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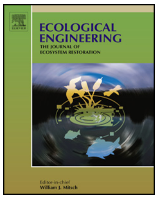

Reuse of drinking water treatment residuals as a substrate in constructed wetlands for sewage tertiary treatment

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ABSTRACT

This work investigated the feasibility of reusing drinking water treatment residuals (WTR) as a substrate in constructed wetlands (WTR-CW) to treat secondary effluent at short hydraulic retention times (HRTs) (1–3 d). The results indicated that both continuous flow operation (CFCW) and tidal flow operation (TFCW) can achieve satisfactory removal of total nitrogen (TN), total phosphorus (TP), chemical oxygen demand and suspended solids although the ammonia nitrogen concentration of the CFCW effluent increased slightly. The WTR was found to be beneficial for denitrification, and the mean nitrate removal rates of CFCW and TFCW were 3.45 and 2.47 g N/m^3 d, respectively. The TP removal efficiency of the two WTR-CWs still remained at 98% after 260 d of operation, and the lifetime regarding P saturation was estimated to be longer than 10 years. The HRT played a more significant role in TN removal, and the most optimal and stable TN removal (>76%) was obtained at 3 d HRT. Moreover, the leaching of Fe and Al from the two WTR-CWs was minor. Based on regulations, it is feasible to reuse the WTR as a substrate in constructed wetlands for the purpose of sewage tertiary treatment and waste recycling.

1. Introduction

Nutrients, including nitrogen (N) and phosphorus (P), from municipal wastewater can lead to eutrophication of the receiving water bodies, including fresh-water and some seawater (Conley et al., 2009; Oleszkiewicz and Barnard, 2006). Normally, it is difficult to maintain the effluent of secondary biological treatment at a cleanliness level that satisfies the environmental standard to enable it to be discharged into the receiving water bodies (SEPA, 2003). Various processes, such as coagulation, ion exchange and adsorption, have been used as tertiary treatments to deal with the remaining contaminants after secondary treatment (Ganrot et al., 2007; Gupta et al., 2012; Wang et al., 2005). Among these tertiary treatment methods, constructed wetlands (CW) have demonstrated advantages in terms of aesthetics, lower energy consumption and more economical construction and operation.

The performance of CW is generally good in terms of the removal of organic matter and suspended solids (SS). Effective N removal can also be achieved by different operation schemes, such as continuous feeding, intermittent feeding, step-feeding and artificial aeration (Albuquerque et al., 2012; Hu et al., 2012a; Vymazal, 2001). Traditionally, CW has a limited capacity for the removal of P unless materials with high P adsorption capacity are used (Vymazal, 2007). Therefore, many researchers have used some industry by-products and wastes as substrates for enhancing P removal (Drizo et al., 2002; Wendling et al., 2012). Recently, significant research effort has been focused on the reuse of drinking water treatment residuals (WTR) in CW (WTR-CW) to facilitate water reuse and waste recycling.

Water treatment residuals, a non-hazardous inevitable by-product generated from drinking water treatment plants, has been demonstrated to exhibit high P retention capabilities (Yang et al., 2006). Babatunde et al. (2010) demonstrated that a pilot field-scale WTR-CW operated in tidal-flow mode exhibited satisfactory performance of the removal of P and organic matter. In addition, Hu et al. (2012a,b) constructed a four-stage WTR-CW and a single-stage WTR-CW with intermittent aeration to treat dairy wastewater, each of which exhibited a high rate of N removal.

Abbreviations: CFCW, continuous flow operated WTR-CW; COD$_{cr}$, chemical oxygen demand; CW, constructed wetlands; DO, dissolved oxygen; HRT, hydraulic retention time; ICP-AES, inductively coupled plasma atomic emission spectroscopy; N, nitrogen; NH$_4$-N, ammonia nitrogen; NO$_2$-N, nitrite; NO$_3$-N, nitrate; P, phosphorus; SS, suspend solids; TFCW, tidal-flow operated WTR-CW; TN, total N; TP, total P; WTR, drinking water treatment residuals; WTR-CW, CW based on WTR.

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Table 1
Wastewater characteristics (mean ± SD) and average loading rates.

	Period 1 (15–100 d)	Period 2 (100–200 d)	Period 3 (200–260 d)	Dairy wastewater[b]	Discharge standard[c]
HRT (d)[a]	1	2	3	–	–
HLR (m^3/m^3 d)[a]	0.45	0.22	0.15	–	–
COD_{cr} (mg/L)	45.03 ± 20.23	53.72 ± 18.87	71.10 ± 45.00	3491 ± 2045	50
NH_4-N (mg/L)	0.65 ± 0.64	0.28 ± 0.21	0.69 ± 0.67	368 ± 114	5
NO_2-N (mg/L)	0.24 ± 0.17	0.04 ± 0.02	0.39 ± 0.29	–	–
NO_3-N (mg/L)	16.70 ± 2.28	15.80 ± 4.15	11.10 ± 1.93	–	–
TN (mg/L)	17.88 ± 2.54	16.61 ± 4.15	12.96 ± 2.74	442 ± 114	15
TP (mg/L)	1.88 ± 0.45	1.83 ± 0.68	1.15 ± 0.50	39 ± 22	0.5
SS (mg/L)	2.10 ± 0.24	2.47 ± 0.44	2.73 ± 0.31	1739 ± 1687	10
pH	8.29 ± 0.18	8.36 ± 0.19	8.18 ± 0.40	7.87 ± 0.3	6–9
OLR (g COD_{cr}/m^3 d)[a]	20.25	11.83	10.67	–	–
NLR (g N/m^3 d)[a]	8.04	3.66	1.95	–	–
PLR (g P/m^3 d)[a]	0.84	0.40	0.18	–	–
COD_{cr}/TN	2.52	3.23	5.48	–	–

[a] HRT: hydraulic retention time; HLR: hydraulic loading rate; OLR: organic loading rate; NLR: nitrogen loading rate; PLR: phosphorus loading rate.
[b] Refer to Hu et al. (2012b).
[c] The first-class requirements of Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB 18918-2002) (SEPA, 2003).

Overall, the WTR-CW has been successful in the treatment of high-strength wastewater (high SS, chemical oxygen demand (COD_{cr}), total N (TN) and total P (TP)), demonstrating a high removal efficiency for pollutants. However, there have been limited data reported regarding the application of WTR-CW for sewage tertiary treatment. Unlike dairy wastewater, secondary effluent is normally characterised by low COD_{cr} and SS levels and a relatively lower nutrient level. Therefore, there is a significant need to determine the feasibility of using WTR-CW to purify secondary effluents.

In this study, two lab-scale single-stage WTR-CWs were constructed to treat nitrate (NO_3-N)-dominated secondary effluent from a municipal wastewater treatment plant. The performance of the two CW operation schemes, including continuous flow (CFCW) and tidal flow (TFCW), was monitored. The objectives of the study were (1) to investigate the effectiveness of WTR-CW under two different operation schemes, (2) to determine the mechanisms of nutrients removal, and (3) to estimate the applicability of WTR-CW as a tertiary treatment technology. The results of this work provide support for the application of WTR-CW for sewage tertiary treatment.

2. Materials and methods

2.1. Sample preparation

Dewatered WTR was collected from Beijing City No. 9 Waterworks in China. The particle sizes of the raw cake of WTR were in the range of 1–3 cm, and the moisture content was 55%. The characteristics of the WTR were available in former studies (Wang et al., 2012a, 2013a): Fe of 101.56 mg/g, Al of 50.36 mg/g, P of 0.61 mg/g, pH of 7.04, organic matter of 57.65 mg/g and surface area of 78.83 m^2/g. Furthermore, a maximum P adsorption capacity of 7.42 mg/g was calculated at pH of 7 using Langmuir isotherm (Fig. S1 in Supplementary Material).

The secondary effluent was collected after an A^2/O process from the Xiaojiahe Sewage Treatment Plant of Beijing. The A^2/O process was a single-sludge suspended growth system incorporating anaerobic, anoxic and aerobic zones in sequence (Wang et al., 2006). After collection, the wastewater was stored at 4 °C. The characteristics and loading rates during the entire waste treatment operation are summarised in Table 1. Compared with the dairy wastewater studied in previous work (Hu et al., 2012b), the secondary wastewater had significantly lower COD_{cr}, SS, TN and TP levels. However, the secondary wastewater (COD_{cr}, TN and TP) still failed to meet the requirements of the standard (SEPA, 2003). In the secondary wastewater, the TN primarily existed in the form of NO_3-N. Overall, tertiary treatment was required to improve the water quality of the secondary wastewater.

2.2. System description and operation

The two lab-scale single-stage WTR-CW systems were implemented with two Plexiglas columns (diameter of 9.3 cm and depth of 90 cm) (Fig. 1). Gravel (depth of 10 cm) was added at the bottom of the columns as the support medium, and a 60-cm depth of dewatered WTR (dry weight of 1.2 kg) was added as the main wetland medium layer, which resulted in a total volume of 5.09 L and an effective volume of 2.0 L (an initial porosity of 39%). Common reeds, *Phragmitesaustralis*, were planted on the top of the two columns. For the CFCW, the influent was continuously introduced into the column from the bottom by a peristaltic pump, while the effluent overflowed from the top. The desired hydraulic retention times (HRTs) were adjusted by controlling the flowrate of the influent. For the TFCW, the influent was introduced into the column from the top, while the effluent was drained from the bottom by peristaltic pumps. The feeding dosage and the discharge dosage were both half of the total volume per cycle, thus maintaining a stationary volume of 1.0 L during the experiments. The wet/dry (h) ratio was maintained at 22:2 by using pre-set programmable timers. The desired HRTs were adjusted by control of the flood and drain stages sequentially. The two WTR-CWs were operated for 260 d at room temperature, and this time was divided into three periods according to the theoretical HRTs (Table 1). Samples were collected from the influent and effluent of the two WTR-CWs 1–2 times per week and were analysed for COD_{cr}, SS, ammonia nitrogen (NH_4-N), nitrite (NO_2-N), NO_3-N, TN, TP, and pH. In addition, the samples for Fe and Al analysis were collected from the effluent once each month.

2.3. Sample analysis

The COD_{cr} level was measured using the potassium dichromate method (Maria et al., 2004), and the SS level was measured using the gravimetric method (Clescerl et al., 1995). The NH_4-N, NO_2-N and NO_3-N levels were detected using a spectrophotometer (UV-2000, Unico) according to the standard methods (Clescerl et al., 1995). The TN level was measured by alkaline potassium persulphate oxidation followed by NO_3-N analysis (Clescerl et al., 1995). The TP was measured by persulphate digestion followed by orthophosphate analysis (Clescerl et al., 1995). The pH was measured using a pH metre (pH-10, Sartorius). Dissolved Fe and