Organics removal of combined wastewater through shallow soil infiltration treatment: A field and laboratory study

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Abstract

Soil infiltration treatment (SIT) was proved to be an effective and low-cost treatment technique for decentralized effluents in the areas without perfect sewage systems. Field-scale experiments were conducted under several conditions to assess organics removals through a shallow soil infiltration treatment (SSIT, with effective depth 0.3 m) of combined wastewater (discharge from toilets, restaurants and a gas station), while bench-scale soil column experiments were performed in laboratory in parallel to investigate biological and abiological effects of this kind of system. From the start-up to the 10th month, the field SSIT trenches experienced the lowest and highest temperatures of the operation period in Shanghai and exhibited effective organics removals after maturation, with the highest removal rate 75.8% of chemical oxygen demand (COD), highest ultraviolet absorption at 254 nm (UV_{254}) decrease by 67.2% and 35.2–100% removals of phenolic and phthalate pollutants. The laboratory results indicated that more organics could be removed in room-temperatured ($25 \pm 2\,°C$) SSIT systems under different influent COD concentrations from 45 mg/l to 406 mg/l, and the highest total COD removal rate could reach 94.0%, in which biological effect accounted for 57.7–71.9%. The results showed that temperature and hydraulic loading rate were the most important factors influencing the removals of COD and organic pollutants in SSIT.
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1. Introduction

The annual discharge amount of wastewater in China exceeded 52.45 billion tonnes in 2005, which inevitably resulted in the further worsening of water quality of the top seven rivers in China, including Yangtze River, Yellow River and Huai River, etc., and there were only 41.0% of these rivers with water quality up to the Environmental Quality Standards (levels I–III) for Surface Water (GB3838-2002) [1]. High capital construction and operation costs are the major constraints limiting the application of municipal sewage treatment plants to a great extent, especially in China. Up to the end of 2005, the treatment rate of municipal sewage was only 52% in China and there were still 278 cities with no municipal sewage treatment plants [2]. It was esti-

mated that 95% of decentralized wastewater around the world was discharged into the environment without any treatment [3]. In rural areas, it is more difficult to handle the wastewater discharge into surface waters than in cities. Being not equipped with perfect sewage systems, many traveling beauty spots, nursing homes, villas and residential areas are undergoing the accelerated pollution by discharging their effluents directly into the environment.

SIT system has proved to be a good alternative for wastewater treatment with the consideration of efficiency and cost. Because of large demand of land area but no requirement of perfect sewage systems, its application was especially suitable for the treatment of decentralized wastewater in suburbs or rural areas. Up to now, SIT technology has been widely used for wastewater treatment and reuse in the United States, France, Israel and other countries [4–7].

In SIT systems, organic compounds, nitrogen, phosphorus, suspended solid (SS), trace metals, bacteria and viruses can

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Nomenclature

BOD$_5$	5-day biochemical oxygen demand (mg/l)
C	column
COD	chemical oxygen demand (mg/l)
H	height of column (cm)
L	length of trench (m)
NH$_4^+$-N	ammonia nitrogen (mg/l)
SIT	soil infiltration treatment
SS	suspended solid (mg/l)
SSIT	shallow soil infiltration treatment
T	trench
TNs	total nitrogen in soil (g/kg)
TNw	total nitrogen in wastewater (mg/l)
TPs	total phosphorus in soil (g/kg)
TPw	total phosphorus in wastewater (mg/l)
UV$_{254}$	ultraviolet absorption at 254 nm
W	width of trench (m)

Greek letter

Φ	diameter of column (cm)

be effectively removed through infiltration, percolation, sorption, chemical reaction, biotransformation, die-off, predation and plant uptake mechanisms or purification processes [5,8]. Extensive field and laboratory studies were undertaken by Sun et al. [9], Viswanathan et al. [10], Reemtsma et al. [11] and Quanrud et al. [12,13]. The removal rates of COD, SS, and viruses were greater than 80% with phosphorus removal nearly 100%. The removal of nitrogen is also reported evident but with comparative difficulty [14]. However, the SIT systems usually used in these studies (including fields and laboratories) were typically designed with effective depths of SIT trenches or columns larger than 0.6 m (always ranging from 0.6 m to 1.2 m) [8] and the wastewaters treated were primary or secondary treatment effluents (always domestic or artificial synthetic wastewaters). Based on the fact that biological degradation was active within the infiltration zone from 0 cm to 15 cm depth [8] or in the upper 30 cm layer of soils [15], the design and application of SSIT with effective depth less than 0.6 m is necessary for the consideration of construction costs and groundwater protection, and its feasibility to various wastewaters should also be taken into consideration.

Because of the fundamental role of organics removal in SIT systems and a close relationship between nutrient removal (nitro-

gen or phosphorus) and COD [16], it is firstly important to investigate organics removal in SSIT systems. The objective of this paper was to concentrate on organics removal by an SSIT system for the treatment of combined wastewater through a 10-month field and laboratory program, and nutrient removal will be included in another separate paper because of paper length. In this study, we tested the effects of hydraulic or organic load, wetting/drying period ratio, temperature, and biological and abiological transformations on organics removal, and the removal of different organic pollutants in this system was also investigated.

2. Materials and methods

2.1. Wastewater characteristics

The influent in this study was a combined wastewater, consisted of domestic wastewater (from toilets, restaurants, etc.) and wastewater from a nearby gas station. The ranges of major water quality indices for the influent were COD 53–180 mg/l, pH 7.06–7.18, SS 34–65 mg/l, total nitrogen (TNw) 8.5–21.4 mg/l, ammonia nitrogen (NH$_4^+$-N) 4.9–14.0 mg/l and total phosphorus (TPw) 0–7.7 mg/l, with an average ratio of 0.6 for 5-day biochemical oxygen demand (BOD$_5$)/COD.

2.2. Field facilities

The SSIT system in the field was composed of pre-aeration tank, sedimentation tank, four infiltration trenches, influent and effluent facilities (Fig. 1). The total area of the system was approximately 150 m^2 ($L \times W = 15$ m $\times$ 10 m), which used to be grassland. Each infiltration trench covered 15 m^2 ($L \times W = 10$ m $\times$ 1.5 m) with total and effective depths about 0.5 m and 0.3 m, respectively. Four trenches (labeled as T1, T2, T3 and T4) were designed in parallel, in which different soil constituents were used (Table 1). The combined wastewater was pumped from a collection well into the pre-aeration tank driven by solar batteries (LC-XA12100CH, Matsushita Electric Industrial Co. Limited). The pre-aerated and settled (pretreated) wastewater then flowed into the four infiltration trenches separately and was collected by water pipe system underneath, then discharged into a nearby stream by siphon.

The field SSIT system was started up in November 2005 and detailed experiments were conducted from February to August in 2006 during which the system became mature gradually. Eight runs were arranged with the consideration of different hydraulic
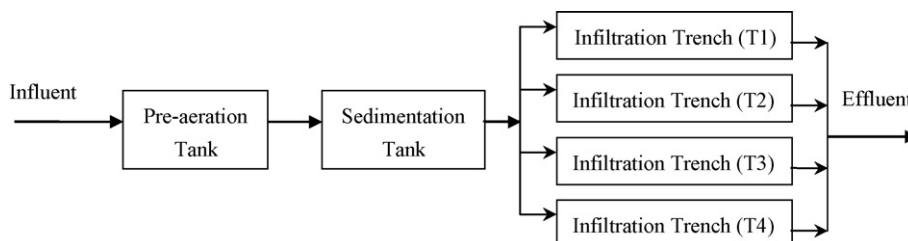

Fig. 1. Schematic flowchart of the SSIT system.

Table 1
Constituents and hydraulic conductivity for the four infiltration trenches in the field

Items	T1	T2	T3	T4
Artificial soil composition				
Local soil (%)	70	60	60	60
Coal slag (%)	20	20	20	20
Dewatered sludge (%)	10	10	10	10
Packing medium (%)	–	10 (Wood chips)	10 (Anthracite)	10 (Zeolite)
Hydraulic conductivity[a] (cm/s)	0.059	1.023	0.445	0.099

The percentage is indicated as volume ratio and the dimension of packing medium used was 1–3 cm in diameter.

[a] Hydraulic conductivity was measured according to the method of Lei et al. [17].

Table 2
Operation conditions in the field study (from February to August in 2006)

Parameters	Runs							
	I	II	III	IV	V	VI	VII	VIII
Date	February 5–February 20	February 27–March 16	March 18–April 10	April 18–May 6	May 18–June 5	June 12–June 27	July 5–July 19	July 27–August 10
Temperature (°C)	0.0–21.8	6.0–19.3	14.0–25.0	16.0–30.5	14.8–37.0	28.8–35.0	30.0–37.0	33.0–37.0
Hydraulic loading rate (m³/m²/d)	0.038	0.019	0.038	0.038	0.038	0.038	0.1	0.038
Influent COD (mg/l)	53–180	57–126	55–120	65–173	64–87	64–99	75–103	90–135
Influent NH_4^+-N (mg/l)	4.95–12.05	6.00–10.85	6.20–11.35	8.23–11.20	6.60–11.80	10.80–12.80	5.10–14.00	7.60–11.20
Influent TPw (mg/l)	0.00–7.68	0.00–0.76	0.00–0.43	0.00–0.35	0.00–0.02	0.27–0.38	0.34–0.40	0.12–0.36
Wetting/drying period ratio (h/h)	1/2	1/5	1/2	1/2	1/2	1/2	1/2	1/2
Air/water ratio (v/v)	14.0/1	14.0/1	14.0/1	7.0/1	3.5/1	No aeration	3.5/1	3.5/1

loading rates, influent COD or pollutant concentrations, wetting/drying period ratios, air/water ratios and temperatures (Table 2).

2.3. Artificial soil constituents

The local soil contained total organics 22.87 g/kg, total nitrogen (TNs) 1.4 g/kg and total phosphorus (TPs) 0.85 g/kg, with hydraulic conductivity 8.33×10^{-5} cm/s. After being repacked uniformly with coal slag, wood chips, anthracite or zeolite, the soil's hydraulic conductivity was remarkably improved (Table 1). In order to enrich the microorganism species and accelerate maturation process, dewatered sludge (from Quyang Sewage Treatment Plant, Shanghai) was mixed with the repacked soils. Besides, graded gravels were used to pile around water pipes to protect distribution and collection systems. The constituents of the four infiltration trenches (T1, T2, T3 and T4) were demonstrated in Table 1.

2.4. Laboratory columns

Two polymethylmethacrylate columns (H 180 cm, Φ 15 cm), labeled as C1 and C2, were used in this study, in which C1 was run just as the same way as the field study to simulate both biological and abiological removal processes, while in C2 only abiological removal process was thought to occur by the following disinfection procedure: the wall of C2 was cleaned with 70–75% (v/v) alcohol at first, then before being packed, artificial soils should be disinfected in an autoclave under 121 °C and

1.1 kg/cm for 1 h. The influent into C2 should also be disinfected for 0.5 h every day, and the disinfection of column and soils must be performed twice a month to avoid biological effects to a great extent.

Both columns were packed with total depth 0.5 m and effective depth 0.3 m of soils, with the same composition as T1 in the field and 3-cm layer of gravels underneath (Fig. 2). The bench-scale soil columns were run at room temperatures (25 ± 2 °C). The infiltration influent, stored at 4 °C in a refrigerator before
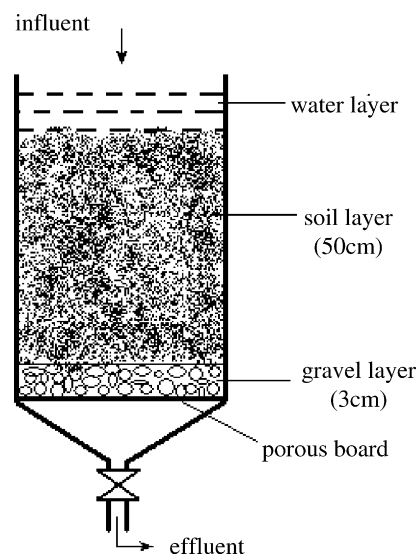

Fig. 2. Bench-scale soil column.

use, with COD concentration varied from 45 mg/l to 406 mg/l prepared with the combined wastewater and different dose of glucose, was continuously supplied to the columns under the highest hydraulic loading rate of the field study (0.1 m^3/m^2/d) and 1/2 of wetting/drying period ratio from February to August in 2006. At least 2 weeks were needed for one influent COD concentration condition for the consideration of process stabilization.

2.5. Sampling

The influent and effluent samples were collected once every 2 or 3 days for the field and once every 2 days for laboratory experiments, and an additional sample (pretreatment sample) was also collected from sedimentation tank in the field at the same time. All the samples were stored at 4 °C and analyzed within 24 h.

2.6. Analytical methods

COD was measured by following the method of No. 14540 of Photolab S12 (WTW, Germany) and used to evaluate the total amount of organics in wastewater.

UV$_{254}$ value is always used as an indicator of aromatic humic and fulvic structure substances, which are thought to be precursors for trihalomethane (THM) formation [18]. Aliquots of water samples were filtered through a 0.45 μm membrane and collected for analysis at 254 nm (UV Spectrumlab 52, Shanghai Lingguang Co.) with ultra-pure water as zero absorbance standard.

Organic component contents in wastewater were obtained by GC/MS analysis using NIST library as standard MS library. Samples were extracted with methylene dichloride immediately after being collected, and chromatogram analysis followed. Organics could be extracted from 500 ml water sample with totally 50 ml methylene dichloride in three times (20 ml + 15 ml + 15 ml). Because of high enough levels of organics in combined wastewater, the traditional XAD8/XAD4 resins adsorption [19] for sample condensation pretreatment was omitted. GC/MS analysis was performed on a gas chromatogram/mass spectrograph (Finnigan Voyager, USA) under the following conditions: mass spectrum detector (70 eV, EI, 200 °C), VF-5ms quartz capillary column (30 m × 0.25 mm, 0.25 μm) with He gas as carrier (1.0 ml/min), split ratio 20:1 and temperature increased by 20 °C per min from 50 °C (keep 2 min) to 300 °C (keep 10 min).

3. Results and discussion

3.1. COD removal

3.1.1. COD removal during start-up period in the field

The field SSIT system was started up from November 2005. During the 3-month immature period, the total COD removal varied between 30.4% and 44.5% for the four trenches, and the effluent COD was unstable because of influent fluctuation (Fig. 3), in which T2 and T3 exhibited better efficiencies for
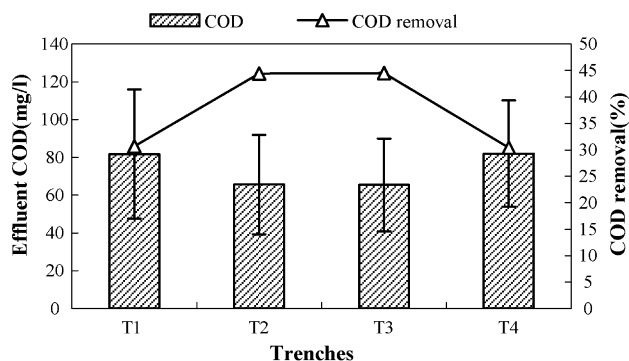

Fig. 3. Average effluent COD and COD removal during start-up: influent COD = 119.9 ± 34.0 mg/l.

COD removal during this period. This phenomenon may be caused by the fact that different packing medium were used (wood chips in T2 and anthracite in T3) with higher hydraulic conductivity resulted in T2 and T3 (Table 1), which may play a positive role in the acceleration of maturation for SSIT systems. And the detailed organics removal mechanisms for the four SSIT trenches are under investigation.

3.1.2. COD removal under different conditions in the field

Figs. 4 and 5 depicted the COD variations of the four SSIT trenches and COD removal rates under the arranged runs.

It was obvious that the influent COD changed randomly sometimes even after pretreatment (pre-aeration and settlement), however, the final effluent COD from the four trenches remained relatively stable and always below 40 mg/l with the variation of influent COD from 53 mg/l to 180 mg/l. The cumulative COD removal rates, about 50.6–75.8%, showed similar increase trends for the four trenches from Runs I to VIII, while only 10.0–35.2% of influent COD could be removed through pretreatment process (Fig. 5). The differences of COD removals between the trenches might be resulted from the different soil compositions of the four trenches and it seemed that T1 and T3 exhibited higher efficiencies (always 5–10% higher than the other two) in removing COD. Lower COD removals got in this study than those of Van Cuyk et al. [8] and Sun et al. [9] may be due to the more complicated wastewater treated and shallower effective depth designed for these SSIT trenches.

3.1.3. Factors of influencing COD removal for SSIT trenches

Hydraulic loading rate and wetting/drying period ratio were the most frequently reported influencing factors in SIT studies [8,14,20,21], while the variations in the duration of wetting/drying periods were not taken for having significant impact on organic removal efficiencies [12,13]. Thus in this study, to simplify the whole experiments, the wetting/drying period ratio was fixed at 1/2 (1/5 only in Run II) according to our preliminary experiment results with hydraulic loading rates being used and changed among the highest values in SIT systems; and the effects of hydraulic loading rate, air/water ratio in pre-aeration tank and temperature on COD removal were considered because of the field situation.
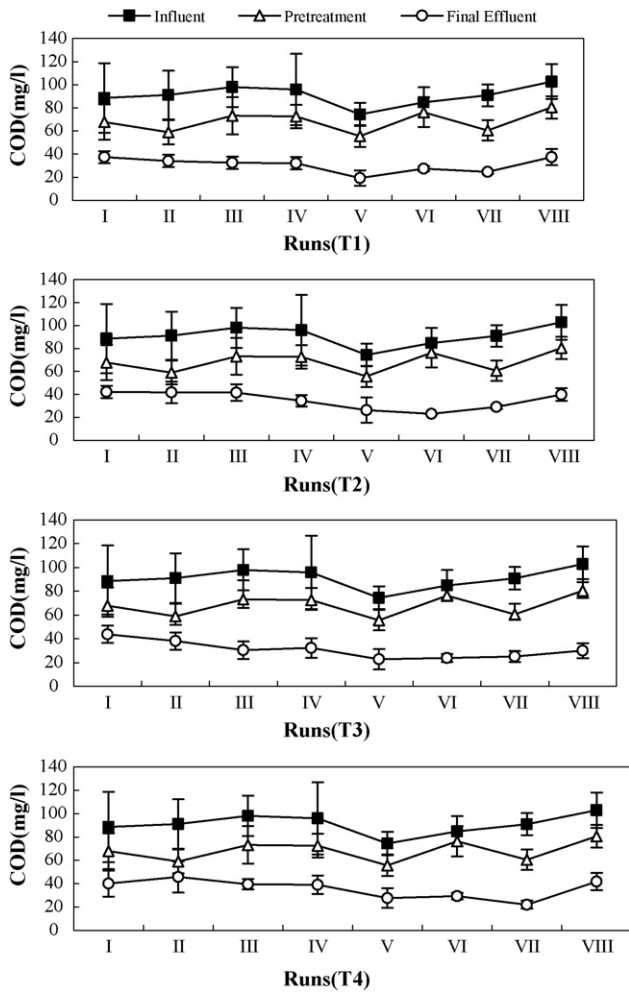
Fig. 4. Average COD variations for the four SSIT trenches at different conditions. The sampling times were 12, 7, 11, 9, 5, 4, 7 and 6 for Runs I, II, III, IV, V, VI, VII and VIII, respectively. The standard deviation here denoted the fluctuation of wastewaters or the stability of treatment systems.

Fig. 6 illustrated the changes of average cumulative COD removal of the four trenches with temperature, hydraulic loading rate, air/water ratio and influent COD. Although distinctive relationships between COD removal and other influencing factors could not be found due to the complex conditions in the field operation, the average COD removal showed an increase trend
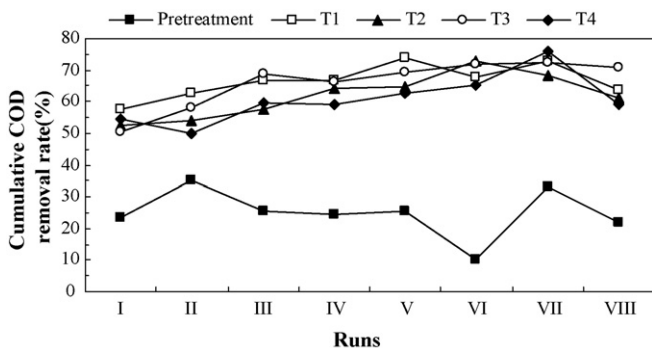

Fig. 5. Average cumulative COD removal rates for the four SSIT trenches at different conditions.
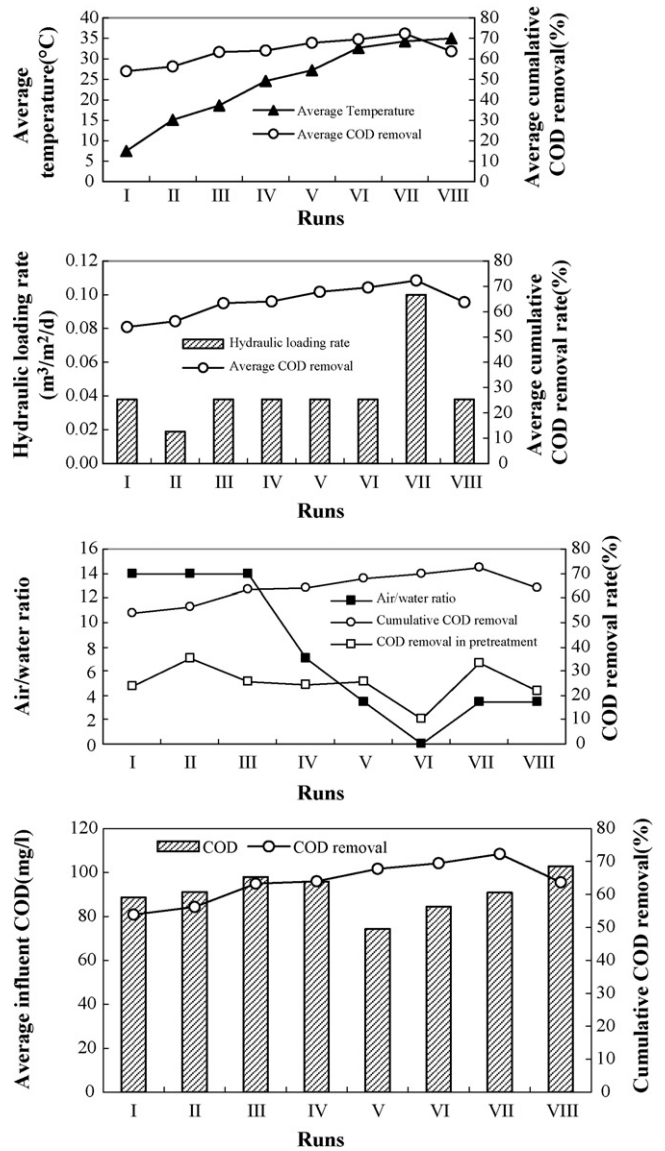

Fig. 6. Variations of average cumulative COD removals in the four trenches with temperature, hydraulic loading rate, air/water ratio and influent COD in the field.

with respect to temperature, indicating that temperature should be the most important factor for COD removal in SSIT trenches, which has been pointed out in SIT system by Sun et al. [9].

The COD removal increased with time going on (from Runs I to VIII), largely contributed by the increase of water temperature. And decrease in COD removal could also be observed when SSIT trenches were operated under higher hydraulic load even at higher temperature. The fact of the COD removal drop in Run VIII might be that the trenches have not been completely recovered from the impact of higher hydraulic loading rate in Run VII. That is to say, some kind of lag effect took place. For the SSIT studied, the maximum of hydraulic loading rate in the field may be 0.1 $m^3/m^2/d$ if effluent COD should meet the Surface Water Standards (GB3838-2002) (COD <40 mg/l for level V). The changes of air/water ratio in pre-aeration tank did have great influence on the water quality of pretreated wastewater,

Table 3
Average concentrations (µg/l) of major organic components in influent and effluent samples (collected at March. 8, 2006)

Main compounds	Influent	Effluent from pretreatment	Effluent from SSIT trenches	Total removal rate (%)
4-Nonyl phenol	1.170	1.028	0.329	71.9
Nonyl phenol	1.343	2.323	0	100
2-Methyl-4-(1,1,3,3-tetramethylbutyl)phenol	5.401	1.797	1.036	80.8
4-(1,1,3,3-Tetramethylbutyl)phenol	1.704	2.117	1.104	35.2
1,2-Diisobutylphthalate	9.286	9.206	5.907	36.4
1,2-Di-n-butylphthalate	9.370	6.412	4.982	46.8
1,2-Di (2-ehylhexyl) phthalate	8.376	4.811	3.739	55.4
n-Hexacosane	4.665	2.300	3.227	30.8
n-Heptacosane	6.975	3.259	4.963	28.8
n-Octacosane	7.654	2.688	3.834	49.9
n-Nonacosane	9.863	3.419	4.896	50.4
n-Triacontane	8.939	2.703	3.716	58.4
n-Hentriacontane	6.946	2.391	3.396	51.1

Table 4
Average concentrations (µg/l) of major organic components in influent and effluent samples (collected at August 5, 2006)

Main compounds	Influent	Effluent from pretreatment	Effluent from SSIT trenches	Total removal rate (%)
Tetrahydrofuran	3.761	1.542	1.059	71.8
Dimethylallyl alcohol	0.558	0.432	0.218	60.9
2,6-Bis(1,1-dimethylethyl)-4-methylphenol	0.793	0.467	0.232	70.7
2-$tert$-Butyl-4-(1,1,3,3-tetramethylbutyl)phenol	0.852	0.809	0.302	64.6
1,2-Di-n-butylphthalate	9.158	7.347	3.701	59.6
1,2-Di(2-ehylhexyl)phthalate	2.004	1.734	1.214	39.4
Ethylidene acetone	0.94	0.925	0.498	47.0
Toluene	4.203	3.614	2.59	38.4
n-Butyl acetate	0.467	0.382	0.339	27.4
2,4-Dimethyl-1-heptene	0.374	0.353	0.278	25.7
4-Methyloctane	0.778	0.705	0.524	32.6
Ethylbenzene	5.791	5.377	4.656	19.6
p-Xylene	4.67	4.437	3.916	16.1
o-Xylene	1.868	1.851	1.357	27.4
Hexachloroethane	0.872	0.911	0.709	18.7
n-Dodecane	1.152	0.999	0.894	22.4
2,6,10-Trimethyldodecane	0.685	0.499	0.401	41.5
Butanedioic acid, bis(2-methylpropyl)ester	1.912	1.557	1.401	26.7
Pentanedioic acid, dibutyl ester	4.919	4.502	3.585	27.1
N-phenyl-1-naphthylamine	4.584	3.861	3.084	32.7

which also can be seen from Tables 3 and 4, but little relationship could be found with the cumulative COD removals.

Besides, no clear relationship could be deduced from the field data of influent COD and COD removal, which was also investigated and manifested by our laboratory results (Fig. 7). It can
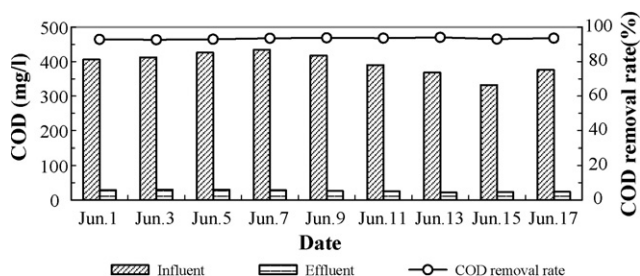

Fig. 7. Average COD removals under higher influent COD concentrations at 0.1 m³/m²/d in laboratory C1 (25 ± 2 °C).

be seen that with influent COD not more than 500 mg/l, the laboratory SSIT system performed very well in removing COD by achieving 92.7–94.0% of COD removal. The results indicated that the potential of SSIT system might be infinite for COD removal, which has been taken into account in our further laboratory investigations by increasing influent COD step by step.

3.2. UV_{254} decrease effect

UV_{254} absorption is always used as an indicator for substances with aromatic humic and fulvic structures. Because of the complex composition of combined wastewater, the changes of UV_{254} versus time seemed difficult to interpret (Fig. 8). However, it was obvious that the average UV_{254} absorption decreased more with time in Runs IV, V, VI and VIII than that in VII, by 49.3% and 23.2%, respectively, which may be caused by
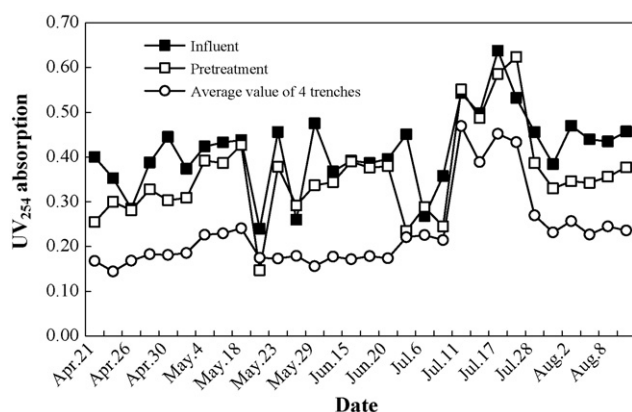
Fig. 8. Average UV$_{254}$ value vs. time for samples collected from four trenches during the period from Runs IV to VIII in the field.
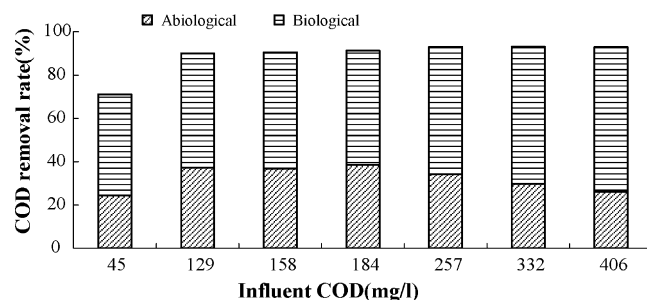

Fig. 9. Biological and abiological effects of COD removal in laboratory study: abiological COD removals were obtained directly from C2 experiments, and biological removals were the differences between the corresponding results of C1 and C2. For each influent COD concentration, the COD removal rate was the average of 2 weeks' experimental results.

the different hydraulic loading rates applied in these conditions. The results showed that under higher hydraulic loading rate (0.1 m^3/m^2/d in this study, that is, Run VII) SSIT trenches exhibited lower performance in removing substances with aromatic humic and fulvic structures, which were also difficult to be removed by other processes, e.g., aeration pretreatment in this study (Fig. 8). From the 10-month field study, generally speaking, 13.5–67.2% of UV$_{254}$ decrease could be achieved, and the lower hydraulic loading rate (0.038 m^3/m^2/d in this study) applied, the more effectiveness could be achieved in UV$_{254}$ decrease through SSIT trenches, which is different from the results of Quanrud et al. [12], who stated that organics attenuation indicated by UV$_{254}$ was essentially independent of mean hydraulic retention time. Little effect of temperature on UV$_{254}$ decrease was observed from the results. The results also indicated that UV$_{254}$ might be used as an indicator of SSIT system operation and management with no such lag effect as COD.

3.3. Removal of different organics

Tables 3 and 4 summarized the average GC/MS results of the major organic components in the influents and corresponding effluents from pretreatment and SSIT trenches in March and August 2006. Abundant in phenolic, phthalate and alkane pollutants, it was obvious that the contents and categories of organics in the combined wastewater changed randomly with time in the field, mainly owing to the arbitrary discharge from the nearby gas station, and many of them were recalcitrant to biodegradation.

It is well-known that phenolic pollutants are common chemicals and do harm to our environment, and phthalates, especially 1,2-di-*n*-butylphthalate and 1,2-di(2-ehylhexyl)phthalate, are typical environmental endocrine disruptors exerting bad impacts on growth and procreation of living creatures [22,23]. According to our previous studies [24,25], it is useful to remove these two kinds of substances for microorganisms by applying microporous carriers under appropriate nutrient or stable oxygen (aerobic/anoxic) conditions, which might be guaranteed by these SSIT systems with porous soil particles, nutrient influent and appropriate duration of wetting/drying periods. The results showed that the SSIT systems exhibited good capabilities of removing phenolic and phthalate pollutants, with removal rates varied between 35.2–100% and 36.4–59.6%, respectively, more effective than that got by Hutchins et al. [26] due to the differences of soil characteristics and operation conditions.

Oudot et al. [15] reported that 83–94% of hydrocarbons could be removed and the undegraded residue was composed of cyclic alkanes and aromatics in the field land-farming treatment and lysimeters. In our field study, it is also found that alkanes were difficult to remove through SSIT, even though the total removal rates varied between 28.8 and 58.4% which were mainly contributed to pretreatment processes. Therefore, alkanes removal still remains to be a challenge for SSIT trenches.

3.4. Biological and abiological effects of COD removals in SSIT system

Fig. 9 showed the results of COD removal, including biological and abiological effects, under the influent COD concentrations varied from 45 mg/l to 406 mg/l at 25 ± 2 °C in laboratory. Although the influents being different in COD concentrations, the biological and abiological removals remained relatively stable, about 46.7–66.8% and 24.4–38.6%, respectively, with total average COD removal rate varied from 71.1% to 93.1%. The results suggested that the temperature-controlled SSIT system could remove COD effectively under higher hydraulic loading rate (0.1 m^3/m^2/d), and the biological effect, accounting for 57.7–71.9% of total COD removal, was mainly contributed to the stable effluents with low COD concentrations varied from 13 mg/l to 29 mg/l. Being shallow in effective depth, the performance of SSIT seemed to agree with the observations of Reemstsma et al. [11] and Quanrud et al. [12,13] that organic removals were attributed primarily to biodegradation. It was also found that under fixed hydraulic loading rate (0.1 m^3/m^2/d) COD removal efficiency remained relatively stable with the increase of organic load, indicating that under the laboratory conditions organic loading rate did not play the same important role as hydraulic loading rate did in the operation of this kind of SIT system, which was partly verified by our field experiments but different from the results of Nema et al. [21].

On the other hand, from our experiments the soil's abiological effect (here mainly adsorption) could not be omitted for SSIT systems, which accounted for 28.1–42.3% of the total COD
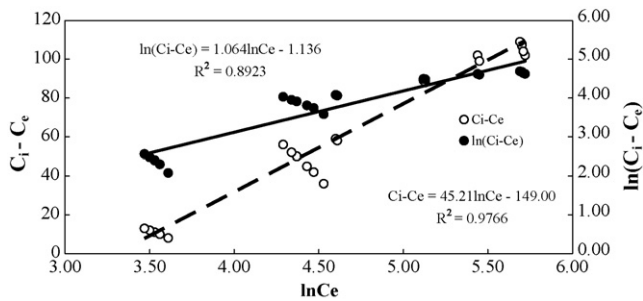
Fig. 10. Freundlich and Temkin isothermals plotted with data obtained from C2 for COD abological adsorption.

removal. Freundlich and Temkin isothermals are commonly used to model the adsorption of substances onto heterogeneous surface of soils [27] and the models could be formulated and linearized as Eqs. (1) and (2), respectively:

$$\ln(C_i - C_e) = \ln k + \frac{1}{n} \ln C_e \tag{1}$$

$$C_i - C_e = a + b \ln C_e \tag{2}$$

where C_i and C_e are initial and equilibrium concentrations, respectively, and k, n, a and b can be regarded as constants.

Using the influent and effluent COD of C2 as C_i and C_e, respectively, the linearized Freundlich and Temkin isothermals were plotted in Fig. 10. From the correlation coefficients obtained ($R^2 = 0.8923$ and 0.9766 for Freundlich and Temkin isothermals, respectively) it appeared that Temkin model fitted the data better than Freundlich model, which is not in accordance with the Zn adsorption onto soils [27], implying that the heat of organics adsorption seemed more likely to decrease linearly with the increment of adsorption.

Because of the complexity of organics removal mechanisms, future research is necessary to make sure whether organics accumulated or biodegraded in the soils of SSIT system. And the relationship between effective depth and maximum hydraulic loading rate should also be paid more attention. The work will be done in our follow-up studies.

4. Conclusions

This study revealed the efficient removal of organics in SSIT systems through both field and laboratory experiments. The following conclusions could be obtained.

The average highest total COD removal rates could reach 75.8% in the field and 94.0% in the laboratory, respectively, and the difference in COD removal might be caused mainly by the different wastewaters being used.

The field results indicated that UV_{254}, with no such lag effect as COD, could be a better indicator to denote the performance of SSIT systems under changing conditions for this kind of combined wastewater. Among the operation parameters being considered, water temperature and hydraulic loading rate influence more on COD removal than the others, and the organic substances, especially phenolic and phthlatant pollutants, can be effectively removed through the designed SSIT trenches.

Laboratory experiments showed that biological effects of SSIT systems were still the main contributor of effective COD removals and Temkin model seemed to fit the abiological adsorption data of the artificial soils better than Freundlich model. Moreover, the effluents from SSIT systems remained at low COD concentrations under frequently changing influent CODs demonstrating strong abilities of anti-fluctuation of influents, partly because of its infinite COD removal potential in this kind of SSIT systems.

Acknowledgements

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