The influence of sludge concentration on its thermophilic anaerobic digestion performance based on low temperature thermal hydrolysis pretreatment

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Abstract: The dewatered sludge with TS of 14.62% was diluted to 4 different concentrations of sludge (TS: 6%, 8%, 9%, 12%) and were pretreated at 90°C for thermal hydrolysis. The performance of thermophilic anaerobic digestion was evaluated with the removal efficiencies of SS, VSS and biochemical methane potential (BMP) experiments were also carried out at (55 ± 1)°C to investigate cumulative gas production and biogas production rate. The results indicated that VSS removal efficiency increased with the increase of sludge concentration up to the peak of 26.5% when the sludge concentration was 9%. The VSS removal efficiencies of the sludge with TS of 8%, 9% and 12% were over 20%. The viscosity of the sludge with 9% sludge concentration was 18400 mPa•s, which was much higher than 2900 mPa•s when the sludge concentration was 8%. The result showed that the thermal hydrolysis of sludge with TS of 8% had the best performance. The cumulative gas production of the thermophilic anaerobic digestion with only thermal hydrolysis pretreatment of sludge with TS of 8% was 210.24 mL/g-VS, gas production rate was 0.0074 h⁻¹ and the removal efficiency of VSS was 22.8%.

1. Introduction

With the increase of the municipal waste water requirement, the sewage sludge production increases rapidly. By
the end of 2010, the number of the urban sewage treatment plant reached 2496. The quantity of the urban sewage sludge generated was more than 20 million ton in 2012\(^1\), in which 60% were generated from typical biological waste water treatment process.\(^2\) According to the 12th Five-year Plan of China, the quantity of urban sewage sludge will increase 5.18 million tons per year, reemphasizing the importance and urgency of urban sewage treatment. Due to the large amount of biomass energy in urban sewage sludge, it is beneficial for China to develop biomass energy recycling technique beside energy conservation and waste emission reduction. Anaerobic digestion can effectively reduce the sludge volume and produce biomass gas at the same time via three stages: hydrolysis, acidification, and methanogenesis.\(^3\)\(^4\)\(^5\)\(^6\) Hydrolysis stage is the rate control step for anaerobic digestion.\(^7\) Under anaerobic condition, anaerobic bacteria break down organic matters into simpler organic matters, before turning them into CH\(_4\) and other inorganic matters, such as CO\(_2\), H\(_2\)O, H\(_2\)S. Sludge hydrolysis rate and efficiency is low due to the difficulty to degrade cell wall, which limits the anaerobic digestion efficiency. Sludge pretreatment can effectively improve the destruction of cell wall and dissolve out intracellular organic compounds, so as to improve the sludge anaerobic digestion performance and maximize the biomass energy recycling efficiency. The current sludge digestion pretreatment technology mainly includes mechanical crushing, thermal hydrolysis, alkali treatment, ultrasonic treatment, ozone oxidation and chlorine oxidation.\(^8\)\(^9\)\(^10\)\(^11\)\(^12\)\(^13\)

Thermal hydrolysis pretreatment can effectively improve the sludge digestion performance and microbial degradation rate.\(^14\) High temperature (130 ~ 210 °C) and short-term (15 ~ 60 mins) pretreatment is a commonly used as pretreatment method, which can do degrade sludge organic matters effectively. However, it has many defects such as large energy consumption, high equipment requirements and operation risk.\(^15\) Low-temperature (50 ~ 100 °C) thermal hydrolysis is an effective way to improve biogas production and organic matter degradation.\(^16\) The high temperature thermal hydrolysis treatment can increase sludge digestion efficiency than low temperature thermal hydrolysis treatment long time (3 ~ 10 h) thermal hydrolysis treatment has been reported to promote cell wall breaking as well.\(^17\) However, long time thermal hydrolysis pretreatment also has defects such as the increase of sludge treatment plant volume as well as and increase the energy consumption. Therefore, the low-temperature and short-term thermal hydrolysis pretreatment will be more suitable for sludge digestion.\(^18\)

2. **Methods**

2.1. **Material**

The sludge samples were taken from the full scale waste water treatment plant of Yixing City, Jiangsu Province. The organic matter content of the sludge was 62.04% and sludge moisture content was 85.38%. Sludge samples were diluted with distilled water to TS 6%, 8%, 9%, 12%.

2.2. **Thermal hydrolysis pretreatment experiment**

According to Mr. Appels’s research results\(^17\), after 30 mins treatment of sludge at 90 °C, its cell rupture proportion, SCOD/TCOD and gas production rate significantly increased. Therefore, low-temperature short-term thermal hydrolysis pretreatment conditions(90°C, 30 mins) was set to be the experiment condition. Thermal hydrolysis treatment was performed in a 2-L reactor (Figure 1). Sludge samples with TS of 6%, 8%, 9%, and 12% were added into the reactor at room temperature, respectively for 30 mins heating at 90 °C. The sludge was stored at 4°C in the laboratory before the experiments. The removal efficiencies of SS and VSS at different sludge concentration conditions were analyzed.
2.3. Biological Methane Potential (BMP) experiments

The experiments was carried out in a device as shown in Figure 2. The gas production volume as measured with a syringe.
Seed sludge was taken from a 5-L thermophilic anaerobic digestion reactor. It was centrifuged at 3000 r/min for 5 mins to remove the supernatant. The remaining sludge with higher viscosity and microbial biomass density was diluted 50 times with 50 ± 5 °C water as seed sludge for BMP.

BMP experiment was carried out in a thermostatic oscillator. Twenty 80 mL anaerobic digesters were set up for BMP experiment. Each reactor contained 10 ±1 g sample sludge and 40±1 g seed sludge. Every experiment conducted in triplicate. The control reactor contained (10 ±1) g distilled water and (40±1) g seed sludge. The un-pretreated samples with TS of 6% and 14.5% (undiluted) were also investigated. Samples were put in the thermostatic oscillator at 55 °C and oscillation frequency 105 times/min. Gas production (G1) was recorded on a regular basis.

The gas production rate was calculated as follows:

Using formula (1) to calculate the unit mass of gas production of blank run, \( V_B \) (g):

\[
V_B = \frac{G_B}{M_B \times 4 / 5}
\]  

(1)

where, \( G_B \), the gas production of blank run (N-mL); \( M_B \), the quantity of total sludge of the blank run (g).

The real cumulative gas production of sample sludge was calculated as formula (2):

\[
G_2 = G_1 - M \times 4 / 5 \times V_B
\]  

(2)

(If the value is negative, change the current value to “0”)

where, \( G_2 \), real cumulative gas production of sample sludge (N-mL); \( G_1 \), the accumulative gas production of each run (N-mL); \( M \), the quantity of the total sludge of each run (g).

The quantity of VS of sample sludge was calculated as formula (3):

\[
VS_2 = \frac{M}{5} \times VS_1
\]  

(3)

where, \( VS_2 \), the quantity of VS of sample sludge(g); \( VS_1 \), the VS of sample sludge after pretreatment (%);

Using formula (2) and (3) to obtain the unit organic matter cumulative gas production of sample sludge:

\[
V = \frac{G_2}{VS_2}
\]  

(4)

where, \( V \), the unit organic matter cumulative gas production (N-mL/g).

Using the formula (5) to fit the accumulative gas production data:

\[
\ln(G - G_t) = (-k_G) \times t + \ln G
\]  

(5)

where, \( t \), the time after gas production begins (h); \( G_t \), the unit organic matter cumulative gas production until \( t \) (N-mL/g); \( G \), the total cumulative gas production at the end of the reaction (N-mL/g); \( k_G \), gas production rate coefficient (h⁻¹).

2.4. Analytical methods and equipment

TS, VS, SS, VSS were determined via the weight method. Gas production volume was measured by syringe. Viscosity was measured by NDJ-8-s digital display viscometer. BMP experiment device was a SHA-C thermostatic oscillator. Thermal reactor was a 2-L GS magnetic force drive high temperature reaction kettle.
3. Results and discussion

3.1. Effects of thermal hydrolysis pretreatment of different concentration of sludge

The SS removal efficiency decreased with the increase of sludge concentration until the concentration reach 9% and then increased gradually. The VSS removal efficiency increased with the increase of sludge concentration to a peak of 26.5% when the sludge concentration was 9% and then decreased. All the VSS removal efficiency were over 20%, except when the less than 10% VSS removal efficiency was obtain at the sludge of 6%. The removal efficiency of TS: 6%, 8%, 9%, 12% was 7.28%, 22.79%, 26.50% and 22.79%, respectively. In the process of anaerobic digestion, the removal of VSS was more effective than SS. The improvement of solubility of solid organic matters promote the utilization of small molecule organic matters by anaerobic bacteria. Therefore, short-time thermal hydrolysis at low temperature did not have a positive effect on low sludge concentration, as sludge with TS of 6%. It was more suitable for higher sludge concentration, as the VSS removal efficiency for TS concentration of 8%, 9%, 12% were all over 20%. However, the SS removal efficiency of sludge with TS of 9% was too low, which meant most of the VSS were solubilized into inorganic suspended particulate matter and were not available for anaerobic digestion. Low moisture content in the sludge with TS of 9% might cause the low SS removal efficiency. The kettle wall with actually higher than 90 °C temperature caused the carbonization of digested organic matters into inorganic suspended matter during the process of thermal hydrolysis. Figure 4 showed that the viscosity increased with the increase of sludge concentration and there was magnitude difference between sludge with TS of 8% and 9% in viscosity, the viscosity of 8% and 9% was 2900 mPa*s and 18400 mPa*s. Therefore, low sludge moisture content as proposed to cause such situation which was supported by the lower SS removal efficiency of sludge with TS of 12% was than sludge with TS of 6% and 9%.
3.2. The influence of sludge concentration on gas production

The gas dynamic data of BMP experiment was calculated and fitted as shown in Table 1. The concentration effect on the thermophilic anaerobic digestion was intuitionistic. Most digesters began to produce gases after 200 hours of running, except the un-pretreated run with TS of 6% started to produce gases within 100 hours. The concentration of the soluble organic matter in the un-pretreated run with TS of 6% was much less than other runs, in which hydrolysis, as a control step, digested more quickly than other runs, so it turned into gas production process with less time.

<table>
<thead>
<tr>
<th>Sludge concentration</th>
<th>The average cumulative gas production G (mL/g-VS)</th>
<th>The average gas production rate coefficient (k_G) (h(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>6% un-pretreated</td>
<td>176.90</td>
<td>0.0059</td>
</tr>
<tr>
<td>6% pretreated</td>
<td>196.87</td>
<td>0.0086</td>
</tr>
<tr>
<td>8% pretreated</td>
<td>210.24</td>
<td>0.0074</td>
</tr>
<tr>
<td>9% pretreated</td>
<td>215.00</td>
<td>0.0068</td>
</tr>
<tr>
<td>12% pretreated</td>
<td>225.41</td>
<td>0.0040</td>
</tr>
<tr>
<td>14.62% un-pretreated</td>
<td>267.91</td>
<td>0.0033</td>
</tr>
</tbody>
</table>
By comparing the gas production rate coefficient and cumulative gas production of the un-pretreated sludge with TS of 6% and the pretreated sludge with TS of 6%, thermal hydrolysis pretreatment had a significant effect on improving sludge anaerobic digestion performance. The gas production rate had improved greatly and cumulative gas production also had a certain growth. It showed that the low-temperature and short-term thermal hydrolysis pretreatment for dewatered sludge could increase the gas production rate significantly and had limited contribution to the growth of gas production. Figure 5 indicated that the gas production increase with the increase of the sludge concentration. By comparing the pretreated sludge with TS of 12% pretreated and the un-pretreated sludge TS with 14.62%, the increase of the concentration of sludge had a greater contribution to gas production growth. From Figure 6, it was shown that gas production rate decreased with the increase of sludge concentration.

It was observed that sludge concentration with TS of 9% had good liquidity while the liquid and gas rate decreased significantly when the sludge concentration was over 9%. The particle size of organic matter in these sludge was
bigger, which probably induced the difficulty of hydrolysis acidification process.

4. Conclusion

- In the thermal hydrolysis pretreatment experiments, VSS removal efficiency increased with the increase of sludge concentration firstly and then decreased. The VSS removal efficiency of the sludge with TS of 8%, 9% and 12% were over 20%, except the VSS removal efficiency of the sludge with TS of 6%. Low moisture content in the sludge with TS of 9% and 12% might cause carbonization of digested organic matters into inorganic suspended matter.
- Thermal hydrolysis pretreatment had a significant effect on improving sludge anaerobic digestion performance. The sludge gas production rate had greatly improved and gas production had a certain growth. The increase of the concentration of sludge had great contribution to gas production growth.
- Gas production rate increased with the increase of sludge concentration. When sludge concentration was over 9%, gas production rate was at a much lower rate. It may be due to the particles of organic matter is bigger in sludge of concentration over 9%, it affected the hydrolysis acidification process of anaerobic digestion reaction, so as to reduce the rate of reaction.
- The results showed that the thermal hydrolysis of the sludge with TS of 8% had the best performance and didn’t have obvious defects. The cumulative gas production of the thermophilic anaerobic digestion with only thermal hydrolysis pretreatment of the sludge with TS of 8% was 210.24 mL/g-VS, gas production rate was 0.0074 h⁻¹ and the removal efficiency of VSS was 22.8% only by thermal hydrolysis.

Acknowledgements

This work was supported by the Fundamental Research Funds for the Central Universities and the Program for the Graduate Research Innovation of Jiangsu Universities (Nos. SILX_0101).

References


