Nitrogen Removal in Column Wetlands Packed with Synthetic Fiber
Treating Piggery Stormwater
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Abstract
A set of lab-scale polymer synthetic fiber packed column wetlands composing three columns (CW1, CW2 and CW3) with different hydraulic regimes, recirculation frequencies and pollutant loading rates, were operated in 2012. Synthetic fiber tested as an alternative wetland medium for soil mixture or gravel which has been widely used, has very high pore size and volume, so that clogging opportunity can be greatly avoided. The inflow to the wetland was artificial stormwater. All the wetlands achieved effective removal of TSS (94%~96%), TCOD (68%~73%), TN (35%~58%), TKN (62%~73%) and NH4-N (85%~99%). Particularly, it was observed that COD was released from the fiber during one distinct period in all wetlands. This was probably due to the degradation of polymer fiber, and the released organic matters were found to serve as carbon source for denitrification. In addition, with longer retention time and frequent recirculation, lower effluent concentration was observed. With higher pollutant loading rate, higher nitrification and denitrification rates were achieved. However, although organic matters were released from the fiber, the lack of carbon source was still the limiting factor for the system since the release persisted only for 40 days.

Key words: column wetland, denitrification, nitrification, piggery stormwater, synthetic fiber

1. Introduction

In Korea, piggery waste pollution (Rico et al., 2012; Borin et al., 2013) has been specifically controlled by government regulations (Korea Ministry of Environment(KME), 2004) based on environmental protection law. However, contamination prevention of piggery stormwater is of vital difficulty due to the dispersibility and uncertainty of the occurrence and the pollution source. Piggery stormwater has attracted more and more attention, since it contains high concentration of nutrients (e.g. nitrogen, phosphorus and organic matters), toxic substances (e.g. ammonia, nitrate and toxic organics) and risky pathogens and bacterial. It pollutes rivers and seas (Al-Hafedh et al., 2003; Mearns et al., 2013) when it enters natural water systems.

BMP (Best management practice) facilities such as constructed
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2. Materials and Methods

2.1 Experimental system

A set of lab-scale wetlands composed of three columns (CW1, CW2 and CW3), which were made of black light-proof acrylic, was set up (Fig.1 (a)).

Fig. 1 (b) shows the fiber purchased from the manufacturer. Fig. 1 (c) shows the fiber photomicrograph. 37cm fiber was cut off from the fiber roll and rolled up into tight donut with the same diameter of the column to supply larger surface area for biofilm growth and easy placement into the columns (Fig. 1 (b) and (d)). 36 fiber donuts were put into each column, so that the total length of the fiber in each column was 20 m, which corresponds to a surface area of 30m² (based on the specific surface area of 1.5m²·m⁻¹ provided by the manufacturer).

In addition, a vermiculite layer was placed instead of soil at the top of the wetland for plant growth and uniform flow distribution and a quartz stone layer at the bottom for the drain. The properties of all the packing materials in the wetlands are given in Table 1.

Artificial piggery stormwater was prepared as an inflow by mixing 60mL piggery wastewater from a livestock farm with 20L tap water, giving the influent COD concentration around 100 mg/L.

Table 1. Properties of the packing material employed in column wetlands.

| Media           | Diameter (cm) | \(d_{10}\) (cm) | \(d_{50}\) (cm) | \(d_{60}\) (cm) | U   | Porosity (%) | BD (kg·m⁻³) | SSA (m²·m⁻¹) |
|-----------------|---------------|-----------------|-----------------|-----------------|-----|---------------|--------------|--------------|
| Synthetic fiber | 4.5           | -               | -               | -               | ≈1.0| 89            | 120          | 1.5          |
| Vermiculite     | 0.48–0.55     | -               | -               | -               | -   | 55            | 482          |              |
| Quartz stone    | 2.2–5.2       | 2.28            | 2.51            | 2.6             | 1.13| 40            | 1706         |              |

U, uniformity coefficient; BD, bulk density; SSA, specific surface area; - , not measured

Fig. 1. (a) schematic diagram of the column wetland (b) fiber from the manufacturer (c) fiber photomicrograph (d) fiber donuts (e) lab-scale column wetlands.

wetlands, infiltration strips and biofilters have been widely used to treat different types of non-point source pollution (Vymazal, 2005; Aslan and Simsek, 2012; Adrados et al., 2014). Among them, vertical flow (VF) wetlands have many advantages such as low space requirement, good treatment, low cost, energy-effective, stable biofilm attachment, and natural oxygen supply by feeding, recirculation and discharge assuring active nitrification (Vymazal, 2007; Saeed and Sun, 2011; Borin et al., 2013; Zinger et al., 2013).

In VF wetland, one of the most important components is the packing material (Kyzas et al., 2015). A packing material with high porosity, large specific surface area and high void content (Kyzas et al., 2015) allows more bio-film adhesion thus retention of more biomass, more contact chances between pollutants and biofilms and also more solid accommodation, which is able to extend the longevity prone to clogging. Conventional packing materials such as gravel, quartz stone and volcanic stone with high availability have been widely utilized. However, their high loads increase transportation expenses and disposal costs of exhausted media during post-treatment (Cai et al., 2014). Organic substrates such as woodchips which were light and easily available have been hotly studied over recent years (Chun et al., 2010; Cameron and Schipper, 2012). However, the impact of the release of nitrogen and organic matters is still questionable (Healy et al., 2012).

Synthetic fiber made from polymers including polypropylene (PP), polyethylene (PE), polyurethane (PU) and polyester (PA) is widely employed as a physical filter substrate because of its good mechanical properties, strong chemical resistance, high thermal stability, high porosity, great specific surface area and low density in rapid filtration processes (Ahammad et al., 2013). It can also be utilized as colonization medium for biofilm (Jurecska et al. 2013). Jurecska et al. (2013) noticed that microorganisms can attach onto the surface if the polymer surface is hydrophilic. On the other hand, it is found that these polymers are susceptible to bacteria and fungi (Loredo-Treviño et al., 2012).

This study used a type of synthetic fiber made from PE, PP and PA having a high specific surface area and high porosity as the main packing material in lab-scale column wetlands. This paper investigated the performance of nitrogen removal in polymer fiber packed column wetlands.
2.2 Operation and sample collection

The operation was designed based on the hypothetical occurrence of rainfall event. Then internal recirculation in the column wetland was carried out once a day until the next rainfall occurs.

The pollutant loading varies significantly due to different rainfall characteristics. In this study, there were three replicate column wetlands simulating different hydraulic retention time (HRT), recirculation frequencies and pollutant loading rates. Operational parameters are given in Table 3. The HRT is the same parameter as number of the antecedent dry days (ADD) because inflow to the wetland occurred only at the time of rainfall activity. 2.1 L of piggery stormwater was fed to each column wetland within 96 seconds, corresponding to an instant hydraulic loading rate of 240 m/day. Sampling was carried out every 2, 4, and 8 days at the effluent of column wetland, respectively. The wetland was operated for 300 days from February to December in 2012.

2.3 Water quality analysis

Basic water quality parameters including temperature, turbidity, pH, electric conductivity (EC), and dissolved oxygen (DO) were measured in situ. Total suspended solids (TSS), total nitrogen (TN), ammonia (NH₄-N), total Kjeldahl nitrogen (TKN), nitrate (NO₃-N), total chemical oxygen demand (TCOD) and soluble chemical oxygen demand (SCOD) were analyzed according to the Standard Methods for the Examination of Water and Wastewater, 21st Edition (APHA et al., 2005). In addition, the bivariate relationship between water parameters was examined using the Pearson correlation coefficient (r) by SPSS (version 19.0).

3. Results and Discussion

3.1 TSS and turbidity

Fig. 2 shows that the effluent TSS and turbidity was much lower than the influent and the removal efficiency almost reached 100% and sustained until the end of the operation. All the column wetlands showed consistent and stable
removal. This result supports that in spite of extremely high porosity (about 90%), synthetic fiber is a great filter medium.

### 3.2 Removal and release of organic matters

Fig. 3 shows the variation of the influent and effluent concentrations of TCOD and SCOD with respect to wetland operational time. The black line denotes the effluent concentration and the area filled with grey shadow is indicative of the release or reduction of organic matters in the wetland. The effluent concentration was much lower than influent except for a distinct period when organic matter was released from the fiber. Release of organic matter was observed in all the column wetlands. However, according to the data in Fig. 3, the beginning of release was retarded with the decrease of COD loading rate. In addition, the amount of the organic matters released increased as internal recirculation increased.

In spite of the release of organic matters in a distinct period lasting for about 40 days, the overall removal of TCOD was fairly good. The average removal efficiency were 69, 75 and 76%, and the mean effluent TCOD concentration was 34, 30 and 30 mg/L, respectively. SCOD shows the similar result with TCOD concentration, indicating that the released organic matter was mostly soluble. However, it should be noted that both TCOD and SCOD concentrations in the effluent were very low before the release started, indicating that the wetland was almost in the lack of carbon source due to the complete removal of organic matters.

Usually, polymers are known to be resistant to microbial degradation. However, they are susceptible to fungi and bacteria (Loredo-Treviño et al., 2012). The bacteria enzymes can recognize some region of the polymer and hydrolyze (Loredo-Treviño et al., 2012). The inflow piggery stormwater was prepared by diluting the piggery wastewater from a livestock farm with tap water. Piggery wastewater contains various kinds of bacteria including those which could degrade polymers (Arkatkar et al., 2009).

When piggery stormwater carrying abundant bacteria flow through the synthetic fiber wetland, the bacteria could colonize on the surface of fiber donuts. Consequently, these colonized bacteria degraded the fiber cell, which resulted in release of the organic matters.

Many studies reported that the biodegradation of the polymer fiber was related with the species and quantities of bacteria (Cacciari et al. 1993). Orhan and Buyukgungor (2000) studied the biodegradability of polyethylene films in soil and found that the soil with higher microbial enrichment showed higher degradability capacity of polyethylene films. However, in our previous study, the same fiber was used to treat urban stormwater but no indication of the release of organic matters was observed, which may be due to the low microbial population in the urban stormwater (Chen et al., 2013).

### 3.3 Type of Nitrogen

**Total nitrogen (TN).** Fig. 4 shows that the TN removal was all poor during the initial period (prior to release) in all three column wetlands. Then, significant removal (maximum 80%) was obtained, and it was increased in the wetland having a longer HRT and more frequent recirculation. However, high removal was not maintained, and it gradually decreased.

The TN removal was probably affected by two factors: carbon source and temperature. Nitrification converts ammonia to nitrate, and denitrification then converts nitrate to nitrogen gas. Since COD was not sufficient, initially TN removal was poor. According to the data in Figs. 3 and 4, the release of organic matters from the fiber contributed to serve as the carbon source to derive denitrification. Many organic substrates have
Fig. 4. TN removal efficiency versus operational time.

been proved to serve as the carbon source (Blowes et al., 1994; Wang et al., 2010; Saeed and Sun, 2011; Ruane et al., 2012).

However, this release persisted only for 40 days. For a short-time operation, the high mean concentration of effluent COD is unavoidable. For a long-time operation, the release would not affect the overall removal. In this study, the lack of carbon source for denitrification restricted nitrogen removal, in which case the released COD became a supplement of carbon.

Ammonia (NH₄⁻N) and total Kjeldahl nitrogen (TKN).

Fig. 5 shows the removal efficiency of NH₄⁻N and TKN. The ammonia nitrogen occupied the major fraction of the total nitrogen in the inflow (about 60% on average). At the initial period, the removal increased gradually over 80%, and then it was sustained. The mean removal was 85, 98 and 99% in three wetlands, respectively. TKN also shows similar changes with NH₄⁻N. The removal of both NH₄⁻N and TKN increased with the increase of HRTs and recirculation.

The reduction of NH₄⁻N or TKN usually represents a portion of nitrification. The active nitrification is probably caused by three reasons. First, the fiber has a great specific surface area, which provided more growth sites for nitrifiers (Jurecska et al., 2013). Second, the amide group at the end of atomic structure makes it negative that microorganism can attach onto the media easily (http://www.sinkanghitec.co.kr/).

In addition, high porosity in fiber-packed wetland gives greater void volume for the accommodation of solid and biomass.

Furthermore, longer retention time and more frequent recirculation provided more contact chances between TKN and nitrifiers. The recirculation during dry days makes the most use of the stormwater facility, extending retention time and enhancing pollutant removal.

Nitrate (NO₃⁻N). Fig. 6 (a) shows the nitrate concentration with respect to operational time. Influent NO₃⁻N concentration was lower than 5 mg/L throughout the entire operational period and the effluent concentration was mostly higher than influent.

The variation of nitrate concentration can be divided into four periods. (a) acclimatization period when nitrate concentration increased continuously; (b) a distinct period which overlapped the COD release period and nitrate concentration decreased significantly; (c) nitrate concentration stayed low stably; (d) nitrate concentration increased and water temperature decreased at the same time (Fig. 6 (b)). It implies that the nitrate concentration during period (b) was affected by the COD released whereas the nitrate concentration during period (d) was more affected by the water temperature.

3.4 Influencing factors on nitrogen removal

Effect of carbon source and temperature. Because significant amount of ammonia was converted to nitrate in column wetlands, large amount of organic carbon was needed to denitrify nitrate. However, organic matters were
almost removed, thus the available carbon source was presumably insufficient, leading to the accumulation of nitrate in the effluent. Fig. 7 illustrates that higher TCOD concentration was significantly related to lower TN concentration (p < 0.001) in the effluent. Since the inflow TCOD concentration was maintained around 100 mg/L, the released organic matters during the distinct period must have been served as the carbon source. This result is consistent with the result that period (b) overlapped the COD release period. Although carbon source was a more affecting factor during period (b), since the water temperature during period (b) was also within the range that denitrification could proceed, temperature was also an important factor.

Effect of pollutant loading rate, recirculation frequency and retention time. Table 4 shows that better removal was obtained in CW2 than CW1, whereas no significant difference was observed in CW3 compared to CW2 except TN. Comparing the removal of TN and NH₄-N, it implis that the removal improvement of TN from CW 1 to 3 was due to the improved removal of nitrate thus the enhanced denitrification.

Referring to Table 5 and Fig. 8, it implies that as pollutant loading rate increases, higher nitrification and denitrification rates were achieved. With frequent recirculation and longer retention time, better removal was accomplished.

In the column fed with high pollutant loading rate, more bacteria were inoculated into the wetland, so that the release started earlier than those receiving other lower loadings. However, bacteria need oxygen to proceed bio-degradation as well. The more frequent recirculation brought more oxygen into the wetland and thereby led to the faster degradation, resulting in the greater release of organic matters in the effluent.
4. Summary and Conclusion

Synthetic fiber was examined as an alternative wetland medium which can replace soil mixture or gravel. According to the operational data, fiber successfully worked as a filter medium and supporter for microbial growth. Particularly, COD was released from the fiber during one distinct period. It was found out that internal release was due to the bio-degradation of synthetic fiber, and the released organic matters were found to serve as carbon source for denitrification. Recirculation during the dry day period greatly enhanced the nitrification by supplying oxygen. The result also proves that recirculation can increase the utility of stormwater facilities, which is left unused unless rainfall activity occurs. In practical, fiber packed wetland is preferred to be used to treat piggery stormwater containing high concentration of nitrogen. Fiber media have several advantages over the conventional grain media, but precise roles and functions of fiber in the wetland need to be examined through further study.

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