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A full-scale treatment of freeway toll-gate domestic sewage using ecology filter integrated constructed rapid infiltration

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ABSTRACT

To explore an economical and manageable wastewater treatment process, a full-scale ecology filter integrated constructed rapid infiltration (Eco-CRI) was conducted and applied to treat freeway toll-gate domestic sewage, and the performances of Eco-CRI were investigated to evaluate its technical and economical suitability. The results showed that chemical oxygen demand, suspended solids, ammonia, and phosphorus could be removed efficiently when 1.0 m d^{-1} of the hydraulic loading rate and 2 h of dosing and 6 h of resting of feed regime were operated, respectively. Clogging, which was by far the biggest operational concern for the soil-based treatment systems, was not observed during the whole operation over a period of 14 months. Based on the results of economical analysis, electrical power consumption of per m^3 wastewater treated was only 0.13 kWh. Besides maintenance of dosing pump, regular maintenance of Eco-CRI was just harvesting reeds and earthworms once a year. The facts indicated that Eco-CRI was a cost-effective and technically feasible process for freeway toll-gate domestic sewage treatment, and might serve as an attractive option for wastewater treatment in remote areas where regular maintenance was not feasible and/or in present developing countries like China where uneconomical approaches were not acceptable due to the local socioeconomic situation.

1. Introduction

Technically, freeway toll-gate domestic sewage is easy to treat to a low level. However, several problems (such as low utilization rate of wastewater treatment equipment, low standard-reaching rate of nutrients removal, and poor design of treatment process) widely existed in treatment in China up to now due to the small quantity of wastewater and its frequently variable discharge. Moreover, most research has been focused on municipal wastewater removal because of its massive quantity of wastewater treated daily (Wang et al., 2008; Li et al., 2009b; Ruiz et al., 2009) and industrial wastewater removal owing to its highly variable composition in past years (Liu et al., 2009; Li et al., 2009a), resulting in lack of preparation for this type of domestic sewage removal. Therefore, an economical and manageable wastewater treatment approach is often required and deserves to be explored.

Soil-based treatment systems such as constructed wetlands, sand filters and bio-filters have proved to be a variable and cost-effective option with the promising organic matter and nitrogen removal performances (Koottatep et al., 2005; Tietz et al., 2008; Zhang et al., 2008; Torrens et al., 2009; Bester and Schäfer, 2009). The purification performance of these nature-oriented techniques is a result of the interaction among microbes, plants and the sandy filter material itself. Oxygen transfer into the media is achieved in different ways: by diluted oxygen present in wastewater, by convection due to batch loading and by diffusion processes (Torrens et al., 2009). This aeration process may enormously reduce operational cost, making the technologies suitable for polishing treatment systems (Zhang et al., 2009). However, clogging, which is one of the worst operational problems for the filter (Turon et al., 2009), is usually observed (Darby et al., 1996; Rodgers et al., 2004; Ruppe, 2005; Leverenz et al., 2009), and can diminish hydraulic conductivity and reduce both infiltration velocity and oxygen supply, thereby threatening the sustainability of the process. Although several publications reported that the phenomenon of clogging could be reduced to a certain extent by suitable improvements in operation and design such as improvement of the filter loading regime, vegetation planted on top of filters (Ruppe, 2005; Bester

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Table 1
Changes of earthworms during the operation period.

Date	08.3.12	08.4.10	08.5.16	08.7.11	08.9.14	08.11.9	09.1.6	09.3.17	09.5.15
Amount	975[a]	575	650	875	850	1125	1050	1225	1275

[a] Earthworms was counted in a 0.04 m^2 of area (*X*), and the amount of earthworms per m^2 was calculated as 25*X*.

and Schäfer, 2009), the desired outcome has not been obtained yet. Furthermore, the low hydraulic loading rate (HLR) and organic loading rate (OLR) of soil-based treatment processes increase the area of treatment systems and construction cost, restricting the technologies in more applications. Additionally, since the only sustainable removal mechanism for phosphorus (Pi) is adsorption, precipitation, plant and microbial uptake (Arias et al., 2001; Zhang et al., 2008), the low Pi removal efficiency of the processes also limits the technologies in further applications especially in the areas of fragile receiving surface water bodies like China.

Earthworms that can accumulate many organic pollutants from the surrounding soil environment, passive absorption through the body wall and also intestinal uptake during the passage of soil through the gut, have been successfully applied in solid wastes removal and contaminated soil remediation (Contreras-Ramos et al., 2009; Suthar, 2009). Further, earthworm-created macropores may have a significant impact on soil renovation of wastewater (Hawkins et al., 2008). Research showed that infiltration rates at the soil surface could be 4–10 times greater in soils with earthworms than in soils without earthworms (Hawkins et al., 2008), and found that the environmental conditions within filters were suitable for earthworms living (Taylor et al., 2003).

In this study, we introduced earthworms to prevent clogging and to increase HLR and OLR, further, a layer of sand filter containing vermiculite was conducted under the earthworms ecological filter to ensure low nutrients (especially Pi) concentration in effluent. The aim of this paper was therefore to examine the performances of the ecological filter integrated constructed rapid infiltration (Eco-CRI) and to evaluate its technical and economical suitability for freeway toll-gate domestic sewage removal.

2. Materials and methods

2.1. Engineering situation

Experiments were performed on a full-scale experimental plant in the freeway toll-gate called Ziqianqiao which was located in Hunan Province, China. About 36 m^3 of domestic sewage was discharged per day, and influent characteristics were as follows: chemical oxygen demand (COD) 126–248 mg L^{-1}, suspended solids (SS) 127–193 mg L^{-1}, ammonia (NH_4^+-N) 21.25–35.67 mg L^{-1}, and Pi 2.93–4.62 mg L^{-1}.

2.2. Characterization of the Eco-CRI

The investigations were carried out at four outdoor Eco-CRIs with a surface area of 9 m^2 each, which were conducted in March 2008 (group scene photographs of Eco-CRIs were presented in supplementary Fig. 1). The filters consisted of three layers consisting of peat (40 cm thickness, detailed physical and chemical properties were represented in supplementary Table 1), sand (60 cm thickness, grain size 0–2 mm), and gravel (30 cm thickness, grain size 5–30 mm) from the top down. A certain amount of earthworms (*Eisenia foetida*, approximately 70 days of the growth stage) and vermiculite (detailed composition of vermiculite was presented in supplementary Table 2) were put into the peat (about 1000 earthworms per m^3) and the sand (70% of sand and 30% of vermiculite by volume) layers, respectively. After establishing this system, 25 reed plants (*Phragmites australis*) were also planted into the peat. Eco-CRIs were intermittently fed (2 h of dosing and 6 h of resting), and each one received 9 m^3 of mechanically settled freeway toll-gate domestic sewage three times per day (HLR of 1.0 m d^{-1}), which resulted in an OLR of approximately 192 g m^{-2} d^{-1}.

2.3. Sampling and analytical methods

For depth profiles, triplicate water samples from different depths (20, 40, 60, 80 and 100 cm) were taken by a drill corer (inner diameter: 10 cm) and combined to composite samples. Water samples from the Eco-CRIs were taken weekly for analysis of COD, SS, NH_4^+-N, NO_2^--N, NO_3^--N and Pi, according to the Chinese National Standard Methods (SEPA of China, 2002). NO_x^--N was calculated as the sum of measured NO_2^--N and NO_3^--N.

3. Results

3.1. Summary of performances of the measured full-scale plant during a 14-month operation

Changes of earthworms were measured during the operation period (Table 1). As seen in Table 1, earthworms decreased during the first month, but gradually increased in next months. At the end of a 14-month operation, approximately 300 of earthworms' increases were detected per m^2. Performances of the Eco-CRIs during a 14-month operation based on 24 samples were summa-

Table 2
Summary of performances of the Eco-CRIs during a 14-month operation.

Item		COD	SS	NH_4^+-N	NO_2^--N	NO_3^--N	Pi
Influent (mg L^{-1})	Max	248	193	35.67	0.25	0.43	4.62
	Min	126	127	21.25	0.08	0.21	2.93
	Avg	192	177	27.43	0.12	0.37	3.47
Effluent (mg L^{-1})	Max	54	19	3.63	0.46	6.11	0.34
	Min	12	5	0.72	0.13	2.91	0.11
	Avg	27	11	1.94	0.38	4.53	0.27
Removal rate (%)	Max	94.8	94.2	97.1			95.6
	Min	83.9	88.6	85.7			89.3
	Avg	90.2	92.5	92.1			91.4

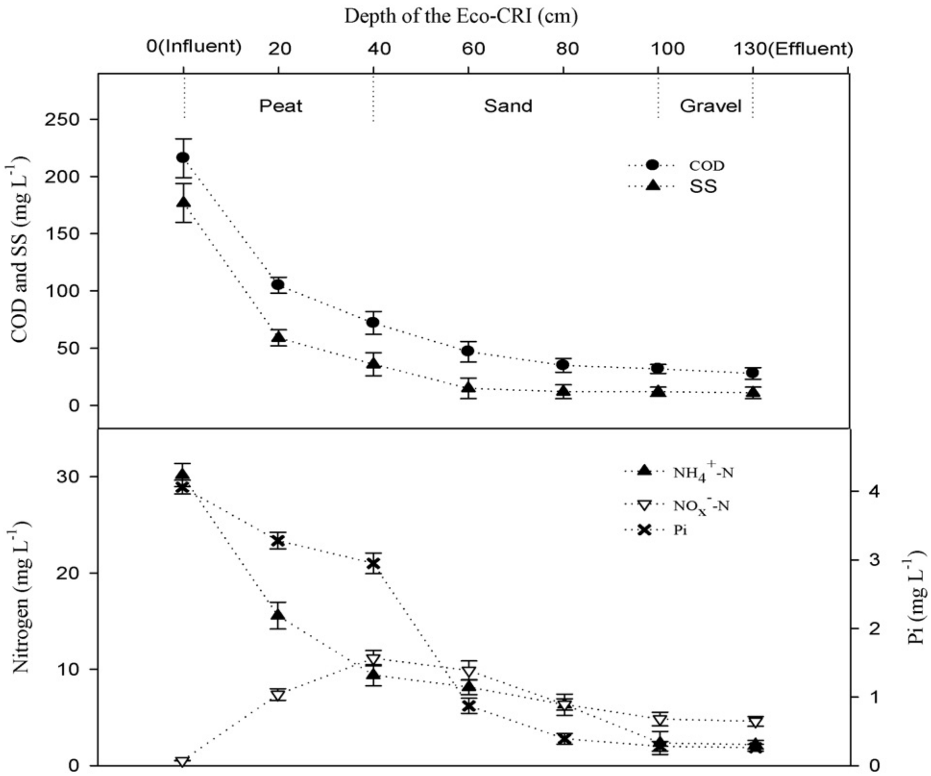

Fig. 1. Variations of pollutants in different depths of the Eco-CRIs (means ± standard deviations of three sampling occasions).

rized in Table 2 (original data were represented in supplementary Table 3). During monitoring, Eco-CRIs showed extremely good performances of pollutants removal. 12–54 mg L^{-1} of COD and 5–19 mg L^{-1} of SS, respectively, were measured in effluent, with average concentrations of 192 mg L^{-1} for COD and 177 mg L^{-1} for SS in influent, which indicated that the average removal efficiencies were 90.2% for COD and 92.5% for SS, respectively. In addition, Eco-CRIs were effective at removing NH_4^+-N (85.7–97.1% of removal rate), even during colder periods, with NH_4^+-N concentration in effluent ≤3.63 mg L^{-1}. The results were similar to those observed in constructed wetlands by other researchers (Torrens et al., 2009; Molle et al., 2006), and were moderately higher than those detected in subsurface constructed wetlands planted with *Canna* and *Heliconia* by Konnerup et al. (2009). Compared with the low retention of Pi in soil-based treatment systems observed by other researchers (Hylander et al., 2006; Torrens et al., 2009), Eco-CRIs performed efficiently on Pi removal (89.3–95.6%) during the 14-month research period, with Pi concentration in effluent ≤0.34 mg L^{-1}. All the above facts strongly exhibited that pollutants removal could be stably and efficiently realized in Eco-CRIs.

3.2. Pollutant variations in different depths of the Eco-CRIs

From the pollutant transformation data in Fig. 1, it can be found that COD and SS concentrations showed much steeper decreases in the top layer (0–20 cm), removing 59.1% and 71.7% of total removal amounts, respectively, and the results were similar to those observed in other soil-based treatment systems by other researchers (Rodgers et al., 2004; Ruppe, 2005). At 20–40 cm depth, 33 mg L^{-1} of COD and 23 mg L^{-1} of SS were, respectively removed, which indicated 66.7% of COD and 79.7% of SS were, respectively removed in the peat layer. In addition, a mass of NH_4^+-N decrease (20.78 mg L^{-1}) along with much NO_x^--N producing (10.64 mg L^{-1}) was observed in the peat layer, which implied that NH_4^+-N was mainly nitrified by nitrobacteria. As suggested by other authors (Panuvatvanich et al., 2009), NH_4^+-N was adsorbed onto bed media and organic matter during loading and nitrified mainly between feeding periods. However, just a slight TP removal was observed in the peat layer. After further purification by the sand layer, COD and SS concentrations decreased to a very low level (35 and 12 mg L^{-1}). NH_4^+-N continued reducing to a low level. However, NO_x^--N producing decreased obviously at 40–100 cm depth, which suggested that denitrification occurred. As expected, Pi was significantly reduced in the sand layer especially at 40–60 cm depth, and was considered as the result of adsorption and precipitation reactions with vermiculite in the sand layer.

3.3. Economical and technical analysis of Eco-CRIs

Besides the performance of pollutant removal, construction and operational costs are two important factors in evaluating the advantage of a wastewater treatment process, especially in developing countries like China. Therefore, the economical and technical analyses were conducted between Eco-CRIs and anaerobic/aerobic (A/O) process which was widely applied in freeway toll-gate domestic wastewater removal in China (Table 3). Since the only wastewater treatment equipment of Eco-CRIs was the dosing pump, much lower construction and operational costs were determined. Unlike A/O process, where microbial biomass is generally maintained in a growth phase, biomass in intermittent filters (such as Eco-CRIs) is characterized by growth during and immediately after dosing and endogenous decay between doses (Leverenz et al., 2009), thus sludge treatment is not required in Eco-CRIs. Besides maintenance of dosing pump, regular maintenance of Eco-CRIs is just harvesting reeds and earthworms once a year. Reeds could be harvested by reaping the stem and earthworms could be caught by the method of sweet food trap. Certainly, compared with A/O process, lower HLR and OLR of Eco-CRIs need larger area. However,

Table 3
The economical and technical analyses between Eco-CRIs and A/O process based on the full-scale wastewater treatment plant during the period of one year operation.

Item	Construction cost		Operation		Management		Area of the plants	
	Total ($)	Per m^3 ($)	Power (kW h/m^3)	Cost ($/$m^3$)	Sludge treatment	Regular maintenance	Total (m^2)	Per m^3 (m^2)
Eco-CRI (36 $m^3\,d^{-1}$)	9,600	267	0.13	0.017	Not required	Pump; harvesting reeds and earthworms once a year	52	1.44
A/O (50 $m^3\,d^{-1}$)	16,667	333	0.52	0.069	Once a week	Pump; jet aerator	25	0.5

freeway toll-gates are almost located in rural areas where enough areas can be utilized. The facts almost always suggested that Eco-CRI was an appropriate and economically attractive wastewater treatment system and had an enormous advantage over other conventional activated sludge processes in remote areas.

4. Discussion

4.1. Clogging conditions of Eco-CRIs

Early soil-based treatment systems were loaded heavily and, as a result, clogged frequently, requiring substantial maintenance and long resting periods to recover the filtration capacity. In subsequent studies, reduced loading rates, pretreatment, and increased dosing frequency were found to result in both improved performance and longer operational periods without clogging (Rodgers et al., 2004; Ruppe, 2005; Leverenz et al., 2009). However, the potential for filter clogging and the associated degradation in filter performance still existed.

There was a paucity of data relating surface clogging and operational parameters because clogging was generally not the desired outcome. Table 4 presents some studies where clogging was investigated in detail. As shown in supplementary Table 3, most of OLR and SS loading rate (SLR) of filters were designed to operate under conditions that were less than 100 $g\,m^{-2}\,d^{-1}$ and 30 $g\,m^{-2}\,d^{-1}$, respectively. However, the phenomenon of clogging was swiftly observed (20–180 days). Zhao et al. (2009) reported that the filter loaded with HLR of 0.85 $m\,d^{-1}$ combined with OLR exceeding 340 $g\,m^{-2}\,d^{-1}$ resulted in filter clogging after only 60 days. In the study of Fu et al. (2004), no clogging was observed in the integrated vertical-flow constructed wetland after running for 52 months, but it should be noted that low OLR and SLR of 50 $g\,m^{-2}\,d^{-1}$ and 11 $g\,m^{-2}\,d^{-1}$ were, respectively operated. Winter and Goetz (2003) suggested that SLR should not exceed 5 $g\,m^{-2}\,d^{-1}$ to completely avoid clogging. However, Eco-CRIs loaded at a rate of 1.0 $m\,d^{-1}$ which implied high OLR of 192 $g\,m^{-2}\,d^{-1}$ and SLR of 177 $g\,m^{-2}\,d^{-1}$ in this study, and no clogging was observed during the 14-month operational period. The results suggested that the added earthworms played a positive role in avoiding Eco-CRI clogging and the main operational concern of clogging was well-controlled in this study even under high organic and SS loading conditions. However, the exact effect of earthworms on clogging control is still unclear and is the focus of our ongoing research program.

4.2. Pi removal in the Eco-CRIs

Most soil-based treatment systems are able to fulfill the requirements for SS and COD removal, and nitrification can also frequently be obtained. However, it is often a problem to remove Pi, because the only sustainable removal mechanism for Pi is adsorption, precipitation, plant and microbial uptake. Moreover, the amount of Pi that can be removed by harvesting the plants constitutes only a small fraction of the amount of Pi loaded into the system with the sewage (Brix, 1997), and the view can be confirmed by the results obtained from this study (Fig. 1). Pi may also be bound to the media of filter mainly as a consequence of adsorption and precipitation reactions with calcium (Ca), aluminium (Al) and iron (Fe), etc. in the sand or gravel substrate (Arias et al., 2001).

In this study, we added 30% (by volume) of vermiculite to the sand layer, and vermiculite contained abundant Al, Fe and magnesium (Mg) oxides (supplementary Table 1). These oxides could adsorb Pi and subsequently form precipitation, ensuring a low level of Pi concentration in effluent. This point could be strongly supported by the result obtained in this study that a significant decrease of Pi was observed in the sand layer (Fig. 1), and was also supported by the observation that Pi removal had been found to be particularly efficient in constructed reed beds containing ferruginous sand (Netter, 1992). However, the Pi removal efficiency is often high initially and then decreases after some time as the Pi sorption capacity of the sand is used up (Arias et al., 2001). Therefore, one might want to know how long a sustained Pi removal could be maintained in such an Eco-CRI.

According to the detailed calculation presented in supplementary material, a sustained Pi removal in such an Eco-CRI would be maintained 9–11 years via above reactions. In addition, Pi removal in full-scale of Eco-CRIs occurs not only by Pi sorption and precipitation to the medium, but also through incorporation into organisms (biofilms, earthworms and plants) and the subsequent accumulation of organic matter in the systems. Therefore, the time of a sustained Pi removal may be longer. However, the real operation time of a sustained Pi removal will be further examined and recorded in this full-scale of Eco-CRIs. When Pi precipitation capacity of vermiculite is used up, the sand

Table 4
Summary of values about clogging obtained from case studies.

Bed depth (m)	HLR ($m\,d^{-1}$)	OLR ($g\,m^{-2}\,d^{-1}$)	SLR ($g\,m^{-2}\,d^{-1}$)	Dosing frequency (dose d^{-1})	Time until failure (d)	Reference
0.46	0.282	60.9	25.9	2	180	Furman et al. (1955)
0.38	0.326	46.9	9.5	24	70	Darby et al. (1996)
0.38	0.652	93.9	19.0	24	20	Darby et al. (1996)
0.35	0.06	75.8	14.5	4	35	Rodgers et al. (2004)
0.15	0.122	20.1	2.8	48	93	Ruppe et al. (2005)
0.15	0.122	20.1	2.8	96	55	Ruppe et al. (2005)
0.5	0.85	340	Not known	Not known	60	Zhao et al. (2009)
1.2	1.0	50	11	6	Not observed	Fu et al. (2004)
1.3	1.0	192	177	3	Not observed	This study

layer of Eco-CRIs will be replaced, and the material that is enriched with Pi can be used as a fertilizer, provided that P is available to the plants, and contents of toxic compounds and pathogens do not restrict such use (Hylander et al., 2006).

5. Conclusions

This study proved that Eco-CRI was a cost-effective and technically appropriate wastewater treatment process. The average removal efficiencies of COD, SS, NH_4^+-N and Pi were obtained at 90.2, 92.5, 92.1and 91.4%, respectively, during a 14-month operation, and clogging was not observed during the whole operation. Based on the results of economical analysis, electrical power consumption of per m^3 wastewater treated was only 0.13 kWh. The results indicated that Eco-CRI was an economical and manageable process for freeway toll-gate domestic sewage treatment, and might serve as an attractive treatment solution for small communities in rural areas and/or other wastewaters in present developing countries like China.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecoleng.2010.03.005.

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