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Performance study of vegetated sequencing batch coal slag bed treating domestic wastewater in suburban area

S.Y. Chan [a,*], Y.F. Tsang [a], H. Chua [b], S.N. Sin [b], L.H. Cui [c]

[a] Civil and Structural Engineering Department, The Hong Kong Polytechnic University, Hong Kong SAR, China
[b] PolyU-HIT Joint Research Centre of Water and Wastewater Treatment Technology, The Hong Kong Polytechnic University, Hong Kong, China
[c] Department of Environment and Resources, The South China Agricultural University, Guangzhou, China

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Abstract

A practical and affordable wastewater treatment system serving small community in suburban areas was studied. The system was a vegetated sequencing batch coal slag bed integrated with the rhythmical movement of wastewater and air like that of a sequencing batch reactor. The removal mechanisms capitalized on the pollutant removal process in conventional constructed wetland. *Cyperus alternifolius* was planted into the coal slag bed to form a novel plant-soil–microbial interactive system. Nutrients in the domestic wastewater, which cause environmental nuisance like eutrophication, were targeted to be eliminated by the process design. Operated with the contact time of 18 h, the treatment systems achieved around 60% removal efficiency for carbonaceous matters. The removals of ammonia nitrogen and phosphorus were about 50% and 40%, respectively, while the removal of total suspended solids was approaching 80%. From the current study, the construction cost of the vegetated sequencing batch coal slag bed was 256 RMB/m^3 and the operation cost was 0.13 RMB/m^3. With the advantages of ease of operation, low costs, desirable treatment efficiency and aesthetic value, the vegetated sequencing batch coal slag bed is proposed to be an alternative for onsite domestic wastewater treatment in suburban areas.

Keywords: Domestic wastewater; Coal slag; *Cyperus alternifolius*; Sequencing batch reactor; Constructed wetland

1. Introduction

This paper presents a performance study of a vegetated sequencing batch coal slag bed for domestic wastewater treatment. The system aimed to cope with the domestic wastewater demand in suburban area where the land availability is under pressure due to the increasing population. Suburban area is defined as the interface between developed urban areas and undeveloped rural areas. Although locating at the boundary of the urban cities, suburban sewer's connection to the existing municipal system in urban core is proved to be cost prohibitive. Meanwhile the costly municipal wastewater facilities are not feasible to be installed in suburban areas too due to the high construction and operating costs.

Moreover, land supply in suburban area is under increasing pressure from the rapid urban development. Some onsite land treatments like constructed wetlands have relatively low construction and operating costs, provide an economic treatment solution to untreated small flows, and are available to isolated or rural locations without the need for electricity. But these treatment systems occupy relatively large areas of land and tend to be used to serve a small population (The Chartered Institution of Water and Environmental Management, 2000), and they also need long retention time to achieve acceptable effluent quality. So these conventional treatment systems are no longer cost-effective in the suburban areas.

In this study, a practical and affordable wastewater treatment system, namely sequencing batch coal slag bed, which capitalizes on the pollutant removal mechanisms of the soil-plant–microbial interactions of constructed wetlands was designed for the domestic wastewater demands

* Corresponding author. Tel.: +852 27666027; fax: +852 23346389.
E-mail address: jackiesychanm@yahoo.com.hk (S.Y. Chan).

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in the suburban area. Coal slag, which is the waste residue from burning coal for electricity generation in Guangdong areas (Cui et al., 2003), was selected as the substrate of the system. The slag from power plant or blast furnace is an economical fill media with high P-sorption capacity to be used in filter bed treatment system (Asuman et al., 2007). *Cyperus alternifolius*, which is a wetland plants commonly found in South China (Chan et al., 2005) was employed in the study. The rhythmical batch flow of wastewater in conventional sequencing batch reactor was integrated into the operation of coal slag bed with vegetation to enhance the oxygen supply in the system, ultimately to increase the pollutant removal efficiency. Nutrients such as nitrogen and phosphorus in the domestic wastewater, which cause environmental nuisance like eutrophication, were targeted to be eliminated by the process design. The cost-effectiveness of similar systems would also be discussed.

2. Methods

Coal slag was selected as the substrate in the system. The porosity of coal slag was 0.5 and it composed of 15721.513 mg/kg of Al, 7294.794 mg/kg of Ca and 12645.736 mg/kg of Fe. The high levels of Al, Ca and Fe contents imply that coal slag has high potential to be a good substrate in wastewater treatment system with regard to phosphorus adsorption (Grüneberg and Kern, 2001; Comeau et al., 2001). On the other hand, *Cyperus alternifolius* was selected as the plant component in the system due to its long root length and tolerances to flooding and organic loadings (Hocking, 1985; Okurut et al., 1999; Liu et al., 2004). Bench experiments were carried out to study the physiochemical properties of the selected substrate. Then both laboratory-scale and pilot-scale bed systems were set up to test the pollutant removal efficiencies under different operating conditions.

2.1. Bench experiment on substrate

2.1.1. Phosphorus adsorption test

The size fractions of the coal slag chosen for adsorption isotherm experiment ranged from 1.18 mm to 475 μm. Approximately 5 g of coal slag were placed in 200-ml flasks, 100 ml deionized water spiked with NaH_2PO_4 to give one of the 15 levels of phosphorus concentrations (0, 2.5, 3.66, 5, 10, 20, 40, 60, 80, 160, 240, 320 and 360, 480 and 540 mg P/L) was added to the flasks (Brix et al., 2001). The flasks were sealed with parafilm and were agitated in an electrical shaker at 2000 rpm for 24 h. The supernatant from each flask was centrifuged at 4000 rpm for 10 min before filtration. The filtrate was then analysed for the concentration of total phosphorus.

2.1.2. Surface observation by scanning electron microscope

Small pieces of coal slag were fixed with the fixative of 4% paraformaldehyde in 0.1 M PBS (phosphate buffer saline). The coal slag was dehydrated in a sequence with different concentrations of 30%, 50%, 70%, 90% and 100% of ethanol for 20–30 min in each concentration. A drying agent – hexamethyldisilazane was used to soak the coal slag to replace the ethanol (Dykstra and Reuss, 2003). Then the coal slag were poured onto filter paper in fumehood and mounted onto aluminium holder by carbon tape. The whole aluminium holder with coal slag was then coated with gold by BAL-TEC SCD 050 Sputter coater. The surface characteristic was then observed under Philips XL 30 Esem-FEG Environmental Scanning Electron Microscope.

2.2. Laboratory-scale system operation

The main objective of the laboratory-scale experiment was to serve as a fundamental study to examine the compatibility of growing the selected plants in the selected adsorbing medium for domestic wastewater treatment. Another objective was to investigate the nutrient balance of the whole system in the study period. Percentages of nitrogen and phosphorus removals by three main pollutant removal mechanisms including adsorption, uptake by vegetation and microbial processing were calculated. The operation of the laboratory-scale system was the preliminary test of the pilot-scale experiment. Laboratory-scale bed systems imitated the operation of the on-site treatment system as much as possible. Coal slag filled up three tanks of 15 cm in height, 40 cm in length and 30 cm in width. The effluent point was at the bottom of one side of the tank. Thin gravel layer was placed at the bottom of the tank to prevent washing out of coal slag from the outlet. Ten young plants of *Cyperus alternifolis* were planted into the systems with their initial fresh weights being recorded. The effective tank volume was 9 L. Municipal wastewater from Tai Po wastewater treatment plant, Hong Kong, was used as the raw influent to the systems.

2.2.1. System operations

The three beds of coal slag were placed in the laboratory, which were subject to sufficient direct and indirect variable natural day-light and artificial light. The range of air temperature was between 18.9 and 22.5 °C throughout the experiment. Wastewater was fed into the system intermittently. Three-month start-up period from November 2003 to February 2004 was allocated to allow extensive plant root development and establishment of biofilm on the coal slag.

After completion of the start up stage, the operating stage of the laboratory-scale experiment began in March 2004. The operating cycle of the laboratory-scale experiment involved ''fill'' phase, ''react'' phase, ''draw'' phase and ''idle'' phase in 24 h. The pollutant removal capacity of the laboratory-scale system with ''react'' phase of 18 h and 0 h was examined. Based on one operating cycle everyday, the system was operated with each ''react'' phase (18 h and 0 h) for a 2-month period. The two ''react'' durations were chosen because 18 h and 0 h were the maximum and the minimum durations respectively, based on a cycle of

24 h a day. With a fixed "fill" phase of 4 h and a "draw" phase of 2 h in the pilot systems, the resulting maximum hours of "react" phase within 24 h is 18 h.

2.2.2. Plant sample analysis

The total N and P input and retention in the systems were monitored. Samples of above-ground biomass (including stems and leaves) of plant and coal slag were collected at the end of February 2004 (after start up stage) and at the end of April 2004 (after 18-h operation period). Coal slag from three different depths of the system including 30, 70 and 110 cm were collected. The plant samples and coal slag samples were freeze-dried and ground into fine powder form for nutrient measurements.

For total phosphorus analysis, about 0.250 g (±0.001 g) of ground samples were weighed into a pre-washed digestion tubes added with 3.5 g potassium persulfate. 50 ml of deionized water was added to wet the sample. 10.0 ml of concentrated H_2SO_4 was added into each tube and vortex (~scale 6). The tubes were then placed in the aluminium heating block and heated for 30 min at 200 °C. The digestion was continued for 2 h at 370 °C. Cooling to room temperature, the solution was poured into centrifuge tube and centrifuged for 4000 rpm for 10 min. The pH of the supernatants was adjusted to 8.2 by adding 40% NaOH. The level of total phosphorus was measured by Acid Persulfate Digestion Method (USEPA accepted for reporting wastewater analysis).

For total Kjeldahl nitrogen analysis, about 0.25 g of dry ground samples were weighted into digestion tubes. 50 ml of deionized water was added to each tube to wet the samples. 3.5 g K_2SO_4-catalyst mixture and 10.0 ml of concentrated H_2SO_4 were added into each tube. The digestion tubes were placed in the aluminium heating block and heated for 30 min at 200 °C. Then the digestion was continued for 2 h at 370 °C. After the digestion, the tubes were placed at room temperature for cooling. Afterwards, 50 ml of ammonia free deionized water was added into each tube. 25 ml of receiving solution and 10 drops of bromocresol green methyl red mixed indicator were filled in an Erlenmeyer flask. The flask was placed in the receiving position in the steam distilling unit. The distilling unit automatically added 50 ml of dilution water and 50 ml of 40% NaOH and performed the distillation process. The resulting solution in the Erlenmeyer flask was titrated with standard H_2SO_4 (0.02 N acid).

2.3. Pilot-scale system operation

2.3.1. Configurations

The pilot-scale experiment was carried out on-site in the South China Agricultural University (SCAU), Guangzhou, People's Republic of China. Three identical tanks in parallel were constructed near a pond in the campus of SCAU. Each system was made of concrete with the dimensions of 5.0 m in length, 3.0 m in width and 1.8 m in depth. Coal slag was filled up in the system as the substrate. The empty bed volume of each system is 27 m^3 with an effective volume of 13.6 m^3. Stones (50–100 mm) were placed around the influent distributor and the effluent collector pipes to reduce the potential of clogging. The domestic sewage collected from the local sewer in the University was drained to a sedimentation tank before entering the pilot-scale treatment systems. Wastewater was then fed into the system from tap opening at the top of the system on one side. The wastewater fell into the inlet zone from the tap would then pass through the perforated partition into the rooted bed matrix. The treated effluent was then drawn out by gravity from the outlet valve at the other side of the system. *Cyperus alternifolius* were introduced into the coal slag bed to imitate the plant components of constructed wetland. Clumps of whole plants of *Cyperus alternifolius* were planted into the systems with a density of 3–4 plant/m^2.

2.3.2. Operating conditions

Different from conventional constructed wetland, the vegetated sequencing batch coal slag bed is a batch reactor. The operating cycle of the coal slag bed is similar to conventional sequencing batch reactor, which involves "fill" phase, "react" phase, "draw" phase and "idle" phase, but without "aerate" phase. The periodical "in" and "out" movement of wastewater was to enhance the oxygen supply in the bed matrix.

About four months of start-up period (November 2004 to April 2005) was allocated to allow plant growth and establishment of biofilm on the coal slag, wastewater was fed into the coal slag bed intermittently. After completion of the start-up period, the systems were operated every alternate day from May 2005 to March 2006. During the operation, wastewater was pumped into coal slag bed in the "fill" phase and retained in the bed in the "react" phase. The operating conditions of the system were mainly varied by different durations of the "react" phase (0, 3, 6, 12 and 18 h). Table 1 shows the durations of different phases accordingly. Every contact time was tested for a 2-month period in total. The resulting hydraulic loading was at a rate of 0.45 m^3/m^2-d.

Distinct seasonal pattern of nutrient removal exists within treatment wetland microcosms (Picard et al., 2005). Seasonal variation in temperate region was considered as the pilot-scale experiment was carried out outdoor. In this experiment, the 5 months from May 05 to September 05 having mean temperature from 22.7 °C to 25.3 °C were classified as warm period while from the 5 months from November 05 to March 06 having mean temperature

Table 1
Durations of different operating stages

Phase	Duration (h)				
Fill	4	4	4	4	4
React	18	12	6	3	0
Draw	2	2	2	2	2
Idle	0	6	12	15	18

Total: 24

from 9.8 °C to 19.1 °C were classified as cool period. Each "react" phase (in sequence of 18, 12, 6, 3 and 0 h) was tested for its effects on pollutant removal for one month in both warm and cold periods.

2.4. Analytical methods

The pH, DO, and temperature of wastewater were measured in situ. BOD_5 COD, NH3–N, total Kjeldahl nitrogen (TKN), NO_3–N, NO_2–N, TP, TSS and VSS of wastewater were analysed in the laboratory in accordance with standard methods (APHA, 1998). The metal contents in the coal slag were analysed by Inductively coupled plasma atomic emission spectrometry (ICP-AES, Perkin–Elmer Optima 3300 DV). Removal efficiencies were obtained by calculating the percentages of pollutant removal from the influent concentrations. Comparisons of the differences of pollutant levels were performed using analysis of variance (ANOVA) by SPSS 10.0.

3. Results and discussions

3.1. Substrate characteristics

The maximum phosphorus adsorption capacity, evaluated from the fit of Langmuir isotherm to the experimental data of bench-scale adsorption test was 1.369 mg P/g. The dominant sizes of particle were the coarse ones with diameter between 2.36 mm and 10 mm. The value of D_{10} was 0.31 mm and that of D_{60} was 9 mm, with the uniformity coefficient ($K_{60} = D_{60}/D_{10}$) of 29. The porous surface of coal slag also favored pollutant adsorption.

3.2. Plant characteristics

The plant species employed in the system was selected after comprehensive literature review of common wetland plants in Guangdong areas. *Cyperus alternifolius* was selected as the plant candidate in the treatment system due to its long root length which can be up to 2 m (Cui et al., 2003). *Cyperus alternifolius* (Umbrella grass) is a perennial herb, which grows in humid areas or swampland. It grows fast with strong root system. Its productivity is high and it can form a good landscape. *Cyperus* spp. has been used successfully in small-scale gravel-bed constructed wetlands in Australia and New Zealand. As identified by Hocking (1985), the attributes that make *Cyperus* spp. as a potentially useful plant for constructed wetlands include: year-round growth in warm temperate regions (withstanding moderate frosts), tolerance of hyper-eutrophic conditions and salinity, ease of propagation, and apparent lack of serious weed potential.

3.3. Pools of nitrogen and phosphorus

As the cell mass (biofilm) is attached on the coal slag, on where the pollutant removal processes take place, the coal slag bed was an attached-growth system. Pollutant removal processes took place in the bed matrix of such attached-growth system, main removal mechanisms including physical adsorption and biochemical degradations occurred on the coal slag surface and the biofilm established on it, as well as certain level of plant uptake.

The proportions of N and P removals by various mechanisms in the laboratory-scale system are shown in Table 2. During the start-up stage from November 2003 to February 2004, adsorption contributed over 60% of nitrogen removal and phosphorus removal. The high proportion of removal by adsorption was due to the availability of adsorption sites on the adsorbing medium in the start-up stage. Apart from the foremost phosphorus removal, media adsorption contributes to ammonia removal until all the adsorption sites are saturated (Reed et al., 2001). Another reason for the high proportion of removal by adsorption was that the biofilm has not been well established in the start-up stage of the experiment. Microorganisms, in turn played a minor role in nutrient degradation in the start-up stage.

The same set of mass balance analysis was carried out again during the operating period with 18-h contact time. Since the establishment of biofilm was confirmed by SEM observations and the re-generative pollutant removal function of microorganisms was reflected by the steady pollutant removal efficiency of the system in the operating period, it could be predicted that microbial removals of nitrogen and phosphorus would play a bigger role among the different removal mechanisms in this stage. As expected, the percentage of nitrogen removal by adsorption decreased while the percentage of removal by microbial processes increased. The percentage of nitrogen removal by microbial processes increased from 19.55% in the

Table 2
Proportions of N and P removals by various mechanisms to the total removals in the laboratory-scale system

	Nitrogen (g)	Percentage of removal (%)	Phosphorus (g)	Percentage of removal (%)
Start-up stage				
In	4.365		1.843	
Out	2.738		1.073	
Removal	1.627		0.770	
Adsorption	1.080	66.38	0.524	68.05
Vegetative biomass	0.229	14.07	0.039	5.1
Microbial processing	0.318	19.55	0.207	26.89
Operating stage				
In	3.492		1.474	
Out	2.191		0.859	
Removal	1.301		0.615	
Adsorption	0.262	20.14	0.425	69.11
Vegetative biomass	0.140	10.76	0.029	4.72
Microbial processing	0.899	69.10	0.161	26.18

start-up stage to 69.10% in the operating stage. As the removal of phosphorus mainly relies on physical adsorption, the percentage of phosphorus removal by physical adsorption remained at 68.05% in the start up stage and 69.11% in the operating stage.

Since the proportion of removal due to microbial processing was calculated only by subtracting the total removal by the proportion of removal due to adsorption and vegetative uptake, the contribution of microbial processing should be less than the calculated value, because the fraction of removal that could not be accounted for was also represented in it.

3.4. Pilot-scale system performance

The pilot-scale system operation was the application study of the vegetated sequencing batch biofilm reactor. Biofilm was formed on the coal slag in the pilot-scale system after 3 months of start-up stage. Table 3 shows the characteristics of influent from the on-site domestic wastewater sources. Since the pilot-scale system operated in every other day, the effect of duration of idle phase was attenuated by the resting of bed for 24 h in between each operating cycle. Based on the maximal durations (18 h) of the "react" phase in the pilot-scale operation, the treatment systems achieved around 60% removal efficiency for carbonaceous matters. The removals of ammonia nitrogen and phosphorus were about 50% and 40%, respectively, while the removal of total suspended solids was approaching 80%. Certain level of pollutant removal was obtained with 0-h react phase because degradations of pollutant in the bed matrix started as early as in the 4-h "fill" phase. Fig. 1 shows the pollutant removals with the five durations of "react" phase. The Pearson correlation coefficients of contact time with removals of BOD_5, COD, NH_3–N, TP, and TSS were 0.601, 0.511, 0.665, 0.070 and 0.690, respectively. Except TP, the removals of BOD_5, COD, NH_3 and TSS associated positively with the contact time, they gave increasing trends of removal with the increases of length of contact time.

Table 3
Influent characteristics of pilot-scale experiment (May 2005–March 2006)

Parameter	Mean	Standard deviation
pH	7.21	0.27
Sewage temperature (°C)	20.47	4.16
BOD_5 (mg/L)	27.59	12.98
COD (mg/L)	80.82	31.52
NH_3–N (mg/L)	32.71	8.37
TKN (mg/L)	35.56	9.69
Nitrate (mg/L)	4.85	4.56
TP (mg/L)	2.61	0.99
TSS (mg/L)	23.26	8.73
DO (mg/L)	1.40	1.04
VSS (mg/L)	21.44	7.38

3.4.1. Carbonaceous matter removal

Average removal efficiencies of BOD_5, and COD in domestic wastewater were at the maximum of 59.72% and 63.58%, respectively (Fig. 1). They increased gradually with the lengthening of contact time as carbonaceous matters removal was dependant on the duration of contact time. Settleable organics are rapidly removed in wetland systems under quiescent conditions by deposition and filtration (Vymazal et al., 1998). Organic compounds are mainly degraded aerobically by microorganisms. Removal of organic compounds is contributed by the decomposition by microorganism in wastewater, and it increases with the extension of time for microbial actions.

3.4.2. Nutrient removal

Average removal efficiency of NH_3–N was at the maximal of 50.51% (Fig. 1) in the system and the removal efficiencies rose with the increase of contact time. Contact time has a direct influence on the removal of ammonia

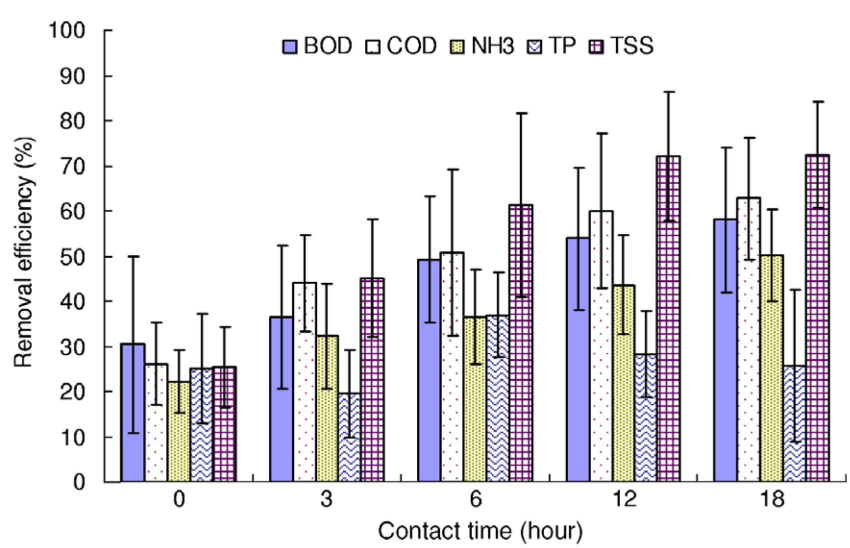

Fig. 1. Pollutant removal efficiencies with different contact time.

nitrogen through the biological process. Ammonia nitrogen is oxidized biologically to nitrate with nitrite as an intermediate in the reaction sequence in nitrification. In the first step, aerobic bacteria like *Nitrosomonas*, which depend on the oxidation of ammonia for the generation of energy for growth, convert the ammonium to nitrite. In the second step, facultative bacteria like *Nitrobacter*, oxidize nitrite to nitrate by using organic compounds and nitrite, for the generation of energy for growth. Microbial activity is the main removal mechanism in the pollutant degradation process. Hence, longer reaction time was favourable to maximize the removal efficiency of ammonia nitrogen removal, and hence the nitrification process.

Average removal efficiencies of TP in the system were 37.89% with 18-h contact time, and 23.42% with 0-h contact time (Fig. 1). The increase of contact time from 0 h to 18 h did not alter much about the total phosphorus removal. The reason was that the removal of phosphorus mainly relied on physical adsorption, complexation and precipitation (Watson et al., 1989), which are different from biological degradation, not a time-dependent process. The removal rate of total phosphorus is basically a function of the degree of adsorption of ion to the soil matrix. The high concentrations of aluminium, iron and calcium of coal slag provided an enormous potential for the system to serve as phosphorus sinks. However, phosphorous adsorption sites can be blocked by a biofilm coating on the soil particles.

3.4.3. Total suspended solid removal

Average removal efficiency of TSS in domestic wastewater was at the maximum of 78.82% (Fig. 1). Removal of TSS also showed a high correlation to the contact time in the vegetated sequencing batch coal slag bed in this study. The removal mechanisms for TSS in the wetland treatment system essentially include sedimentation where the suspended solids ultimately settle to the bottom, retention time and contact with plant materials enhance this process. Besides facilitate sedimentation, the long contact time promoted more complete biodegradation because high proportion of the TSS in the domestic wastewater being used onsite were volatile suspended solid, which were readily biodegradable. The extension of time definitely facilitated the reduction of the organic contents in the suspended solids by microorganisms.

3.5. Controlling factors

3.5.1. Temperature

Analysis of the removal efficiencies of COD, TP and TSS with respect to warm and cool periods indicates that temperature appeared to have negligible treatment effects (ANOVA, $p > 0.05$). However, the removal efficiencies of ammonia nitrogen in warm and cool seasons showed significant differences with the durations of "react" phase of 0, 3, 6 and 12 h (p-values <0.05) (Table 4). It implied that the temperature had determinant effects on the removal of ammonia nitrogen in the vegetated sequencing batch coal slag bed. Water temperature has a strong effect on the growth rate of nitrifying bacteria. Numerous researchers have documented that nitrification episodes are more common during the warmer months (Watson and Danzig, 1993; Williams et al., 1994; Taylor and Bishop, 1989). Most strains of nitrifiers grow optimally at temperatures between 25 and 30 °C (Watson et al., 1981) but nitrification has occurred over a wide range of temperatures (8–26 °C) (Kirmeyer et al., 1995).

Table 4
p-values of different pollutant removal efficiencies in warm and cool periods

Parameters	Contact time (h)				
	0	3	6	12	18
NH_3–N	0.023	0.040	0.048	0.000	0.209
BOD_5	0.917	0.317	0.034	0.005	0.994
COD	0.290	0.337	0.710	0.219	0.737
TP	0.688	0.372	0.137	0.771	0.248
TSS	0.205	0.458	0.067	0.775	0.758

3.5.2. Dissolved oxygen

The DO level in the sequencing batch coal slag bed system was 2.10 ± 1.18 mg/L. Different pollutant removal processes are favoured in specific ranges of dissolved oxygen concentrations. Carbonaceous BOD removal is favoured with DO level of 1–2 mg/L, nitrification is facilitated with DO level of 2–3 mg/L while denitrification is facilitated with DO level <0.5 mg/L. And nitrification took place in all locations where DO levels were higher than the critical threshold of 0.5 mg/L (Taylor and Bishop, 1989). With the oxygen levels usually over 0.5 mg/L in the vegetated sequencing batch coal slag bed, nitrification was favoured to convert ammonia nitrogen into nitrate.

The sequencing batch coal slag bed was a vertical flow gravel-based system integrated with the periodic feeding like that of a sequencing batch reactor. The air drawn into sequencing batch beds during the "draw" phase was used as an oxygen source to biodegrade the pollutants. The oxygen transport and consumption rate in the beds could be greatly improved by the rhythmical water and air movement in the bed matrix (Sun et al., 1999). These alternating phases of "feed" and "rest" are fundamental to control the growth of the attached biomass on the adsorbing medium, to maintain aerobic conditions within the filter bed and to mineralize the organic deposits. Besides the removal of nitrogen, Miller and Wolf (1975) have shown that P adsorption capacity of vertical filtration bed can be regenerated if the system is allowed to rest and dry. In other words, intermittent loadings are feasible to optimize P removal.

3.6. Applications and cost-effectiveness of the system

Cyperus alternifolius showed satisfying growth and survival in the operation of sequencing batch coal slag bed and it served as a good component in the soil-plant–microbial interactive system. The coal slag also provided fulfilling removal capacity of pollutant through physical adsorption.

The coal slag bed performed well in providing hydraulic conductivity in the system and no clogging was observed throughout the experiment. Significant phosphorus removal was observed by adsorption on the coal slag. The expected lifetime of the coal slag bed in the system can be estimated by multiplying the P adsorption maximum capacity with the total mass of the coal slag bed. If the maximum adsorption capacity is 1.369 g P/kg, and the volume of the coal slag bed is 27 m^3 with the coal slag density as 1.818 kg/L, the predicted amount of phosphorus could be adsorbed is 67.20 kg. But the field adsorption capacity was estimated to be 50% of the capacity measured with batch experiments (Drizo et al., 2002) due to the presence of solids and organic matter in the inlet wastewater in the field test. The other reason for the discrepancy was suggested by Ádám et al. (2006) that the inlet concentration of phosphorus is lower in full-scale system than in bench experiment. Moreover, the loading of real wastewater and thus enhance the potential development of biofilm, something which may reduce the adsorption capacity of the material compared to the bench experiment. As a result, the predicted value of phosphorus adsorbed by the coal slag in the pilot system was multiplied by 50%, equals to 33.6 kg of phosphorus. Taking the average value from the data in the pilot experiment, the removal of phosphorus in every operation was equal to 10,880 mg (0.8 mg/L $\times$ 13.6 m^3). Then under the current operating conditions and loadings to the system, the system could remove 3.97 kg (10,880 mg $\times$ 365 days) in one year. Basing on a daily operation, the life span of system for phosphorus removal by adsorption is about 8 years (33.6 kg to 3.97 kg/year). In the other way of saying, knowing that one person produces about 1.5 g P/day (equals 547.5 g/year) (Holtan et al., 1988), about 7437 kg of coal slag is needed for one person over 8 years for phosphorus removal.

Based on a treatment capacity for 500–10,000 p.e. of domestic wastewater, with effluent quality meeting the general discharge limits of secondary treatment, that is defined as BOD_5 and TSS concentrations of less than 20 mg/L (Tsagarakis et al., 2003 and UNEP, 1997), the vegetated sequencing batch coal slag bed achieved 40–50% of ammonia nitrogen removal after contact time of 10–18 h and with a hydraulic loading rate of 0.45 m^3/m^2 d. The activated sludge process requires only 4–8 h for efficient treatment with 50–60% ammonia nitrogen removal and a hydraulic loading rate of 30–50 m^3/m^2 d. and the conventional constructed wetland usually requires 4–15 days (Tsagarakis et al., 2003) and a hydraulic loading rate of 0.014–0.047 m^3/m^2 d for similar treatment targets. Compare to constructed wetland, the vegetated sequencing batch coal slag bed in this study require only several hours (within 24 h) to decrease the pollutants concentrations to acceptable discharge levels. Although activated sludge process requires relatively short retention time, the required costs and expertise are much higher due to its sophistication. A cost comparison was made based on the costs of a conventional activated sludge process in Shanghai (Yang et al., 2004) and that of a conventional constructed wetland in Shandong (Gao and Ma, 2006). From the current study, the construction cost of vegetated sequencing batch coal slag bed was 256 RMB/m^3 (Table 5), and the resulting operation cost was 0.13 RMB/m^3 by considering the costs of electricity, manpower and E&M maintenance. From the cases from Shanghai and Shandong, the construction and operating cost of activated sludge process were 782 RMB/m^3 and 0.79 RMB/m^3 respectively while those of conventional constructed wetland were 196 RMB/m^3 and 0.15 MB/m^3, respectively. Though activated sludge process is an efficient wastewater treatment method, its cost-effectiveness can only be achieved when it is applied on the usage of large populations in urban areas. In contrast, the use of vegetated sequencing batch coal slag bed is more affordable for the wastewater treatment demands in small communities in suburban areas.

Table 5
Cost comparisons of conventional activated sludge treatment process and conventional constructed wetland with the vegetated sequencing batch coal slag bed for domestic wastewater treatment

	Conventional activated sludge process[a] (RMB/m^3)	Conventional constructed wetland[b] (RMB/m^3)	Vegetated sequencing batch coal slag bed (RMB/m^3)
Construction	782	196	256
Operation			
Electricity	0.38	0.08	0.09
Manpower	0.15	0.04	0.01
Chemicals	0.06	–	–
E&M maintenance	0.20	0.03	0.03
Total	0.79	0.15	0.13

[a] Yang et al. (2004).
[b] Gao and Ma (2006).

4. Conclusions

With comparable costs, skills and manpower, the benefits of using the vegetated sequencing batch coal slag bed in this study are the shortening of retention time from several days to several hours and the decrease of land requirement by amplifying the hydraulic loading rate by more than 10 times for equivalent pollutant removal efficiency, when compared to conventional constructed wetland for domestic wastewater treatment purposes. On the other hand, the cost and the skill requirements are lower, when compared to conventional activated sludge process. With the advantages of ease of operation, low costs, desirable treatment efficiency and aesthetic value, the vegetated sequencing batch coal slag bed is proposed to be an alternative for onsite domestic wastewater treatment in suburban areas.

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