

Treatment of landfill leachate using an up-flow anaerobic sludge semi-fixed filter

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Abstract. In the present work, an up-flow anaerobic sludge semi-fixed filter (UASSF) was developed for landfill leachate treatment by packing the soft polyurethane belt as the supporting carrier. The performance of the hybrid reactor was evaluated in terms of COD removal and carbon flux distribution, also, the biomass effectiveness was investigated by restarting the reactor without the supporting carrier. The COD removal increased with the stepwise increment of the organic loading rate (OLR), while the sulfate removal decreased slowly. When the reactor was operated at design load (9 kgCOD/m³·d), COD and sulfate removal remained around 81% and 90%, respectively. The results indicate that this kind of semi-fixed carrier is capable to form the active biofilm in the anaerobic process, and the UASSF system can perform well in the leachate treatment.

1. Introduction

Landfill leachate, a kind of high-strength wastewater, has a very hazardous impact upon human health and the environment. The concentration and composition of leachate are often determined by the age and type of landfill [1]. Impacts of leachate on environment will last for scores of years, and many treatment processes, such as physical, chemical and biological methods, have been proposed [2, 3]. Biological treatment method, especially anaerobic technology, is mainly the first stage in high-strength wastewater treatment [2-4].

As for suspended-growth biomass processes, the up-flow anaerobic sludge blanket (UASB) reactor is regarded as a successful and extensively applied device due to its advantages, including high loading rate, long solid retention time and flexibility of process operation [5, 6]. Still, UASB might be faced with the problems of slow start-up [7, 8] and sludge washout if granular sludge is not obtained [9]. Among attached-growth biomass processes, anaerobic filter (AF) is more favorable because of its higher biomass, smaller volume and shock loadings tolerance [10-12]. Types of carriers have been employed in AF to treat wastewater: natural materials (bamboo rings, coconut fibers, zeolite and perlite) [13-17], waste materials (glass, brick granules and automobile tires) [10, 18-20] and synthetic organic chemicals (polyurethane, polyethylene and nylon fiber) [21-24]. However, the major drawback of the AF is clogging of the filter, which may result in short circuiting of wastewater yielding unacceptable effluent quality [25-27]. Apart from the high suspended solids concentration in wastewater [28], another reason for filter clogging is the packed carrier itself. For most filter reactors, the carrier packed in them is of the fixed type, which is immobilized in the moving fluid. With the



increase in biofilm thickness and continuous operation, the filter is clogged.

In the study, an up-flow anaerobic sludge semi-fixed filter (UASSF) was developed for landfill leachate treatment by integrating UASB and AF. The semi-fixed carrier in UASSF could move with the up-flow liquid, which contributed to avoiding biomass washout and clogging. The study focused on the performance of UASSF by COD removal efficiency (RE_{COD}) and influent carbon distribution. Additionally, the effectiveness and contribution of biomass were also evaluated by restarting the reactor without the supporting carrier.

2. Materials and methods

2.1. Leachate analysis

The leachate used in the research was collected from currently operating landfill located in Chengdu, China. The main physicochemical characteristics of leachate are listed in table 1.

Table 1. Characteristics of influent leachate.

Parameter	Mean	Range
pH	5.0	4.8-5.2
COD (mg/L)	68500	40000-75000
BOD ₅ (mg/L)	28000	20000-35000
BOD/COD	0.41	0.34-0.47
SS (mg/L)	3000	1600-4000
NH ₃ -N (mg/L)	950	800-1100
NO ₃ -N (mg/L)	120	85-170
TN (mg/L)	8200	5000-9500
TP (mg/L)	148	120-175
SO ₄ ²⁻ (mg/L)	2120	1790-2450

2.2. Reactor setup

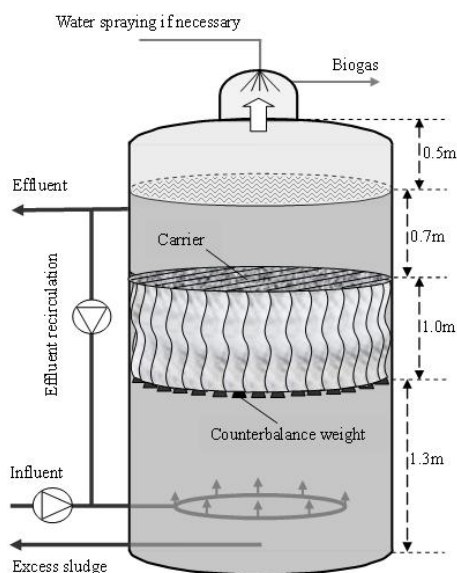


Figure 1. UASSF Schematic diagram.



Figure 2. The belt carrier used in the UASSF.

The schematic diagram of the study is shown in figure 1. The pilot scale UASSF, which is 1.95 m in diameter and 3.5 m in height, is cylindrical and made of carbon steel. The active volumes of the

reactor are 9.0 m³ and the total volumes are 10.6 m³. Two pumps are used separately for leachate feeding and effluent recirculation, providing an up-flow velocity of 0.6 m/h for liquid in the reactor. The influent flow and gas production are measured by an electromagnetic meter and a wet-gas meter, respectively.

As carrier material, soft polyurethane belts (0.05 cm × 3 cm × 100 cm) are hung vertically in the reactor (see figure 2). The upper end of the belt is attached to a metal net which is parallel with the lateral section of the reactor, and the end lap is linked to a counterbalance weight, avoiding the belts twining with each other. Besides providing surface microbial attachment, the belts acted like a three-phase (gas–liquid–solid) separator.

2.3. Inoculation and start up

The inoculums in the reactor were from digested sludge which was obtained from a plant treating sewage. The total solids and volatile suspended solids concentration were 61200 mg/L and 10800 mg/L, respectively. The reactor structure was laid in a room whose temperature was kept at 35°C by a thermostat.

During the initial period of the operation, the suspended solid (SS) with poor settling properties was washed out by the up-flow of the liquid, while microorganisms and SS with good settleability aggregated and settled at the bottom of the reactor. Organic macromolecules began to be absorbed on the surface of the carrier, and the planktonic cells moved and adhered to the belt at the same time. It was the adherent microorganisms that constituted the first layers of the biofilm.

2.4. Analytical methods

COD, sulfate and volatile fatty acids (VFA) were analyzed by colorimetric tests on a HACH-DR 2800 photometer. Bicarbonate measurement was conducted with an analyser (GDYS-103SD, Nuoji instrument Co., Ltd, China). Biogas was checked via gas chromatography (BFRL-SP-2100, Beijing Analytical Instrument Factory, China), and total organic carbon (TOC) was determined through a TOC-500 analyser (Shimadzu Corp. Japan). Alkalinity, pH and SS were measured according to the standard methods [29].

2.5. Calculation methods

During the treatment process, part of COD would be eliminated by sulfate-reducing bacteria (SRB) [30]. 64g of COD was needed when one mol of sulfate was reduced, so the percentage of COD removed by SRB (COD_{SRB}) could be calculated based on the amount of sulfate reduced and the total COD removed [31]. The influent organic carbon is distributed in catabolic reactions (i.e. formation of biogas, bicarbonate and VFA) and anabolic reactions (i.e. biomass production) [6]. TOC and other carbon species were measured directly, so a part of carbon transformed to biomass could be deduced from the carbon mass balance.

3. Results and discussion

3.1. The performance of UASSF

The UASSF reactor was operated continuously for 112 days. Figure 3 gives the process performance of the hybrid reactor. According to the RE_{COD}, the operation could be divided into three phases roughly.

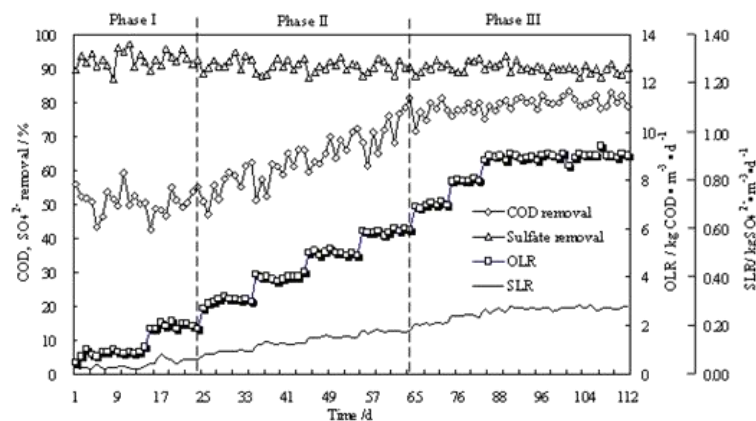


Figure 3. The performance of UASSF.

3.1.1. Phase I (day 1-24). When landfill leachate containing sulfate was introduced into the UASSF, the organic matter was removed via sulfate reduction and methanogenesis. As the organic loading rate (OLR) increased from 0.5 to 2 kgCOD/m³·d, RE_{COD} varied between 42% and 59%. The biogas production was suppressed during this period, and methane content was lower than 38%. The biomass in the reactor seemed unable to handle the increased OLR, which was probably because some active biomass was washed out, or was due to physiological modifications resulting from physical constraints [17]. However, at sulfate loading rate (SLR) of 0.03-0.06 kgSO₄²⁻/m³·d in this phase, the sulfate removal was relatively high (87% to 97%), and a certain amount of the COD elimination (5.5-5.9%) was accomplished through sulfate reduction (see figure 4). It could be concluded that SRB inhibited the growth and activity of methane-producing bacteria (MPB) to some extent, though the inhibition was not strong due to the higher COD/SO₄²⁻ ratio [32].

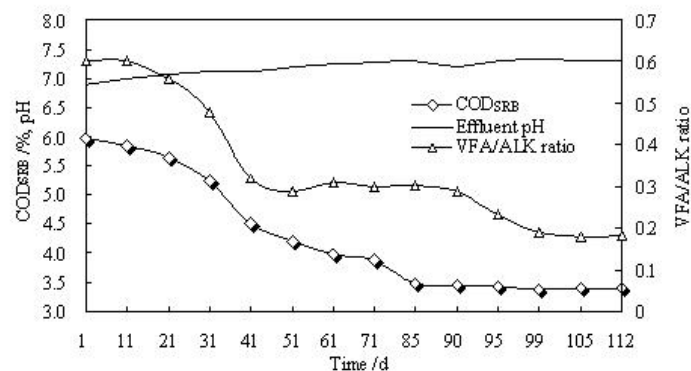


Figure 4. Variation of COD_{SRB}, pH and VFA/ALK ratio.

The organic carbon distribution in metabolism can also reflect the performance of UASSF. Figure 5 illustrates the distribution of metabolized organic carbon in the treatment process, while the unmetabolized is not included. At the initial time, there was a slow accumulation of biomass, and the corresponding carbon distribution (anabolic carbon) was only 4% at day 14. The catabolic carbon flux to VFA (45%) was much higher than that to biogas (28%) or bicarbonate (23%), which might result from the incomplete organic substrate degradation and methanogenesis inhibition. Although the influent pH was low (between 4.8 and 5.2), the corresponding value in the reactor still maintained at 6.9, and the alkalinity concentration in influent was always lower than that in effluent, indicating that the anaerobic metabolism itself produced the alkalinity [33]. Since the effluent recirculation could keep a near neutral pH in the reactor [34, 35], there was no alkalinity addition throughout this

experiment. Effluent recirculation could also produce an internal dilution to reduce the impact of high OLR [7, 34] and hence improve the performance of the anaerobic reactor [36, 37]. As a result, MPB became more active and accommodated to the new circumstance in the late period of phase I. Although so, the VFA/ALK ratio was still higher than 0.4 in this period, which meant that the adequate buffering capacity had not been reached for anaerobes [38].

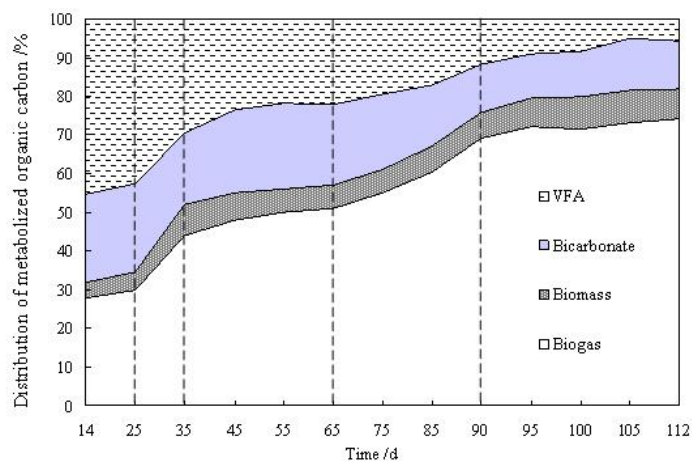


Figure 5. Distribution of metabolized organic carbon.

3.1.2. Phase II (day 25-64). With the OLR increasing from 3 to 6 kgCOD/m³•d in this phase, the RE_{COD} grew more quickly than in phase I, indicating improvement in microbial activity of the MPB. This was supported by the continuous decrease of COD_{SRB} from 5.4 to 3.9%, though the SLR had increased from 0.08 to 0.18 kgSO₄²⁻/m³•d. In addition, in each stepwise increase of loading rate, the RE_{COD} increased accordingly. As for the carbon distribution from day 25 to day 35, the portion of residual VFA further decreased, while those of biomass and biogas increased from 4.5 to 8% and 30 to 44%, respectively. This aggressive increment and the rapid increase in RE_{COD} (figure 3) could be considered the result of the adjustment of microorganisms to their new growth mode [39]. In the following period (day 36-64), however, the carbon distributions did not change drastically due to the interaction between more activated MPB and increased OLR. At the end of this period, the VFA/ALK ratio and effluent pH were 0.29 and 7.2, respectively, which also suggested that the system was more stable than in phase I. This stability could be owed to the carbonate/bicarbonate cushion resulting from CO₂ generation in the anaerobic digestion process [40-42]. Another factor was the ammonia appearing when the nitrogenous compounds were degraded anaerobically. The ammonia (1350 mg/L) could buffer volatile acids by preserving a high concentration of bicarbonate [43].

3.1.3. Phase III (day 65-112). During the last phase, the removal rates of COD and sulfate did not change much, though the loading rates were still increasing in the period of day 65-84. When the OLR and SLR increased separately to 9kgCOD/m³•d (design value) and 0.27 kgSO₄²⁻/m³•d from day 85, the RE_{COD} and sulfate removal remained steadily at about 81% and 90%, respectively, which portended that the competition process between SRB and MPB seemed to reach a state of equilibrium. This result was supported by the nearly constant COD_{SRB} (3.4%) from day 90. During day 65-90, the portion of carbon flux to biogas increased rapidly from 51 to 69%, indicating that the growing conditions of MPB were much better than previous phases, which was also in conformity with the high RE_{COD} and continuous decrease of carbon flux to VFA. During day 91-112, most carbon mass (72%) was transformed to biogas, but that to biomass, VFA and bicarbonate did not change much. By the end of this period, the portions of the three had reached 7.8, 8.0 and 12.2%, respectively. Therefore, the carbon distribution between anabolic reactions and catabolic reactions seemed to be in a balance. In the late period of this phase, the VFA/ALK ratio and the effluent pH were 0.18 and 7.3, respectively,

this also meant that enough buffering capacity was presented in the reactor and a stable operation of the system had been performed [38, 44]. In this reactor, total alkalinity as CaCO_3 was 3100 mg/L, which was enough to stop the pH dropping.

With increasing loading rates, the production of methane and total gas increased throughout the experiment, though there were small fluctuations sometimes. The increase also showed the biomass in the UASSF was becoming more active, and it could handle more output of the leachate.

3.2. Effectiveness and contribution of biomass

To compare the effectiveness and contribution of biomass, the semi-fixed carrier was taken out of the reactor soon after day 112, and a new reactor without the supporting carrier was restarted immediately.

3.2.1. Determination of attached biomass. Based on visual observation, the biofilm on the belt carrier was black, dense and slimy. Thicker film was found mostly at the lower end of the carrier while thinner film was at the top of belt. Film thickness varied dependently upon the belt height where the biomass attached, which was estimated to be about 2 to 3 mm on the lower end of the belt and 1 to 2 mm on the upper end, respectively.

The belts were air-dried and cut into 20 cm-pieces. The pieces were divided into five groups based on their height on the belts, and the biofilm was then scraped from the carrier surface for biomass determination. As a result, the average concentration of attached biomass was calculated to be 1.28 g/L. The distributions of attached biomass on the carrier are presented in figure 6.

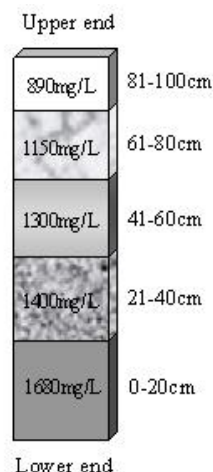


Figure 6. The distribution of attached biomass on the belt carrier.

3.2.2. Performance of suspended biomass. Owing to the acclimated anaerobic sludge, the restart of the reactor was easily accomplished within fifty days (figure 7). The reactor was operated with a stepwise increase of OLR from 2 to 8 $\text{kgCOD/m}^3\cdot\text{d}$, and the RE_{COD} increased, though the reactor was instable during the first two weeks due to the high initial OLR and the new environment in the reactor. From day 15 to day 43, the RE_{COD} gradually increased from about 40 to 60%, which corresponded to the OLR of 4 to 7 $\text{kgCOD/m}^3\cdot\text{d}$. However, the RE_{COD} , which nearly kept constant from day 36 to day 43, decreased sharply below about 40% when the OLR was further increased to 8 $\text{kgCOD/m}^3\cdot\text{d}$ from day 44. It seemed that the reactor was not able to deal with the increased OLR, i.e. to avoid the collapse of the new system without the supporting carrier, the influent OLR of 7 $\text{kgCOD/m}^3\cdot\text{d}$ should not be exceeded.

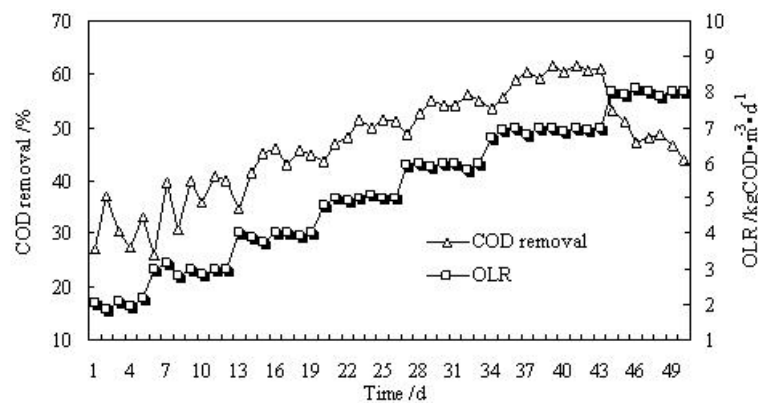


Figure 7. The performance of the new reactor without carrier.

3.2.3. Biomass comparison. After the restart test, the suspended biomass concentration (BCT) was measured to be 4.32 g/L. For the convenience of comparison, the BCT is supposed to be constant throughout the restart experiment, and the effective OLR ($OLR_{\text{effective}}$), the biomass contribution (BCB) and biomass effectiveness (BE) are defined as follows:

$$OLR_{\text{effective}} = OLR \times RE_{\text{COD}}$$

$$BCB = (OLR_{\text{effective}} / OLR_{\text{effective of UASSF}}) \times 100\%$$

$$BE = OLR_{\text{effective}} / BCT$$

Therefore, the biomass comparison can be performed by assuming that there is a virtual reactor with only attached biomass (table 2).

Table 2. The results of biomass comparison.

Reactor	UASSF	New reactor	Virtual reactor
Carrier	Belt carrier	No carrier	Belt carrier
Biomass	Overall	Suspended	Attached
OLR	9 kg COD/m ³ ·d	7 kg COD/m ³ ·d	...
RE_{COD}	80%	60%	...
$OLR_{\text{effective}}$	7.2 kg COD/m ³ ·d	4.2 kg COD/m ³ ·d	3.0 kg COD/m ³ ·d
BCT	...	4.32 g/L	1.28 g/L
BCB	...	58%	42%
BE	...	0.97/d	2.34/d

As presented in table 2, the contribution of attached biomass accounted for 42% of the whole COD inversion. More importantly, the effectiveness of the attached biomass was 2.34/d, more than twice that of suspended biomass, which indicated that the activity of biofilm was higher than that of sludge. Though the semi-fixed carriers could act as three-phase separator to accumulate more suspended sludge, the principal role of the belt was to function as supports to immobilize bacteria. Therefore, in terms of this new carrier, the most attractive strength was its high build-up of active biomass. Other strengths, such as no clogging and sludge washout, strong resistance to environmental changes and small land area requirements were also appreciable.

4. Conclusions

In this research, a pilot scale UASSF reactor was used for landfill leachate treatment. According to the experiment, the conclusions were as follows:

- The operation of UASSF could be divided into three phases roughly. The RE_{COD} increased

with the stepwise increment of OLR, while the COD_{SRB} decreased from 5.9% to 3.4% during the operation. The UASSF performed well in the treatment process, and the RE_{COD} remained around 81% at the design loading rate of 9kgCOD/m³•d.

- The metabolized carbon distributed into four parts. The portion of carbon flux to biogas increased with the operation time, while that to VFA decreased gradually. In the later stage of the operation, the portions of biogas, VFA, bicarbonate and biomass were 72, 8.0, 12.2 and 7.8% respectively, which indicated that the treatment system was operated at a steady state.
- Though the influent pH value was usually low (4.8-5.2), the effluent pH and VFA/ALK ratio were 7.3 and 0.18, respectively, in the late period of the operation, which meant that the system had a sufficient buffering capacity.
- Based on the results of reactor restart, the contribution of attached biomass accounted for 42% of the total COD conversion, while the effectiveness of it was more than twice higher than that of suspended biomass. This suggested that the semi-fixed carrier in the UASSF system was capable to form the active biofilm during the leachate treatment.
- The effluent from UASSF system needs further treatment before discharging into surface waters, which can be fulfilled using conventional aerobic treatment systems, membrane separation technology or the hybrid treatment process.

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