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ORIGINAL PAPER

Treatment of food processing wastewater in a full-scale jet biogas internal loop anaerobic fluidized bed reactor

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Abstract A full-scale jet biogas internal loop anaerobic fluidized bed (JBILAFB) reactor, which requires low energy input and allows enhanced mass transfer, was constructed for the treatment of food processing wastewater. This reactor has an active volume of 798 m^3 and can treat 33.3 m^3 wastewater per hour. After pre-treating the raw wastewater by settling, oil separating and coagulation-air floating processes, the reactor was operated with a relatively shorter start-up time (55 days). Samples for the influent and effluent of the JBILAFB reactor were taken and analyzed daily for the whole process including both the start-up and stable running periods. When the volumetric COD loading fluctuated in the range of 1.6–5.6 kg COD m^{-3} day^{-1}, the COD removal efficiency, the volatile fatty acid(VFA)/alkalinity ratio, the maximum biogas production and the content of CH_4 in total biogas of the reactor were found to be 80.1 ± 5%, 0.2–0.5, 348.5 m^3 day^{-1} and 94.5 ± 2.5%, respectively. Furthermore, the scanning electron microscope (SEM) results showed that anaerobic granular sludge and microorganism particles with biofilm coexisted in the reactor, and that the bacteria mainly in bacilli and cocci were observed as predominant species. All the data demonstrated that the enhanced mass transfer for gas, liquid and solid phases was achieved, and that the formation of microorganism granules and the removal of inhibitors increased the stability of the system.

Keywords Anaerobic treatment · Jet biogas internal loop anaerobic fluidized bed · Granular sludge · Food processing wastewater

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Introduction

Food processing and fermentation industries are experiencing a rapid growth in China, but simultaneously generate a large quantity of wastewater effluents up to 2.5 × 10^9 m^3 per year (Wang et al. 2005). Their wastewaters are typically composed of carbohydrates, lipid and salinity (Berardino et al. 1997; Oliva et al. 1995; Guerrero et al. 1999) and characterized by high organic loading (>4,000 mg/l) and good biodegradability. In recent years, anaerobic treatment have been widely used for digesting these wastewaters because it offers distinct advantages such as low energy requirement, low waste sludge and high biogas production (Cronin and Lo 1998; Ginkel et al. 2005; Oh and Logan 2005).

To date, the high-rate anaerobic reactors in wide-spread use in the full-scale wastewater treatment include upward-flow anaerobic sludge blanket (UASB), expanded granular sludge bed reactor (EGSB), and internal circulation (IC) reactor. These reactors, featuring with high organic loading and low energy input, are efficient in treating wastewaters which are easily degraded, but show difficulty for the treatment of less degradable or high-salinity wastewaters. This lies in the fact that the inhibition of methane bacteria growth causes the limited production of biogas (that is expected to enable effective mixing or mass transfer). To address this issue, an anaerobic fluidized bed reactor (AFBR) which is fluidized by the upflow liquid has been proposed (Buffiere et al. 1998; Wei et al. 2007; Zhang et al. 2009) and its potential applications for the treatment of hazardous or recalcitrant compositions have been well documented (Suidan et al. 1996; Moteleb et al. 2002). As shown in these reports, a high liquid recirculation ratio reaching about 10–50 (sometimes even more than 50) is essential to sustain the fluidization of the granular sludge in the AFBR. This high value, however, is not beneficial because of high energy demands for pumping and creation of strong shear force which may prevent the formation of biofilm on the carrier and prolong the start-up time of AFBR (Heijnen et al. 1989). Moreover, from the viewpoint of dynamics, it decreases the impetus and velocity of the reaction.

In order to solve this problem, some researchers have carried out experiments with the concurrent gas and liquid upflow in the AFBR (Diez Blanco et al. 1995; Hidalgo and Garcia-Encina 2002). When gas is introduced into the reactor, it can relatively better expand the sludge bed along the height of the reactor, even with lower liquid upflow velocity (Suvajittanont and Chaiprasert 2003). Moreover, some other beneficial features such as efficient liquid mixing and fluidization, moderate shear force and short start-up period can be ensured by gas-lift systems (Beeftink and Van den Heuvel 1987). The gas introduced into the reactor can be nitrogen or biogas produced in anaerobic environments. It is impractical to use nitrogen in the full-scale treatment due to the high operation costs. In contrast, biogas, as the metabolic product in the anaerobic process, is more cost-effective and extensively investigated (Smith et al. 1996; Suvajittanont and Chaiprasert 2003; Wu et al. 2009).

In order to develop the AFBR which is driven by the self-produced biogas, we have previously performed a series of bench-scale and pilot-scale studies on the jet biogas internal loop anaerobic fluidized bed (JBILAFB) reactor (Wei et al. 2007; Deng et al. 2008). The purpose of this study is to explore the feasibility of using the JBILAFB reactor in the full-scale wastewater treatment engineering. To this end, a full-scale JBILAFB reactor was designed and constructed, serving as the anaerobic treatment unit of the whole food processing wastewater treatment plant. As the biogas is collected and recirculated into the anaerobic reactor, it can enhance the mass transfer rate and afford appropriate shear to form compact granular sludge. Furthermore, some poisonous gases (e.g., H_2S, N_2O) which inhibit the anaerobic metabolic activity can be vent out by stripping of the recirculation biogas and absorbed in the alkaline solution outside (Wei et al. 2007). In this study, we examine the start-up time of this full-scale reactor followed by the investigation of performances of JBILAFB reactor for the stable operation in terms of the optimal recirculation ratio, chemical oxygen demand (COD) removal, volatile fatty acid (VFA) fluctuating and biogas yield coefficient. Furthermore, the appropriate operational conditions for anaerobic granular sludge formation are analyzed and the nature of granular sludge in the stable full-scale JBILAFB reactor is investigated.

Materials and methods

Wastewater

The wastewater was from the effluent of a real food processing factory (Lee Kum Kee Condiment Corporation, Guangdong, China). The raw material for this factory is variable including flour, soybean, tomato, pepper and salt, hence causing the large variation in the composition of food-processing wastewaters. The basic characteristics of the investigated wastewater are listed in columns 3 and 4 of Table 1. The results represent the means of measurements performed in 3 months. The data indicate that the wastewater contains high-concentration organics with a high biochemical oxygen demand/chemical oxygen demand (BOD/COD) value around 0.5 and a sufficient concentration of nutrient elements such as nitrogen and phosphorus. This suggests that the biological treatment is suitable for the wastewater.

Table 1 Main characteristics of the food processing wastewater

Parameter	Unit	Raw wastewater		Wastewater after pre-treatment	
		Range	Average	Range	Average
Temperature	°C	23.5–38.2	28.5	22.6–37.5	27.8
pH	–	3.4–11.2	5.1	6.4–9.5	7.5
COD_{Cr}	mg l^{-1}	957.6–7891.5	4018.1	721.9–5648.8	2815.1
BOD_5	mg l^{-1}	600.0–4406.8	2045.3	473.5–2979.3	1512.5
NH_3–N	mg l^{-1}	11.5–49.6	33.6	11.5–48.7	32.5
TP[a]	mg l^{-1}	0.3–2.6	1.5	0–0.3	0.05
Colority	Times	150–750	450	16–64	32
SS[b]	mg l^{-1}	50.3–982.5	455.3	37.2–128.3	65.4
Oil	mg l^{-1}	6.2–22.7	18.4	1.3–5.6	3.3

[a] Total phosphorus (TP);
[b] suspended solids (SS)

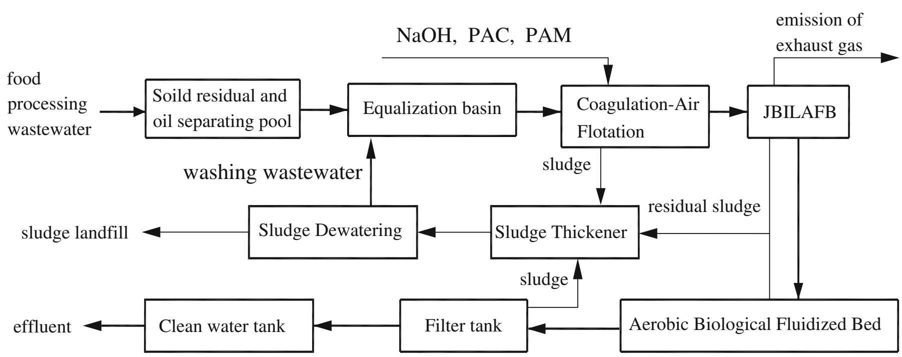

Fig. 1 Process flow diagram of full-scale wastewater treatment plant

Moreover, the pretreatment is required before the biological process because the wastewater has a low pH value, a high suspended solids (SS) concentration and a high colority.

Based on the above analysis about the raw wastewater, a full-scale anaerobic–aerobic biological treatment process was designed, as shown in Fig. 1. The raw wastewater was firstly fed to a separating tank to remove the solid and oil; otherwise, their presence may seriously influence the mass transfer from the bulk water to the sludge. In order to ensure a continuous flow and a stable concentration of influent, the effluent was then moved to an equalization basin. Subsequently, the effluent from the equalization basin was pumped into a coagulation-air floating tank (CAFT), where SS removal, color removal and pH adjustment were completely simultaneously. All the above procedures belong to the pretreatment process, which can guarantee the stability for the subsequent biological treatment. The wastewater characteristics after the pretreatment are shown in columns 5 and 6 of Table 1. The average removal rates of COD, SS and colority were 29.9, 85.6 and 92.9%, respectively and pH was controlled at 6.4–9.5. Phosphorus is essential for microorganism growth, but the total phosphorous (TP) concentration after the pre-treatment is too low (0.05 mg l^{-1}) to sustain the growth of microorganisms. Therefore, NaH_2PO_4 was amended to the wastewater as the phosphorus source. The residual COD and BOD in the wastewater after the pretreatment was still high (COD $\sim$ 3,000 mg/l, BOD $\sim$ 1,500 mg/l). A high-rate anaerobic reactor (JBILAFB) was thus employed to treat this wastewater. Except otherwise specified, the influent and effluent represent samples taken from the bulk wastewater after the pretreatment and from the JBILAFB reactor, respectively.

JBILAFB Reactor

The field JBILAFB reactor constructed with armored concrete has three different zones including a reaction zone, a separation zone and an auxiliary zone, as illustrated in the schematic diagram (Fig. 2a). The reaction zone is in the middle of the whole reactor; the auxiliary zone and separation zone are located bilaterally. The reaction zone is connected with the auxiliary zone by the top space that is occupied by biogas, and connected with the separation zone by two orifices in the middle and bottom. The total effective volume of the reaction zone and separation zone reactor is 798 m^3 which was measured by filling the reactor with a metering pump. Their total dimensions are 6 m × 12 m × 12 m (Height × Length × Width). Figures 2b and c are the field photographs of gas and liquid recirculation system taken from the top of the reaction zone and the separation zone, respectively.

The reaction zone is composed of two coaxal cuboids. The draft channel in the internal cuboid is the riser where the mixture of biogas and liquid move upward; the annule area between the two cuboids packed with elasticity cubic carriers is the downcomer where the mixture move downward. The reaction zone is fully airproofed and the biogas can be accumulated at the top. Eight PVC pipes are vertically inserted into the reactor to convey the accumulated biogas. It should be noted that one of these pipes is connected with a water seal bottle to control the pressure of the biogas, when the pressure is beyond the static pressure of water in the bottle. Another pipe is connected with a manometer to display the real-time pressure in the reactor. The remaining six pipes are connected with a jet. When high-speed recirculation liquid passes through the "throat" of the jet, the accumulated biogas is sucked into the jet, mixed with the recirculation liquid and released again by perforated pipes from the bottom of the reactor. The released mixture of biogas and recirculation liquid enable the reactor to sustain a fluidizing status with a rather low liquid recirculation ratio.

The separation zone consists of a buffer section, an inclined pipes section and an outflow trough. The mixed liquid in the annule of the reaction zone flows into the buffer section of the separation zone through a middle connection orifice. After passing through the buffer section, the mixed liquid flows upward and through the inclined pipes section. Then the granular sludge is intercepted and slides into the reaction zone. The recirculation liquid for biogas sucking is withdrawn under the inclined pipes section, thus reducing the settling loading of the inclined pipes. The effluent is collected and drained through a weir at the top of the separation zone. The auxiliary zone is set to remove poisonous gases such as H_2S and N_2O, which can inhibit the anaerobic process. The biogas pumped from the top of the reaction zone is released from the bottom of the auxiliary zone, while the alkaline solution is sprayed from the top. Therefore, they move in an opposite direction and react on the surface of stuffing packed in the auxiliary zone. The purified biogas naturally flows into the top space of reactor by the suction effect of pump. The alkaline solution is collected at the bottom and reused until it is exhausted.

Carrier and inoculums

The wood powder, a waste produced in the process of wood processing, was used as the carrier for microorganism in the JBILAFB reactor. Its dry bulk density was about 0.65 g l^{-1}. The reactor was inoculated with the sludge obtained from an anaerobic digester of a municipal wastewater treatment plant in Guangzhou City, China. The initial inoculation volume was about 4% (V/V) and suspended solids concentration was 8.5 gVSS l^{-1}.

Start-up strategy

The JBILAFB reactor was first operated over 55 days to obtain proper concentrations of microorganisms and to acclimate the anaerobic sludge. During this start-up period, volumetric COD loading (VL) was gradually increased by varying the feeding rate and the hydraulic retention time (HRT). In the first 9 days, the flow rate was controlled at 15.0 m^3 h^{-1}, corresponding to the HRT about 53 h. The feed flow rate was changed to 20.0 (HRT $\sim$ 40 h) and 25.0 m^3 h^{-1} (HRT $\sim$ 32 h) for the following 10–19 and 20–28 days, respectively. Finally the feed flow rate was fixed at 33.3 m^3 h^{-1} (HRT $\sim$ 24 h). The influent pH of wastewater for the start-up period of JBILAFB was in the range of 7.0–7.5 adjusted by adding NaOH solution. Based on experimental results of the pilot-scale JBILAFB reactor (Deng et al. 2008), the amount of recycling biogas was controlled by the valve on the PVC pipe to assure that the sludge and wastewater in reactor were mixed completely. The liquid upflow velocity in the reactor was mainly determined by the biogas holdup in the inner riser.

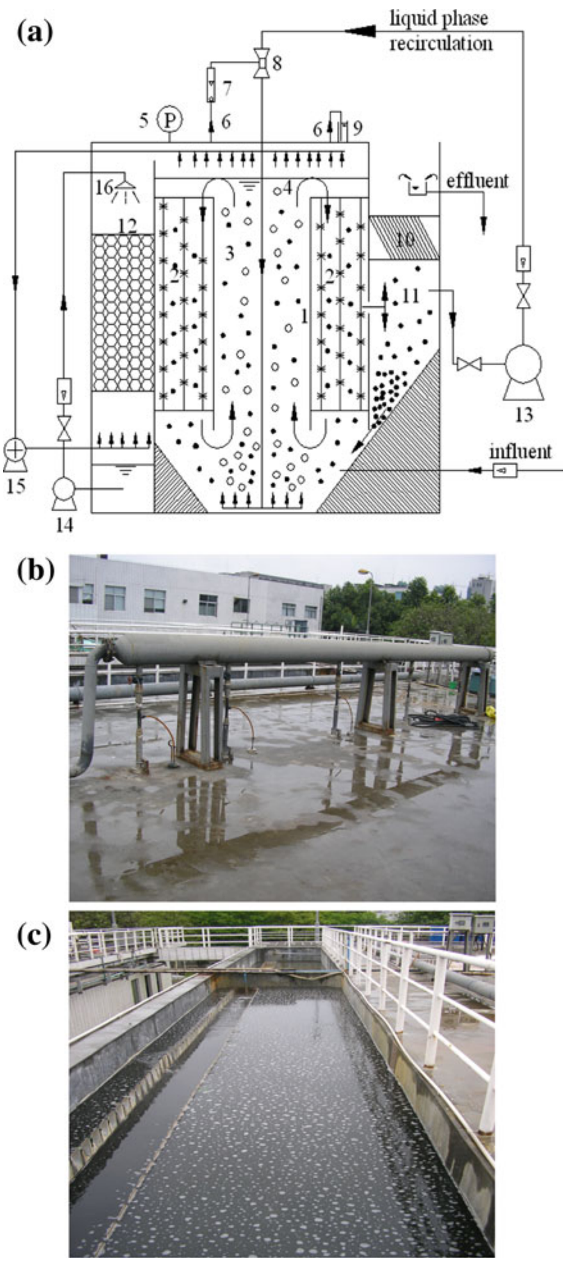

Fig. 2 Schematic diagram and photograph of the full-scale JBILAFB reactor

The amount of biogas sucked by the recirculation liquid was manipulated by the valve of biogas transport pipe and the mixture liquid recirculation ratio. In our field test, the flow rate of biogas was maintained constant, causing a steady liquid upflow velocity of about 40 cm s^{-1}.

Analytical methods

All samples were collected and analyzed for the following parameters: influent and effluent COD concentration, SS and volatile suspended solids (VSS), NH_3–N, TP, pH, temperature, volatile fatty acids (VFA) and total alkalinity, sludge volume (SV) and sludge volume index (SVI). Analyses were performed according to the standard methods (APHA/AWWA/WEF 1995). VFA and the alkalinity were measured by a gas chromatograph and Bromcresol Green-methyl red indicator standard acid–alkali titration method, respectively (Wei et al. 2007). The amount of biogas produced was measured three times per day using a gas meter, at 9:00 a.m., 15:00 p.m. and 21:00 p.m., respectively. Its composition was analyzed by gas chromatography (Agilent 6820-gas chromatography with thermal conductivity detector). All parameters were measured once per 3 days and data represent the average value of triplicate experiments.

The morphologies of steady-state anaerobic sludge and biofilm in the JBILAFB reactor were observed by scanning electron microscopic (SEM) using a Philips scanning electron microscope (XL-30). The sludge age (θ_c) and specific sludge production were determined during apparent steady-state. The sludge age (θ_c) can be calculated by the following Eq. 1 (Mendonca et al. 2004):

$$\theta_c = \left(W_{wp}X_{wp} + X_{ss}V_L\right)/QX_e \quad (1)$$

where W_{wp} is the weight of wood powder (wp) in the reactor, mg; X_{wp} is the biofilm mass per unit weight of wood powder (mgVSS mg^{-1}); X_{ss} is the suspended biomass in the reactor (mgVSS l^{-1}); V_L is the volume of the reaction zone not occupied by carrier, L; Q is the influent flow rate (l day^{-1}); and X_e is the suspended biomass concentration of effluent (mgVSS l^{-1}).

Results and discussion

Efficiency of the JBILAFB reactor

The performance of the JBILAFB reactor at the food processing plant was studied over a period of 12 months. The final effluent from the reactor had a pH value between 6.3 and 8.0. During the first 9 days of operation, the feed flow rate was controlled at 15 $m^3 h^{-1}$ and the initial volumetric loading applied amounted to 41–82% of the potential removal capacity. The purpose was to acclimate the anaerobic biomass to the wastewater gradually. Because the amount of anaerobic sludge (about 8.5 kgVSS m^{-3}) was lower than the value published by Lettinga and Hulshoff Pol (1991), excess activated sludge of the following aerobic fluidized bed was recycled back to the JBILAFB reactor in the 1st week. Then, the feed flow rate was increased to 20, 25 and 33.3 $m^3 h^{-1}$ stepwisely, which corresponded to the volumetric loading of 1.1, 1.8 and 3.0 kgCOD m^{-3} day^{-1}, respectively. When the reactor reached a steady state with the anaerobic sludge concentration of 16.9 ± 4.2 kgVSS m^{-3}, SV of 39.8 ± 6.4 ml g^{-1}, and SVI in the range from 140 to 230 ml g^{-1}, the rate of COD removal reached a high value up to 80.5%. After start-up, the reactor was allowed to run with the food processing wastewater over 10 months. It can be seen in Figs. 3 and 4 that although the COD of influent varied greatly, most values of the effluent COD concentration were lower than 500 mg l^{-1}. When the volumetric COD loadings of treatment system were changed from 1.6 to 5.6 kgCOD m^{-3} day^{-1}, the COD removal rate of 85.3 ± 5% was achieved.

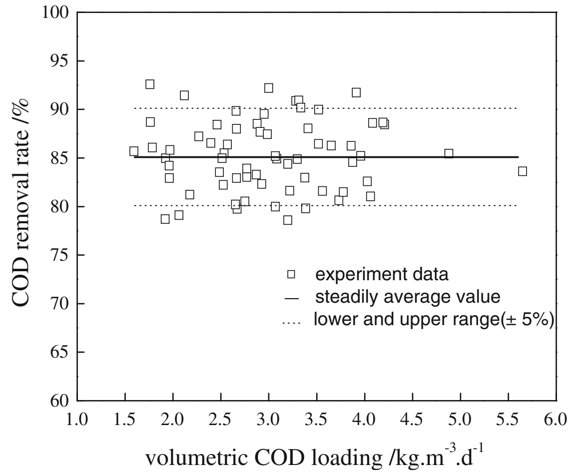

Fig. 4 COD removal rate versus volumetric COD loading during steady-state period

A comparison with previously studied reactors treating the similar kind of wastewater was performed. Table 2 shows the design parameters and the average COD removal efficiencies obtained in the anaerobic filter (AF), UASB, EGSB and anaerobic fluidized reactor (AFB) systems for treating the wastewaters originated from cannery, meat, potato or beer processing industries. All of the treatment

Fig. 3 COD concentration and its removal rate during experimental period

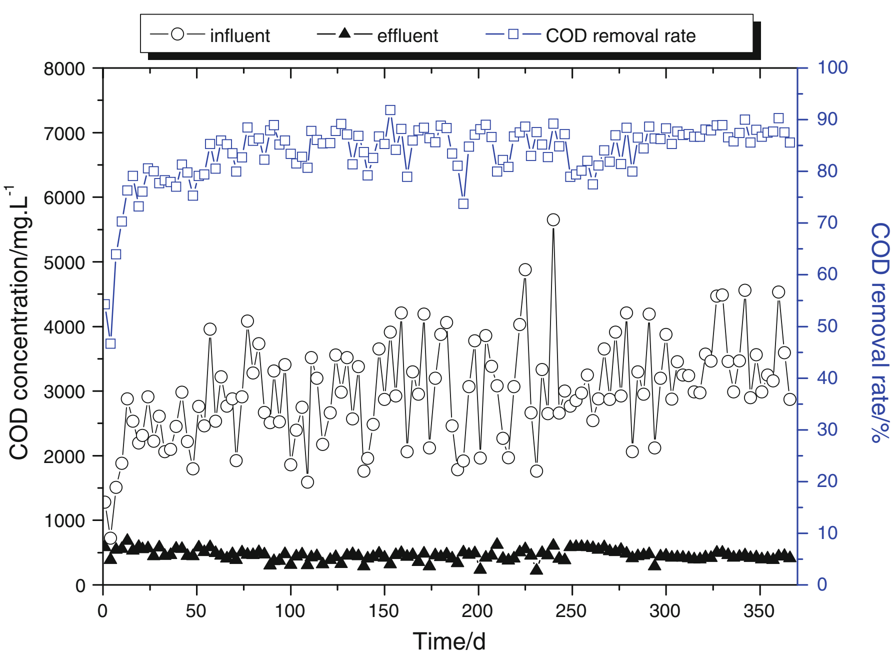

Table 2 Design and operation parameters of some full-scale AF, UASB, AFB and EGSB reactors treating food processing wastewater

Industry or state	Design and operation parameters					
	Q	Type	HRT	Volume loading	*E*	Reference
Guangzhou, China	800	JBILAFB	24	1.6–5.6	80.1 ± 5	–
Fábrica de Salames Rio Preto	200	AF	18	2.00	80–85	Oliva et al. (1995)
Sofruta Industria Alimentícia Ltda	1400	UASB	24	2.14	>85	
Fábricas Peixe	2160	AF	18	1.20	~80	
Conservas Colombo	1200	UASB	12	0.53	>90	
Indústria Alimentícias Hero S. A.	250	UASB	8	1.40	>85	
Germany	1700	EGSB	\	\	70–85	Austermann-Haun et al. (1997)
Dorr-Oliver Muscatine	32	AFB	19	11	<75	Heijnen et al. (1989)
Gist-brocades Delft	180	AFB	2.4	22	60–70	
Gist-brocades Prouvy	50	AFB	3.2	20	<75	

Q daily flow rate (m^3 day^{-1}); *HRT* hydraulic retention time (h); *VL* volumetric COD loadings (kgCOD m^{-3} day^{-1}); *E* COD removal efficiency (%)

systems are provided with grit-removal devices. Some of them have a sedimentation unit before the anaerobic reactors. Most of them have a flow equalization unit and some of the canneries are equipped with a pH adjustment system. Moreover, some reactors were operated in a two-stage mode. It is clear from Table 2 that the traditional AFB reactor has a high volumetric loading rate and a high COD removal efficiency, but the amount of wastewater treated is relatively low. The JBILAFB reactor enabled large amount of wastewater treatment because of the lower liquid recycling ratio that minimized the volume of the reactor. The COD removal efficiency for JBILAFB reactor was competitive with the UASB and AF reactors when the volumetric loading is in the range of 0.53–5.6 kgCOD m^{-3} day^{-1}.

VFA and alkalinity

The VFA/alkalinity ratio can often be used as a representation of process stability. When its value is less than 0.3–0.4, the process is considered to be operating favorably without acidification (Borja and Banks 1995). During the steady-state period, the anaerobic effluents of VFA and alkalinity are illustrated in Fig. 5. It can be seen that the VFA/alkalinity ratio (0.34) was lower than the suggested limit value in all cases. Moreover, the VFA concentration was below 100 mg l^{-1} with an average value of 60 ± 14.9 mg l^{-1} and the alkalinity of effluent had an average value of 174.7 ± 32.1 mg l^{-1}. These results indicate that the activity of acidification microorganisms and methanogenic microorganisms are coordinated and the JBILAFB reactor system possesses a good stability and efficiency.

Biogas production

Figure 6 shows the biogas production per day and volumetric COD loading of the JBILAFB reactor throughout the whole experimental period. It can be seen that in the phase a (start-up period), the biogas production per day increased with an increase in the volumetric COD loading. In the phase b, the COD loading reached a relatively steady status, while an obvious lag period (about 40 days) for biogas production was observed. This observation can be attributed to the slower reproduction ratio for the methanogen. In the phase c, the biogas production reached a relatively steady status and fluctuated with the variation of influent COD loading. It is thus can be concluded that, at the steadily running period, the reactor has a capability to deal with wastewaters with various COD loadings and the activity of methanogenic is sufficiently high to transfer organic carbon to methane and to avoid the accumulation of VFA. When the influent volumetric COD loadings were changed from 1.6 to 5.6 kgCOD m^{-3} day^{-1}, the biogas production was more than 140 m^3 day^{-1} and the maximal biogas production of the reactor was 348.5 m^3 day^{-1}. As a result, the ratio of methanogen

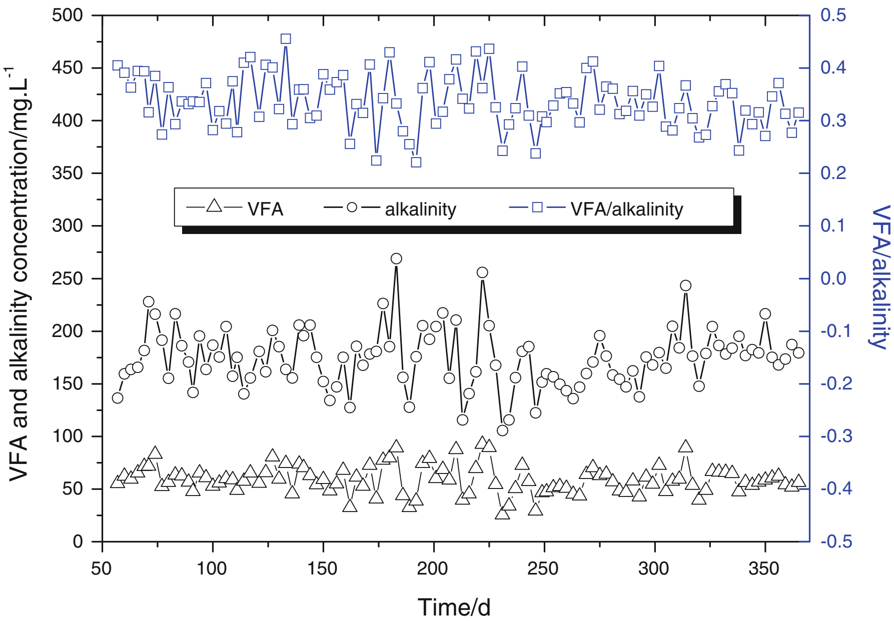

Fig. 5 The variation of VFA and alkalinity concentration in reactor during steady-state period

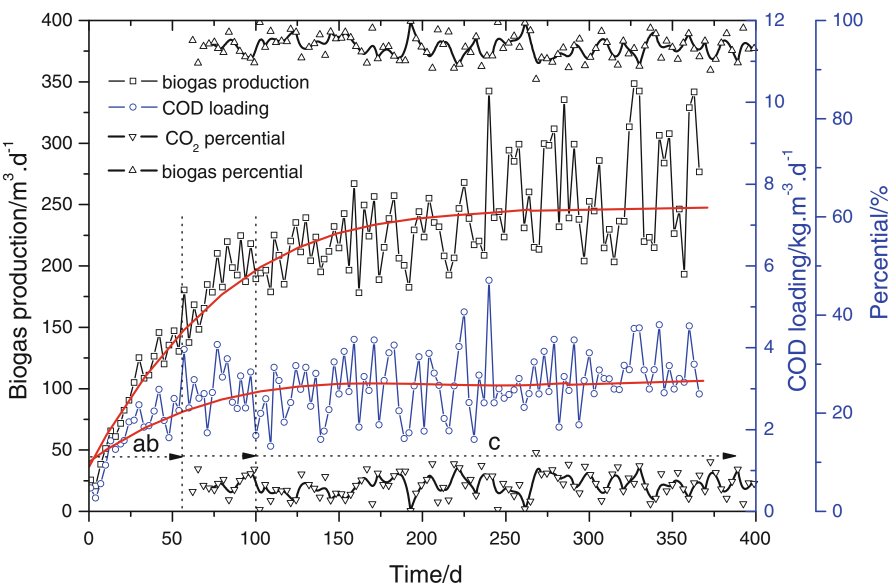

Fig. 6 Biogas production, COD loading and biogas percential during the experimental period (*a*, start-up period; *b*, lag period; *c*, steady period)

and non-methanogen should be in a balance so that the slowest-growing methanogen can keep up with the variety of compounds generated by non-methanogens (Suvajittanont and Chaiprasert 2003). Figure 6 also shows the composition of biogas of the JBI-LAFB reactor during the steady-state period. Methane (CH_4) accounted for the larger proportion (94.5 $\pm$ 2.5%) of the total biogas produced in the reactor, in which the proportion of CO_2 was significantly low (5.5 $\pm$ 2.5%). The proportion of CH_4 was highly greater than the data reported in the literature (Zhao et al. 2008). This is due to the fact that the alkaline absorption system has been adopted in the reactor, causing most of CO_2 to be removed.

In order to evaluate the efficiency of the biogas production, the experimental data were compared with those predicated according to following equation. In general, the biogas production can be considered to be proportional to the COD removal. Provided with the constant value of biogas yield ratio (Y_{gas}), the organic loading rate (OLR) and the reactor volume (V), the time average biogas production (Q_{gas}) can be expressed in the Eq. 2 (Diez Blanco et al. 1995).

$$Q_{gas} = Y_{gas}Q(S_0 - S_e) \quad (2)$$

Where Q (m^3 day^{-1}) is the influent volumetric flow rate; S_0, S_e (mg l^{-1}) is the influent and effluent COD concentration, respectively. The biogas yields ratio (Y_{gas}) varied between 0.07 and 0.18 l biogas g^{-1} COD_{rem}. The average biogas yield achieved was about 0.12 l biogas g^{-1} COD_{rem}. Theoretically, 350 l of biogas is produced per kg COD removed (0.35 l biogas g^{-1} COD_{rem}) by taking into account glucose as the starting compound. When a biogas condensed factor about 1.6 is accounted, the average biogas yield achieved is about 0.192 l biogas g^{-1} COD_{rem}. In such a case, the rate of biogas production in the JBILAFB reactor can be attained about 55% of the theoretical production rate. The low value is probably due to the biogas leakage at the head of the reactor and the feature of the food processing wastewater (that is more complex than glucose).

Anaerobic biofilm and granular sludge

During the steady-state period, the anaerobic sludge age as a function of operation time is presented in Fig. 7. An average concentration of attached and granular sludge biomass was found to be 2.9 ± 1.7 and 13.8 ± 3.8 mgVSS l^{-1}, respectively. It is apparent that the biomass grew mainly in granules and partly in a biofilm under the conditions of long HRT and low upward liquid velocity. The anaerobic sludge age in the reactor was about 28 ± 2 days, which was larger than the values reported previously (Mendonca et al. 2004). However, the long sludge retention time (SRT) was beneficial to the stability of the anaerobic treatment system. Morphological characterization of the anaerobic sludge and biofilm was performed by SEM. The pictures of typical granular sludge and biofilm obtained from the JBILAFB reactor are shown in Fig. 8. The biofilm was also

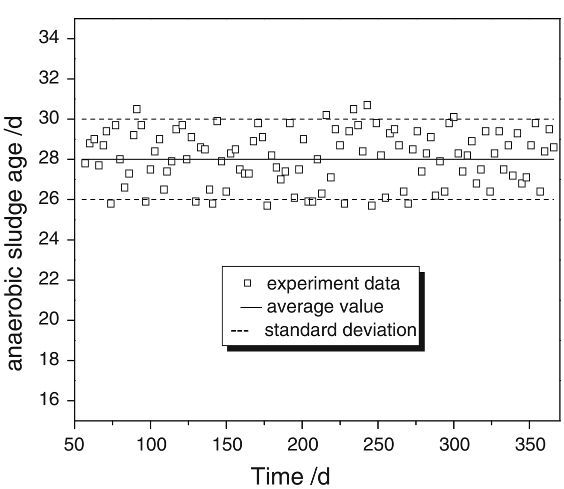

Fig. 7 Percential of biogas during the steady-state period. Anaerobic sludge age in the reactor during the steady-state period

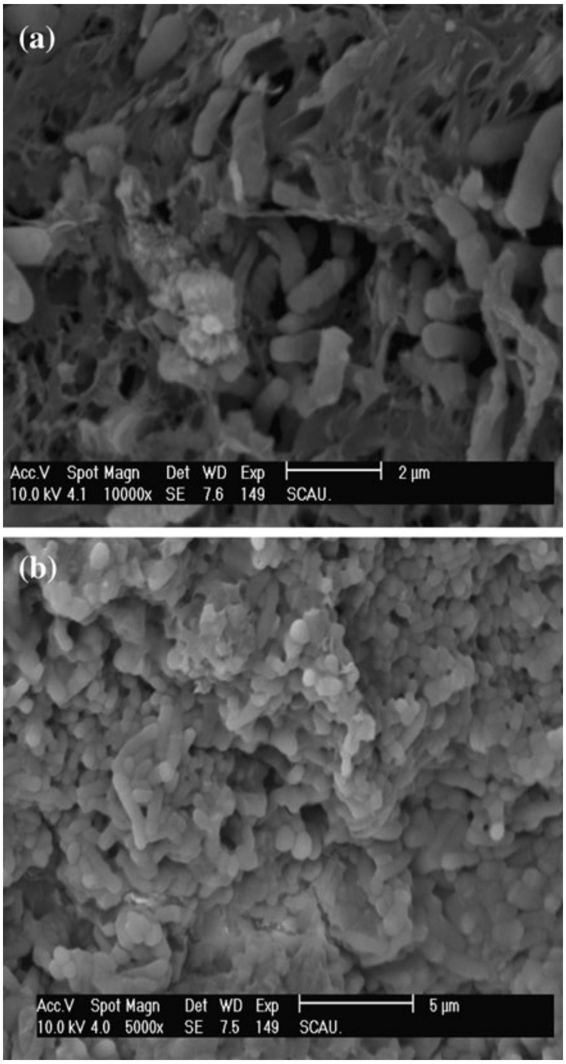

Fig. 8 Anaerobic biofilm and sludge granules in the JBILAFB reactor. **a** anaerobic biofilm on the carrier; **b** surface of the granules

present on the surface of the wood powder and sludge granules during the experimental period. The surface observation of the granule revealed that it was composed of many micro-holes that could be the channels for the microorganism acquiring nourishment from outside and removing excretion from inside. The SEM images also indicated that the bacilli and cocci bacteria were observed as predominant species existed on the surface of anaerobic biofilm and granular sludge.

Energy requirement analysis

The essential energy input for the JBILAFB reactor includes three parts: the energy for pumping the recirculation liquid, the energy for releasing the biogas for removing the poisonous gas and the energy for alkaline solution recycling. The first part consumes most of the energy in comparison with the second and third parts. Because the recirculation of biogas efficiently used the turbulent energy of gas, the energy for mixing and fluidizing the reactor was dramatically reduced. Moreover, high mass transfer rate and microorganism activity reduced the HRT and increased the COD removal rate; therefore, the specific energy requirement for sludge stirring and recycling in the reactor was much lower when compared with other full-scale food processing wastewater anaerobic reactors. According to the literature, when the anaerobic/SBR process was used to treat dehydrated vegetables-processing wastewater, the specific energy input for anaerobic reactor was 0.18 kWh/m^3 and the total equipment input power was 5.2 kW (Xiaolian and Xifeng 2009). When the UASB and aerobic biofilm process was used for beer wastewater treatment, the total equipment input power for the UASB reactor was 4 kW and the specific energy input was 0.1 kWh/m^3 (Hongjun et al. 2008). For the JBILAFB reactor in this study, the total equipments input power were 3.75 kW and the specific energy input was 0.12 kWh/m^3. It can be seen that the energy consumption for this reactor is relatively lower than that for the SBR, but slightly higher than that for the UASB. It thus can be concluded that the advantages of the process include the ability to enhance mass transfer and to afford complete fluidized status by gas driven stirring. The elimination of forced convection by gas driven stirring and sludge recycling by on site sludge separation which need an external energy source, results in the save of energy.

Conclusions

The food processing wastewater is easily biodegradable and hence it is suited to be treated with an anaerobic process. A novel JBILAFB reactor was designed, constructed and run in a full-scale food processing wastewater treatment system. The prominent characters of this reactor were that the fluidization effect and mass transfer rate was enhanced by biogas recirculation and that microorganism activity was increased by stripping and removing of poisonous gas. The reactor was started up in 55 days and it treated the food processing wastewater effectively and stably. When the HRT was controlled at about 24 h and the volumetric COD loading was fluctuated in the range between 1.6 and 5.6 kgCOD m^{-3} day^{-1}, the COD removal rate achieved was 80.1 ± 5% and the effluent COD was lower than 500 mg/l. This anaerobic process produced biogas with the maximum value of 348.5 m^3 day^{-1} which contains 94.5 ± 2.5% CH_4. Both the anaerobic biofilm and the granular sludge coexisted in the reactor. The formation of microorganism granules, enhancement of mixing and mass transfer for gas–liquid–solid phases and stripping of poisonous gas contributed to the stability and increased treatment effect for the JBILAFB reactor. The specific energy input for the anaerobic reactor was 0.12 kWh/m^3. The full-scale anaerobic reactor, used for the food processing wastewater treatment engineering, has been continuously and stably run over 12 months.

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