ABSTRACT

On the basis of the two-phase fermentation process, solar energy technology, ultrasonic cracking technology, and tourmaline-enhanced microbiology technology have been introduced to develop a new type of anaerobic fermentation device suitable for use in cold regions. The operational characteristics and gas production of the device were studied experimentally. Test results showed that the solar temperature control was 35°C ± 0.5°C. Fresh cow dung was used as the substrate for fermentation. In the acid-producing phase, if the initial TS percentage concentration was high, the pH dropped quickly and the acid production rate increased. However, local volatile fatty acid accumulation occurred. For the partial or staged accumulation of volatile fatty acids, acid-phase 40-day organic acid terminal fermentation products starting with 8% TS were suitable as the methanogenic substrates. Increasing the organic load in the IC methanogenic phases increased the biogas production. However, it also easily led to an excessive accumulation of volatile acids, making the system unstable. While increasing the organic load of the system is a strategy to increase biogas production, an appropriate increase in HRT is needed to maintain stable and efficient system operation. When the HRT was 40 days and the OLR was 2.5 kgVS_adgdm⁻³d⁻¹ in the methanogenic phase, the maximum volumetric capacity of biogas reached a high value of 1,280 L m⁻³reactor d⁻¹, with the entire fermentation system remaining both stable and efficient.

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INTRODUCTION

The development and application of anaerobic fermentation biogas production technology for organic waste has long been valued by various countries in the world, achieving good returns [1, 2]. However, at high latitudes, because of the constraints of low temperatures in winter, the method has not been widely used as a carrier for clean energy. The key to realizing the industrialization of biogas energy in cold regions is the development of an efficient and stable low-temperature biogas fermentation device to promote low-temperature microbial metabolic activity and increase gas production efficiency.

The two-phase fermentation process in the treatment of livestock and poultry manure biogas production has a strong application type: throughout the fermentation process, the separation of the acid-producing phase and the methanogenic two-phase biological phase can effectively improve the gas production rate and process stability [3]. Ultrasonic cracking is a new type of pretreatment technique developed in the 1990s. Studies have shown that the organic matter breaks down after the ultrasonic cracking, the cells disintegrate, and the intracellular organic substances are easily hydrolyzed to smaller substances under the action of extracellular enzymes (from anaerobic bacteria). For the molecules released, the biodegradability of organic matter and the anaerobic digestion performance have been considerably improved[4–7]. Tourmaline is a special crystal with spontaneous polarity. Studies have shown that tourmaline can regulate the microenvironment and promote the metabolism of microorganisms [8-10]. Tourmaline has become a research hotspot in the field of water treatment [11-13], but there is no relevant research report on its application to organic anaerobic fermentation.

Anaerobic fermentation is hindered by the cold temperatures in cold regions. In this study, we attempted to develop a new type of low-temperature and high-efficiency biogas fermentation device. On the basis of the two-phase anaerobic reactor, solar energy, ultrasonic cracking, and tourmaline biofortification technologies have been introduced to experimentally test the operating characteristics of this device. This device is expected to effectively increase the efficiency of low-temperature methane conversion to provide a theoretical basis and technical support for the design of biogas projects in severely cold regions.

EXPERIMENTAL MATERIALS AND METHODS

Reaction Device Design

The two-phase anaerobic reactor used in the experiment was made of organic glass, including a pretreatment reactor, a hydrolytic acidification phase, a methanogenic reactor, and a secondary settling tank. The hydrolytic acidification phase was designed using a modified continuous stirred-tank reactor (CSTR) anaerobic acid production system. The volume of the hydrolysis and the
Acidification phase of the CSTR was \( \Phi 32 \text{ cm} \times 40 \text{ cm} \), and the stirrer was set to timed-stirring for 5 min every 2 h. The methanogenic phase was carried out in an internal cycling (IC) reactor, a cylindrical plexiglass reactor with a volume of \( \Phi 15 \text{ cm} \times 76 \text{ cm} \), and a bioreactor with the inner diameter of 15 mm in the IC reactor with a diameter to height ratio of 5:1[14]. External gas flow meters and gas collection cylinders were used to measure the amounts of biogas, hydrogen, and metered gas produced.

The pretreatment device adopted the ultrasonic pretreatment method and ultrasonic cracking with a KQ-5200DE-type ultrasonic cleaner, the effective volume was 10 L, frequency was 40 kHz, and power was 250 W (continuously adjustable). The doped tourmaline was crushed and put through a 100-mesh sieve, then, it was evenly mixed with the matrix. The heating device used a solar heating temperature control device with a Pt100 temperature controller to automatically control the acid phase and methane phase temperatures at 35\(^\circ\text{C} \pm 0.5\,^\circ\text{C} \). A wet gas flow meter was installed to measure the amount of gas in the gas collection device. Figure 1 shows the structural design of the two-phase fermentation system.

1 Pretreatment reactor  2 Mechanical stirrer  3 Peristaltic pump  4 Acid phase reactor  5 Water seal  6 Gas flowmeter  7-9 sampling port  10 Methanogenic reactor  11-17 sampling port  18 precipitation tank  19 solar heating device

Figure 1. Schematic diagram of anaerobic digestion device.
Matrix and Dosing

Fresh cow dung from a farm in JinZhou City was used as the matrix, and batch-wise dosing was performed. The cow dung was sonicated by a pretreatment device every day. The sound energy density was 0.6 W/ml, and the mixture entered the pretreatment mixing reactor after cracking for 30 min. The flowmeter was dosed to the acid-producing phase, and the waste flowed from the acid-producing phase to the methanogenic phase. After the methane-producing phase, the organic waste was further digested and stabilized by the sedimentation tank and discharged to the storage tank. The entire process was performed automatically.

Reactor Startup And Operation

COW DUNG AS THE SUBSTATE IN THE CSTR ACID PHASE STRART AND RUN

The CSTR acid production phase used fresh cow dung as the fermentation substrate. This was taken from a cattle farm in Jinzhou in the summer. The samples were collected and stored in a refrigerator at 4°C. The physical and chemical properties of fresh cow dung are shown in Table 1. In this study, the active inoculants used in the reactor start-up were all taken from a single-phase semi-continuous mode in which the cow manure was the fermentation substrate and normal gas production was performed in a large biogas digester. The properties of the biogas slurry are shown in Table 1. The start-up and operation reactors included the CSTR acid production phase and the IC methanogen phase reactor. The initial TS percentage of the reactors that were started was 8%, and the inoculation of the biogas slurry was 30%, while the rest were filled with distilled water and mixed well. High-purity nitrogen gas was passed for 5 min before start-up to drive off the excess dissolved oxygen and provide a suitable growth environment for the anaerobic microorganisms. The oxygen concentration in the high-purity nitrogen gas used was ≤2 ppm. Batch fermentation was run continuously at 35°C for 30 days, and the substrate was stirred every 2 h. After 5 min, the properties of acid production and the types of volatile organic acids obtained at the end of the liquid phase were measured, along with the yield. After normal operation, biogas production, methane production, and the pH of the pretreatment reactor in the acid-producing phase and the methanogenic phase were measured daily. The VFA was tested every 2 to 3 days.

<table>
<thead>
<tr>
<th>Tested sample</th>
<th>TS (%)</th>
<th>VS (%)</th>
<th>TOC (%)</th>
<th>TKN (%)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh cow dung</td>
<td>17.5</td>
<td>75.8</td>
<td>34.5</td>
<td>1.7</td>
<td>7.05</td>
</tr>
<tr>
<td>Biogas slurry</td>
<td>6.2</td>
<td>5.3</td>
<td>22.3</td>
<td>1.45</td>
<td>7.16</td>
</tr>
</tbody>
</table>
IC METHANOGEN PHASE STARTUP AND OPERATION

Before the operation of the IC methanogenic phase, enrichment and acclimation were first carried out. The methane-producing phase was added with a total volume of 85% of the volume of the biogas slurry. To accelerate the enrichment of the methanogenic bacteria to a total of 1% before the start of the methane production, high-purity nitrogen gas was introduced into the IC for 5 min. The acidified substrate was characterized by an OLP and HRT of 1.0 KgVSm$^{-3}$d$^{-1}$ and 30 days. In the semi-continuous mode, the temperature is 35°C enriched for 10 days. The effect of different OLR and HRT on methane production efficiency was investigated. Methane conversion was measured when OLR was 1.0, 1.5, 2 and 2.5 KgVSm$^{-3}$d$^{-1}$ and HRT was 20, 30 and 40 days, respectively.

Chemical Analysis of Indicators

During the test, chemical analysis of routine analysis of all raw materials and samples collected, including the percentage of total solids (TS%), the percentage of volatile materials (VS%), and the chemical oxygen demand (COD). The total organic carbon (TOC) and total nitrogen (TKN) were measured using the standard methods [15]. The determination of short-chain volatile organic acids and the methane content was conducted using an Agilent 6890 gas chromatograph. The pH of the fermentation broth was measured using Shanghai Lei Magnetic pH-3C.

RESULTS AND DISCUSSION

Fermentation Acid Production Characteristics with Different Initial TS%

The CSTR acid-producing phase was started with dry matter concentrations of 8% and 12%, and the temperature was 35°C. Batch fermentation was carried out for 80 days.

As shown in Figure 2, changes in the types and contents of volatile organic acids were brought about by degrading cow manure in the acidogenic phase. As 30% of the biogas slurry in the mid-temperature biogas digester was inoculated before start-up, a highly active group of microorganisms with hydrolysis and acid-producing functions was provided, thus accelerating the degradation of cow manure and the rate of acid production.

For the CSTR acidity phase with a high initial TS % concentration, the pH decreased from the initial 7.16 to 6.48 after operation for 20 days. The initial acidity phase of the CSTR with a high TS% concentration decreased from the initial 7.16 to 6.48 after 20 days of initial operation. this result was higher than that of 8% TS. The type and the concentration of volatile organic acids at the end of the liquid phase
were determined. Further, the two types of volatile organic acids with different TS% concentrations produced acetic acid, propionic acid, and butyric acid. The content of valeric acid and ethanol was very low. Because of the suitable C/N characteristics of cow dung, the degradation of microorganisms and the metabolic process of acid production were relatively mild, and the accumulation of volatile fatty acids did not occur. However, when the initial concentration of TS % was too high, organic substances rapidly degraded and were prone to the accumulation of volatile fatty acids, either locally or in stages. These results showed that the yield of the total volatile fatty acids in the acidogenic phase was lower at 8% TS and reached its maximum on day 50 of operation, with acetic acid (2059.7 mg/L), propionic acid (433.1 mg/L), and butyric acid (71.1 mg/L). In the 12% TS acid production phase, 20 days after the start-up operation, the total volatile organic acid produced was 2400 mg/L, and the total amount of acetic acid in the volatile acids was more than 72.7%. Therefore, the organic acid terminal fermentation product type on day 40 of the acid production phase running at 8% TS was more suitable for the later methanogenesis process.

<table>
<thead>
<tr>
<th>Time /d</th>
<th>Acetic Acid</th>
<th>Propionic Acid</th>
<th>Butyric Acid</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>600</td>
<td>1200</td>
<td>1800</td>
</tr>
<tr>
<td>5</td>
<td>1200</td>
<td>2400</td>
<td>3000</td>
</tr>
<tr>
<td>6</td>
<td>1800</td>
<td>3000</td>
<td>3600</td>
</tr>
</tbody>
</table>

Figure 2. Variation of pH and VFA operated at different TS% during acidogenesis in CSTR.
Methanogenic Phase Operation Characteristics

ORGANIC LOAD ON METHANE PRODUCTION Gas Produccion Efficiency

High-efficiency anaerobic bioreactors have operational advantages by ensuring continuous, stable, and desirable methane conversion efficiency for high OLR and short HRT process parameters. A single substrate, cow dung, was used as the fermentation raw material. Its raw material properties had a C/N value suitable for anaerobic fermentation and a small pH fluctuation in the fermentation process. The main purpose was to estimate the methane conversion efficiency and the operational stability of the methanogenic phase of the two-phase process, to determine methanogenic process IC, and to examine the effects of the important operating parameters OLR and HRT on the methanogenesis characteristics.

After enrichment and acclimatization, five identical IC methanogenic phases were added to the acidified substrates running in the acidogenic phase for 40 days. The operating parameters were HRT for 30 days, and the OLRs were 1 kgVS/dm³d⁻¹, 1.5 kgVS/dm³d⁻¹, 2 kgVS/dm³d⁻¹, 2.5 kgVS/dm³d⁻¹ and 3 kgVS/dm³d⁻¹. The biogas production under different OLR operations is shown in Figure 3A. The results show that after the enrichment and acclimation process with an OLR of 1 kgVS/dm³d⁻¹ for 10 days, the daily biogas production rate of the IC methanogens reached 685 mL, which was different from the previously reported value. When the OLR was running, a significant difference was observed in the biogas production. When the OLR was operated at 2 and 2.5 kgVS/dm³d⁻¹, the production of methane from the IC increased rapidly to 2980 mL and 3150 mL, respectively, on day 18 and remained almost stable after 20 days of operation. Methane-based biogas production from ICs operating at an OLR of 1 and 1.5 kgVS/dm³d⁻¹ was significantly lower than that of IC-producing methane with OLR operating at 2 and 2.5 kgVS/dm³d⁻¹. When the OLR was 3 kgVS/dm³d⁻¹, the production of methane in the methane-produced phase of the IC grew the fastest during the initial period. On day 14 of operation, the biogas production reached 2800 mL and then declined sharply. On 23 day of operation, gas production was halted (the daily biogas output was less than 30 mL).
(A) Daily biogas productivity. (B) Volumetric biogas productivity. (C) Methane productivity. (*) OLR = 1.0 kg VS\text{d}^{-3}\text{d}^{-1}. (●) OLR = 1.5 kg VS\text{d}^{-3}\text{d}^{-1}. (▲) OLR = 2.0 kg VS\text{d}^{-3}\text{d}^{-1}. (□) OLR = 2.5 kg VS\text{d}^{-3}\text{d}^{-1}. (▼) OLR = 3 kg VS\text{d}^{-3}\text{d}^{-1}

Figure 3. Biogas productivity in IC reactor operated at different OLR.
The main reason was that when operating with an OLR of 3 kg VS\(_{\text{add}}\)m\(^{-3}\)d\(^{-1}\), the excess methanogens initially supplied to the methanogenic phase of the IC directly used the substrates to rapidly increase the biogas production. However, the methanogenic flora operated with this organic load. The acid-producing bacteria group could not achieve metabolic equilibrium, so the acid-producing microbial flora exhibited strong metabolic activity and volatile fatty acids gradually accumulated, severely inhibiting the activity of the methanogen group. The concentration of acetic acid and propionic acid at the time of stopping gas production was 1980 mg/L and 820 mg/L, respectively. This was the main reason for the decrease in the biogas production and the stopping of the gas production. The general reason for the decrease in the gas production and system conversion was the excessive accumulation of volatile organic acids and the inhibition of the acetic acid and acetic acid-producing bacteria utilizing the propionic acid and butyric acid in the methanogenic bacteria. Studies have shown that when the concentration of propionic acid reaches 900 mg/L, the growth of methanogenic bacteria is inhibited, which directly affects the efficiency of methane conversion.

Figure 3 B shows the volumetric gas production rate of biogas. When the OLR was 1.0 kg VS\(_{\text{add}}\)m\(^{-3}\)d\(^{-1}\) and 1.5 kg VS\(_{\text{add}}\)m\(^{-3}\)d\(^{-1}\), the average volumetric gas production rate of the biogas was 0.32 ± 0.013 m\(^3\)m\(^{-3}\)reactor and 0.55 ± 0.036m\(^3\)m\(^{-3}\)reactor, respectively. When the OLR was 2.0 kg VS\(_{\text{add}}\)m\(^{-3}\)d\(^{-1}\) and 2.5 kg VS\(_{\text{add}}\)m\(^{-3}\)d\(^{-1}\), the average volumetric gas production rate was 0.885 ± 0.087 m\(^3\)m\(^{-3}\)reactor and 0.927 ± 0.097 m\(^3\)m\(^{-3}\)reactor, respectively. The maximum volumetric gas yield reached 0.988 m\(^3\)m\(^{-3}\)reactor and 1.125 m\(^3\)m\(^{-3}\)reactor, respectively. Further, the gas production rate of methane from the IC at OLR 2.0 kgVS\(_{\text{add}}\)m\(^{-3}\)d\(^{-1}\) and 2.5 kgVS\(_{\text{add}}\)m\(^{-3}\)d\(^{-1}\) was significantly higher than when under low organic load operation. A biogas volumetric yield higher than 1:1 was achieved.

Figure 3 C shows the production of methane per unit of volatile matter with increasing OLR. Within the range of the organic load impact that the methanogens could withstand, an appropriate increase in the organic load of the methanogenic matrix increased the methane production and contributed to the metabolic activity of the acid-producing bacteria population.

However, once the imbalance occurred, the easily degradable organic substrates gradually accumulated, and the acid production metabolism gradually increased, eventually leading to the failure of the system organisms. When operating at an OLR of 2.5 kgVS\(_{\text{add}}\)m\(^{-3}\)d\(^{-1}\), the biogas production increased to some extent, but the methane conversion efficiencies were lower than those at OLR 2.0 kgVS\(_{\text{add}}\)m\(^{-3}\)d\(^{-1}\). When the cow dung underwent the acid production phase, the volatile substances contained in the volatile matter increased, which, in turn, significantly increased the utilization efficiency of the acid-producing bacteria. As a result, when the IC methane phase was operated at an OLR of 2.0 kgVS\(_{\text{add}}\)m\(^{-3}\)d\(^{-1}\), the average methane conversion yields were up to 240.5 ± 51.2 L kg\(^{-1}\)VS\(_{\text{add}}\). When the organic load continued to increase, biogas production increased further, but if the other process
parameters or the adopted microbial regulation strategies were not adjusted, a large amount of easily degradable organic substances accumulated, eventually leading to an excessive accumulation of volatile acids and the suppression of methanogenesis. The microbial activity decreased the methane yield, and the system entered the unstable operating state.

INFLUENCE OF RESIDENCE TIME OF RESIDENCE TIME ON GAS PRODUCITON EFFICIENCY IN METHANOGENIC PHASE

During the process of methane production using organic waste, the hydraulic retention time (HRT) also played an important role in determining the system operation efficiency and stability, except for the organic load impact on the system operation. As shown in Fig. 3-14, the effects of IC methanogen production on the biogas production changes were investigated when the organic load was 2.0 kgVSadd and 2.5 kg VSadd, and HRT was 20, 30, and 40 days, respectively.

(A) Volumetric biogas productivity. (B) Methane productivity. (▲)OLR=2.0 kgVSaddm^-3d^-1. (□)OLR=2.5 kgVSaddm^-3d^-1.

Figure 4. Biogas productivity in IC reactor operated at different HRT.
In general, in the actual process of operation, when operating at high organic loads, an appropriate increase in HRT was enhanced the stable metabolism of the microorganisms in the system and increased the efficiency of substrate degradation. However, at the same time, it affected the operating efficiency of the entire system. As the acidified substrate utilized by the IC-producing methane phase was easily degraded by the acid-producing bacteria and utilized by the methanogenic bacteria, the mass transfer between the microorganisms and the substrate was promoted by the internal and external circulation, leading to higher methane conversion efficiency and operating efficiency. When the HRT was operated for 40 days, the volume of the biogas under the two organic loads increased to some extent. The maximum volumetric biogas production at an organic load of 2.0 kgVS$_{ad}$m$^{-3}$d$^{-1}$ and 2.5 kgVS$_{ad}$m$^{-3}$d$^{-1}$ was 1170 L m$^{-3}$ reactor d$^{-1}$ and 1280 L m$^{-3}$ reactor d$^{-1}$, respectively (Figure 3-14A). The biogas production increased by an average of 26.2% and 28.2% when compared to HRT for 30 days (Table 3-6). When the HRT was 20 days, the impact of the organic load was larger, showing a significant downward trend in the biogas production, compared with HRT for the 30-day operation, the average daily biogas volume decreased by 18.7% and 21.8%. The methanobacteria activity and stability under the OLR and HRT operations were more seriously affected and could not reach a stable equilibrium state at this time. Without time regulation, the system soon entered the unstable operation state, resulting in a significant reduction in efficiency until the operation failed.

**TABLE II. PERFORMANCE OF IC REACTOR OPERATED UNDER DIFFERENT PROCESSING PARAMETER.**

<table>
<thead>
<tr>
<th>Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRT (d)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>40</td>
<td>20</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>OLR (kgVS$\text{m}^{-3}$d$^{-1}$)</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>2.0</td>
<td>2.0</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>pH</td>
<td>7.85 ± 0.04</td>
<td>7.65 ± 0.05</td>
<td>7.44 ± 0.04</td>
<td>7.74 ± 0.06</td>
<td>7.64 ± 0.05</td>
<td>7.68 ± 0.04</td>
<td>7.91 ± 0.06</td>
<td>7.88 ± 0.05</td>
</tr>
<tr>
<td>Daily biogas production (ml)</td>
<td>879 ± 74</td>
<td>1733 ± 247</td>
<td>2621 ± 564</td>
<td>2850 ± 682</td>
<td>3306 ± 139</td>
<td>2691 ± 276</td>
<td>3654 ± 132</td>
<td>2859 ± 390</td>
</tr>
<tr>
<td>Methane conversion rate (%)</td>
<td>164.7 ± 52.2</td>
<td>223.3 ± 50.4</td>
<td>240.1 ± 51.1</td>
<td>218.3 ± 52.4</td>
<td>282.6 ± 7.8</td>
<td>236.2 ± 27.2</td>
<td>252.6 ± 8.4</td>
<td>180.7 ± 33.3</td>
</tr>
<tr>
<td>Biogas conversion rate (%)</td>
<td>0.31 ± 0.013</td>
<td>0.56 ± 0.036</td>
<td>0.883 ± 0.087</td>
<td>0.925 ± 0.097</td>
<td>1.121 ± 0.029</td>
<td>0.872 ± 0.047</td>
<td>1.210 ± 0.047</td>
<td>0.91 ± 0.048</td>
</tr>
<tr>
<td>VS degradation rate (%)</td>
<td>36.3 ± 7.7</td>
<td>48.3 ± 8.1</td>
<td>56.3 ± 5.5</td>
<td>48.7 ± 9.3</td>
<td>47.9 ± 8.2</td>
<td>53.8 ± 7.2</td>
<td>67.5 ± 8.6</td>
<td>41.6 ± 4.7</td>
</tr>
<tr>
<td>Methane content (%)</td>
<td>54.6 ± 0.9</td>
<td>53.7 ± 1.1</td>
<td>54.4 ± 1.3</td>
<td>53.8 ± 1.4</td>
<td>53.2 ± 1.8</td>
<td>52.7 ± 1.3</td>
<td>54.2 ± 2.1</td>
<td>52.7 ± 1.4</td>
</tr>
</tbody>
</table>
As shown in Fig. 4 B, when the HRT was 40 days, the average methane conversion of the volatile substrates increased by 17.7% and 15.7% compared with the HRT of 30 days. The degradation efficiencies of volatile materials were 48.7 ± 9.3 and 67.5 ± 8.6. The methane conversion efficiency was more pronounced when the HRT was shortened to 20 days, particularly at the organic load of 2.5 kgVSadd m⁻³ d⁻¹, with a reduction of 17.2% and 28.5% compared to an HRT of 30 days and 40 days, respectively. The efficiency of the volatile matter degradation also decreased from 48.7% ± 9.3% and 67.5% ± 8.6% to 41.6% ± 4.7%. Thus, increasing the biogas output while increasing the biogas production and increasing the organic load in the system operation led to a matching optimal balance operation state and ideal gas production efficiency. The system showed no significant difference in the methane gas content under various parameters. It varied between 52.7% ± 1.4% and 54.6% ± 0.9%.

CONCLUSIONS

Using cow dung as a fermentation substrate, ultrasonic pretreatment and tourmaline-enhanced microbial technologies were introduced to develop a new type of two-phase anaerobic fermentation device for cold regions. The solar energy technology was used to control the temperature at 35°C ± 0.5°C. The following conclusions were drawn from this study:

The acid phase of CSTR with a high initial TS% concentration caused a rapid pH decrease and the acid production rate was high but prone to the local or periodic accumulation of volatile fatty acids at 8% TS running acid production. However, the total output of the volatile fatty acids was relatively low. The acid-phase 40-day organic acid terminal fermentation product type running at 8% TS was more suitable for the later methanogenesis process.

Using acidified materials run for 40 days in the acid-producing phase as the substrate, we studied the methanogenic characteristics of the methanogenic phase under different OLR and HRT conditions. Increasing the organic load in the methane production phase of the integrated circuits increased the biogas production, but this could easily lead to an excessive accumulation of volatile acids and, as a result, the instability of the system operation. With HRT at 40 days and OLR at 2.5 kgVSadd m⁻³ d⁻¹, the methanogenic phase stability and the operating efficiency were high. The average biogas volume production rate was 1.21 ± 0.047 m³ m⁻³ reactor, the methane conversion rate was 252.6 ± 8.4 L kg⁻¹ VSadd, and the average methane content was 54.2% ± 2.1%.

The solar temperature control system was stable during operation. The ultrasonic pretreatment and tourmaline had some promotion and regulation effects on the acid hydrolysis and the growth of methanogenic bacteria. It is recommended that subsequent studies should screen for excellent bacterial populations and then, carry out microbial ecological regulation during acid production and methanogenesis to make the system operate more efficiently and stably.
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