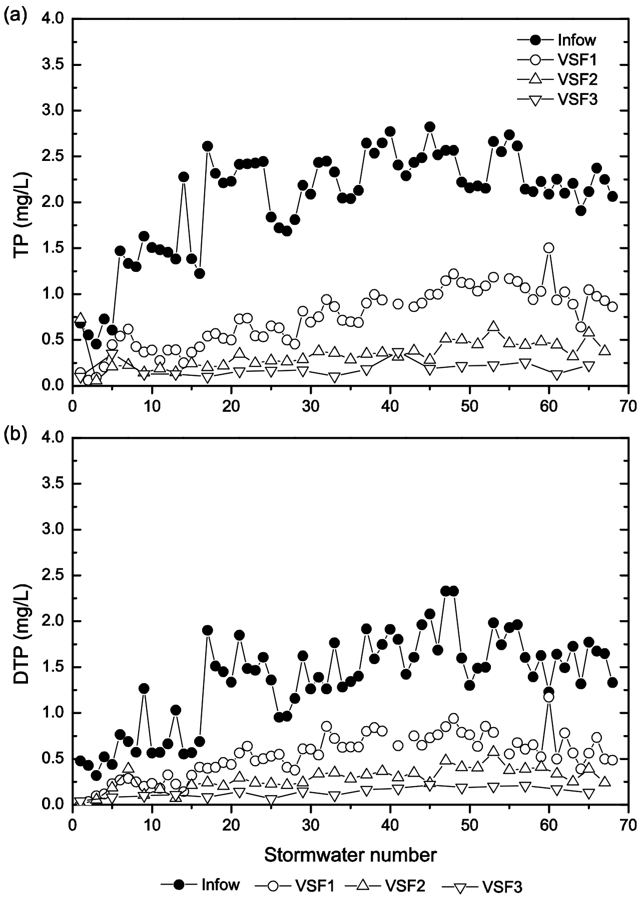

Fig. 6. Comparison of the phosphorus concentrations in the influent and effluent (a) TP; (b) DTP.

Table 3
Removal rates of TCOD, TN, NH_4-N and TP in three wetlands

Wetland	TCOD ($g\ m^{-2}\ d^{-1}$)	TN ($g\ m^{-2}\ d^{-1}$)	NH_4-N ($g\ m^{-2}\ d^{-1}$)	TP ($g\ m^{-2}\ d^{-1}$)
VSF1 (2 dry d)	9.33 ± 2.92	0.82 ± 0.31	0.43 ± 0.23	0.17 ± 0.05
VSF2 (4 dry d)	12.22 ± 2.62	1.32 ± 0.52	0.88 ± 0.32	0.23 ± 0.08
VSF3 (8 dry d)	3.61 ± 0.46	0.37 ± 0.10	0.31 ± 0.10	0.06 ± 0.02

Though biological assimilation and uptake by plants can play an important role in the sink of phosphorus [19], the phosphorus entering subsurface flow wetlands is mainly sorbed or precipitated, depending on the physical–chemical and hydrological properties of filter materials in wetlands [29]. Hence, the removal of phosphorus from wetlands is an unsustainable process over the long-term [30,31]. In our study, the phosphorus retention capacity did not appear to decrease, suggesting that the phosphorus sorption of pumice remained unsaturated throughout the experimental period. The saturated phosphorus sorption capacity of pumice should be determined in a further study.

3.5. Removal rate during the period of dry days

Removal rate is an important parameter in terms of estimating treatment performance. Usually, it can be calculated based on the wetland area or wetland substrate volume. In this study, the area-based removal rates of TCOD, TN, NH_4-N and TP are investigated and summarized in Table 3. As might be expected, it was observed that the removal rates over 8 dry d were lower than that over 4 dry d, which indicates that there is probably an optimum retention time at which the removal rate is the highest, and this should be determined through further study.

In the study by Langergraber et al. [32], the removal rates in VSF wetlands were 16.48 $g\ m^{-2}\ d^{-1}$ for COD, 1.99 $g\ m^{-2}\ d^{-1}$for NH_4-N and 0.92 $g\ m^{-2}\ d^{-1}$ for TN. It means that the removal rates in this study are lower, which might be attributed to the lower loading rates, as which are usually positively correlated to loading rate [33].

4. Conclusions

The pumice VSF wetlands proved to be effective in removing the suspended solids, organic matters, nitrogen and phosphorus from animal feeding-lot stormwater; and they could give a great reduction to the pollutants concentrations within a period of 4 dry d. Solid particles were mainly captured in the surface of the wetland bed and the removal efficiency was not enhanced by the increase in the number of filtering times via recirculation. The mechanisms of organics removal were the biodegradation for soluble forms and the filtration for the particle forms. The sink of nitrogen was mainly due to the denitrification process; however, the denitrification was limited by the deficiency of organic matters when the retention time was more than 4 d. The application of internal recirculation exerted a significantly positive effect on the biodegradation of organic matter as well as on nitrification. The optimal removal rates for organics and nutrients occurred at a medium retention time which should be determined by further experiment. Stable and effective pollutant removal performances indicate that the potential application of VSF wetland systems packed with pumice to treat stormwater arising from animal feeding-lots. However, before this wetland system is put into the practice of industrial use, the following pilot-scale and field study should be conducted to find out the optimum operation and the lifespan in terms of clogging as well as pollutants reduction.

Acknowledgments

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Symbols

PN — Percentage of specific form nitrogen occupying the total nitrogen, %
CN — Concentration of specific form nitrogen, mg/L
CTN — Concentration of total nitrogen, mg/L

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