Empirical analysis of mass flow and operation performance of a full-scale biogas plant for human feces treatment

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Abstract: With the rapid development of urbanization in China, the existing municipal network cannot cover all areas and solve all human waste treatment problems. Biogas plants, as an important nationally developmental strategy for cleaner energy production and environmental protection, have been widely used in many industrial and agricultural fields. This research analyzed the mass flow and operation performance in a biogas plant treating human feces at a practical rather than laboratory scale. The biogas plant operated on mesophilic semi-continuous mode at the organic loading rates (OLRs) of 0.56 kg volatile solid (VS)/(m^3·d) and average total solid (TS) contents of 3.50%. Results showed that the average biogas production and methane yield were (145±10) m^3/d and (471±17) m^3 CH_4/(t VS), respectively. Annual total feeding amount was 2555.0 t. Among these, there were 58.04 t biogas and 2496.97 t digestate, including 43.07 t solid residues and 2453.90 t liquid digestate. For the full-scale biogas plant, anaerobic bacteria could acclimatize to high total ammonia nitrogen (TAN) concentration (3659 mg/L) and tolerate high free ammonia nitrogen (FAN) concentration of 561 mg/L. It also had strong autoregulation for adapting the large range (2.02-15.18 g/L) and high concentration (15.18 g/L) of influent volatile fatty acid (VFA). In order to achieve its sustainable development and high efficient operation, it is very important to improve the feeding concentration, using digestate to dilute raw material and adding some high C/N raw material in human feces. In conclusion, the biogas plant was an excellent alternative technology for treating human feces.

Keywords: biogas plant, human feces, mass flow, operation performance, methane
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1 Introduction

China has become the largest energy consumer and CO_2 emitter of the world due to the large population and rapidly growing economy[1]. From 1995 to 2014, China's annual energy consumption increased from 1.31 to 4.26 billion tons of standard coal equivalent[2]. While carbon emissions reached to 7.95 billion tons by 2012[1]. Great economic achievements caused the excessive consumption of non-renewable resources and severe environmental destruction[3]. In 2014, the Intergovernmental Panel on Climate Change (IPCC) emphasized the urgency to reduce greenhouse gas emissions and alleviate the effects of climate change[4]. Meanwhile, the ever-increasing energy consumption in the future make China should further expand the energy development intensity[5]. Under these circumstances, the development of renewable, sustainable and environment-friendly energy has become an important

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national development strategy[6]. As an effective way to generate renewable energy, anaerobic digestion technology is playing an increasingly important role in waste treatment, energy supply and environmental conservation, and is being developed rapidly and globally[7]. By 2013, China had built 43 million of biogas digesters with an output of 16 billion m^3 biogas, what's more, about 100 000 scale biogas plants were constructed with a total biogas capacity of 2 billion m^3, which was 12.4% of natgas annual consumption in the country[8].

With the acceleration of urbanization, the amount of urban wastes shows a sustainable growth[9]. In China, manure cleansing amount reached about 15.52 million tons in 2014, of this, almost 13.92% was produced in Beijing[2]. Human feces have become the spreading source of certain human diseases because of containing a variety of intestinal pathogenic bacteria, parasite eggs and viruses. If there is no reasonable and effective method to deal with the human feces coming from septic-tank and aqua privy, it would trigger potential environment and health risks. Since the 1980s, in view of many factors, like fertilizer quality, food safety, etc. the amount of urban wastes used for agricultural production declined rapidly[10]. In addition, the municipal network system of China is limited for disposing excreta for a long time[11]. Therefore, an environmental and high-efficiency treatment measure should be adopted. Fortunately, human waste is not only a source of pollution, but also rich in variety of organic matter and nutrients, such as nitrogen, phosphorus and potassium[12]. Anaerobic digestion can be considered as an alternative method to minimize the amount of these wastes and recover energy by the production of methane[13].

Many researchers studied the efficiency and sustainability of biogas plant treating various feedstocks, such as pig manure[7], wastes of aquaculture and breeding production[14], domestic wastewater[15], straw and manure[16], and so on. However, there are few reports that analyzed the mass flow and operation performance of a full-scale biogas plant treating human feces. In this research, a biogas plant treating human feces was investigated, which is located in Cuigezhuang village, Chaoyang district of Beijing, China. Firstly, the mass flow of the anaerobic digestion system, including feeding stage, fermentation stage and solid-liquid separation stage was analyzed. Secondly, the operation performance, such as gas production, digestate properties and others, was discussed. And then, according to the results, advices were provided on how to improve the efficiency and sustainability of the full-scale biogas plant treating human feces.

2 Materials and methods

2.1 Biogas plant overview

The biogas plant located in Cuigezhuang village, Chaoyang district of Beijing, China, and formally started to run in 2010. It was operated under mesophilic condition (38±1)°C with hydraulic retention time (HRT) of 54 d. The core of the biogas plant is a 400 m^3 continuous stirred tank reactor (CSTR) and a 225 m^3 secondary fermentation reactor with a 200 m^3 space for gas storage, surrounded by a set of auxiliary devices for raw material pretreatment, biogas purification, and digestate separation (Figure 1). A clearance car intensively collected human feces from surrounding villages (Naidong village, Naixi village and Hegezhuang village) every week. In pretreatment tank, the wastes were filtered by a sieve, and then, the total solid (TS) concentration was adjusted to 3.50%±0.50%. In order to accelerate substrate degradation, kill pathogenic microorganisms and reduce heat loss, solar energy system (75 m^3) and biogas boiler were used to provide heat. The raw material in acidification heating tank was heated to (50±2)°C. The biogas plant deals with 1633 kg human feces every day and daily biogas production is 145±10 m^3. According to actual statistics, the annual biogas production was about 5.29×10^4 m^3, corresponding to 63 t CO_2 emission reduction and the released heat of 38 t standard coal.

The biogas plant adopts "energy-ecology" mode, which has significant advantages over conventional agricultural practices and waste treating process. On the one hand, it disposes human feces from surrounding villages, improving the local environment. On the other hand, the by-products (biogas and digestate) are utilized synthetically in both energy supply and agricultural cultivation, achieving cyclic utilization of wastes. After the desulfurization and dehydration of the biogas, it is mainly used in the following aspects: cooking, generating electricity and heating boiler and greenhouse. In order to avoid secondary contamination, increase soil fertility and reduce agricultural investment, residues in sedimentation tank-1 and liquid digestate in sedimentation tank-2 are utilized as base fertilizers and top dressing, respectively.

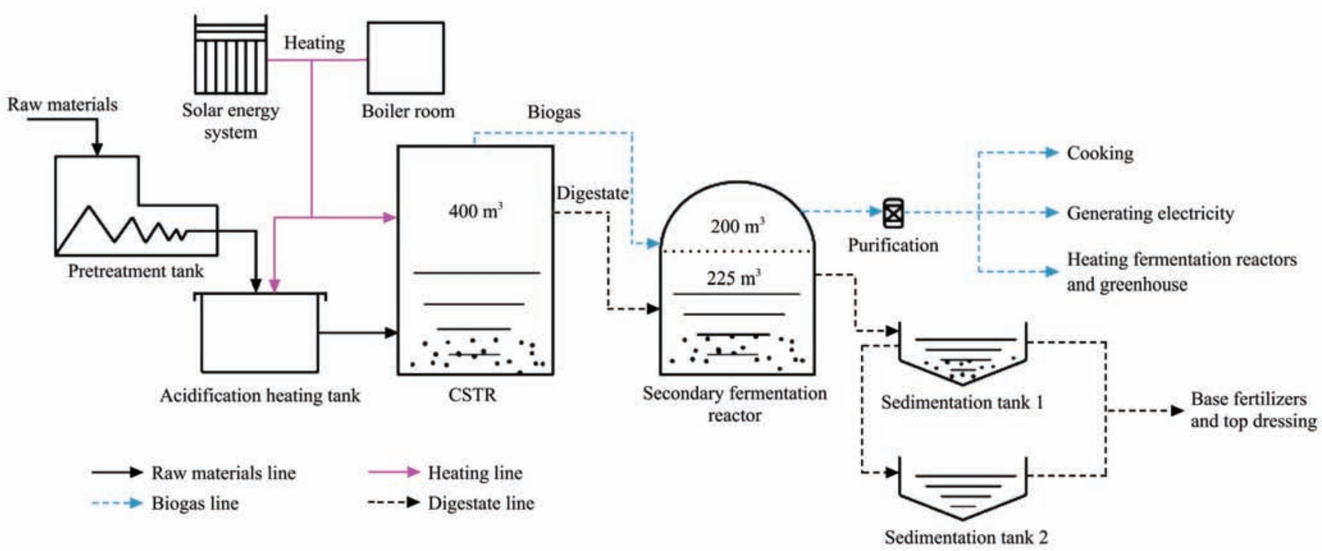


Figure 1 Technical overview of the biogas plant treating human feces

2.2 Data source

All of the raw data were surveyed from the biogas plant from November 2014 to October 2015. Biogas and liquid samples were taken from the biogas plant per month to analyze the mass flow and operation performance. Biogas samples were obtained from a gas outlet after desulfurization and dehydration to test methane content. Influent and effluent samples were taken from pretreatment tank and sedimentation tank 1, respectively. TS, volatile solid (VS), pH, volatile organic acid (VFA), total ammonia nitrogen (TAN) and free ammonia nitrogen (FAN) were analyzed.

2.3 Analytical methods

Biogas production was measured by a gas flowmeter every day and taken the average value of each month for analysis. Methane content was analyzed by a gas chromatograph (1490, Agilent Technologies, USA) equipped with a thermal conductivity detector and a 3 m stainless column packed with Porapak Q (60-80 mesh). The operational temperatures of the injector port, column oven and detector were 120°C, 150°C and 120°C, respectively. Pure nitrogen was used as the carrier gas at a flow rate of 50 mL/min.

TS and VS were measured according to the standard methods[17]. Liquid samples were centrifuged at 4000 r/min for 10 min at room temperature and then used for the chemical analysis. A pH meter (PHS-3C, Shanghai Precision & Scientific Instrument Co., Ltd., Shanghai, China) was used to determine the pH. The VFAs concentrations were measured by a high performance liquid chromatography (LC-10A, Shimadzu Corporation, Kyoto, Japan) equipped with an ultraviolet detector at the wavelength of 210 nm. Before VFAs analysis, the samples should be filtered through a 0.22 μm membrane. H_2SO_4 (5 mM) was used as mobile phase at a flow rate of 0.80 mL/min. C18 column (4.60× 150.0 mm) was used as the separation column at 30°C. Salicylic acid spectrophotometry was used to analyze TAN. FAN was calculated through TAN, temperature and pH.

3 Results and discussion

3.1 Mass flow analysis

Table 1 shows the characteristics, theoretical and actual biogas potential of human feces, which used for calculating material-energy transforming efficiency. From Table 1, the theoretical biogas potential of human feces is 692 m³/(t TS), higher than straw, pig manure and cow dung[18]. As for the C/N ratio of human feces, it is lower than the desired range of 15-30 for high-efficiency anaerobic digestion[13]. However, the actual biogas potential of 592 m³/(t TS) was 85.55% of theoretical biogas potential and VS removal rate reached 80.0%. This phenomenon may be owes to the secondary fermentation which could not only store digestate and biogas tentatively, but also make the best use of substrate.

Table 1 Characteristics and biogas potential of human feces

	Water Content/%	TS/%	VS/TS	C/N	Theoretical biogas potential /m³·(t TS)$^{-1}$	Actual biogas potential/ m³·(t TS)$^{-1}$	VS removal rate/%
Values	85	15	0.87	9	692	592	80

Material-energy transforming parameters of the human feces biogas plant are given in Table 2. Average TS concentration of influent and daily feeding amount are 3.50% and 7.0 t, respectively, amounting to the organic loading rates (OLRs) of 0.56 kg VS/(m³·d). Compared to the average volume gas productivity of a large-scale biogas plant dealing with pig manure in Jiangsu (0.25 m³/(m³·d))[19], there is obvious advantage for the biogas plant (0.38 m³/(m³·d)) treating human feces, but compared with the biogas plants in Europe, which TS concentration of influent is 8%-13% and volume gas productivity reaches 1.0-5.0 m³/(m³·d)[20], the biogas plant of human feces should properly increase the influent concentration to obtain higher biogas production. Subtracting the materials for producing biogas, the rest is discharged into sedimentation tank 1, in a total amount of 6841 kg/d. Material-energy transforming efficiency of this biogas plant is 11.26 kg/m³, which means that producing 1 m³ biogas needs 11.26 kg fresh human feces, which overmatches other biogas plants studied by Li[21].

Table 2 Material-energy transforming parameters of the human feces biogas plant

Parameters	Values
Feeding amount of human feces/kg·d^{-1}	1633
Total volume of CSTR/m³	400
Effective volume of CSTR/m³	380
Total volume of secondary fermentation reactor/m³	225
Fermentation temperature/°C	38±1
TS concentration of influent/%	3.50
HRT/d	54
Daily biogas production/m³	145
Volume gas productivity/m³·m^{-3}·d^{-1}	0.38
Daily digestate production/kg·d^{-1}	6841

The mass flow balance is presented in Figure 2. Through it, we can summarize that annual total feeding amount was 2555.0 t, among these, 58.04 t was used to produce biogas, the amount of digestate was 2496.97 t, including 43.07 t solid residues and 2453.90 t liquid digestate. From the results, water accounts for a large part due to the low TS concentration of influent. In other words, raw material needs to consume large amount of water resource (1958.96 t) to adjust the feeding concentration each year. In order to improve this situation, the feeding TS concentration should be increased properly and use a certain amount of digestate to dilute raw material.

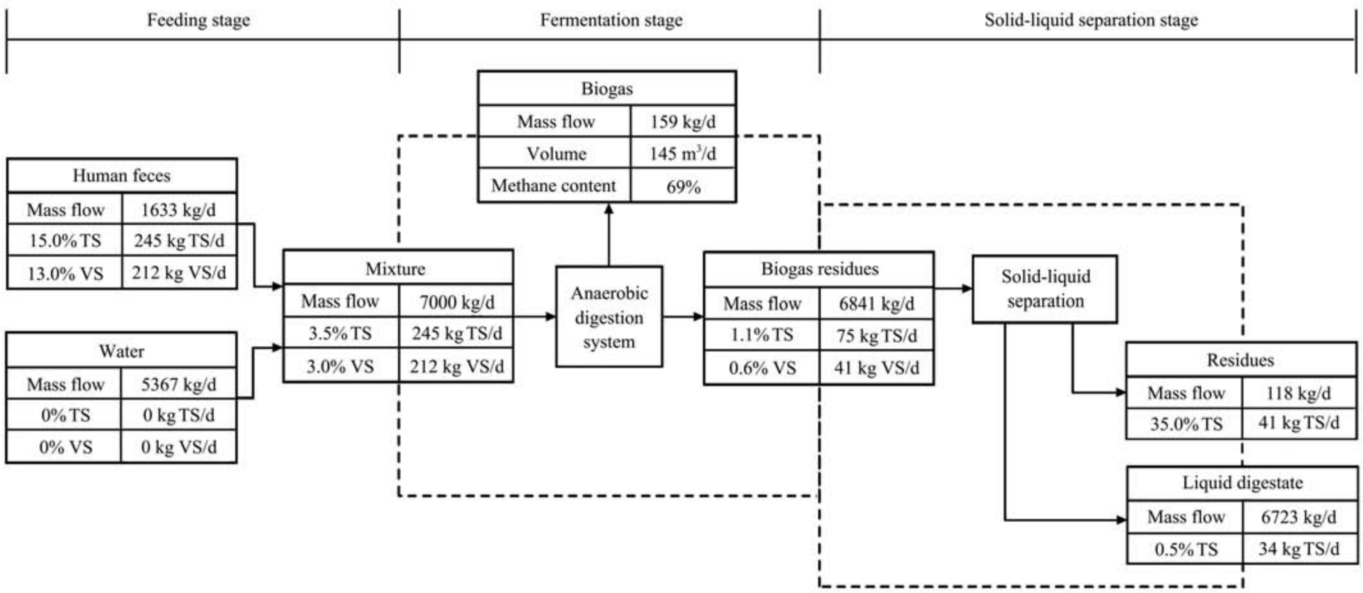


Figure 2 Mass flow balance diagram of the biogas plant treating human feces

3.2 Biogas production

Figures 3 and 4 exhibit the average daily biogas production, methane yield and methane content, respectively. It could be detected that the maximal biogas production (160 m³/d) was obtained in April, but the highest methane yield (506 m³ CH_4/t VS) was presented in November. As is well-known, methane yield is decided by biogas production, methane content and VS feeding amount. Thus, the variation tendency of methane yield in different months was similar to the biogas production, meanwhile influenced by the methane content and VS feeding amount of each month. The VS feeding amount of November was 13 kg/d lower than that of April, but the methane content of November was 6% higher than that of April, which contributed to the highest methane yield of November. With the same VS feeding amount, the biogas production of March was 10 m³/d less than that of April, and had the lowest methane yield and methane content. The biogas production in other months is also discrepant. February had the lowest biogas production and productions in June to October were also relatively low. It was mainly caused by two reasons. Firstly, feeding amounts of each month had slight difference, such as in February, feeding amount (6.2 t/d) was the minimum. Next, solar energy system and biogas boiler provided heat for CSTR in the whole year except for summer, thus biogas production was influenced by the instability of the weather temperatures.

In the whole year, average biogas production, methane content and methane yield were (145±10) m³/d, 69%±3% and (471±17) m³ CH_4/(t VS), respectively. Methane content in the present study was higher than that of other wastes, like activated sludge (64%) and perennial ryegrass (54%)[22]. This may be explained by two reasons. One is that the secondary fermentation was carried out in this biogas plant, which could improve the utilization rate of raw materials. The other reason is that biogas samples were taken after desulfurization and dehydration, which indirectly increased the methane content. The theoretical methane yield of human feces is 551 m³ CH_4/(t VS), showing methane conversion efficiency is 85.48%. In other research, methane yield of other wastes, such as poultry slaughterhouse waste (670 m³ CH_4/(t VS))[23] and thickened grease trap sludge (845-928 m³ CH_4/(t VS))[24] from restaurants and institutional kitchens, are respectively 1.42 times and 1.79-1.97 times greater than human feces. The lower methane yield may be related to the low C/N. Thus, some raw material with high C/N is advised to be added in human feces for achieving the highest methane yield.

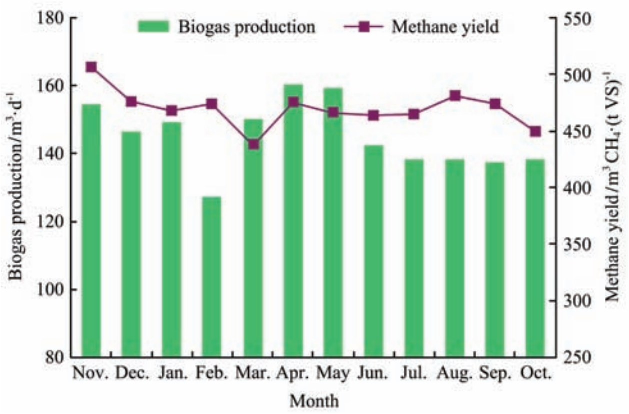


Figure 3 Average daily biogas production and methane yield in different months

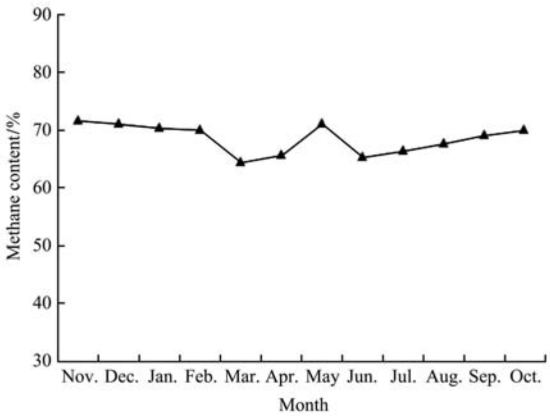


Figure 4 Methane content in different months

3.3 TAN and FAN concentration

Human feces contain high levels of nitrogen due to uric acid and undigested proteins. TAN and FAN can accumulate as the proteins breakdown, and they are the foremost inhibitors to the anaerobic digestion process if they are available at high concentrations[25]. Fermentation temperature, pH, OLR and acclimation of inoculum are directly or indirectly effect the inhibitory concentrations of TAN and FAN. As mentioned above, a mesothermal semi-continuous reactor dealing with sludge at pH of 8.0 was inhibited when the TAN concentration reached 2800 mg/L[26]. TAN concentrations of around 1700-1800 mg/L were completely inhibitory with unacclimated inoculum.

However, when microorganisms were acclimated, inhibitory TAN level could increase up to 5000 mg/L[27]. Some researchers suggested that FAN was the most important component causing ammonia inhibition[28,29] and the advised value of it was below 150 mg/L[30]. The FAN which was determined by three parameters (TAN, temperature and pH) could be calculated by the Equation (1)[31].

$$\mathrm{FAN}=\frac{\mathrm{TAN}\times 10^{pH}}{e^{\frac{6344}{273.15+T}}+10^{pH}} \tag{1}$$

The concentration of TAN and FAN are observed in Figure 5. It was found that both the TAN and FAN concentration of effluent were always higher than that of influent. In terms of effluent, the concentration of TAN increased to 3659 mg/L from November 2014 to March 2015, and then, it started decline to 2323 mg/L at July 2015. The highest TAN concentration of March influenced the activities of the methanogens resulting in the lowest methane content and methane yield in March. For other months, the various TAN concentrations of effluent may be caused by its influent and variation of raw material composition in different month. Average TAN concentration of effluent was (2864±469) mg/L, and average TAN concentration of influent (2183±458 mg/L) was little bit lower than it. It is possible that the raw material had been decomposed naturally in the pretreatment tank. Compared with other biogas plants, the TAN concentration of 500-890 mg/L, 400-660 mg/L for the digestate of pig manure and cow dung, respectively, was much less than the TAN concentration in this study[32].

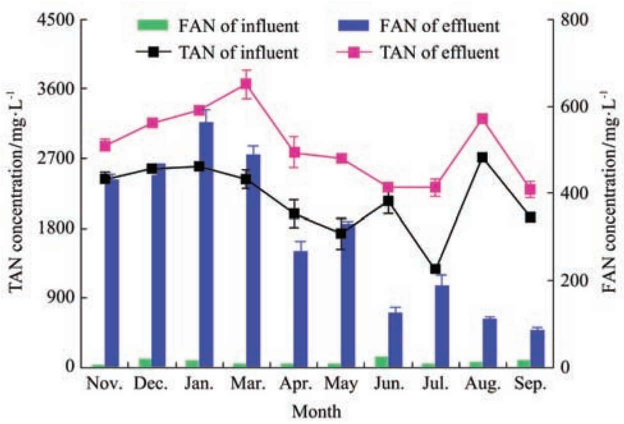


Figure 5 TAN and FAN concentration of influent and effluent in different months

Based on the Equation (1), FAN in this study can be calculated, and it can be found that the maximum FAN value of influent and effluent were (22±1) mg/L and (561±29) mg/L, respectively. Even though the TAN concentration of influent was close to that of effluent, the FAN concentration of influent was much smaller than that of effluent due to the lower temperature outside. As for influent, the different temperature of each month is one of the significant factors to decide the value of FAN concentrations. However, due to the same temperature (38°C) in reactors, effluent FAN concentration only depends on pH and TAN concentration in the whole year except for summer. In summer, FAN concentration is also decided by ambient temperatures which are usually lower than 38°C, making the low FAN concentration. In this system, the FAN concentration of all months except for June, August and September, were higher than 150mg/L, but anaerobic digestion process was not remarkably affected, which illustrated that the microorganisms were acclimated for adapting the high FAN.

3.4 pH and VFAs concentration

PH is a very pivotal indicator for evaluating the stability of anaerobic digestion systems[33] and it has a significant impact on the methanogenic and acidogenic microorganisms. Although it has been proven that the optimal pH range for methanogens working effectively is 6.5-8.2[34], the range is relative wide in the plant scale and the optimal pH varies with substrate and digestion craft[35]. Many parameters, such as VFAs concentration, bicarbonate concentration, alkalinity and CO_2 produced during the process, can influence the pH of anaerobic digestion system[36]. As for the wastes consisted of high protein content, like human feces, it is reported that acetate is easily converted to ammonium acetate or ammonium bicarbonate, which lead to high pH[37]. The pH of effluent was always higher than that of influent in Figure 6. Compared to pH of influent, only little fluctuation occurred in effluent. The average pHs of influent and effluent were slightly alkaline of 7.24±0.32 and 7.96±0.22, respectively. Compared to other wastes, such as pig manure and cow dung, the pH of digestate was 7.35-7.62 and 7.53-7.74, respectively, which also weakly-alkaline as to human feces[32].

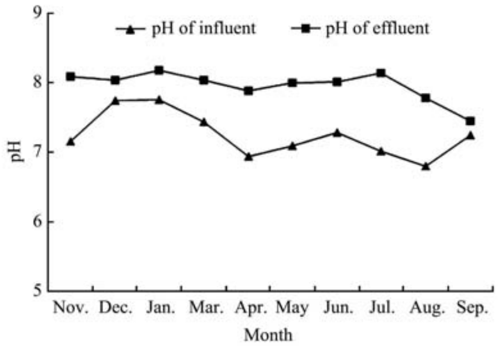
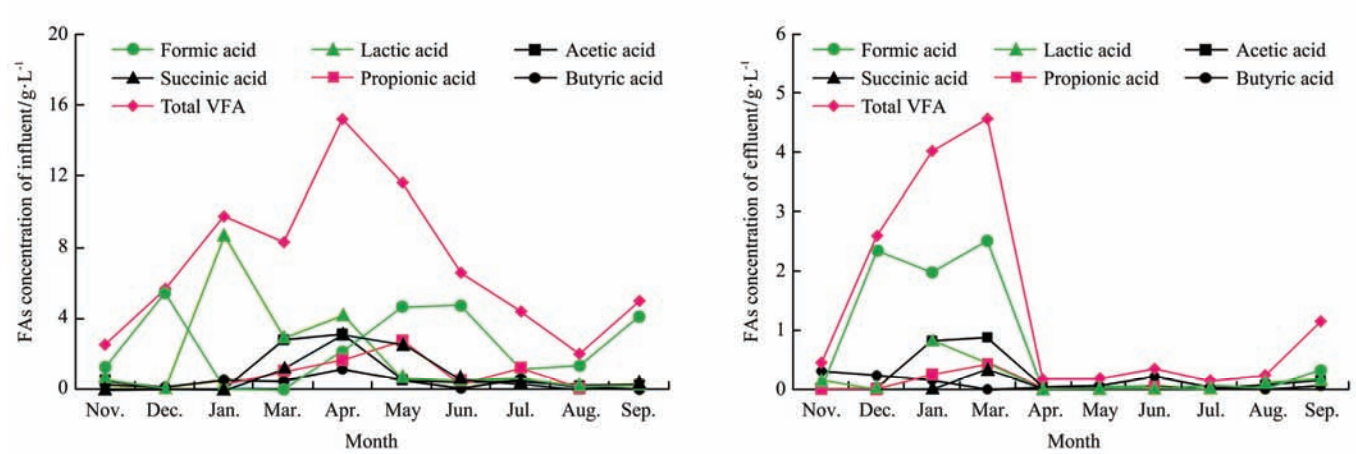


Figure 6 pHs of influent and effluent in different months

The variations of total VFAs and individual VFA concentrations of influent and effluent in each month are shown in Figure 7. VFAs concentration of influent increased gradually from 2.50 g/L at November 2014 to 15.18 g/L at April 2015, and then slowly declined in the following months (in Figure 7a). The decomposed degrees of substrate varied due to the different retention time in pretreatment tank by collecting human feces every week and shifty ambient temperature of each month, so that the VFAs concentration of different month changed continually. Horiuchi et al.[38] studied the selective production of organic acids by pH control, summarizing that the main product was butyric acid under acidic and neutral conditions. Considering the weak alkaline environment of influent, butyric acid concentrations of influent in the whole year were minimum and most stable, with variation range of 0.01-1.10 g/L, which conforms to the previous research. Formic acid accounted for above 50% of total VFAs in November, December of 2014, June, August and September of 2015, proving formic acid is the most accessible product during the degradation of human feces. From the above discussions, the full-scale biogas plant can not only accept the high concentration of VFAs (15.18 g/L), but also adapt the large range of influent VFAs concentration.



a b

Figure 7 Total VFAs and individual VFA concentrations of (a) influent and (b) effluent in different months

For total VFAs and individual VFA concentrations of effluent (in Figure 7b), the highest total VFAs values appeared in March (4.57 g/L), which mainly consisted of formic acid. Coincidently, March had the maximum TAN concentration, stating that higher TAN concentration can decrease the utilization efficiency of VFAs by poisoning microorganisms. For the other months, the total VFAs concentrations were less than 4.0 g/L. Horiuchi et al.[38] found that anaerobic digestion process was slightly inhibited when the VFAs concentration was higher than 4.0 g/L and the biogas composition changed obviously with the VFAs concentrations over 6.0 g/L. Although the methane production was slightly inhibited by VFAs accumulation in March, that of April began to rise. It was indicated that the biogas production was not affected by VFAs, which proved the full-scale biogas plant has strong ability to realize autoregulation. Different acids have different degradation speeds, for example, propionic acid degrades much more slowly than other acids[39]. Wang et al.[40] and Demirel et al.[41] concluded propionic acid was the most sensitive factor among the individual acids, and the limited propionate acid concentration for methanogens was less than 1.0 g/L[42]. Lactic acid was the direct substrate for propionic acid production[43], but it is produced in the optimal pH of 5-6[44]. Matching the previous studies, lactic acid and propionate acid concentration kept a lower level in this study, with the maximum value of 0.83 g/L and 0.42 g/L, respectively. Propionate acid concentrations of all months were under the upper limit, within the acceptable range for anaerobic digestion process. The average acetic acid concentration (0.21 g/L) was only 14.91% of total VFAs existed in the anaerobic digestion system, illustrating methanobacteria utilized acetic acid efficiently.

4 Conclusions

Mesophilic semi-continuous anaerobic digestion was effective for treating human feces, especially the secondary fermentation process, which could promote an efficient utilization of substrate and achieve the higher methane conversion efficiency (85.48%). The full-scale biogas plant with annual output of 5.29×10^4 m³ biogas has strong autoregulation for adapting the large range (2.02-15.18 g/L) and high concentration (15.18 g/L) of influent VFAs. As for the low C/N raw material, the maximum TAN concentration reached 3659 mg/L in the fermentation system of human feces, respectively, which not remarkably influenced the biogas production, but decreased the efficient utilization of VFAs and methane content. Each year, large amount of water resource (1958.96 t) is consumed to adjust the feeding concentration to 3.50% and the methane yield of human feces is only (471±17) m³ CH_4/(t VS). Therefore, suggestions have been proposed to achieve its sustainable development and high efficient operation. Firstly, feeding concentration should be increased properly. Secondly, digestate in sedimentation tank can be used to dilute raw material. Finally, some high C/N raw material could be added in human feces.

Acknowledgments

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[References]

[1] Shen L, Sun Y. Review on carbon emissions, energy consumption and low-carbon economy in China from a perspective of global climate change. J Geogr Sci, 2016; 26(7): 855–870.

[2] National Bureau of Statistics. China Statistical Yearbook. China: China Statistics Press, 2015. (in Chinese)

[3] Zhang T, Yang Y, Xie D. Insights into the production potential and trends of China's rural biogas. Int J Energ Res, 2015; 39(8): 1068–1082.

[4] Qin D. Climate change science and sustainable development. Progress in Geography, 2014; 33(7): 874–883.

[5] Fan J, Wang Q, Sun W. The failure of China′s energy development strategy 2050 and its impact on carbon emissions. Renewable & Sustainable Energy Reviews, 2015; 49: 1160–1170.

[6] Menegaki A. Valuation for renewable energy: A comparative review. Renewable & Sustainable Energy Reviews, 2008; 12(9): 2422–2437.

[7] Wang X L, Chen Y Q, Sui P, Gao W S, Qin F, Wu X, et al. Efficiency and sustainability analysis of biogas and electricity production from a large-scale biogas project in China: an emergy evaluation based on LCA. J Clean Prod, 2014; 65: 234–245.

[8] Li Y, Sun Y M, Li D, Yuan Z H, Kong X Y, Xu J, et al. Analysis of Biogas Industrial Policy in China and Foreign Countries. Advances in New & Renewable Energy, 2014; 2(6): 413–422. (in Chinese)

[9] Chen Z L, Tang Y Z, Feng Q L, Liu J Y, Tao H, Li G S. Study on development strategy for urban night-soil treatment technology. Journal of Wuhan Urban Construction Institute, 1998; 15: 35–40. (in Chinese)

[10] Chen Z L, Tan Y Z. Study on sustainable use of urban night-soil in China. Urban Environment & Urban Ecology, 1999; 12(2): 42–49. (in Chinese)

[11] Xiong H B, Zhang Z, Gu N P. Influence of centralized treatment of urban excrement on wastewater treatment plant. China Water & Wastewater, 2009; 25(14): 17–21. (in Chinese)

[12] Cofie O, Kone D, Rothenberger S, Moser D, Zubruegg C. Co-composting of faecal sludge and organic solid waste for agriculture: Process dynamics. Water Res, 2009; 43(18): 4665–4675.

[13] Dalkılıc K, Ugurlu A. Biogas production from chicken manure at different organic loading rates in a mesophilic-thermopilic two stage anaerobic system. J. Biosci Bioeng, 2015; 120(3): 315–322.

[14] Chen S, Chen B. Energy efficiency and sustainability of complex biogas systems: A 3-level emergetic evaluation. Appl Energ, 2014; 115: 151–163.

[15] Chen S, Chen B. Net energy production and emissions mitigation of domestic wastewater treatment system: A comparison of different biogas–sludge use alternatives.

Bioresour Technol, 2013; 144: 296–303.

[16] Chen S, Chen B, Song D. Life-cycle energy production and emissions mitigation by comprehensive biogas–digestate utilization. Bioresour Technol, 2012; 114: 357–364.

[17] American Public Health Association. Standard methods for the examination of water and wastewater. Washington D.C.: American Public Health Association, 2005.

[18] Wang Z H, Liu S H. Study on energy conversion efficiency of biogas fermentation. Journal of Liaoning Teachers College, 2002; 4: 84–87. (in Chinese)

[19] Quan G. Research on dry fermentation of rice straw in household digester. Master dissertation. Nangjing: Nanjing Agricultural University, 2008. (in Chinese)

[20] Wang S, Zhang G, Cao M. Discussion of large biogas engineering technology in European by localization method. China Biogas, 2009; 27(2): 42–44. (in Chinese)

[21] Li X. Study on empirical analysis and optimization of centralized biogas supply running. PhD dissertation. Beijing: China Agriculture University, 2015. (in Chinese)

[22] Dai X H, Li X S, Zhang D, Chen Y G, Dai L L. Simultaneous enhancement of methane production and methane content in biogas from waste activated sludge and perennial ryegrass anaerobic co-digestion: The effects of pH and C/N ratio. Bioresour Technol, 2016; 216: 323–330.

[23] Salminen E A, Rintala J A. Semi-continuous anaerobic digestion of solid poultry slaughterhouse waste: effect of hydraulic retention time and loading. Water Res, 2002; 36(13): 3175–3182.

[24] Davidsson Å, Lövstedt C, la Cour Jansen J, Gruvberger C, Aspegren H. Co-digestion of grease trap sludge and sewage sludge. Waste Manage, 2008; 28(6): 986–992.

[25] Yenigün O, Demirel B. Ammonia inhibition in anaerobic digestion: A review. Process Biochem, 2013; 48(5-6): 901–911.

[26] Poggi-Varaldo H M, Rodríguez-Vázquez R, Fernández-Villagómez G, Esparza-García F. Inhibition of mesophilic solid-substrate anaerobic digestion by ammonia nitrogen. Applied Microbiology & amp Biotechnology, 1997; 47: 284–291.

[27] Kroeker E J, Schulte D D, Sparling A B, Lapp H M. Anaerobic treatment process stability. J. Water Pollut Control Fed, 1979; 51: 718–727.

[28] Astals S, Nolla-Ardèvol V, Mata-Alvarez J. Anaerobic co-digestion of pig manure and crude glycerol at mesophilic conditions: Biogas and digestate. Bioresour Technol, 2012; 110: 63–70.

[29] Hansen K H, Angelidaki I, Ahring B K R. Anaerobic digestion of swine manure inhibition by ammonia. Water Res, 1998; 32: 5–12.

[30] Mccarty P L, Mckinney R E. Salt toxicity in anaerobic digestion. J Water Pollut Control Fed, 1961; 33: 399–415.

[31] Anthonisen A C, Loehr R C, Prakasam T B S, Srinath E G. Inhibition of nitrification by ammonia and nitrous acid. J Water Pollut Control Fed, 1976; 48: 835–849.

[32] Jin H M, Chang Z Z, Ye X M, Ma Y, Zhu J. Physical and chemical characteristics of anaerobically digested slurry from large-scale biogas project in Jiangsu Province. Transactions of the CSAE, 2011; 27(1): 291–296.(in Chinese)

[33] Liu R H. New energy engineering. Beijing: China Agriculture Press, 2006. (in Chinese)

[34] Yechi D Y. Methane fermentation. Beijing: Chemical Industry Press, 2014.

[35] Liu C, Yuan X, Zeng G, Li W, Li J. Prediction of methane yield at optimum pH for anaerobic digestion of organic fraction of municipal solid waste. Bioresour Technol, 2008; 99(4): 882–888.

[36] Kondusamy D, Kalamdhad A S. Pre-treatment and anaerobic digestion of food waste for high rate methane production-A review. J. Environ. Chem. Eng., 2014; 2: 1821–1830.

[37] Shanmugam P, Horan N J. Optimising the biogas production from leather fleshing waste by co-digestion with MSW. Bioresour Technol, 2009; 100(18): 4117–4120.

[38] Horiuchi J I, Shimizu T, Tada K, Kanno T, Kobayashi M. Selective production of organic acids in anaerobic acid reactor by pH control. Bioresour Technol, 2002; 82: 209–213.

[39] Izumi K, Okishio Y, Nagao N, Niwa C, Yamamoto S, Toda T. Effects of particle size on anaerobic digestion of food waste. Int Biodeter Biodegr, 2010; 64(7): 601–608.

[40] Wang Y Y, Zhang Y L, Wang J B, Meng L. Effects of volatile fatty acid concentrations on methane yield and methanogenic bacteria. Biomass and Bioenergy, 2009; 33(5): 848–853.

[41] Demirel B, Yenigün O. The Effects of Change in Volatile Fatty Acid (VFA) Composition on Methanogenic Upflow Filter Reactor (UFAF) Performance. Environ Technol, 2002; 23: 1179–1187.

[42] Hanaki K, Hirunmasuwan S, Matsuo T. Protection of methanogenic bacteria from low pH and toxic materials by immobilization using polyvinyl alcohol. Water Res, 1994; 28: 877–885.

[43] Li X, Chen Y G, Zhao S, Wang D B, Zheng X, Luo J Y. Lactic acid accumulation from sludge and food waste to improve the yield of propionic acid-enriched VFA. Biochem Eng J, 2014; 84: 28–35.

[44] Fu W, Mathews A P. Lactic acid production from lactose by Lactobacillus plantarum: kinetic model and effects of pH, substrate, and oxygen. Biochem Eng J, 1999; 3(3): 163–170.