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Advanced treatment of landfill leachate by a new combination process in a full-scale plant

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ABSTRACT

Advanced treatment of mature landfill leachate from a municipal landfill located in southern China (Jiangmen) was carried out in a full-scale plant using a new process. The combined process has a sequencing batch reactor (SBR) serving as the primary treatment, with polyferric sulfate (PFS) coagulation coupled with a Fenton system as secondary treatment, and a pair of upflow biological aerated filters (UBAFs) in parallel as tertiary treatment. The overall removal efficiency of chemical oxygen demand (COD) in this process was 97.3%, with an effluent COD less than 100 mg/L. Up to 99% ammonia ($N–NH_3$) removal efficiency was achieved in the SBR, with an effluent of less than 3 mg/L, which meets the discharge standard (≤25 mg/L) with only primary treatment. The total phosphorus (TP) and suspended solids (SS) in the final effluent were reduced to less than 1 mg/L and 10 mg/L, respectively. The experience gained in the operation and maintenance will lead to a more stable performance of this combined process. An economic analysis shows that the overall operating cost of the advanced treatment was $2.70/m^3. This new combination process was proved to be highly compatible and efficient in a small-scale landfill leachate treatment plant and is recommended for small-scale landfill leachate treatment plants.

1. Introduction

Landfill is one of the most widely employed methods for the disposal of municipal solid wastes (MSW). Up to 95% of the total MSW collected worldwide is disposed of in landfills [1,2]. Although some promising alternative methods, such as incineration and composting, are nowadays used, not all MSW can be composted or incinerated; incineration leaves a residue of approximately 10–20% that must be landfilled [3].

Leachate generated from landfills is a high-strength wastewater that may contain large amounts of organic matter and inorganic matter, with humic-type substances an important group, as well as ammonia nitrogen, heavy metals, chlorinated organics and inorganic salts. Untreated leachate can permeate ground water or mix with surface waters and contribute to the pollution of soil, ground water, and surface water [4]. The potential dangers of landfill leachate have been confirmed and it is generally necessary to treat it so that it meets the standards for discharge into sewer or into natural waters.

However, as more stringent discharge requirements are continuously being imposed regarding ground and surface waters, the treatment of landfill leachate becomes a both environmental and economic concern, in that much stricter discharge standards impose greater cost for treatment. So it is of great importance to determine the most appropriate treatment option as well as the optimal operating conditions required to achieve compatibility in combination treatment processes and the maximum removal of pollutants from landfill leachate.

For many years, conventional biological treatments and classical physicochemical methods were considered the most appropriate technologies for manipulation and management of high-strength effluents like landfill leachate [5]. Various techniques, such as SBR and its modification [6–10], upflow anaerobic sludge blanket (UASB) [11–13], coagulation–flocculation [14–17], adsorption [18,19], air stripping [20–22], and so on, have been used to treat landfill leachate. For biodegradable (BOD_5/COD ratio >0.3) landfill leachate, biological techniques can be effective in simultaneous removal of organic carbon and nitrogen. Physicochemical treatments can then act as a refining step for the stabilized effluent of biologically treated leachate.

However, with the ageing of landfill sites and with more stabilized leachate, as well as with the more stringent discharge standards, conventional biological treatments followed by classical physicochemical methods are no longer adequate to achieve

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the levels of purification needed to reduce the negative effects of landfill leachate on ecology and humankind. This implies that, in order to meet the new standards, further treatment is needed, or new treatment alternatives must be found. Membrane technologies, particularly reverse osmosis (RO), one of the most promising new processes, seem to be a more effective alternative than conventional methods for mature landfill leachate treatment. But even the membrane technologies have obvious drawbacks, which remain unsolved: extensive application is inhibited due to the expensive facilities and European patents, membrane fouling that results in a short lifetime of membranes and decreases productivity, and the generation of large quantities of residual concentrate that is unusable and which needs further treatment.

The Fenton process has been proposed and studied extensively in recent years [23–30], and it has been confirmed as a highly effective alternative for degrading recalcitrant organic matter in a variety of wastewaters, including landfill leachate. With the Fenton process, the high fraction of high molecular weight organics is degraded and partially removed, enhancing biodegradability. The potential of prior chemical oxidation to convert initially recalcitrant compounds to more readily biodegradable intermediates, which can then be removed through subsequent biological treatment, has been reported [31,32]. The technology of UBAF has been developed extensively due to its advantages, such as small footprint and excellent performance at much higher loading rates than that of conventional biological processes, with high removal efficiencies and capacities for carbonaceous organic substances, total nitrogen (TN), ammonia and SS [33]. So the Fenton-treated effluent could be purified by a subsequent UBAF. However, the reported application of Fenton's reagent or combined processes incorporates Fenton reaction to the treatment of landfill leachate which were nearly all on the bench or pilot scale, the reported practical application is scarce.

Using an SBR as the primary stage, PFS coagulation and a Fenton system as secondary treatment and UBAF as the tertiary treatment may be a new combined approach to advanced landfill leachate treatment. Our aim was to evaluate the feasibility and compatibility of this multistage process for the advanced treatment of a stabilized landfill leachate in a full-scale plant, to reduce the concentrations of organic matter, phosphorus and, nitrogen.

2. Materials and methods

2.1. Landfill leachate characteristics

The landfill has been in operation for 10 years and is located in Jiangmen, a city in Southern China. The total area of the landfill is 140,000 m^2 and about 750 tons of municipal solid waste is disposed daily. Leachate generation in the landfill was about 150–200 m^3/day. It was collected in ponds with 8000 m^3 capacity and was then treated at the landfill site. The composition of the landfill leachate varies greatly depending on the season, leachate collection system, and particularly the age of landfill. The average physicochemical characteristics of raw leachate based on 3 years' statistics are shown in Table 1. It was a dark black alkaline mixture. The average BOD_5/COD ratio was below 0.20, indicating low biodegradability. Other major components present in the leachate were ammonia and chloride.

2.2. SBR treatment

Biological treatment of the raw leachate was carried out in a SBR with a working volume of 1200 m^3. Air was supplied by air compressors through air pipes and ventilated on the bottom of the reactor, and mechanical agitation was performed by vertical vanes. Sludge was drawn by siphon, and the solid residence time was controlled at about 20 days. The reactor was operated at normal atmospheric temperature, and in the sequence of 1 h fill and concurrent agitation, 4 h mechanical agitation, 5 h aeration, 2 h mechanical agitation, 3 h aeration, 8 h settling, and 1 h decant. These processes were controlled automatically. Sludge was sampled and examined regularly to assess the performance of the SBR.

Table 1
Landfill leachate average composition.

Parameter	Unit	Range	Average
pH		8.00–9.34	8.75
Conductivity	mS/cm	7.56–12.5	9.50
Total suspended solids	mg/L	285–50	350
COD	mg/L	930–26,000	3000
BOD_5	mg/L	200–5500	650
TOC	mg/L	1400–23,000	1600
$N–NH_3$	mg/L	450–2450	1200
Cl^-	mg/L	1300–2500	1500
SO_4^{2-}	mg/L	50–400	200
TP	mg/L	8–45	15

2.3. PFS coagulation

The supernatant from the SBR was collected in a buffer pool and then fed into a partition board flocculation basin with a working volume of 55 m^3. The coagulant PFS was mixed with leachate in the pipe before being pumped into the basin. Coagulation and sedimentation was performed in the basin. An overflow weir was fixed at the end of the basin for floc separation. The hydraulic retention time (HRT) was controlled at approximately 5.5 h. The dose of coagulant was determined by jar test when a new batch of coagulant was used, or the water quality from SBR effluent varied noticeably, or when temperature varied because of seasonal transition. No pH adjustment was needed before coagulation.

2.4. Fenton system

The PFS-treated leachate was then fed into a Fenton system for further treatment. The Fenton system includes four stages: oxidation, neutralization, flocculation, and sedimentation. It was operated in intermittent mode that works continuously for about 8 h every day after the PFS-treated effluent was fed. In the oxidation stage, ferrous sulfate and hydrogen peroxide were added in a 55-m^3 reaction tank for the oxidation. At the end of the oxidation, neutralization was carried out by addition of sodium hydroxide. The pH was conditioned to approximately 7.0–8.0. Then a small amount of polyacrylamide (PAM: 0.2%, w/w) was added and mixed in the pipeline mixer to perform flocculation. Finally, the solution was allowed to settle in a plug-flow sedimentation tank. Supernatant from the Fenton treatment overflowed a weir at the end of the tank. The working volume of the settler is 55 m^3, and the HRT was controlled at 5.5 h.

2.5. UBAF filtration

Filtration was carried out by two UBAFs in parallel. The Fenton-treated leachate was collected in a buffer pool and then pumped into the BAFs for final treatment. The two UBAFs are of the same design, each with a working volume of 25 m^3. The medium is ceramic and ranged in size from 3 mm to 5 mm. The air was introduced into the reactors from the bottom and the air flux was controlled with an air flow meter. The HRT were maintained at about 3 h, and the ratio of aeration gas to water was about 5:1. Backwash of the reactors was determined by the effluent quality. The landfill leachate advanced treatment process is sketched in Fig. 1.

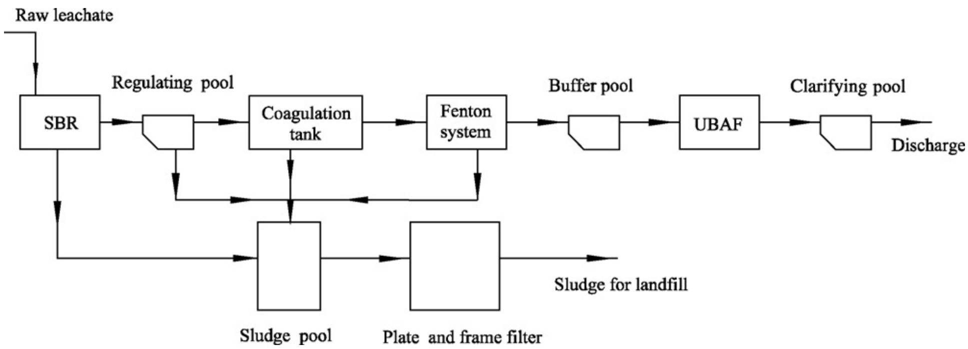

Fig. 1. Schematic of the landfill leachate advanced treatment process.

2.6. Analytical methods

Measurement for the concentrations of COD, ammonium, TP in influent and effluent of each operating unit was made using standard methods [34]. Other parameters, such as 5-day biochemical oxygen demand (BOD_5), pH, alkalinity, color, temperature, dissolved oxygen (DO) and volatile suspended solids (VSS) were monitored regularly.

2.7. Economic analysis

The overall operating cost of this multistage process for landfill leachate advanced treatment, including the reagents and energy consumption in each unit, was assessed and then the economic feasibility was evaluated by comparison with other combined processes.

3. Results

3.1. SBR treatment

The landfill leachate collected in the regulating pools was fed into the SBR for primary treatment. Fig. 2 shows the COD variation in SBR influent and effluent. There were large fluctuations in influent COD, which ranged between 930 mg/L and 9000 mg/L, as shown in Fig. 2. There are many factors affecting the quality of landfill leachates, i.e., age, precipitation, season, waste type and composition [5]. In this case, the COD fluctuation was mainly related to the seasonal weather and waste type. It should be noted that the sharp increase of influent COD from days 170 to 200 was mainly due to the mixing of municipal fecal supernatant with raw leachate for only a month. The COD removal by SBR was rather steady, with an average removal efficiency of 76% and an average effluent COD of 640 mg/L, in spite of the COD fluctuation in raw leachate. The slight change in effluent COD during the seasonal transitions (days 26–40, days 100–121, and days 167–189) indicated that temperature variation could pose noticeable but not severe effects on the biological treatment. The biggest adverse factor was lower temperatures (5–15 °C) in winter, but did not upset the system. The BOD_5/COD ratio of the supernatant of SBR was less than 0.05 (data not shown), almost non-biodegradable, so that any further treatment needed to be physicochemical means.

The variation of ammonia concentration in the influent and effluent of the SBR is shown in Fig. 3. A surge of effluent ammonia was observed because of temperature change as winter arrived (days 38–43). However, after a couple of days for adaptation, effluent ammonia dropped quickly. Highly effective ammonia removal was achieved throughout the operating periods (except days 38–43), even when the influent ammonia rose as high as 1500 mg/L. The average removal efficiency exceeded 99%, with the effluent having an average of less than 3 mg/L. The effluent ammonia reached the local discharge standards ($\leq$25 mg/L), no ammonia treatment was needed in the subsequent process. The mixing of municipal fecal supernatant with raw leachate from days 170 to 200 imposed little effect on ammonia conversion.

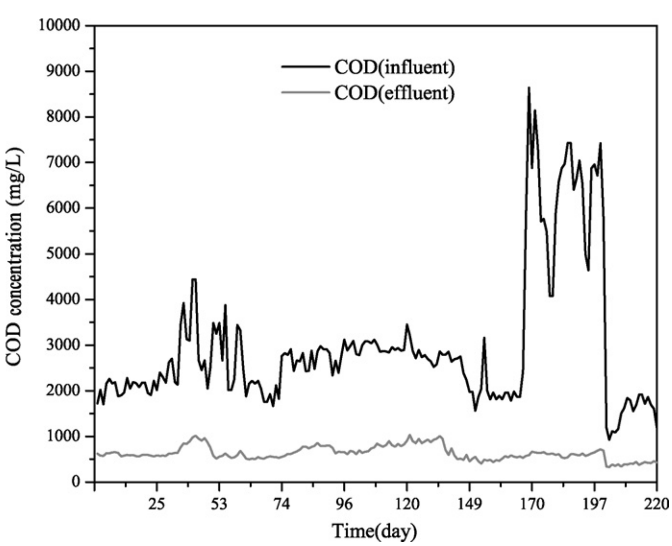

Fig. 2. COD concentration in influent and effluent of SBR during the operating periods.

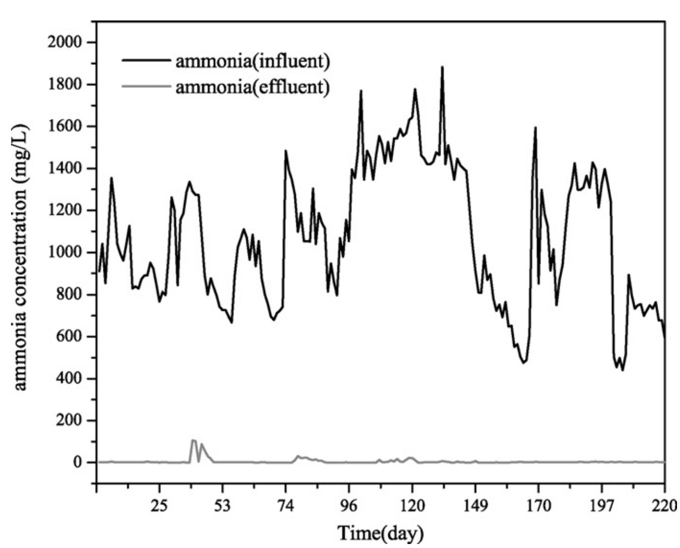

Fig. 3. Ammonia concentration in influent and effluent of SBR during the operating periods.

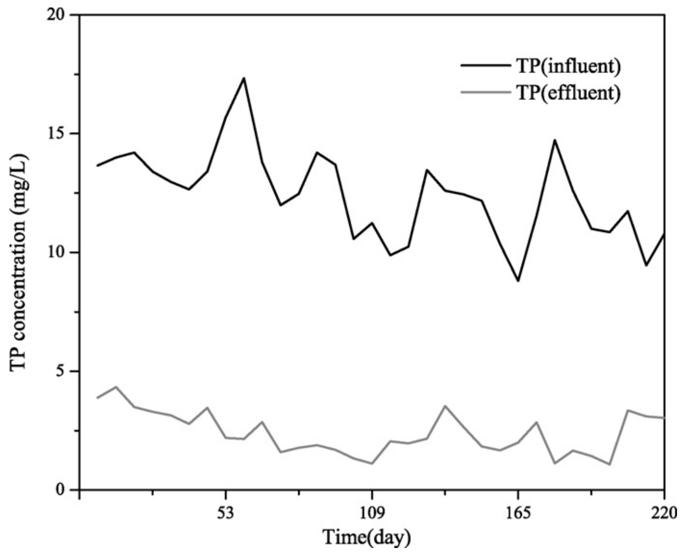

Fig. 4. TP concentration in influent and effluent of SBR during the operating periods.

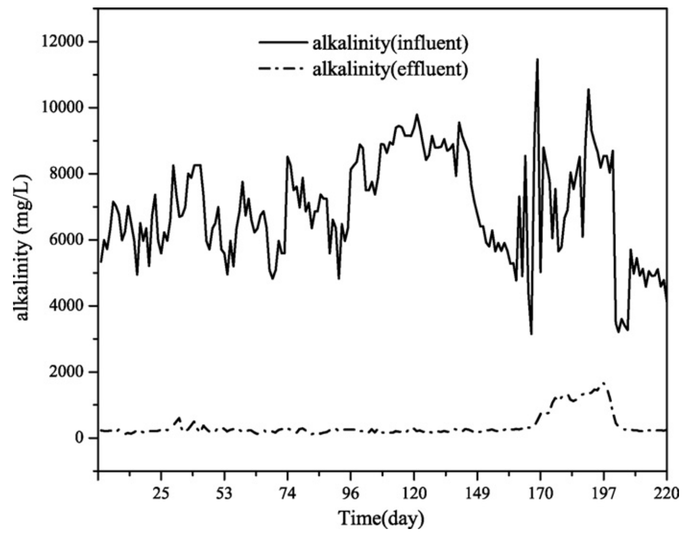

Fig. 6. Alkalinity in influent and effluent of SBR during the operating periods.

The SBR treatment is not only effective for ammonia conversion, but also helpful for phosphorus removal. Fig. 4 shows the TP variation in SBR treatment. When the influent TP ranged from 7 mg/L to 18 mg/L, the effluent TP was less than 5 mg/L and the average removal efficiency was 81%. Further treatment of phosphate was needed, since the TP in SBR effluent sometimes exceeded the discharge permit requirement of <3 mg/L.

The pH and alkalinity are indicators of the nitrification and denitrification performance in biological treatment. The pH and alkalinity variations are shown in Figs. 5 and 6. Fig. 5 shows that pH in the influent (range from 7.9 to 9.1) was higher than that in effluent (range from 5.5 to 8.5), except from days 170 to 200, when the pH suddenly rose from 7.0 to above 8.0. Fig. 6 shows that influent alkalinity was consistently higher than effluent alkalinity, and a similar rise in effluent alkalinity can be found from days 170 to 200. Nitrification produces H^+ and consumes alkalinity, while denitrification consumes H^+ and produces alkalinity. Therefore, during this period, an increase in organic carbon (in Fig. 2) due to the addition of municipal fecal supernatant in influent resulted in the activation of denitrification performance, and concomitantly led to the surge of effluent pH and alkalinity. It should be noted that the steady rise of SBR effluent pH from days 130 to 170 was mainly due to the decrease of ammonia (Fig. 3) and the consequent abatement of nitrification.

3.2. PFS coagulation coupled with a Fenton system

The SBR-treated leachate needed physicochemical treatment because of its extremely low biodegradability. PFS coagulation was used to remove the suspended matter and colloids that are an important group of refractory compounds contained in the biologically treated leachate. A subsequent Fenton system was used to eliminate the dissolved organic matter still remaining in the coagulation-treated leachate.

Fig. 7 shows the COD variation in the secondary treatment system. When the influent COD ranged from 330 mg/L to 1050 mg/L, the PFS coagulation effluent was maintained with COD between 200 mg/L and 300 mg/L, except days 43–47, because of a surge in the SBR effluent and between days 196 and 200, because of the poor quality of the coagulant. The average COD removal efficiency was 63%. The COD of the Fenton-treated leachate steadily ranged

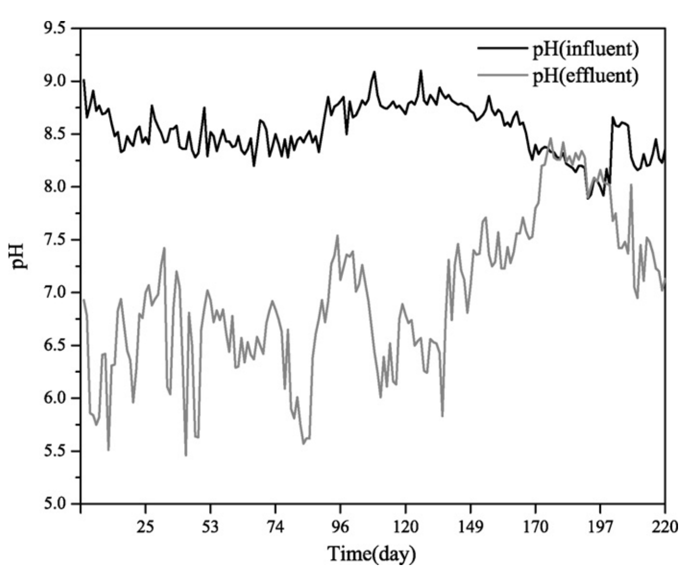

Fig. 5. pH of influent and effluent of SBR during the operating periods.

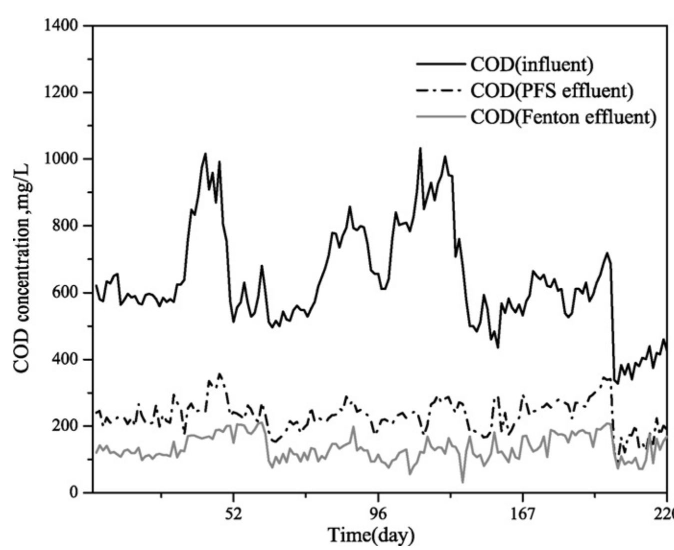

Fig. 7. COD concentration in influent and effluent of PFS coagulation and Fenton system during the operating periods.

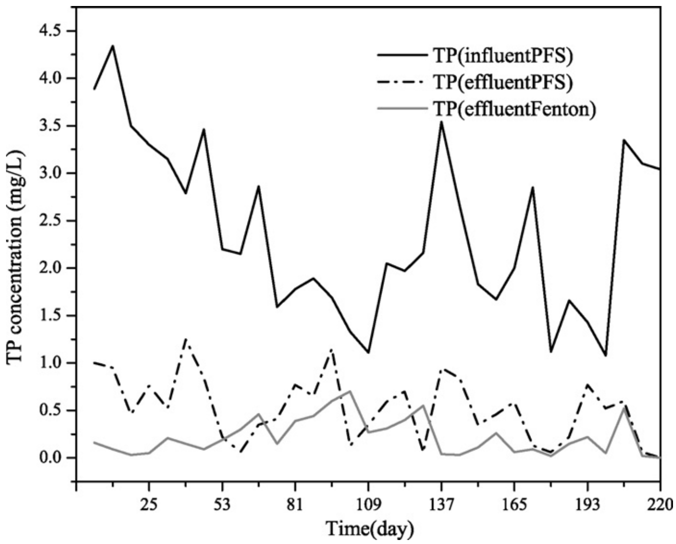

Fig. 8. TP variation in influent and effluent of PFS coagulation and Fenton system during the operating periods.

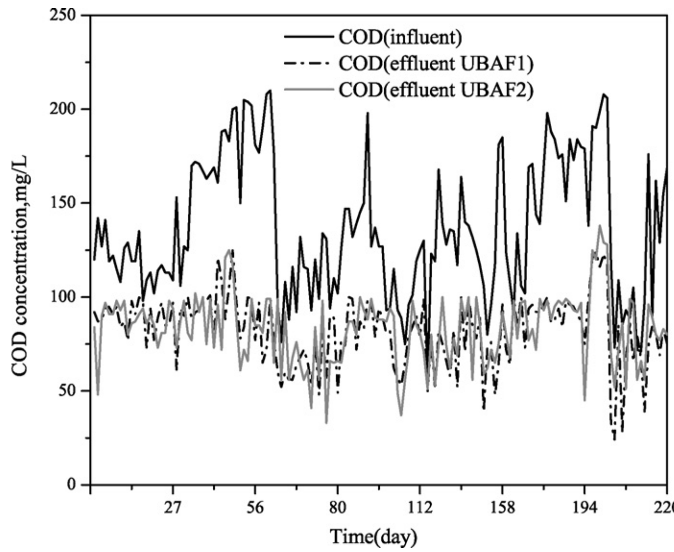

Fig. 10. COD variation in influent and effluent of UBAF1 and UBAF2 during the operating periods.

from 80 mg/L to 200 mg/L, with an average COD removal efficiency of 41%. The quality problem with the coagulant PFS between days 196 and 200 led to a rise in the non-biodegradable COD in both the PFS coagulation and the Fenton-treated effluent. This issue indicates that PFS coagulation is the key point in the physicochemical treatment for refractory organic matter removal.

The results of TP removal from SBR-treated leachate by the treatment of PFS coagulation and Fenton system are given in Fig. 8. The TP in PFS coagulation effluent was less than 1.5 mg/L, well below the discharge standards 3 mg/L, with an average TP removal efficiency of 76%. The TP was further polished by Fenton treatment, with an average concentration less than 0.3 mg/L. The results shown in Fig. 8 reveal that the microbiological treatment followed by chemical precipitation for phosphorus removal was extremely effective.

The pH variation in the secondary treatment system is shown in Fig. 9. The pH of PFS-treated effluent was much lower than that in the influent, because the hydrolysis of PFS produced H^+. In the Fenton system, oxidation requires an initial pH between 3 and 5. The pH in PFS effluent just meets this requirement. Before flocculation,

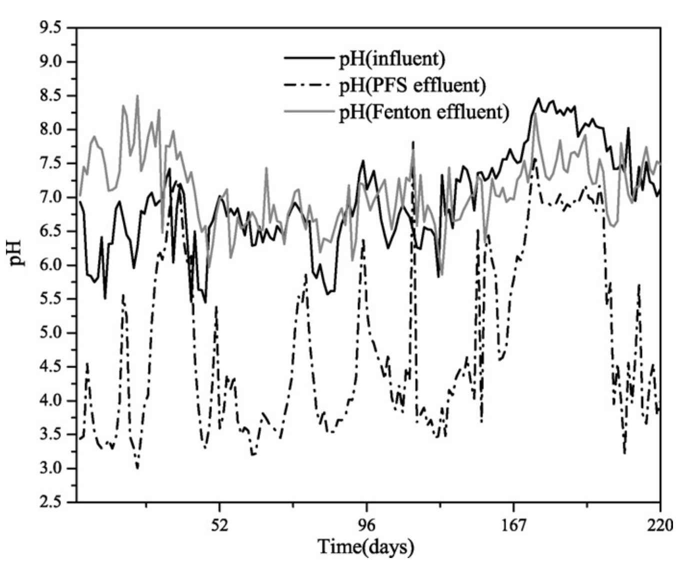

Fig. 9. pH variation in influent and effluent of PFS coagulation and Fenton system during the operating periods.

a pH adjustment was made since PAM flocculation needs a pH level above 7.0. The effluent from the Fenton system had pH between 6.5 and 9.0, suitable for the following UBAF treatment.

3.3. *UBAF filtration*

To ensure that the final effluent COD was below 100 mg/L, a UBAF system was used as a refining step for the physicochemical treatment process. The COD removal by UBAF1 and UBAF2 treatment is shown in Fig. 10. The COD in the effluent of UBAF1 and UBAF2 was consistently below 100 mg/L (except in periods affected by the dramatic flocculation of leachate and the coagulant quality problem), and average COD removal efficiencies of 37.5% and 36.5% were achieved.

The pH of the Fenton-treated effluent was controlled within the range 7.0–8.5 after UBAF treatment. The effluent of UBAF was collected in a clarifying pool and can be discharged directly into surface water. Fish were able to live in the clarifying pool.

4. Discussion

4.1. *Process analysis*

4.1.1. *Process selection analysis*

The selection of the advanced treatment process is of crucial importance to meet the discharge standards.

The SBR is used as a primary treatment, for rough elimination of carbon, nitrogen, phosphorus, color and SS to a relative low range. It facilitates the subsequent physicochemical treatment and reduces the cost of reagents in coagulation and in advanced oxidation processes (AOPs). The sequencing selection is also important for the simultaneous removal of carbon, nitrogen and phosphorus. In this sequencing regime, two batches alternating aerobic and anaerobic scheme, were employed. The alternating oxic and anoxic conditions created by this sequencing scheme contribute to the diversity of flora in the activated sludge, which enables the various microorganisms to perform specific functions for the removal of specific pollutants.

The physicochemical treatment serves as a secondary treatment, because the SBR effluent had such a low biodegradability that further biological treatment would not be effective. Coagulation and chemical oxidation are recommended among methods (such as chemical precipitation, activated carbon adsorption, and membrane processes), for treating stabilized leachate [35,36]. In view of the relatively small volume of leachate to be treated (about 150–200 m^3/day), coagulation and chemical oxidation are feasible. So coagulation and chemical oxidation were chosen as the secondary treatment process.

The coagulant selection was determined by both its pollutant removal performance and cost. Laboratory tests and a pilot study indicated that PFS should be selected for its efficient floc aggregation, excellent sludge settleability and relatively low cost. Two advantages of using PFS coagulation can be found. One is that PFS coagulation can reduce the cost of the subsequent AOP treatment. The other is that the PFS-treated leachate is compatible with a Fenton system, because the acidic effluent of PFS coagulation treatment is suitable as influent to a Fenton system (optimal initial pH of a Fenton is between 3 and 4, and it must be below 6). So no initial pH adjustment was needed.

Fenton oxidation is often considered when treating leachate with chemical oxidation. The Fenton oxidation process can break down or rearrange molecular structures of organic matter and convert the non-biodegradable organic compounds to more biodegradable forms [37]. The initial pH, dosage of Fenton reagents and reaction time were important controls of the Fenton system. The order in which the two Fenton reagents are added also impacts the treatment efficiency. We added ferrous sulfate first, followed by hydrogen peroxide solution, and then NaOH solution added to condition the pH, finally PAM was added for flocculation. Experience showed that if the hydrogen peroxide solution was added prior to the ferrous sulfate, the COD removal decreased by 11%.

UBAF filtration, capable of the physical interception and biological degradation of pollutants, served as the last polishing step of the advanced treatment process. Since the Fenton system effluent has a light yellow color (unavoidable, because of a small residue of iron) and relatively more biodegradable organics, employing the UABF filtration process can perform the physical interception and biological degradation function to reduce the residual color and COD, ensuring the water quality meets the discharge standard. Practice showed that the performance of UBAF was adequate for further removal of the residual COD and color.

4.1.2. Process compatibility analysis

A summary of the major parameters of the treatment in each unit is shown in Table 2. Table 2 shows that the SBR treatment is indispensable in this multistage process, for its high efficiency of biodegradable carbon elimination (76%), ammonia conversion (>99%) and phosphorus removal (81%), in a cost-effective manner. The effluent of ammonia ($\leq$3 mg/L) was routinely less than the discharge requirement ($\leq$25 mg/L) from just this first stage treatment. The color of raw leachate turned from dark black to transparent brown, and SS and sulfate were also greatly reduced after SBR treatment.

The PFS coagulation is crucial to the removal of non-biodegradable organic matter. The data (Figs. 7 and 8) in full-scale practice during periods in days 43 to 47 and days 196 to 200 clearly showed that when coagulation efficiency was not good enough, the subsequent treatment was not as effective. So it is necessary to control the PFS coagulation in an efficient state, and problems must be avoided by daily examination. After the PFS coagulation treatment, an average COD of 230 mg/L remained, and the color was reduced to 40°. The TP in the PFS Coagulation effluent was less than 1.5 mg/L, meeting the local discharge standards ($\leq$3 mg/L). The Fenton system is essential to the transformation of the non-biodegradable dissolved organic matter that cannot be removed by coagulation into more degradable forms. The COD was further reduced to about 140 mg/L, and the biodegradability of its effluent rose from 0.05 to 0.17, making subsequent biological treatment possible.

The final UBAF filtration as a tertiary treatment is necessary and effective to perform the physical interception and biological degradation function to further reduce the COD below 100 mg/L. A clear water stream with color less than 4° and SS below 10 mg/L was obtained. The compatibility of this multistage process proved to be excellent.

It should be noted that PFS coagulation and Fenton process introduce sulfate and iron in the treated leachate. Although iron is removed by neutralization and precipitation, sulfate still remains. The sulfate concentration rises to 500–800 mg/L in PFS coagulation effluent, and to 1000–1500 mg/L in Fenton-treated leachate, and to 900–1400 mg/L in UBAF effluent. The potential danger posed by sulfate is H_2S release when it is present in an anaerobic environment. Some sulfate reduction research [38,39] has been carried out. In this case, for the sake of safety, avoiding the introduction of sulfate would be the best option. To find out the optimal substitutes for PFS and ferrous sulfate that introduce the sulfate, further investigation was needed.

4.2. Operation and maintenance of the advanced treatment system

Since the mature leachate is a strongly ammonia-containing wastewater (ammonia often above 1100 mg/L), and a high concentration of ammonia is toxic to bacteria, recirculation from the end to the front of the SBR was necessary when the raw leachate was being fed. Another issue must be avoided too, that is, when large amounts of ammonia was converted by nitrification, and in the same time, biodegradable carbon was insufficient for denitrification, the pH dropped sharply and alkalinity became inadequate to the conversion of the remaining ammonia, addition of lime was needed to balance the pH and alkalinity equilibrium that is appropriate to nitrification.

The sludge properties were monitored regularly by the parameters of SS, sludge volume (SV), sludge volumetric index (SVI) and VSS. Microscopic observation was also carried out to assess the performance of sludge in terms of the protozoa species. When the sludge was operating well, the ciliated protozoa were dominant, and ciliates that attach to floc particles with a stalk, rather than the free-swimming ciliates, are the best indicators of a stable sludge.

Because PFS coagulation and Fenton treatment are sensitive to any changes in the effluent quality at the preceding unit, close attention must be paid to changes in effluent quality in each unit operation. So jar tests are a must to re-determine the dosage of PFS and the Fenton's reagent when the treatment efficiencies appear to have decreased. The coagulant quality and dosage should be determined by periodic jar tests. Because the reagents used in coagulation and in a Fenton system are highly corrosive, tap water must be use to wash the dosing pipeline after the reagents have been pumped.

The two major controlling factors for UBAF filtration are the HRT and gas to water ratio. These need to be adjusted according to the quality of the effluent from the preceding unit. Full-scale tests shows that the best HRT was 3 h, and a gas to water ratio 5:1 when the preceding units were all operating well, which was consistent with the laboratory and pilot study. Backwash was needed when the effluent quality decreases. Experience revealed that a 3-week interval between the backwashes of the UABF was desirable.

The sludge generated from the SBR and the chemical coagulation and flocculation was removed by a plate and frame filter, and then landfilled.

4.3. Economic analysis

The reagents consumption is listed in Table 3. Table 3 shows that total reagents cost was \$1.37/m^3. The average electric power

Table 2
Major parameters of advanced treatment in each unit operation.

Parameters	Color (°)	COD ($mg\,L^{-1}$)	BOD ($mg\,L^{-1}$)	Ammonia ($mg\,L^{-1}$)	TP ($mg\,L^{-1}$)	SS ($mg\,L^{-1}$)	Sulfate ($mg\,L^{-1}$)
Raw leachate	2000	3000	600	1100	13	250	50–400
SBR	>500	640	30	<3	<5	10–60	20–40
PFS	40	230	15	<3	<1	<10	500–800
Fenton	<16	140	20	Not detected	<0.5	<10	1000–1500
UBAF	<4	82	10	Not detected	<1	<10	900–1400

Table 3
Reagents cost in each unit for advanced treatment.

Items	Lime	PFS	$FeSO_4{\cdot}7H_2O$	H_2O_2	NaOH	PAM
Price ($/ton)	100.0	400.0	85.7	357.1	257.1	4285.7
Dosage (kg/m^3)	1.5	1.0	0.8	1.0	1.5	2×10^{-6}
Operating cost ($/m^3)	0.15	0.40	0.07	0.36	0.39	1×10^{-5}

consumption was 1940 (kW h)/day, and the average electric pricing was $0.12/(kW h). The energy cost was $1.33/m^3 for an average daily leachate volume of 175 m^3/day. So the overall operating cost of was $2.70/m^3, which is considered acceptable for the advanced treatment of landfill leachate. The cost of advanced treatment employing a membrane is always up to $5–7/m^3. In a small-scale landfill leachate treatment plant, this multistage process has proved to be an effective alternative for successful manipulation and management of this high-strength wastewater.

5. Conclusions

1. As a primary treatment, SBR treatment is an effective method for simultaneous removal of biodegradable carbon, ammonia and phosphorus. The average removal efficiencies of COD, ammonia and TP in the SBR were 76%, >99% and 81%, respectively. The ammonia concentration met the discharge standard after only this primary treatment.
2. PFS coagulation and the Fenton system served as secondary treatments for the non-biodegradable leachate from the SBR. The average COD removal efficiencies in PFS coagulation and Fenton system were 63% and 41%, respectively, with an average COD concentration of 140 mg/L and a color of less than 10° in Fenton-treated effluent. Phosphorus was further eliminated by the secondary treatment, and an effluent with TP less than 0.5 mg/L was achieved.
3. Two UBAFs, capable of the physical interception and biological degradation of pollutants, served as the final polishing step of the combined advanced treatment process. Average COD removal efficiencies of 37.5% in UBAF1 and of 36.5% in UBAF2 were attained, with final effluent COD less than 100 mg/L and color less than 4°.
4. Close attention must be paid to the daily operation and maintenance because of the great variation in leachate strength. Jar tests are necessary to re-determine the dosage of PFS and the Fenton reagents when conditions change.
5. Economic analysis shows that the overall operating cost of the advanced treatment was $2.70/m^3. This multistage process of SBR followed by coagulation/Fenton/UBAF is useful in small-scale landfill leachate treatment plants.

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References

[1] E. Diamadopoulos, Characterization and treatment of recirculation-stabilized leachate, Water Res. 28 (1994) 2439–2445.
[2] T.A. Kurniawan, W. Lo, G.Y.S. Chan, Radicals-catalyzed oxidation reactions for degradation of recalcitrant compounds from landfill leachate, Chem. Eng. J. 125 (2006) 35–57.
[3] O. Primo, A. Rueda, M.J. Rivero, I. Ortiz, An integrated process, Fenton reaction-ultrafiltration, for the treatment of landfill leachate: pilot plant operation and analysis, Ind. Eng. Chem. Res. 47 (2008) 946–952.
[4] Y. Deng, J.D. Englehardt, Treatment of landfill leachate by the Fenton process, Water Res. 40 (2006) 3683–3694.
[5] S. Renou, J.G. Givaudan, S. Poulain, F. Dirassouyan, P. Moulin, Landfill leachate treatment: review and opportunity, J. Hazard. Mater. 150 (2008) 468–493.
[6] P.J. He, X. Qu, L.M. Shao, G.J. Li, D.J. Lee, Leachate pretreatment for enhancing organic matter conversion in landfill bioreactor, J. Hazard. Mater. 142 (2007) 288–296.
[7] J. Tsilogeorgis, A. Zouboulis, P. Samaras, D. Zamboulis, Application of a membrane sequencing batch reactor for landfill leachate treatment, Desalination 221 (2008) 483–493.
[8] A. Uygur, F. Kargi, Biological nutrient removal from pre-treated landfill leachate in a sequencing batch reactor, J. Environ. Manage. 71 (2004) 9–14.
[9] Z.Q. Yang, S.Q. Zhou, The biological treatment of landfill leachate using a simultaneous aerobic and anaerobic (SAA) bio-reactor system, Chemosphere 72 (2008) 1751–1756.
[10] S. Alessandro, M.L. Stefano, Nitrogen removal via nitrite in a sequencing batch reactor treating sanitary landfill leachate, Bioresour. Technol. 100 (2009) 609–614.
[11] C.Y. Lin, F.Y. Chang, C.H. Chang, Co-digestion of leachate with septage using a UASB reactor, Bioresour. Technol. 73 (2000) 175–178.
[12] E. Castillo, M. Vergara, Y. Moreno, Landfill leachate treatment using a rotating biological contactor and an upward-flow anaerobic sludge bed reactor, Waste Manage. 27 (2007) 720–726.
[13] Z.J. Li, S.Q. Zhou, J.H. Qiu, Combined treatment of landfill leachate by biological and membrane technology, Environ. Eng. Sci. (2007) 497–507.
[14] A. Zouboulis, X. Chai, I. Katsoyiannis, The application of bioflocculant for the removal of humic acids from stabilized landfill leachates, J. Environ. Manage. 70 (2004) 35–41.
[15] F.J. Rivas, F. Beltran, F. Carvalho, B. Acedo, O. Gimeno, Stabilized leachates: sequential coagulation–floculation + chemical oxidation process, J. Hazard. Mater. 116 (2004) 95–102.
[16] I. Monje-Ramirez, M.T. Orta de Velásquez, Removal and transformation of recalcitrant organic matter from stabilized saline landfill leachates by coagulation–ozonation coupling processes, Water Res. 38 (2004) 2359–2367.
[17] E. Marañón, L. Castrillón, Y. Fernández-Nava, A. Fernández-Méndez, A. Fernández-Sánchez, Coagulation–flocculation as a pretreatment process at a landfill leachate nitrification–denitrification plant, J. Hazard. Mater. 156 (2008) 538–544.
[18] F. Kargi, M. Pamukoglu, Simultaneous adsorption and biological treatment of pre-treated landfill leachate by fed-batch operation, Process Biochem. 38 (2003) 1413–1420.
[19] T.A. Kurniawan, W.H. Lo, G.Y.S. Chan, Degradation of recalcitrant compounds from stabilized landfill leachate using a combination of ozone-GAC adsorption treatment, J. Hazard. Mater. 137 (2006) 443–455.
[20] K.W. Pi, Z. Li, D.J. Wan, L.X. Gao, Pretreatment of municipal landfill leachate by a combined process, Process Saf. Environ. Prot. 87 (2009) 191–196.
[21] I. Ozturk, M. Altinbas, I. Koyuncu, O. Arikan, C. Gomec-Yangin, Advanced physico-chemical treatment experiences on young municipal landfill leachates, Waste Manage. 23 (2003) 441–446.

[22] A.C. Silva, M. Dezotti, G.L. Sant'Anna Jr., Treatment and detoxication of a sanitary landfill leachate, Chemosphere 55 (2004) 207–214.
[23] E. Atmaca, Treatment of landfill leachate by using electro-Fenton method, J. Hazard. Mater. 163 (2009) 109–114.
[24] A. Altin, An alternative type of photoelectro-Fenton process for the treatment of landfill leachate, Sep. Purif. Technol. 61 (2008) 391–397.
[25] J. Kochany, E. Lipczynska-Kochany, Utilization of landfill leachate parameters for pretreatment by Fenton reaction and struvite precipitation—a comparative study, J. Hazard. Mater. 166 (2009) 248–254.
[26] O. Primo, M.J. Rivero, I. Ortiz, Photo-Fenton process as an efficient alternative to the treatment of landfill leachates, J. Hazard. Mater. 153 (2008) 834–842.
[27] A.A. Burbano, D.D. Dionysiou, M.T. Suidan, Effect of oxidant-to-substrate ratios on the degradation of MTBE with Fenton reagent, Water Res. 42 (2008) 3225–3239.
[28] A. Lopez, M. Pagano, A. Volpe, A. Dipinto, Fentons pretreatment of mature landfill leachate, Chemosphere 54 (2004) 1000–1005.
[29] H. Zhang, H.J. Choi, P. Canazo, C.P. Huang, Multivariate approach to the Fenton process for the treatment of landfill leachate, J. Hazard. Mater. 161 (2009) 1306–1312.
[30] A. Urtiaga, A. Rueda, Á. Anglada, I. Ortiz, Integrated treatment of landfill leachates including electrooxidation at pilot plant scale, J. Hazard. Mater. 166 (2009) 1530–1534.
[31] E. Otal, C. Arnaiz, J.C. Gutierrez, J. Lebrato, Anaerobic degradation of p-coumaric acid and pre-ozonated synthetic water containing this compound, Biochem. Eng. J. 20 (2004) 29–34.
[32] X.J. Lu, B. Yang, J.H. Chen, R. Sun, Treatment of wastewater containing azo dye reactive brilliant red X-3B using sequential ozonation and upflow biological aerated filter process, J. Hazard. Mater. 161 (2009) 241–245.
[33] C. Wang, J. Li, B.Z. Wang, G.Z. Zhang, Development of an empirical model for domestic wastewater treatment by biological aerated filter, Process Biochem. 41 (2006) 778–782.
[34] EPA of PR China, Standard Monitoring & Analytical Methods for the Examination of Water and Wastewater, 4th ed., China Environmental Science Press, Peking, China, 2002.
[35] R.S. Qasim, W. Chiang, Sanitary Landfill Leachate: Generation, Control and Treatment, Technomic Publ., Lancaster, PA, 1994.
[36] A. Amokrane, V.J. Comel, Landfill leachates pretreatment by coagulation–flocculation, Water Res. 31 (1997) 2775–2782.
[37] M.J. Lopez, Z.P. Peralta, Use of advanced oxidation processes to improve the biodegradability of mature landfill leachates, J. Hazard. Mater. 123 (2005) 181–186.
[38] O.B.D. Thabet, H. Bouallagui, J.L. Cayol, B. Ollivier, M.L. Fardeau, M. Hamdi, Anaerobic degradation of landfill leachate using an upflow anaerobic fixed-bed reactor with microbial sulfate reduction, J. Hazard. Mater. (2009), doi:10.1016/j.jhazmat.2009.01.114.
[39] A.E. Gonzalias, P. Kuschk, A. Wiessner, M. Jank, M. Kästner, H. Köser, Treatment of an artificial sulphide containing wastewater in subsurface horizontal flow laboratory-scale constructed wetlands, Ecol. Eng. 31 (2007) 259–268.