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Economic and Technological Feasibility Analysis of Biogas Production from Biomass Wastes by Adding Hydrochar and Hydrothermal Pre-treatment

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Abstract

This paper aims at the technology of producing biogas and maximizing the production by anaerobic digestion of fish processing wastes and tofu residue with hydrochar obtained from bamboo residue at a certain temperature (200°C) according to hydrothermal carbonization, and making an economic and technological analysis of production process. Through a Break-even point analysis, producing biogas using hydrothermal pretreatment and adding hydrochar has more advantages than the without pretreatment method in both production volume and investment recovery duration. It was demonstrated that the comparison and evaluation of without pretreatment and adding hydrochar, hydrothermal pretreatment approach, the investment recovery duration could be reduced from 419 days to 256 days with the large-scale biogas plants of 1 000 m^3 as a criterion.

Keywords: Hydrochar, Hydrothermal Pretreatment, Food Processing Waste, Biogas, Break- Even Analysis.

Introduction

Introduction

Many serious problems such as environmental pollution and depletion of fossil fuels are being posed with continuous changes and developments of human civilization and economy. In particular, the shortage and depletion of fossil fuels (coal, oil and natural gas, etc.) is emerging as one of the important issues to be urgently solved around the world. Therefore, many countries are focusing on the development of eco-friendly and sustainable new energy.

In 2016, the total output of fish in China was 49.2 million tons, accounting for approximately 62% of the world’s total fish output (FAO, 2018). Fish processing wastes generated in the process of fish treatment account for more than 10% of the fish weight, which means that in 2016, the annual output of fish processing wastes in China was 4.9 million tons (Xu et al., 2016). Traditionally, fish processing wastes are disposed by burying down the earth or burning into fire, but these methods cause problems of groundwater pollution, greenhouse gas or even toxic gas emissions, occupying potentially arable land, and spending much money.

Next, tofu residue (TR) is a byproduct of tofu production or soybean beverage manufacturing. Generally, every 1 000 L of soymilk produces about 250 kg of tofu residue (Nguyen et al., 2013). It is estimated that approximately 14 million tons of tofu residue is generated all over the world each year, bringing environmental burden.

In addition, rice straw is one of the most abundant lignin fiber crop wastes in China. This lignocellulosic biomass is not biodegraded easily and has a complex structure (Mustafa et al., 2017; Mustafa et al., 2018; Mustafa et al., 2019). The co-digestion by lignocellulosic biomass pretreated hydrothermally is very useful in improving the effectiveness of biogas production. Hydrothermal pretreatment becomes an interesting technique for the pretreatment of lignocellulosic material (Reza et al., 2014; Reza et al., 2015). Hydrothermal pretreatment technology has considerable advantages of being very effective, eco-friendly with low energy requirements, and reducing emissions of toxic substances. (Choe et al., 2019; Choe et al., 2020; Xia et al., 2016; Xu et al., 2016)

This study focuses on three subjects; (1) the co-digestion of hydrochar produced by bamboo residues, fish processing wastes and liquid fraction of hydrothermal carbonization; (2) a method of producing biogas with tofu residue and rice straw pretreated hydrothermally; (3) economic and technological analysis of maximizing methane yield and net energy output from methane.

Technological principle of biogas production process by hydrothermal carbonization and hydrothermal pretreatment

The detailed principle of the process for manufacturing biogas is shown in Fig. 1. (Choe et al., 2019)

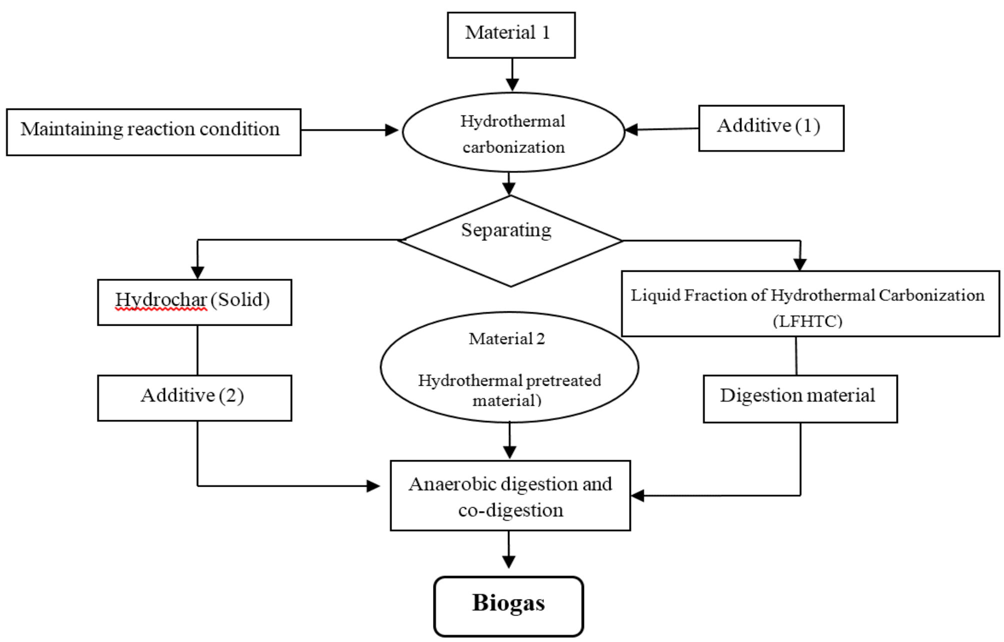

Fig. 1: Technological principle diagram of biogas production process by hydrothermal carbonization and hydrothermal pretreatment

Material 1: bamboo residue (substrate: distilled water=1:10); additive (1): dilute hydrochloric acid; ferrites.

Material 2: tofu residue; rice straw; additive (2): hydrochar; liquid fraction of hydrothermal carbonization (LFHTC).

First, as shown in Fig. 1, hydrothermal carbonization is carried out at a certain hydrothermal carbonization temperature (200°C) for hydrothermal reaction time of 1 hour to obtain bamboo hydrochar, using bamboo reside (substrate: distilled water=1:10) as raw materials. Optimal reaction conditions are ensured during this hydrothermal carbonization process, and diluted hydrochloric acid and iron oxide are added as additives. (Yan et al., 2017)

The reaction temperature conditions and additive parameters are shown in detail in Table 1 and Table 2 below.

Table 1: Parameters for hydrothermal carbonization reaction conditions

Reaction condition	Parameter	Unit
Mixing ratio of water and bamboo residue	1:10	-
Temperature	200	°C
Pressure	15	bar
Heating rate	3	°C/min

Table 2: Additive parameters of hydrothermal carbonization

Additive	Parameter	Unit
Dilute hydrochloric acid	10	ml/L
Ferrites	3	g/L

Second, the obtained hydrochar is separated into solid hydrochar and liquid fraction of hydrothermal carbonization (Choe et al., 2019; Choe et al., 2020). Additives are mixed with separated solid hydrochar, and liquid fraction of hydrothermal carbonization is used as the raw material to carry out anaerobic co-digestion.

Third, tofu residue and rice straw is pretreated in the optimal hydrothermal pretreatment conditions (tofu residue; 140°C (Choe et al., 2021), rice straw; 160°C), and anaerobic co-digestion is carried out with hydrochar (mixing ratio 2:1 (Choe et al., 2019)) and liquid fraction of hydrothermal carbonization (mixing ratio 25%:75% (Choe et al., 2020)) to produce biogas.

The technological parameters for manufacturing biogas

Tables 3 and 4 below show the technological parameters of the biogas production by hydrothermal carbonization and hydrothermal pretreatment by processes.

Table 3: Additive parameters of anaerobic digestion and co-digestion

Additive	Parameter	Unit
Hydrochar	4	g/L
Liquid fraction of hydrothermal carbonization and Material 2	25+75	%

Table 4: Parameters of hydrothermal pretreatment

Material	Pretreatment temperature (°C)	Pretreatment time (min)
Tofu residue	140	30
Rice straw	160	30

Biogas production process

Raw material processing

Fish processing wastes: After removing bones, thorns and scales from the mixture containing fish intestines, fat, swim bladder, bones, fins, and scales from the fish processing, the mixture is cut into the size of 3-5 mm by using a grinder. (Choe et al., 2019)

Bamboo residue: After cutting bamboos, they are allowed to leave to dry overnight at 60°C. When moisture in the chopped samples is less than 3%, they are pulverized into small particles by a turbine grinder and passed through a 60-mesh screen. The prepared bamboo powder has an average particle size of 250-300 µm and is used as feedstock for hydrothermal carbonization. (Choe et al., 2019)

Tofu residue: The tofu residue is pulverized with a blender and then mixed evenly to be used as feedstock for anaerobic digestion. (Choe et al., 2021)

Lignocellulosic biomass (rice straw): The rice straw is first dried in the air to contain moisture of less than 10%, then subsequently cut into the size of 425µm and stored in plastic bags at room temperature until further use. (Mustafa et al., 2018)

Inoculum: The inoculum is collected from the bottom settlement of anaerobic fermentation tank that was fed with food and kitchen wastes.

Production of hydrochar

After bamboo residue is dried at 60°C overnight, dry bamboo powder is mixed with deionized water in a ratio of 1:10 (Zhang et al., 2014) and transferred into a cylindrical stainless steel reactor. The experimental conditions are set at 200°C, a heating rate of 3°C/min and a reaction time of 1 hour. The content is continuously stirred at 90 rpm, and when the hydrothermal carbonization is finished, the content temperature is cooled down to room temperature and the gaseous product is then released via the gas valve. The liquid product is separated by vacuum filtration with 0.45 µm pore-size cellulose filter paper. The residue is the bamboo hydrochar and is dried overnight in an oven at 105°C. The dried hydrochar is stored in a plastic bag and later used as an additive in anaerobic digestion. (Choe et al., 2019)

Hydrothermal pretreatment of tofu residue and rice straw

Cooperative anaerobic fermentation is carried out using the tofu residue and rice straw pretreated with hydrothermal pretreatment at different temperatures between 130℃ and 180℃ as substrates. The pre-treatment method for hydrothermal carbonization of tofu residue and rice straw is as follows. Mix the substrate and deionized water in a ratio of 1:1 and mix evenly. The mixed material is placed in a column-shaped high-temperature and high-pressure reactor (4848, Parr Instrument Company, USA), and a stirrer is installed. The conditions of the hydrothermal carbonization process are that the temperature range is between 130°C and 180°C (Choe et al., 2021), the heating rate is 3°C/min, and the reaction time is 1 hour at the required temperature. The reaction temperature is controlled with a thermostat (4848 Parr Instrument Company, USA). The reaction contents are continuously stirred at 90 rpm, and the stirring speed is controlled by a speed controller. At the end of the hydrothermal carbonization reaction, the heater is turned off and the reactor is cooled to room temperature. It takes about 4-5 h to cool the reactor down to room temperature of 25°C, and the pressure is reduced from 8-12 bar to 3-4 bar. After the temperature is lowered to 25°C, turn on the gas valve to remove gas products, and separate liquid products with a vacuum pompom using 0.45 µm-sized cellulose filter paper. The filtered tofu residue and the hydrothermal liquid of rice straw are stored at -20°C and used as raw materials for anaerobic fermentation.

Anaerobic decomposition and cooperative fermentation

An anaerobic reaction is performed by putting the substrate and inoculum in the reaction tank. Add diluted hydrochloric acid to the gas collection tank to set the pH 3 or less to prevent the decomposition of CO2. (Mustafa et al., 2016)

Argon gas was introduced into the reactor for 5 min to ensure anaerobic conditions. The reactor was then incubated in a constant-temperature water bath (DK-S28, Shanghai Jinghong) (Fig. 2). The temperature of the water bath is controlled at 37 ± 1°C in mesophilic anaerobic fermentation. (Kafle & Kim, 2013)

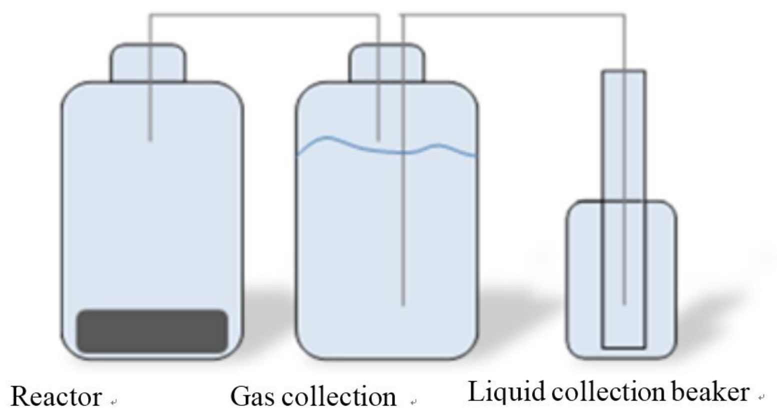

Fig. 2: Schematic diagram of batch anaerobic digestion system

Fig. 3 below shows the biogas production process diagram by hydrothermal carbonization and hydrothermal pretreatment. (Choe et al., 2019; Choe et al., 2020; Choe et al., 2021)

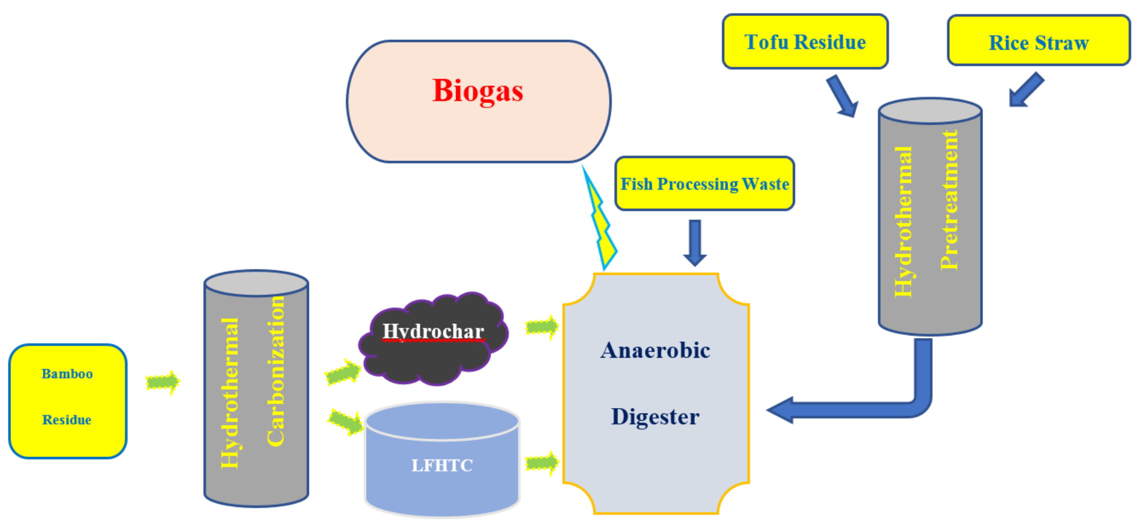

Fig. 3: Biogas production process diagram by hydrothermal carbonization and hydrothermal pretreatment

Economic and technological analysis of biogas production process

Technological analysis of biogas production process

1) Since hydrochar is used as a carrier for anaerobic fermentation microorganisms, it is possible to increase the biogas productivity using anaerobic fermentation microorganisms by ensuring a habitat for the growth and proliferation of methane gas-generating microorganisms during anaerobic fermentation.

2) The effectiveness of anaerobic fermentation can be increased by allowing the anaerobic decomposition of raw materials for fermentation to proceed well because substances that are biologically difficult to decompose are converted into substances with low molecular weight through hydrothermal pretreatment.

3) Since hydrochar is used as an additive, when biomaterials with high nitrogen content are used as raw materials for anaerobic fermentation, the effectiveness of anaerobic fermentation can be increased by rationally controlling the carbon/nitrogen ratio of the fermentation substrate.

4) Since a biological material with high moisture content is used as the raw material for hydrothermal carbonization, the drying process is not required in the preparation of the fermentation raw materials, so the energy required for drying the biological material can be saved.

5) Since the hydrothermal liquid generated in the hydrothermal carbonization process can be used as an anaerobic fermentation raw material, there is an eco-friendly advantage in that it prevents secondary pollution that may occur in the hydrothermal carbonization process and converts hydrothermal liquid waste into biomass energy.

There is a significant difference in methane yields when raw materials without hydrothermal pretreatment are used as they are and when raw materials subjected to hydrothermal pretreatment are used.

Fish processing waste

The maximum methane yields was 219 mL/g-VS when a mixture of fish processing wastes and hydrothermal liquid was used, and the methane yields increased by 64% compared to when only fish processing wastes were used. At this time, the highest pure methane energy production is 3 410 kJ/kg-VS. (Choe et al., 2019; Choe et al., 2020)

Tofu residue

The maximum methane yields is 200.1 mL CH4/g-VS when tofu residue with hydrothermal pretreatment is used, which indicates that its methane yields is 34% higher than when tofu residue without hydrothermal pretreatment is used. (Choe et al., 2021)

Rice straw

The highest methane production yields of rice straw added 5% NaOH was 132.7 mL/g VS, which the hydrothermal pretreatment was given for 10 min at 200°C. (Chandra R., 2012)

Table 5 shows the changes in methane yields by hydrothermal pretreatment and without pretreatment of several substrates during anaerobic digestion.

Table 5: Methane yields change by hydrothermal pretreatment

Substrate		Methane yields (mL/g-VS)	Increment rate (%)
Method 1 (Hydrothermal pretreatment is not undergone)	Fish processing waste	97.0	
	Tofu residue	150.6	
	Raw straw	97	

Method 2 (Hydrothermal pretreatment is undergone)	Fish processing waste	219.0	125.8
	Tofu residue	207.0	37.5
	Raw straw	132.7	36.8

Economic analysis

The analysis of capital investment in year

Equation 1 below shows the model of calculating gross investment in biogas production when using two different methods. Fixed costs and variable costs required for biogas production are shown in Equation 2 and 3 where

$$C_t = C_e + C_r \quad (1)$$

$$C_e = C_{ep} + C_{em} + C_{en} + C_{ec} \quad (2)$$

$$C_r = C_{rh} + C_{ri} + C_{rj} \quad (3)$$

C_t: gross investment; C_e: fixed costs; C_r: variable costs; C_{ep}: costs of hydrolysis precipitation equipment for pretreatment processes of raw materials; C_{em}: methane gas production equipment costs; C_{en}: costs of equipment for treating methane fermentation liquid and fermentation waste; C_{ec}: costs of methane gas trapping equipment; C_{rh}: labour costs; C_{ri}: power rates; C_{rj}: raw materials purchase costs.

(1) Fixed costs

According to research data, the costs of relevant equipment have been identified on the basis of methane gas production equipment of 1 000 m3.

Table 6: Fixed costs, Cost unit: 10 000 RMB

Cost / Production method	Equipment cost				
	Before-treatment equipment of raw materials	Gas production equipment	Fermentation waste treating equipment	Gas trapping equipment	Total
Method 1	3	2 500	1.5	2	2 506.5
Method 2	30	2 500	1.5	2	2 533.5

Method 1 in the table above is a general mode of biogas production where the hydrothermal pretreatment of raw materials is not undergone whereas Method 2 is a mode of biogas production where the hydrothermal pretreatment of raw materials is undergone. Here, there is a certain gap in their costs because pretreatment of raw materials is undergone in Method 2. Investment in biogas production processes is 25 065 000 RMB in Method 1, and 25 335 000 RMB in Method 2.

(2) Yearly variable costs

Variable costs include labor costs and raw materials purchase costs. According to investigation, the number of working staff is 160 among whom 140 are field workers and 20 are management staff. Hydrothermal pretreatment process requires 10 more labour staff. Monthly salary of field workers is 2 500 RMB, which is the average salary amount in the city, and that of management staff is 4 000 RMB.

As power rates equal to 0.5 RMB/kWh, daily power consumption is 1 250 kW, and daily raw material treatment amount is 100 tons.

Table 7: Operation costs in year, Cost unit: 10 000 RMB

Cost / Production method	Operation cost					
	Labour cost		Power rates	Raw materials purchase costs		Total
	Number of field workers	Management staff		Raw materials cost	Transportation cost	
Method 1	420.000	96.000	22.8125	91.2500	109.5000	739.5625
Method 2	450.000	96.000	23.7250	91.2500	109.5000	770.4750

Profitability analysis

In this paper, we did a Break-even point analysis of traditional method of treating biomass wastes and hydrothermal pretreatment method, and based on this, we compared and evaluated the profitability of each method.

(1) Break-even point analysis

Break-even point is equal to fixed costs divided by the retail price per unit, minus the variable costs per unit. (Kampf et al., 2016)

$$BEP = FC/((p - vc) \quad (4)$$

Where: BEP - production volume in Break-even point, FC - fixed costs, p - price, vc - variable cost per unit.

Break-even point analysis is one of the useful tools for researching into the relationship between fixed costs, variable costs and revenue. Break-even point determines the point when an investment generates positive revenue.

Break-even point analysis helps to calculate the production volume at a given cost necessary for making up all the costs. It also helps to figure out the proper price which can compensate for all the costs at a given level of production volume.

(2) Break-even point analysis of two methods

Regarding daily production volume, the production volume of Method 1 is 20 000 ㎥ and Method 2 is 30 000 ㎥, which means the yearly production volume of Method 1 equals to 7 300 000 ㎥/year, and that of Method 2 amounts to 10 950 000 ㎥/year.

Operation cost in Method 1 in year is 7 395 625 RMB/year, and 7 704 750 RMB/year in Method 2. Therefore, the variable cost per unit in Method 1 is – 1.013 RMB/㎥, and 0.703 RMB/㎥ in Method 2.

The price of biogas is 4 RMB/㎥.

Production volume required to reach Break-even point (BEP)

$$BEP_1 = \frac{FC}{p - vc} = \frac{25\,065\,000}{4 - 1.013} = \frac{25\,065\,000}{2.987} = 8\,391\,362.57$$

$$BEP_2 = \frac{FC}{p - vc} = \frac{2\,5\,335\,000}{4 - 0.703} = \frac{2\,5\,335\,000}{3.297} = 7\,684\,258.41$$

BEP_1: Production volume at BEP in Method 1

BEP_2: Production volume at BEP in Method 2

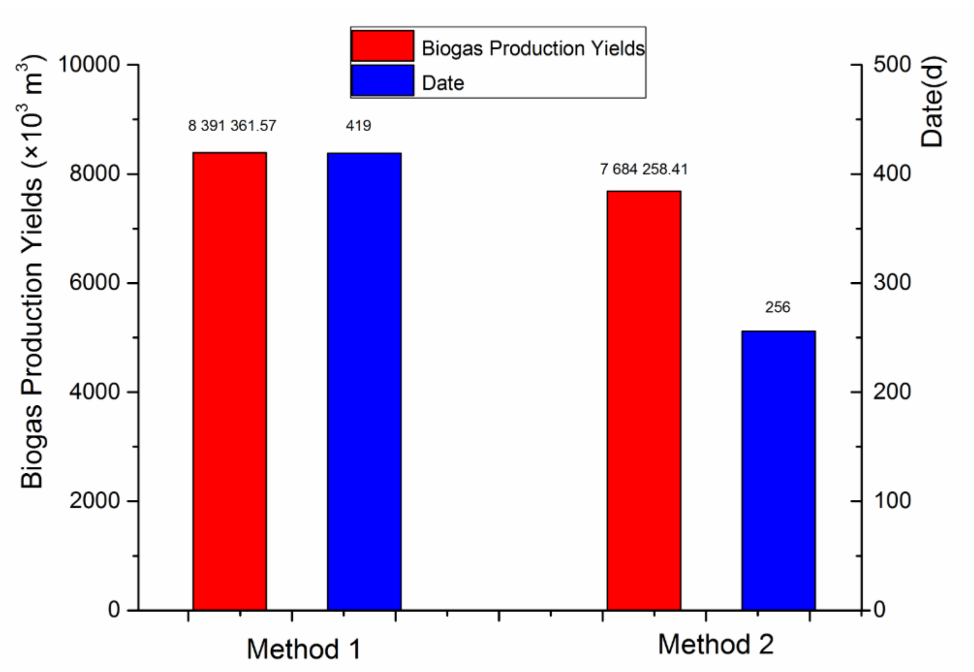

Fig. 4: Break-even point analysis of two methods

As shown Fig. 4, It was demonstrated that the Break-even point after producing 8 391 362.57 ㎥ of biogas, and investment recovery duration required is 419 days in Method 1. Meanwhile, in Method 2, it was calculated that the Break-even point after producing 7 684 258.41 ㎥ of biogas, and the investment recovery duration required is 256 days.

As above mentioned in Break-even point analysis, producing biogas using hydrothermal pretreatment of biomass wastes has more advantages than the previous traditional method in both production volume and investment recovery duration.

Conclusion

Traditionally, food processing wastes have been treated by burial or burning, but this method is expensive and poses environmental problems. Burying in the ground occupies a lot of land resources, and after burial, it pollutes leaching groundwater, and the method of burning has a defect in releasing global warming gas and toxic gas. This study investigated the effect of hydrochar made from bamboo residue on the anaerobic fermentation of fish and tofu residue. Then, researches were made on the effect of the addition of bamboo hydrochar on the anaerobic fermentation of fish processing wastes, the cooperative fermentation characteristics and optimal mixing ratio between fish processing wastes and hydrothermal carbonization liquid, and the optimal hydrothermal pretreatment temperature of tofu residue and rice straw. Furthermore, this study delved into the mixing ratio and mixed fermentation characteristics of the fermentation liquid of tofu residue and rice straw according to the optimal temperature of hydrothermal pretreatment. Next, it was discovered that when fermentation raw materials are used that have undergone hydrochar addition and hydrothermal pretreatment, biogas production, methane production, methane content in biogas, and pure energy gain are maximized, and the inhibition of anaerobic fermentation due to ammonia nitrogen by the addition of hydrothermal carbon is eliminated. In this research, as a result of doing Break-even point analysis, comparison and evaluation of traditional fish processing wastes treating method and hydrothermal pretreatment approach, investment recovery duration could be reduced from 419 days to 256 days using Method 2 with the large-scale biogas plants of 1 000 m^3 as a criterion. Finally, the research revealed that when producing biogas from food processing wastes using hydrothermal carbonization and hydrothermal pretreatment, biogas production volume could be increased in comparison to the traditional way of not using pretreatment approach, and investment recovery duration could be reduced to 163 days.

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