



Treatment of landfill leachate using a combined stripping, Fenton, SBR, and coagulation process

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ABSTRACT

The leachate from Changshengqiao landfill (Chongqing, China) was characterized and submitted to a combined process of air stripping, Fenton, sequencing batch reactor (SBR), and coagulation. Optimum operating conditions for each process were identified. The performance of the treatment was assessed by monitoring the removal of organic matter (COD and BOD₅) and ammonia nitrogen (NH₃-N). It has been confirmed that air stripping (at pH 11.0 and aeration time 18 h) effectively removed 96.6% of the ammonia. The Fenton process was investigated under optimum conditions (pH 3.0, FeSO₄·7H₂O of 20 g l⁻¹ and H₂O₂ of 20 ml l⁻¹), COD removal of up to 60.8% was achieved. Biodegradability (BOD₅/COD ratio) increased from 0.18 to 0.38. Thereafter the Fenton effluent was mixed with sewage at dilutions to a ratio of 1:3 before it was subjected to the SBR reactor; under the optimum aeration time of 20 h, up to 82.8% BOD₅ removal and 83.1% COD removal were achieved. The optimum coagulant (Fe₂(SO₄)₃) was a dosage of 800 mg l⁻¹ at pH of 5.0, which reduced COD to an amount of 280 mg l⁻¹. These combined processes were successfully employed and very effectively decreased pollutant loading.

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1. Introduction

Landfill is one of the most widely employed methods for the disposal of municipal solid waste (MSW) and up to 95% of such waste collected worldwide is disposed of in landfills [1]. After landfilling, solid waste undergoes physicochemical and biological changes. Consequently, the degradation of the organic fraction of the wastes in combination with percolating rainwater leads to the generation of a highly contaminated liquid called "leachate". The characteristics of landfill leachate depend on the type of MSW being dumped, the degree of solid waste stabilization, site hydrology, moisture content, seasonal weather variations, landfill age, and the stage of decomposition in the landfill. The common features of stabilized leachate are high strengths of ammonia (NH₃-N, 3000–5000 mg l⁻¹) and moderately high strengths of chemical oxygen demand COD (5000–20,000 mg l⁻¹), as well as a low ratio of BOD₅/COD (<0.1) [2]. In general, the appropriate leachate treatment methods are mainly based on specific characteristics of leachates under examination [3,4].

The landfill leachate treatment methods are physical, chemical, and biological. Air stripping, adsorption, and membrane filtration

are major physical leachate treatment methods [5,6]; coagulation flocculation, chemical precipitation, and chemical and electrochemical oxidation methods are the common chemical methods used for the landfill leachate treatment [5–8]. The most popular biological treatments of landfill leachate are the anaerobic digestion or aerobic activated sludge methods [3]. Biological processes are quite effective to treat leachate, when applied to relatively younger leachates, but they are less efficient for the treatment of older ones [5]. Bio-refractory contaminants, contained mainly in older leachates, are not amenable to conventional biological processes, whereas the high ammonia content might also be inhibitory to activated sludge microorganisms [9]. Furthermore, a supplementary addition of phosphorus is often necessary, as landfill leachates are generally phosphorus deficient [5]. Therefore, a combination of physicochemical and biological methods is often required for the efficient treatment of leachate [10–13].

Ammonium or air stripping is the most widely employed treatment for the removal of NH₃-N from landfill leachate [8,14–16]. NH₃-N is transferred from the waste stream into the air and is then absorbed from the air into a strong acid such as sulphuric acid or directly fluxed into the ambient air. Ammonium stripping gives an NH₃-N treatment performance in the range of 85–95% with concentrations ranging from 220 to 3260 mg l⁻¹ [17]. Chemical oxidation is a widely studied method for the treatment of effluents containing refractory compounds such as landfill leachate. Growing interest has been recently focused on advanced oxidation processes

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(AOP) [18–20]. Among these processes, Fenton's process seems to be the best compromise because the process is technologically simple, there is no mass transfer limitation (homogeneous nature), and both iron and hydrogen peroxide are cheap and non-toxic. But Fenton's process requires a low pH and a modification of this parameter is necessary [21,22]. Coagulation–flocculation has been employed for the removal of suspended solids (SS), colloid particles, non-biodegradable organic compounds, and heavy metals from landfill leachate [5,16]. The coagulation process destabilizes colloidal particles by the addition of a coagulant. To increase the particle size, coagulation is usually followed by flocculation of the unstable particles into bulky flocs so that they can settle more easily [23]. The general approach for this technique includes pH adjustment and the addition of ferric/alum salts as the coagulant to overcome the repulsive forces between the particles [24]. Iron salts have been proven to be a more efficient coagulant than aluminium ones [16]. Landfill leachates are often co-treated with municipal sewage in the biological process. Aerobic biological processes based on suspended-growth biomass, such as aerated lagoons, conventional activated sludge processes, and sequencing batch reactors (SBR), have been widely studied and adopted [25–27]. Biological treatment, often SBR, is the most economically efficient method for the removal of biodegradable organic compounds [28]. However, problems with the high concentration of suspended solids in the effluent of activated sludge systems have been observed due to sludge bulking or dispersed growth phenomena [29].

In the present study, leachate generated from Changshengqiao landfill in Chongqing city (China) was collected. A combined treatment method for removal of the crucial pollutants ($\text{NH}_3\text{-N}$, COD and BOD_5) from the leachate to meet the Chinese discharge standard (GB16889-1997) was investigated. Therefore, a combination of physicochemical and biological processes could be applied: (i) air stripping to remove ammonia, (ii) Fenton's reagent to remove bio-refractory compounds, (iii) SBR to remove biodegradable components, and (iv) a coagulation process used as a polishing treatment stage to remove colloids.

2. Materials and methods

2.1. Chemicals and analytical methods

All chemicals used were of analytical grade. COD, biological oxygen demand (BOD_5), $\text{NH}_3\text{-N}$, total organic carbon (TOC), SS, volatile fatty acid (VFA), and pH were measured according to the Standard Methods for the Examination of Water and Wastewater [30]. pH adjustment was done by using $1 \text{ mol l}^{-1} \text{ H}_2\text{SO}_4$ and $1 \text{ mol l}^{-1} \text{ NaOH}$. All the experiments were carried out at room temperature $25 \pm 2^\circ\text{C}$ under normal lab daylight lamp conditions. Selected samples have been repeatedly analyzed in order to validate/evaluate the produced results and they were found within accepted analytical error ($\pm 5\%$). The results are means of triplicate determinations.

2.2. Leachate

The leachate sample was provided from Changshengqiao landfill site in Chongqing city in the southwest of China. The Changshengqiao landfill is the largest landfill in the three Gorges reservoir region; it was put into service in July 2003, is planned to operate onsite for 32 years, and has an average leachate generation of $500 \text{ m}^3 \text{ day}^{-1}$. A 50L leachate sample was obtained from a wastewater pond in the landfill site. Then, the sample was transported to the laboratory in sealed plastic barrels, and stored at 4°C before being used and analyzed. The collected leachate was filtered through a glass fiber filter to remove coarse suspended solids. pH, SS, COD, BOD_5 , $\text{NH}_3\text{-N}$, TOC, and VFA of the leachate were determined.

2.3. Individual processes

The air stripping process was carried out in the following sequential steps: (1) leachate sample was put in 10L plastic barrels; (2) its pH was adjusted to a certain value; (3) the mixture was aerated for a specific period of air stripping time through diffusers at a rate of 15 L min^{-1} and (4) the mixtures were let to settle for 1 h. The $\text{NH}_3\text{-N}$ of the supernatant was measured. The optimum pH value and aeration times were investigated.

The Fenton process was carried out in the following sequential steps: (1) leachate sample (400 ml) was put in a beaker (1000 ml); (2) its pH was adjusted to a fixed value ($\text{pH}=3$); (3) the scheduled Fe^{2+} dosage was achieved by adding the necessary amount of solid $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$; (4) A known volume of 30% (w/w) H_2O_2 solution was added in a single step. (5) The mixture was stirred for 15 min with velocity 200 rpm using a jar-test device ZR-6; (6) the mixtures were allowed to settle for 1 h; (7) the pH values of the samples were adjusted to 8.0 to remove residual Fe^{2+} (Fe^{3+}); (8) the mixture was stirred for 15 min with velocity 80 rpm and (9) the mixtures were allowed to settle for 1 h. The COD of the supernatant was measured. The optimum pH, $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ dose, and H_2O_2 dose were investigated.

The investigation was carried out using a lab-scale sequencing batch reactor (SBR) made of a cylindrical reactor (8 L plastic barrels). It operates on the principle of five phases: fill, react, settle, draw, and idle. The reactor was filled with wastewater mixture with a ratio of 1:3 of leachate effluent from the Fenton process and municipal sewage wastewater. The addition of raw municipal sewage wastewater was necessary because of the low biodegradability (BOD_5/COD ratio < 0.3) of the leachate effluent obtained from the Fenton process. The mixed wastewater was seeded with activated sludge (3097 mg l^{-1} mixed liquor suspended solids, MLSS) obtained from Tangjiaheqiao sewage treatment plant. The wastewater mixture was continuously aerated at an air flow rate of 15 L min^{-1} for a specific period of aeration time. Glucose was added to the reactor for domesticated sludge performance stability. Dissolved oxygen (DO) was maintained at $2.5\text{--}4.0 \text{ mg l}^{-1}$, pH was maintained at $6.5\text{--}8.5$. Samples were taken from the discharged clear effluent for COD and $\text{NH}_3\text{-N}$ measurements. Also, the MLSS concentration at the beginning of each cycle was monitored. The optimum aeration time was investigated.

The coagulation process was performed in a conventional jar-test apparatus ZR-6. The experimental process consisted of the following stages: (1) one liter of the filtered leachate was placed in a jar; (2) a desired dose of $\text{Fe}_2(\text{SO}_4)_3$ was added as coagulant to the leachate; (3) the stirrer was turned on for a rapid mixing stage of 2 min at 250 rpm; (4) one milliliter of 0.1% polyacrylamide was added to the sample as flocculent to increase the flocculation settling rate; (5) the stirrer speed was reset for a slow mixing stage of 15 min at 80 rpm and (6) the ensuing natural settling lasted 1 h. The supernatant was withdrawn from a point located about 2 cm below the top of the liquid level in the beaker. The COD of the supernatant was measured. The optimum pH value and $\text{Fe}_2(\text{SO}_4)_3$ dose were investigated.

2.4. Combined processes

In a combined sequential treatment test run, the landfill leachate was first fed to the air stripping for pre-treatment to remove ammonia. The effluent from that unit was then oxidized in the Fenton reactor to remove bio-refractory compounds. Then, the effluent from the Fenton process was mixed with municipal sewage wastewater at a ratio of 1:3 and fed to the SBR unit to enhance the removal of organic matter. Finally, the effluent was fed to the chemical coagulation reaction to remove suspended solids. The combined treatment was operated under the optimum conditions

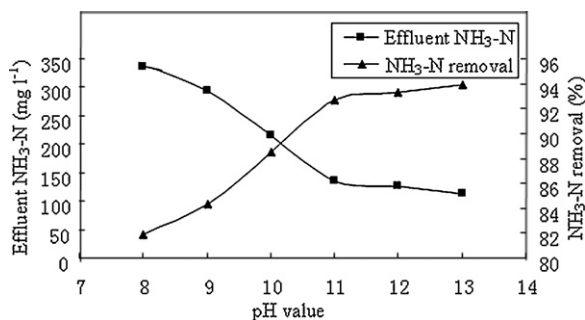


Fig. 1. The effect of pH on NH₃-N removal by air stripping.

for all the processes. COD, BOD₅, and NH₃-N of the effluents were measured at the end of each process. The overall efficiency of the combined treatment was investigated.

3. Results and discussion

3.1. Leachate characteristics

The leachate samples collected from the landfill site were analyzed. The leachate characteristics were as follows: pH = 7.90–8.47, COD = 3000–4500 mg l⁻¹, BOD₅ = 374–824 mg l⁻¹, NH₃-N = 1000–1750 mg l⁻¹, TOC = 831–946 mg l⁻¹, SS = 812–979 mg l⁻¹, and VFA = 384–782 mg l⁻¹. The BOD₅/COD ratio of leachate was 0.09–0.22. The landfill leachate was considered to have a low BOD₅/COD ratio and high content of NH₃-N. Thus it was classified as stabilized or “old” and non-biodegradable leachate.

3.2. Air stripping

The optimum pH was determined using different pH values from 8 to 13 as shown in Fig. 1. The ammonia removals have significant linear increases at pH ≤ 11; beyond this the increase in ammonia removal was not significant. Therefore, the optimum pH was 11. This result is mainly due to the fact that the reaction of NH₃ with water can be represented by Eq. (1). From this equation, raising the pH (as represented by the OH⁻) will drive the reaction to the left, increasing the concentration of NH₃. This makes ammonia more easily removed by stripping:



Fig. 2 shows the effect of air stripping time on the NH₃-N removal. NH₃-N removal increased significantly with increases in the air stripping time up to 18 h. Thereafter, the increase in NH₃-N removal was not significant. The optimum air stripping time was 18 h, beyond which the pH started to decrease due to the re-carbonation of lime in leachate by the absorption of CO₂ from the ambient air [14–17].

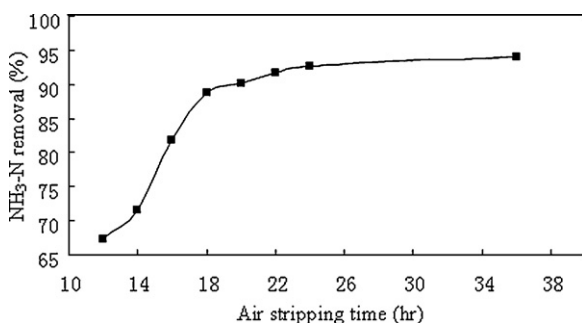


Fig. 2. The relationship between NH₃-N removal effects and air stripping time.

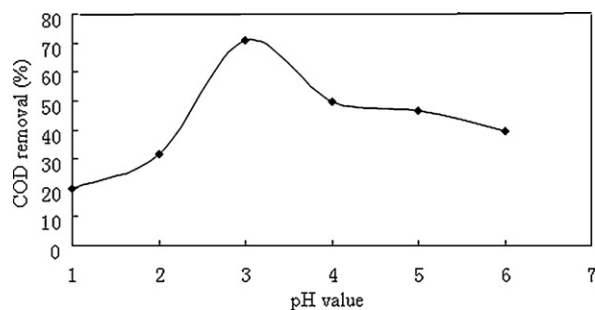


Fig. 3. The effect of pH on COD removal and effluent of Fenton process.

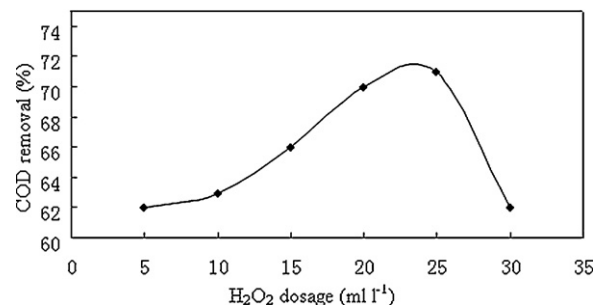


Fig. 4. The effect of H₂O₂ dosages on COD removal and effluent of Fenton process.

3.3. Fenton process

Fenton process is a reaction between hydrogen peroxide (H₂O₂) and ferrous ion (Fe²⁺), producing the hydroxyl radical (•OH) (Eq. (2)). •OH radical is a strong oxidant capable of oxidizing and degradation various organic compounds into carbon dioxide and water. Thus, the degradation process could be increase with increasing •OH concentration and vice versa [31–35]:



pH values have a significant effect on the degradation of organics by the Fenton reaction, and acidic conditions are required to produce the maximum amount of hydroxyl radicals (•OH) by the decomposition of hydrogen peroxide (H₂O₂) catalyzed by ferrous ions [31,32]. Generally, the optimum pH value is about 2.5–3.0 [33,34]. At a reaction pH higher than 5, it has been observed that the COD removal efficiency by oxidation decreases, not only due to decomposition of hydrogen peroxide [33,34], but also because of deactivation of the ferrous catalyst with the formation of ferric hydroxo complexes [33]. In this study, the effect of pH was also assessed. The conditions of experiments were: pH values of the leachate were adjusted to different values and then 10 g l⁻¹ of

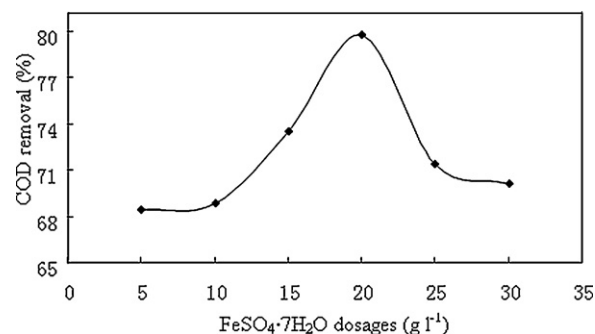


Fig. 5. The effect of FeSO₄·7H₂O dosages on COD removal and effluent of Fenton process.

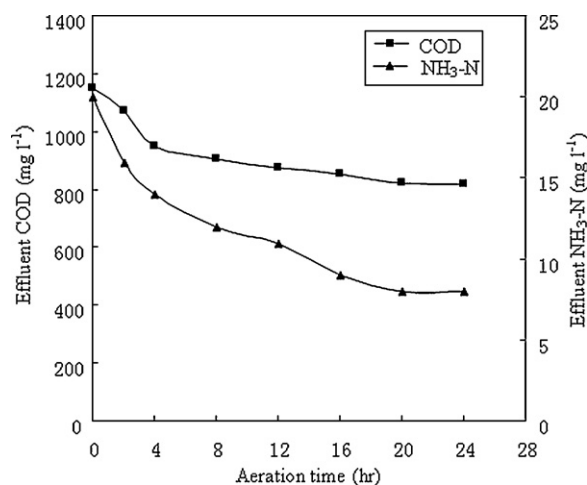


Fig. 6. The effect of aeration time on removal of pollutants by SBR reactor.

FeSO₄·7H₂O and 40 ml l⁻¹ of 30% H₂O₂ were added in each beaker. Fig. 3 shows the effect of pH on the COD removal efficiencies. Clearly, the COD removal is significantly influenced by the pH, with the optimum pH value being 3. As the pH decreases, the scavenging effect of the •OH by H⁺ becomes stronger [32], and at a pH higher than 3.0, the hydrolysis of Fe³⁺ in the solution reduces the rate of •OH production [34].

The H₂O₂ plays an important role in the Fenton process. The main cost of the Fenton reaction process is the cost of H₂O₂. So, it is important to optimize the amount of H₂O₂. Generally, the degradation rate for organic compounds increases as H₂O₂ concentration increases until a critical H₂O₂ concentration is achieved [34]. Above this critical concentration, the degradation rate for organic com-

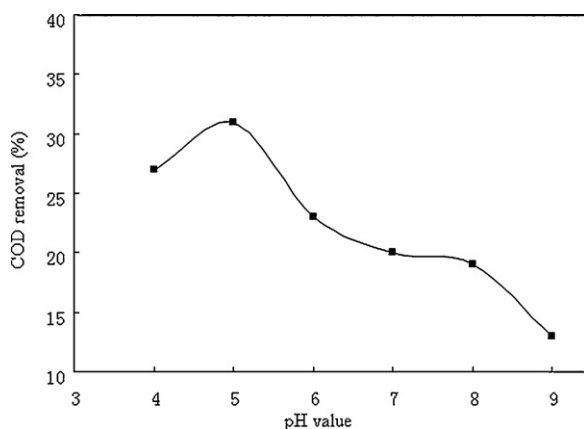


Fig. 7. The effects of pH on the COD removal by the coagulation process.

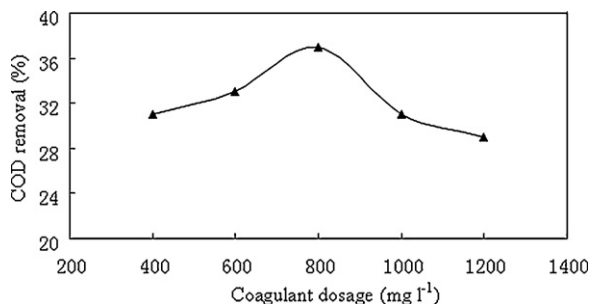


Fig. 8. The effects of the coagulation dosages on the COD removal by the coagulation process.

pounds decreases as a result of the so-called scavenging effect, according to Eq. (3) [34]:



In this study, the effect of H₂O₂ was also assessed. The conditions of the experiments were: leachate pH values were adjusted to 3 and then 10 g l⁻¹ of FeSO₄·7H₂O and different dosages of 30% H₂O₂ were added in each beaker. It is shown clearly in Fig. 4 that increasing the H₂O₂ concentration leads to increases in the removal efficiency up to 72% at a dose of 24 ml l⁻¹ of H₂O₂. A further increase in H₂O₂ dose leads to a decrease in the removal efficiency. The removal efficiency increased due to the concentration of •OH increasing as a result of the addition of H₂O₂. However, at a high dosage of H₂O₂, the removal efficiency decreased due to the •OH scavenging effect of H₂O₂ (Eqs. (3) and (4)) and the recombination of •OH (Eq. (5)) [35]. Nevertheless, the small difference between the COD removal attained with 20 and 24 ml l⁻¹ of H₂O₂ indicates that improvements in terms of degradation may not be worth the large loads of oxidant expended. Thus, the optimum H₂O₂ dosage was 20 ml l⁻¹:



Ferrous sulphate heptahydrate (FeSO₄·7H₂O) was used as a source of ferrous ions (Fe²⁺) in the Fenton process. The effect of Fe²⁺ concentrations on COD removal efficiency is shown in Fig. 5. It can be seen that the addition of Fe²⁺ greatly improved COD removal. COD removal efficiency increased rapidly when Fe²⁺ concentrations increased. It achieved 80% of the highest removal efficiency at 20 g l⁻¹ of FeSO₄·7H₂O. This is due to the fact that Fe²⁺ plays a very important role in initiating the decomposition of H₂O₂ to generate •OH in the Fenton process according to Eq. (2). A further increase in Fe²⁺ dosage would lead to a decrease in COD, because when concentrations of Fe²⁺ radicals are high, Fe²⁺ recombines with •OH and Fe²⁺ reacts with •OH as a scavenger according to Eq. (6). Hence, the excess ferrous ions consumed •OH with a high oxidative potential. This caused a decrease in the efficiency of COD removal. Otherwise, a large quantity of ferric oxide sludge will be generated, resulting in much greater requirements for separation and disposal of the sludge. So the optimum FeSO₄·7H₂O dose was 20 g l⁻¹:



3.4. SBR

The SBR process was selected and tested in the present work as a next treatment step for leachate effluent from the Fenton process. Although the BOD₅/COD ratio of the leachate effluent from the Fenton reactor was improved to 0.3, it was still not sufficient to sustain a good biological treatment. To remedy this deficiency, the leachate effluent was mixed with municipal sewage wastewater to a ratio of 1:3 before it was subjected to the SBR treatment. The air compressor was used only during the aerobic period to ensure an oxygen concentration equal to 2.5–4.0 mg l⁻¹. The reactor was operated

Table 1
The optimum conditions for each process.

Process	Optimum process parameters
Air stripping	pH = 11, air stripping time = 18 h
Fenton	pH = 3, [H ₂ O ₂] = 20 ml l ⁻¹ , [FeSO ₄ ·7H ₂ O] = 20 g l ⁻¹
SBR	Cycle time = 24 h, aeration time = 20 h, pH = 7, HRT = 5 days, SRT = 15 days, DO = 2.5–4 mg l ⁻¹ , sludge concentration = 3.0–3.2 g l ⁻¹
Coagulation	pH = 5, [Fe ₂ (SO ₄) ₃] = 800 mg l ⁻¹

Table 2
Concentration and removal percentage of pollutants in effluent for each treatment process.

Process	Concentration (mg l ⁻¹)			Removal (%)			BOD ₅ /COD
	COD	BOD ₅	NH ₃ -N	COD	BOD ₅	NH ₃ -N	
Influent	4150	730.8	1169	–	–	–	0.18
Air stripping	3275	690.7	40	21.1	5.5	96.6	0.21
Fenton	1625	619.3	30	60.8	15.3	97.4	0.38
SBR	700	125.8	25	83.1	82.8	97.9	0.18
Coagulation	280	113.5	20	93.3	84.5	98.3	0.41

Table 3
Comparison of the water quality of final effluent with the Chinese Standard for pollution control in landfill sites for domestic waste (GB16889-1997).

	COD (mg l ⁻¹)	NH ₃ -N (mg l ⁻¹)	BOD ₅ (mg l ⁻¹)
Class I	100	15	30
Class II	300	25	150
Class III	1000	–	600
Effluent	280	20	113.5

in a 24 h cycle, with a hydraulic retention time (HRT) of 5 days and sludge retention time (SRT) of 15 days. The systems reached steady state within 10–11 days of acclimatization. The SBR systems were operated with 3.0–3.2 g l⁻¹ sludge concentration. After the acclimatization process, different aeration times were investigated as shown in Fig. 6.

As is clear from Fig. 6, COD and NH₃-N concentrations decreased significantly with increases in the air stripping time up to 20 h. Thereafter, COD and NH₃-N concentrations did not decrease significantly. Therefore, the optimum aeration time was 20 h, at which COD can be reduced to 825 mg l⁻¹ and NH₃-N can be reduced to 8 mg l⁻¹.

3.5. Coagulation

In the chemical coagulation, the important operating conditions including the initial pH and dosage of coagulant were determined as shown in Figs. 7 and 8.

The pH of initial samples was varied from 4 to 9. The coagulation process runs by the addition of 600 mg l⁻¹ Fe₂(SO₄)₃ in leachate samples. Fig. 7 presents the effect of pH values on the coagulation. It can be seen that the highest COD removal percentage, 32%, was achieved at the optimum pH value of 5. The results also clearly indicate that the removal efficiency was increased with increases in pH up to pH 5. Then, the removal efficiency decreased for pH > 5. In general, chemical coagulation is a process which is highly pH dependent. The pH influences the nature of produced polymeric metal species that will be formed as soon as the metal coagulants are dissolved in water. The influence of pH on chemical coagulation may be considered as a balance of two competitive forces: (1) between hydrogen ions H⁺ and metal hydrolysis products for interaction with organic ligands and (2) between OH⁻ and organic

anions for interaction with metal hydrolysis products [36]. At low pH values (pH ≤ 5), H⁺ out-competes metal hydrolysis products for organic ligands, and hence poor removal rates occur and some of the generated organic acids will not precipitate. At higher pH values (pH > 5), •OH competes with organic compounds for metal adsorption sites and the precipitation of metal-hydroxides occurs mainly by co-precipitation [36].

The effect of Fe₂(SO₄)₃ on the efficiency of COD removal was also investigated. Fig. 8 shows the removal of COD by different dosages of Fe₂(SO₄)₃ at a pH of 5. Coagulant dosage varied from 400 to 1200 mg l⁻¹. As shown in Fig. 8, the optimum dosage to attain a better COD removal percentage of 36% was 800 mg l⁻¹. COD removal increased with increasing coagulant dosages up to the optimum dosage. Then, the COD removal decreased. This result is mainly due to the fact that the optimum coagulant dosage produced flocs having a good structure and consistency. But in doses lower than optimum, the produced flocs are small and influence the settling velocity of the sludge. In doses higher than the optimum, in addition to the small size of floc, rest ability of floc can happen.

3.6. Combined processes

The optimum conditions of combined treatment of leachate by air stripping, Fenton, SBR, and coagulation process are shown in Table 1. The overall performances of combined treatment under the optimum conditions are listed in Table 2. It is seen in this table that COD, NH₃-N, and BOD₅ removal were 93.3%, 98.3%, and 84.5%, respectively. The BOD₅/COD ratio is also improved from 0.18 to near 0.38. Hence the overall treatment results by the combined methods are indeed quite good. A comparison of water quality of the final effluent with the standard for pollution control on landfill sites for domestic waste (GB16889-1997) is presented in Table 3. It is seen that the water quality of the final effluent could achieve the second class of discharge water for directly discharged or non-potable use.

To evaluate the performances of the combined treatment with respect to other combined treatments, Table 4 shows a comparative study in terms of initial concentrations ranges of COD and NH₃-N in leachate. Although it has a relative meaning due to different testing conditions (pH, temperature, strength of wastewater, seasonal climate, and hydrology site), this comparison is useful to evaluate the overall treatment performance of each technique to assist the decision-making process. As seen from

Table 4
Comparison of the current combination processes with other previous combinations for landfill leachate treatment.

Combination process	Landfill location	Influent leachate (mg l ⁻¹)		Effluent removal (%)	
		COD	NH ₃ -N	COD	NH ₃ -N
Air stripping + Fenton + SBR + coagulation [current study]	Chongqing (China)	4150	1169	93.3	98.3
Struvite + upflow anaerobic sludge bed (USAB) [37]	Kemerburgaz (Turkey)	8900	2130	83	86
Struvite + ammonia stripping [38]	Istanbul (Turkey)	4560	2170	80	90
Coagulation + electro-Fenton + SBR [39]	Taiwan	1941	150.9	85	81
Coagulation + ammonia stripping + granular activated carbon (GAC) adsorption [40]	Bursa (Turkey)	23,700	1140	99.3	NA
Coagulation + Fenton oxidation + biological aerated filtering [41]	Guangdong (China)	600–700	NA	88	NA
Struvite + sequencing batch biofilter granular reactor (SBBGR) + Fenton [42]	Apulia (Italy)	24,400	3190	97	99.7
SBR + coagulation + Fenton + upflow biological aerated filter (UBAF) [43]	Jiangmen (China)	3000	1100	97.3	99

NA: not available.

Table 4, $\text{NH}_3\text{-N}$ removal was in the range 81–99.7% and COD removal was in the range 80–99.3%. Among the combined treatments reviewed above, it is observed that the combination of air stripping–Fenton–SBR–coagulation demonstrated outstanding treatment performances in the removal of COD (93.3%) and $\text{NH}_3\text{-N}$ (98.3%).

4. Conclusions

The landfill leachate obtained from Changshengqiao landfill (China) was treated using a combined air stripping, Fenton, SBR, and coagulation process. The combined treatment method offers an attractive alternative in dealing with the high-strength wastewater. Based on the results obtained from tests of an individual unit, the optimum operating conditions were identified as shown in **Table 1**. The test results shown in **Table 2** revealed the following information:

1. The landfill leachate is characterized as low BOD_5/COD and high content of $\text{NH}_3\text{-N}$, showing that the leachate can be classified as “old” and non-biodegradable.
2. Air stripping is simple and less expensive than other physico-chemical methods available. It appears to be a cost-effective pre-treatment option for landfill leachate to remove ammonia. The ammonia removal achieved was 96.6% at the optimum pH and aeration time of 11 and 18 h, respectively.
3. The Fenton oxidation employed was able to remove refractory compounds (non-biodegradable organic matter) of the leachate effluent. At an optimum pH of 3, H_2O_2 dosage of 20 ml l^{-1} , and $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ dosage of 20 g l^{-1} , the oxidation process applied to the leachate effluent yields a very good COD removal (60.8%).
4. The SBR process was more effective to remove biodegradable organic matter. The BOD_5 and $\text{NH}_3\text{-N}$ removal were 82.8% and 97.9%, respectively, at an optimum aeration time of 20 h.
5. The final treatment of the leachate effluent was by chemical coagulation. It can be beneficially used to remove dissolved and suspended solids and many organic and inorganic compounds remaining in wastewater after the Fenton process and SBR. An optimum initial pH of around 5 and an optimum $\text{Fe}_2(\text{SO}_4)_3$ dosage of 800 mg l^{-1} were observed for chemical coagulation that yields good COD and $\text{NH}_3\text{-N}$ removal.
6. The final leachate effluent of the combined treatment was good, and it could be directly discharged or considered for non-potable use. It approached the second class of discharge water in the Chinese Standard for pollution control on landfill sites for domestic waste (GB16889-1997) as shown in **Table 3**.
7. Among the combined treatments reviewed above in **Table 4**, it is observed that the combination of air stripping–Fenton–SBR–coagulation demonstrated outstanding treatment performances in the overall removal of COD (93.3%) and $\text{NH}_3\text{-N}$ (98.3%).

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