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Enhancement of Biogas Production Through Solid-State Anaerobic Co-Digestion of Food Waste and Corn Cobs

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Enhancement of Biogas Production Through Solid-State Anaerobic Co-Digestion of Food Waste and Corn Cobs

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Abstract

Although biogas has been primarily produced through liquid anaerobic digestion, this method leads to the floating and stratification of fibers and non-homogeneous mixing, which can reduce the biogas yield. Alternatively, biogas can be produced by the solid-state anaerobic digestion (SS-AD) of organic material with a high solid content, such as corn cobs. We investigated the co-digestion of food waste and corn cobs as a biomass feedstock for SS-AD in biogas production. We measured the effects of the total solid (TS) content, percentage of food waste, and reduction in volatile solids (VS), from which we determined its appropriate kinetic model. We found that the SS-AD of food waste with corn cobs produced a high biogas yield of 543 mL/g VS at a TS content of 22% and a food waste content of 20%. The first-order kinetics model for biogas production during SS-AD of the tested corn cob and food waste yielded an R^2 value in the range of 0.91–0.94. The main contributor to the biogas production during the SS-AD of the corn cobs and food waste was the reduction in VS. A positive linear relationship was observed between the biogas yield and the reduction of VS.

Abstrak

Peningkatan Produksi Biogas Melalui Solid-State Anaerobic Co-Digestion dari Sisa Makanan dan Tongkol Jagung. Biogas sebagian besar diproduksi melalui liquid anaerobic digestion (L-AD). Tetapi, metode ini mengakibatkan serat mengapung, stratifikasi dan pencampuran yang tidak homogen sehingga menurunkan yield biogas. Biogas dapat diproduksi menggunakan solid-state anaerobic digestion (SS-AD) pada kandungan padatan tinggi, seperti tongkol jagung. Penelitian ini mengkaji limbah makananan sebagai co-digestion dan tongkol jagung sebagai bahan baku biomassa untuk produksi biogas melalui SS-AD. Penelitian juga mengkaji pengaruh dari total padatan (TS), persentase limbah makanan, dan reduksi volatil solid (VS) serta menentukan model kinetika. Hasil penelitian menunjukkan bahwa SS-AD limbah makanan dan tongkol jagung menghasilkan yield biogas tertinggi sebesar 543 mL/g VS pada TS 22% dan limbah makanan 20%. Produksi biogas dari tongkol jagung dan limbah makanan yang diuji mengikuti model kinetika orde pertama dengan R^2 0,91-0,94. Faktor utama pada produksi biogas dari tongkol jagung dan limbah makanan adalah reduksi VS. Yield biogas dan limbah makanan. Biogas yield berhubungan linier dengan reduksi VS.

Keywords: anaerobic digestion, biogas, lignocellulosic biomass, solid fermentation, volatile solid

1. Introduction

The amount of energy consumed globally is increasing daily [1], whereas the volume of fossil fuel resources is being progressively depleted. To overcome the energy crisis, sources of energy must be provided to meet future needs [2]. The BP Statistical Review of World Energy [3] reveals that in 2019 the global fuel consumption was 13,946.22 million tons and that in Indonesia was 212.81 million tons. Indonesia's energy needs are also estimated to increase from 1648 million barrel oil equivalents (BOEs) in 2016 to 3221 million BOEs in 2030 [4].

The use of renewable fuels can reduce fossil-fuel dependence and mitigate the social and environmental degradation associated with fossil fuels [5]. One renewable fuel option is biogas. Currently, the demand for biogas shows a positive trend in the global market for various energy needs [6]. The global biogas production capacity in 2019 was 19453 MW [7]. The raw materials used to produce biogas can be obtained from organic wastes such as agricultural, food, and animal wastes [8].

With a total corn production of 12.6 million tons in 2018/2019, corn cobs are an abundant agricultural waste in Indonesia [9]. With respect to producing biogas from food wastes, the Food and Agriculture Organization [10] reported that 14% of food is wasted during its post-harvest distribution. Food waste is also reported to generate a greenhouse-gas content 25 times greater than CO_2 over a 100-year period [11]. Food waste also generates two types of environmentally clean gas, i.e., hydrogen and methane [5]. In addition, food waste contains many nutrients such as natural fibers, carbons, proteins, fats and lipids, which can improve its degradability by microorganisms [12].

Biogas is produced via anaerobic digestion, which is classified into two types based on the total solids (TS) content, namely, liquid anaerobic digestion (L-AD) and solid-state anaerobic digestion (SS-AD). L-AD is used on waste with a TS content less than 15%, and SS-AD on that with a TS content of higher than 15% [13]. The TS content is an important parameter in SS-AD, affecting both the process performance and volume of biogas produced [14]. A study conducted by Yang and Li [15] revealed that the TS content can be changed to reduce the methane yield.

The addition of food waste for co-digestion can increase the biogas yield. Food waste can improve microbial growth due to its high content of organic macromolecules [16]. Although Brown and Li [17] reported that the addition of food waste can increase the biogas yield, there has been no study of the utilization of corn cobs and food waste for co-digestion during SS-AD to produce biogas. In this study, we determined the effect of the TS and food-waste contents on biogas production from corn cobs by SS-AD. We also identified the appropriate kinetic model and analyzed the volatile solid (VS) content.

2. Material and Methods

Feedstock and inoculum. The corn cobs used in this study were obtained from a farm in Bantul, Yogyakarta, Indonesia. These corn cobs were dried in the open air and chopped into 2–3-cm lengths by a chopper, and then dried and stored at room temperature. The food wastes used as co-digestives, including rice, noodles, and vegetables were collected from canteens around the university campus in Yogyakarta, Indonesia. These food wastes were ground in a 1-L blender-food processor and then sealed in plastic bags. The bovine rumen fluid used as inoculum was obtained from a slaughterhouse in Yogyakarta, Indonesia.

Solid-state anaerobic digestion. The biogas production process was performed in 2-L batch digesters, into which corn cobs, food waste, and inoculum were fed at respective TS contents of 20%, 22%, and 24% with food-waste contents of 0%, 5%, 10%, and 20%. Water was added to adjust the TS content. We set the initial pH was to 7.25–7.31 by adding 2 N NaOH solution. All experiments were conducted at room temperature. The biogas volume was measured every two days using the water displacement method, as illustrated in Figure 1.

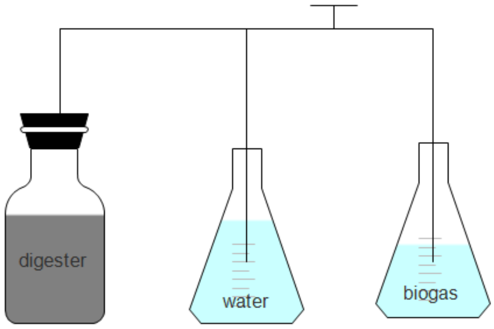

Figure 1. Schematic Showing Water Displacement Method

Analytical and statistical analyses. The biogas yield (mL/g VS) was determined based on the daily volumetric biogas divided by the initial mass of VS in the corn cobs. The VS content was determined using the standard methods of the American Public Health Association [18]. The samples were dried at 103–105°C for one hour in an oven, then cooled, weighed, and stored in desiccators until ready for use. The dried samples were incinerated in a furnace at 550°C for one hour, and were then cooled and weighed. This incineration, cooling, and weighing cycle was repeated until the resulting weight change was less than 4% or 50 mg. The method used to calculate the VS content is shown in Equation 1.

$$\% VS = \frac{A-D}{A-B} \times 100 \tag{1}$$

A = weight of dried sample and dish (mg)
B = weight of dish (mg)
D = weight of incinerated sample and dish (mg)

An analysis of variance was performed to determine whether the results were statistically significant, with a p-value of 0.05. $p < 0.05$ denoting a statistically significant difference, and $p > 0.05$ indicating no statistically significant difference [19–20].

3. Results and Discussion

Effect of TS content on biogas production. The effect of TS content on biogas production was analyzed by varying the TS content, i.e., 20%, 22%, and 24%. Figures 2(a) and 2(b) present the biogas volume as the daily and cumulative biogas yields for 30 days, respectively.

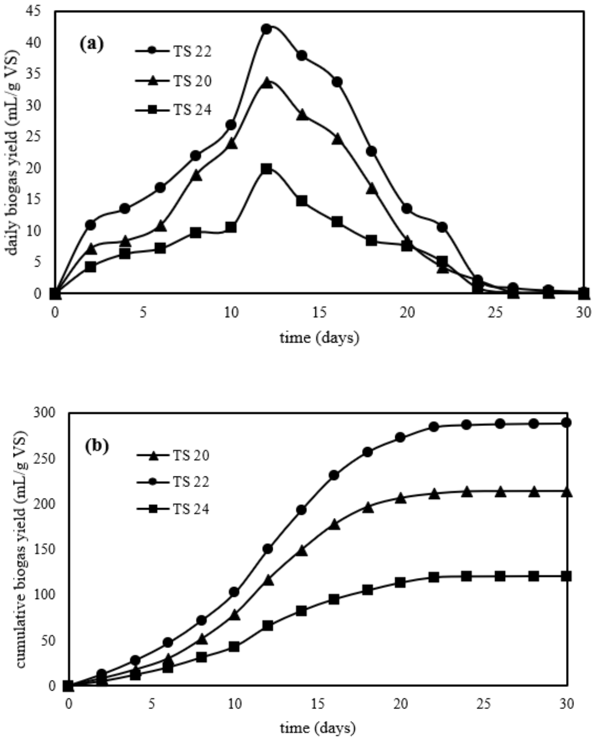

Figure 2. Biogas Yields at the Variation of TS Content: (a) Daily Biogas Yield; (b) Cumulative Biogas Yield

As shown in Figure 2a, the biogas yields began on Day 2 and then increased regularly until reaching peak values of 33.6 mL/g VS, 42.0 mL/g VS, and 19.74 mL/g VS on Day 12 at TS contents of 20%, 22%, and 24%, respectively. The biogas yields then decreased gradually from Day 14 to Day 30. In Figure 2b, we can see that the highest cumulative biogas yield of 288.03 mL/g VS was obtained at a TS content of 22%, followed by cumulative yields of 213.72 mL/g VS and 120.15 mL/g VS at TS contents of 20% and 24%, respectively. These results indicate that the TS content was associated with significantly different biogas yields ($p < 0.05$). A previous study conducted by Su *et al.* [21] reported that increasing the TS content had a positive effect on biogas production. Paritosh *et al.* [22] also reported that TS contents of 20% and 25% generated maximum yields, whereas an increase in the TS content beyond 25% had no significant effect on biogas production

The TS content of 22% produced a higher biogas yield than one of 20% because the higher TS content enables the microbes to degrade more substrates, which leads to a higher biogas production [23]. However, a TS content of 24% generated a smaller biogas yield than a TS content of 22% because too high a TS content can inhibit hydrolysis and limit the mass transfer between the microbes and feedstock, which reduces the hydrolysis product content and biogas conversion [24].

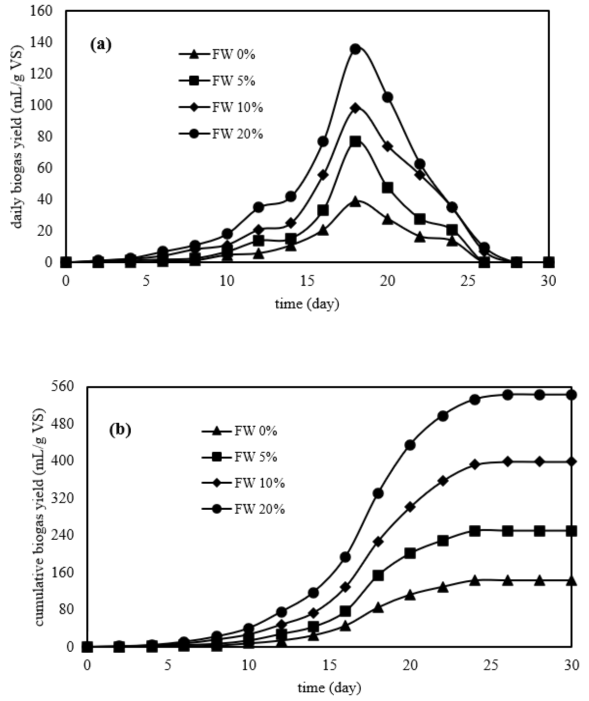

Figure 3. Biogas Yields at Different Food-waste Percentage (TS Content = 22%): (a) Daily Biogas Yield, (b) Cumulative Biogas Yield

Effect of food waste on biogas production. Next, food-waste percentages of 0%, 5%, 10%, and 20% were investigated to determine the effect of the food-waste content on biogas production. Figures 3(a) and 3(b) present the daily and cumulative biogas yields, respectively.

As shown in Figure 3a, biogas production started on Day 2 with daily biogas yields of 0.07 mL/g, 0.42 mL/g VS, 1.12 mL/g VS, and 1.4 mL/g VS for food-waste contents of 0%, 5%, 10%, and 20%, respectively. The biogas yields then increased slowly until reaching their peaks on Day 18, with maximum daily yields of 39.18 mL/g VS, 76.95 mL/g VS, 97.94 mL VS, and 135.72 mL/g VS at food-waste contents of 0 %, 5%, 10%, and 20%, respectively. The biogas yields then decreased gradually, with the lowest yields obtained on Day 30.

As shown in Figure 2b, the highest cumulative biogas yield of 543.08 mL/g VS was obtained at a food waste content of 20%, followed by cumulative yields of 399.26 mL/g VS, 250.34 mL/g VS, and 143.81 mL/g VS at food-waste contents of 10%, 5%, and 0%, respectively. The results of our statistical analysis show that the content of food waste had a significant effect on the biogas yield ($p < 0.05$).

A study conducted by Zahan *et al.* [25] reported that biogas production could be increased by 25% to 50% by the addition of 1%–5% food waste. A similar result was reported by Brown and Li [17], who found that an increase in the food-waste content from 10% to 20% increased the biogas yield. The highest reported biogas yield was obtained at a high food-waste percentage because the food waste used had a high protein content, which generates high biogas yield during protein degradation [26]. Food waste also has substantial nutrient contents that can enhance the degradability of microorganisms [27].

Volatile solid reduction. The VS reduction was calculated using Equation 2.

$$VS_{reduction} = 1 - \frac{VS_{output} \times (1 - VS_{input})}{VS_{input} \times (1 - VS_{output})} \qquad (2)$$

$VS_{reduction}$ = reduction in amount of volatile solids (%)
VS_{input} = amount of volatile solids input (%)
VS_{output} = amount of volatile solids output (%)

Figures 4(a) and 4(b) show the amount of VS reduction at various TS contents and food-waste concentrations, respectively.

As shown in Figure 4(a), the highest VS reduction of 30.5% was obtained at a TS content of 22%. With respect to the variation in TS content, the highest cumulative biogas yield was also obtained at a TS content of 22%. The presence of VS indicates the presence of organic material in the waste [28]. A greater the conversion of organic materials will produce a higher biogas yield, with the VS reduction proportional to the biogas yield, i.e., a higher VS reduction generates a higher biogas yield. Therefore, VS reduction has a linear relationship with the biogas yield.

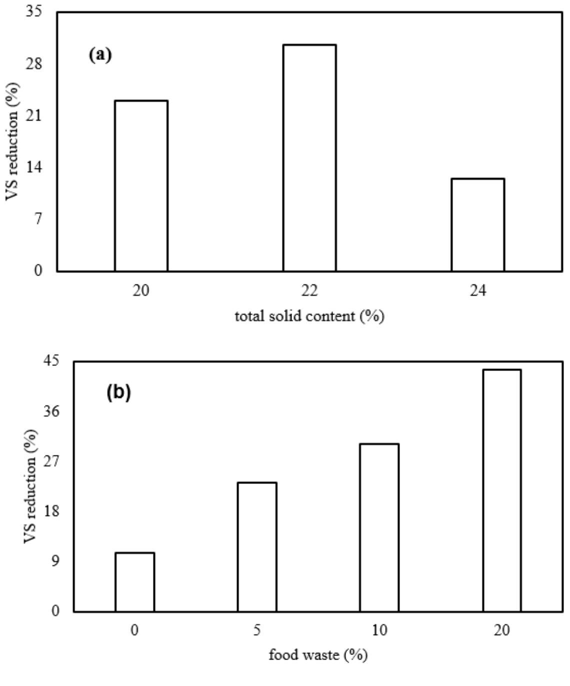

Figure 4. VS Reduction (%) During 30-day SS-AD of Food Waste and Corn Cobs: (a) Total Solid Content, (b) Food-waste Percentage

The same result is evident in Figure 4(b), with the highest VS reduction of 43.5% obtained at the highest biogas yield (food-waste content of 20%). A high VS reduction indicates that the microbes are able to digest the organic materials efficiently to produce a higher biogas yield. A study by Brown and Li [17] also reported that the highest VS reduction was obtained at the highest food-waste concentration.

First-order kinetic model. In this study, we assumed a first-order kinetic model, based on the hypothesis that hydrolysis becomes the rate-limiting step that controls the whole process and the availability of the substrate in anaerobic digestion [29]. This model is supported by studies of SS-AD, which have shown that biogas production decreases when the TS content is increased. This result is obtained because of a reduction in the hydrolysis rate, thus indicating that hydrolysis is a limiting factor [19]. The corresponding first-order kinetic model, which has been used by Liew *et al.* [8], Mirmohamadsadeghi *et al.* [30], and Brown *et al.* [31], is as follows:

$$ln\left(\frac{y_u}{y_u - y_t}\right) = kt \qquad (1)$$

where t (day) is time; y_u is the biogas yield obtained in 30 days (mL g^{-1} VS^{-1}); y_t is the biogas yield obtained at time t (mL g^{-1} VS^{-1}), and k is a specific rate constant (day^{-1}).

Table 1 lists the rate constants for biogas production.

Table 1. Rate Constants and Regression Values of Biogas Production From Corn Cobs And Food Waste

Parameter (%)		k (day^{-1})	R^2
Food waste	0	0.0478	0.9228
	5	0.0302	0.9170
	10	0.0846	0.9214
	20	0.1030	0.9234
Total solid	20	0.0146	0.9399
	22	0.1143	0.9458
	24	0.0814	0.9228

The k values are rate constants for biogas production, whereby a greater k value denotes a faster biogas production rate. As shown in Table 1, we obtained the highest rate constant at a food-waste content of 20% and a TS content of 22%. The higher is the food-waste concentration, the higher is the rate constant.

The obtained regression values ($R^2 > 0.90$) indicate that the production of biogas follows a first-order kinetic model [30]. As shown in Table 1, the regression values are larger than 0.90, which means biogas production from corn cobs and food waste follows a first-order kinetic model.

4. Conclusions

In this study, we found the total solids content (TS) and the percentage of food waste to have a significant effect on biogas production ($p < 0.05$). The obtained biogas yields were enhanced by an increase in the food-waste content. A food waste content of 20% produced the highest biogas yield of 543.08 mL/g VS at a TS content of 22%. A higher VS reduction generated a greater biogas yield. We found the VS reduction to have a linear relationship with the biogas yield. The SS-AD process involving the co-digestion of corn cobs and food waste follows a first-order kinetic model ($R^2 > 0.9$).

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