Characteristics and Optimization of Anaerobic Digestion of Tea Waste for Biogas Production

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Abstract. The tea residue from the production of beverage tea is used as anaerobic fermentation biogas production material. The anaerobic fermentation biogas-production experiment is conducted at an intermediate temperature of 35°C, and the biogas potential of the tea residue is reviewed. Using orthogonal experiment method, the effects of temperature, moisture and inoculation rate on the degradation property of tea residue are studied by designing L9 (3^3) experiment with 3 factors and 3 levels. The primary and secondary review factors and the optimum process conditions are determined. The experimental results show that: the cumulative biogas production after tea residue’s anaerobic fermentation for 40 days is 5270 ml, and the biogas production rate is 658 mL/g-ITS; methane production rate is 227.7 CH4-ml/g-ts. Orthogonal experimental results show that the optimum process conditions are 85% moisture content, 55°C for temperature, and inoculation rate is 20%. The highest TS degradation rate is 45.3%, the VS degradation rate is 61.52%.

1. Introduction

Biomass energy is the safest and most stable energy source, and it is also a new energy field that the country is currently encouraging. Tea residue is a kind of biomass waste. In recent years, with the rapid increase in the production of deep processing products of tea beverages, the production of tea residue has also rapidly increased. Due to the large production of tea residue, it has great large space for utilization and potential. Most tea residue is discarded without being used effectively, which not only causes environmental pollution but also seriously wastes biomass resources. Tea leaf contains more available ingredients, but also contains a certain amount of organic matter, vitamins, tea polyphenols, caffeine and a small amount of tea saponin[1]. At present, the recovery and utilization of tea residue is mainly the tea residue feed[2-4] and fertilizer production[5-7], adsorbent[8-11], renewable energy[12-14], protein extraction[15-17], etc.. However, there is little research on the production of biogas by anaerobic digestion of tea residue. Due to the nature of biomass, anaerobic digestion is the most desirable method of energy recovery. The objective of present study was to Characteristics and optimization of anaerobic digestion of tea waste for biogas production.
2. Material and Method of Experiment

2.1. Experiment Materials
The fermented material is derived from the end waste produced by Peony tea beverage. Tea beverage main materials are peony, rose, honeysuckle, folium ginkgo, licorice, spine date seed and clove. The inoculation is taken from anaerobic digestion sludge of a sewage treatment plant. The determination of tea residue and inoculation properties is shown in Table 1.

Table 1. The determination of tea residue and inoculation properties.

| Raw material       | Moisture (%) | TS (%) | VS (%) | C/N | pH   |
|--------------------|--------------|--------|--------|-----|------|
| Tea residue        | 20.71        | 79.29  | 95.39  | 25.46| 7.56 |
| Wastewater sludge  | 93.65        | 6.36   | 36.94  | 9.25 | 6.50 |

2.2. Experiment on the Potential of Producing Biogas from Tea Residue
Take 10 g residue, 30 mL inoculation sludge, and 120 mL distilled water. Mix and place them in a 500 mL anaerobic fermentation bottle and make them three parallel samples. Another 30 mL of activated sludge and 120 mL of distilled water are placed in the bottle as an experimental blank control group. The digestion bottle is purged with nitrogen for approximately 3 minutes to drive off the remaining air in the reaction bottle, and then the bottle mouth is quickly sealed with a rubber plug. The reaction bottle is incubated at 35°C for 40 days. Measurements of biogas production, methane concentration, and pH are recorded at intervals of 1 to 3 days.

2.3. Determination Experiment of Optimum Process Parameters for Anaerobic Digestion of Tea Residue
The selected temperature, water content and inoculation rate are three factors for L9 (34) orthogonal test. The reaction bottle is cultured for 40 days in 25°C, 35°C and 55°C. Biogas production, methane concentration and pH are recorded at intervals of 1-3 days. The TS and VS values are measured before and after digestion of anaerobic fermentation. Taking the cumulative biogas production as the evaluation index, and the optimum process parameter combination of anaerobic fermentation was determined without considering the interactions among various factors. Orthogonal experiment factor levels are shown in Table 2.

Table 2. The factors and levels of orthogonal test.

| levels | factors |
|--------|---------|
|        | A (temperature/°C) | B (water content/%) | C (inoculation rate/%) |
| 1      | 25      | 80      | 10     |
| 2      | 35      | 85      | 20     |
| 3      | 55      | 90      | 30     |

2.4. Analytical Method
The TS and VS contents of tea residue and inoculation sludge are determined by standard methods. The pH value is measured using a pH meter (LRH250, Mettler Toledo, USA). A pressure detector (3151WAL-BMP-Test, Germany) is used to determine the pressure difference at the top of the anaerobic digestion reaction bottle to convert biogas production rate. The methane content in the biogas is determined by biogas chromatography (7890B, Agilent USA) using nitrogen as the carrier biogas. The daily biogas production of biogas is calculated according to formula (1):

\[ V = \frac{PV_m}{RT} \] (1)
V: biogas production rate, mL;
P: absolute pressure difference;
Vh: headspace in the anaerobic digestion reaction bottle, mL;
Vm: biogas mole volume in the standard state, 22.4 L/mol;
R: universal biogas constant, 8.314 L·kPa/(k·mol);
T: degree kelvin, K;

3. Result and Discussion

3.1. Result Analysis of Experiment on the Potential of Producing Biogas from Tea Residue

3.1.1. Daily Biogas Production Rate and Cumulative Biogas Production Rate. From Fig. 1, it can be seen that the daily biogas production fluctuates greatly and can be divided into two biogas production peaks. In the early stage of fermentation, the daily biogas production is not obvious. Since the experimental material contains a large amount of cellulose and hemicellulose, and the surface structure of tea residue particles is denser, so the hydrolysis stage in the early stage of fermentation is relatively slow. The gradual increase of biogas production begins on the 6th day, reaching the first biogas peak (1050 ml) on the 14th day. This may be because the easily decomposable simple acids and carbohydrates contained in tea dregs are decomposed and converted into biogas. Later, the daily fermented biogas production gradually decreased, reaching the second peak of biogas production (521 ml) on the 23rd day. This may be because some of the hard-to-degrade cellulose and hemicellulose materials in tea residue are degraded. The daily biogas production of tea residue is reduced steadily, and the fermentation period ends on about the 40th day.
The cumulative production rate of tea residue is 5270 ml. The cumulative biogas production of tea residue in the first 14 days of anaerobic digestion accounts for 37% of total capacity. The cumulative biogas production in the first 21 days accounts for about 65% of the total capacity, while that in the first 28 days accounts for 85%. On the 35th day, the cumulative biogas production reaches 93%. This indicates that most of the substances that can be degraded at 35 days have been fermented and converted into biogas. In the production of biogas projects, the recommended fermentation time of such tea residue materials is approximately 4 weeks, and potentially more than 80% of biogas of tea residue fermentation can be obtained.

3.1.2. Daily Production Rate and Cumulative Rate of Methane. The daily methane production rate and the cumulative methane production rate are shown in Fig.2. The anaerobic digestion is divided into three stages, the initial stage of methane biogas production is not obvious, and the biogas production begins to increase gradually on the 6th day. This is mainly because the initial stage of the reaction is the acid production stage of hydrolysis and fermentation. In the first few days of the reaction, the main component of biogas is CO2, and a small amount of H2 and CH4. The intermediate stage of anaerobic fermentation is from the 14th to the 28th day. During this period, the daily methane production is relatively high. On the 23rd day, the peak value of daily methane production rate reaches 236.41ml, and the methane concentration reaches more than 50%. During the later stage of anaerobic fermentation, from the 29th to the 40th day, the daily production of methane gradually decreases.
The accumulated methane content of tea residue after 40 days of fermentation is 1822 ml. The cumulative biogas production of tea residue in the first 10 days of anaerobic digestion accounts for 5% of total capacity. The cumulative biogas production in the first 20 days accounts for about 44% of the total capacity, while that in the first 30 days accounts for 84%. Daily production of methane is high from the 14th to the 28th day. During this period, the accumulated methane content is 973.6ml, accounting
for 72% of the total production capacity. In the production of biogas projects, the use of tea residue materials of such composition for a fermentation time of more than 30 days will result in the recovery of more than 80% of methane biogas in the tea residue fermentation biogas production.

3.1.3. Analysis of Biogas Potential of Tea Residue. The cumulative biogas production after tea residue’s anaerobic fermentation for 40 days is 5270 ml with 132 ml average daily biogas production and the biogas production rate is 658 ml·g·1TS; the cumulative methane content is 1822 CH4·ml with 45.55 CH4·ml average daily methane production. The methane production rate per unit mass of materials is 227.7 CH4·ml·g·1TS. Because the main ingredient of raw tea residue is lignocellulose, it is similar to the biomass of straw. In literature\cite{18-19}, the efficiency of anaerobic digestion of corn, rice husk and straw is reported as 309 CH4·ml·g·1TS, 229.8 CH4·ml·g·1TS and 246.6 CH4·ml·g·1TS. Although different methane fermentation and pretreatment methods have been used in the study of different methane fermentation potentials which results in different results, it generally reflects the ability of tea residue to decompose methane and its potential to produce biogas.
3.2. Orthogonal Experiment Result

3.2.1. Determination of Optimum Combination Parameters. From table 3, it can be known that for the factor temperature: k3>k1>k2, so the Level 3 (55 °C) is the excellent level of the temperature factor; for the water content factor: k1> k2> k3, so the level k1 (80%) is the excellent level of water content factor; for the inoculation rate factor: k2>k3>k1, so the level k2 (20%) is the optimal level of the inoculation rate factor. Therefore, the optimal combination of this orthogonal experiment is A3B1C2, that is: anaerobic digestion temperature is 55 °C, water content is 80% and sludge inoculation rate is 20%.

3.2.2. Analysis of Reaction Process. It can be seen from the Fig.3 that the cumulative biogas rate of different experimental groups varies greatly. The experiment lasted about 40 days. The biogas production is rapid at the beginning of the experimental group 7#, 8#, and 9#. This shows that at high temperature (55°C), the microbial flora can quickly enter the biogas production stage at the initial stage of the reaction. However, the biogas production capacity is also affected by the temperature and the concentration of organic solids. The cumulative biogas production of 2# (5560ml), 4# (5580ml), and 9# (5675ml) of the experimental group with 20% inoculation rate is higher than that of other groups, and the cumulative biogas production of 1# (2010ml), 6# (1535ml), and 8# (2576ml) of the experimental group with 10% inoculation rate is lower than that of other groups, and basically no biogas was produced during the later period, indicating that the low concentration of the inoculation rate obviously affects the biogas production rate and speed. The cumulative biogas production and the degradation rates of TS and VS in each group are also different. The TS degradation rate is 9.18% to 45.37%, the VS degradation rate is 22.49% to 61.52%.
### Table 3. Analysis of variance orthogonal.

| NO. | Factors     | cumulative biogas(ml) |
|-----|-------------|-----------------------|
|     | Temperature /℃ |       | Water content % | Inoculation rate % |                     |
| 1   | 1(25)       |           | 1(80)           | 1(10)              | 2010                |
| 2   | 1           | 2(85)     | 2(20)           |                     | 5560                |
| 3   | 1           | 3(90)     | 3(30)           |                     | 4568                |
| 4   | 2(35)       |           | 1               | 2                   | 5580                |
| 5   | 2           | 2         | 3               |                     | 4130                |
| 6   | 2           | 3         | 1               |                     | 1535                |
| 7   | 3(55)       |           | 1               | 3                   | 5120                |
| 8   | 3           | 2         | 1               |                     | 2576                |
| 9   | 3           | 3         | 2               |                     | 5675                |
| K1  | 12,138      |           | 12,710          | 6,121               |
| K2  | 11,245      |           | 12,266          | 16,815              |
| K3  | 13,371      |           | 11,778          | 13,818              |
| k1  | 4,046       |           | 4,237           | 2,040               |
| k2  | 3,748       |           | 4,089           | 5,605               |
| k3  | 4,457       |           | 3,926           | 4,606               |
| R   | 709         |           | 311             | 3,565               |

4. Conclusion

The anaerobic fermentation biogas-production experiment is conducted at an intermediate temperature of 35°C, and the biogas potential of the tea residue is reviewed. Using orthogonal experiment method, the effects of temperature, moisture and inoculation rate on the degradation property of tea residue are studied by designing L9 (3³) experiment with 3 factors and 3 levels. The primary and secondary review factors and the optimum process conditions are determined. The following points are the conclusion of the investigation:

1) The cumulative biogas production after tea residue’s anaerobic fermentation for 40 days is 5270 ml with 132 ml average daily biogas production and the biogas production rate is 658 ml·g⁻¹TS; the cumulative methane content is 1822 CH₄·ml with 45.55CH₄·ml average daily methane production. The methane production rate per unit mass of materials is 227.7 CH₄·ml·g⁻¹TS. It can be seen that tea residue has good potential for biogas production, which is a good material for biogas fermentation, and has a very good usage value of biomass energy.

2) Orthogonal experimental results show that the optimum conditions are 85% moisture content, 55°C for temperature, and sludge inoculation rate is 20%.

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