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Co-digestion of Sorghum Stalk and Sludge for Biogas Production

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Abstract

The recycling of residual agricultural biomass using anaerobic digestion allows for the recovery of biomass carbon and nutrients as sources of energy and fertilizer. The obstacles that are encountered in this process include the lignocellulosic structure of biomass tissue and its high carbon-to-nitrogen (C:N) ratio. This study evaluates the co-digestion system of pretreated sorghum stalks and wastewater sludge. The stalks were pretreated by partial bio-oxidation to improve their bacterial accessibility. The digesters were fed a mixture of stalk and sludge at ratios of 100:0, 80:20, 60:40, and 40:60 (total solids [TS] basis). The digesters were run in batches at 35-36 °C, with an initial TS of 15%. The digesters' performance was evaluated in terms of biogas production rate and yield. The digesters that were run with feed ratios of 80:20 and 60:40 showed shorter lag phase, higher biogas generation rates, and higher biogas yields compared to those run with feed ratios of 100:0 and 40:60. The highest specific biogas production (of 122 L/kg TS) was achieved by the digesters run at ratios of 80:20 and 60:40. The digesters run only with stalks (ratio 100:0) resulted in specific gas production of 67 L/kg TS, whereas those fed on a feed ratio of 40:60 generated only 13 L/kg TS. We conclude that the co-digestion of sorghum stalks and wastewater sludge at a proper ratio improves biogas production.

Abstrak

Pencernaan Campuran Batang Sorgum dan Sludge untuk Produksi Biogas. Daur ulang residu biomassa pertanian menggunakan pencernaan anaerobik memungkinkan untuk memanfaatkan karbon dan nutrisi dari biomassa tersebut sebagai sumber energi dan pupuk. Kendala yang dihadapi dalam proses ini meliputi struktur lignoselulosa biomassa dan nisbah karbon terhadap nitrogen (C:N) yang tinggi. Studi ini mengevaluasi sistem pencernaan campuran batang sorgum dan *sludge* penanganan limbah cair industri. Sebelumnya dilakukan perlakuan awal terhadap batang sorgum dengan bio-oksidasi parsial untuk meningkatkan aksesibilitas bakteri terhadap biomassa tersebut. Digester diberi umpan campuran batang sorgum dan lumpur pada nisbah 100:0, 80:20, 60:40, dan 40:60 (basis total padatan [TS]). Digester dioperasikan secara curah pada 35-36 °C, dengan TS awal 15%. Kinerja digester dievaluasi berdasarkan laju produksi dan volume biogas. Digester yang dioperasikan dengan rasio umpan 80:20 dan 60:40 menunjukkan fase adaptasi yang lebih pendek, laju generasi biogas yang lebih tinggi, dan volume produksi biogas yang lebih tinggi dibandingkan dengan hasil yang diperoleh dari digester yang dioperasikan dengan rasio umpan 100:0 dan 40:60. Produksi biogas spesifik tertinggi (122 L/kg TS) dicapai pada digester yang dioperasikan pada nisbah 80:20 dan 60:40. Digester yang dioperasikan dengan umpan batang sorgum saja (nisbah 100:0) menghasilkan produksi biogas spesifik 67 L/kg TS, sedangkan yang diberi umpan dengan nisbah 40:60 hanya menghasilkan 13 L/kg TS. Disimpulkan bahwa pencernaan campuran batang sorgum dan *sludge* pada proporsi yang tepat meningkatkan produksi biogas.

Keywords: agricultural biomass, biogas, bio-oxidation, co-digestion, sludge, sorghum stalk

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Introduction

The availability of agricultural biomass in large quantities represents a potential source of feedstock for renewable bioenergy production, especially biogas [1]. The current global trend indicates that there is growing concern about the use of organic materials for biogas production. Several studies have indicated that the conversion of organic materials into energy occupies the highest priority in the management and handling of organic waste, due to the increasing scarcity of fossil fuels [2-3]. In Indonesia, a large proportion of residual agricultural biomass is currently underexploited; in most cases, it has even become a burden to the environment because it is often treated improperly by burning or being left to decompose without proper controls.

Land-based agricultural biomass and marine biomass [4-5] can actually be hydrolyzed into short-chain carbohydrates, either chemically or microbiologically. The products of hydrolysis can then be fermented into methane (as the main constituent of biogas) or bioethanol. Because creating the latter involves a more complex process and is less cost-effective, the conversion into biogas methane is a more strategic choice [6-7].

Agricultural biomass, despite containing highly degradable organic matter, has intrinsic characteristics of high lignocellulose and high carbon:nitrogen (C:N) ratio, and deficiency in macro- and micro-nutrients, all of which often result in sub-optimum anaerobic decomposition [8-9]. The mixing of two or more types of biomass in a single digester system ("co-digestion") can increase methane yields and can improve digester stability. In addition, co-digestion is considered to be a better method of waste management, because it enables a wider spectrum of biomass to be fed to anaerobic digesters, thus improving its economy of scale.

The key reason for the success of the co-digestion system is the balanced composition of mixed biomass. Nutrient balance, proper C:N ratio, and stable pH are prerequisites for good digester performance. An overly high C:N ratio causes a shortage of nitrogen, whereas an overly low C:N ratio may lead to ammonia toxicity. With co-digestion, the nitrogen deficit in one biomass will be balanced by a nutrient-rich biomass, whereas ammonia toxicity will be diluted by the high-carbon biomass. Researchers have reported on several successful co-digestion systems using various mixtures of biomass. For example, Komatsu *et al.* [10] reported that a mixture of a fraction of organic solid waste and hotel waste with garden and paper wastes was successfully operated in stable conditions using dry thermophilic digesters, with biogas production of 820 m^3/ton volatile solids (VS). Li *et al.* [11] reported that mixed oil and food wastes (fruits, vegetables, meat/fish, and carbohydrates) with 40% total solids (TS) oil content was degraded at more than 85% oil removal, producing 60–65% methane at an organic loading rate of 20 kg COD (chemical oxygen demand) /m^3/day (hydraulic retention time [HRT] 15 days, mesophilic).

Although current research on agricultural biomass conversion to biogas remains limited, there have been indications of its high potential applications [12] [13]. Recovery rates of 180–940 L of biogas per kg of TS might be achievable, depending on the type of substrate used. For example, chopped rice straw could be converted into 250–350 L biogas per kg of TS [14]. Gurung *et al.* [4] reported that a cumulative CH_4 production of 256 ± 28 and 179 ± 35 L/kg VS could be obtained from the use of green and brown algae, respectively, after 60 days of fermentation processing.

This research work investigates the co-digestion of sorghum stalks with sludge from a slaughterhouse effluent treatment plant. The work is based on our earlier work with rice straw, and the pretreatment of biomass by partial bio-oxidation-enhanced biogas rate and yield [15]. The biological method was preferred due to its low energy requirement, low costs, and simplicity [16] [17]. Pretreated stalks were therefore used in co-digestion with sludge in this work. The specific objectives of this work include the evaluation of the effect of co-digestion on digester performance, and the determination of sorghum stalk–to–sludge ratio for optimum biogas production.

Materials and Methods

Materials. The stalks of 70-day-old sweet sorghum (*Sorghum bicolor* L) were used for the study. The sludge was obtained from a slaughterhouse effluent treatment plant. A commercial inoculum of effective microorganisms (Biofarm®) was used in the bio-oxidation process; it contained photosynthetic bacteria *Rhodopseudomonas* spp., *Lactobacillus* spp., *Saccharomyces* spp., *Actinomycetes*, *Aspergillus*, and *Penicillium*. Cattle manure was used to seed the digester.

Equipment. A 20-L composting bin made of plastic was used for the stalk pretreatment. A set of 8 units of 500-mL Erlenmeyer flasks was used as digesters. These flasks were put in a thermostat shaker water bath operated at 35–36°C; each was connected with tubing to a 1-L measuring cylinder used for measuring gas production by the liquid displacement method.

Experiments. The stalks were chopped to roughly 1 cm in size to enhance their substrate accessibility during bio-oxidation and digestion [18] [19]. Bio-oxidation was carried out in the composting bin by adding 1 mL Biofarm®/kg biomass, adjusting it to 80% moisture, and allowing it to incubate for 9 days. Temperature and pH were monitored daily. The co-digestion of pretreated stalks with sludge was conducted at 4 different stalk-to-sludge ratios, namely 100:0 (stalk only), 80:20, 60:40, and 40:60 (TS basis). Each digester was fed with a 300 g mixture of stalk, sludge, and seed (10%), and were adjusted to an initial TS of 15%. Digestion was carried out in batches for roughly 100 days, with two replicates; biogas production was monitored daily. Four units of smaller digesters (100-mL Erlenmeyer flasks)—each filled with 60 g of feed at a ratio 60:40, and operated at the same conditions as the larger digester—were prepared for analysis (biweekly) of digestate and leachate during digestion. The analysis of biomass, digestate, and leachate (moisture, TS, VS, ash, total Kjeldahl nitrogen [TKN], and COD) followed the standard method of the American Public Health Association (APHA) [20-21]. The leachate's volatile fatty acids (VFAs) were determined using GC

Chrompack 9002 with FID detector and column WCOT-fused silica 25 m x 0.32 mm ID coating FFAP-CB. The temperatures of the column, injector, and detector were 115 °C, 270 °C, and 270°C, respectively. Nitrogen and hydrogen were used as the carrier gases. Sulfo-5-salicylic acid and rumen VFA (Supelco) were used for sample preparation and standards.

Results and Discussion

The characteristics of sorghum stalk, wastewater sludge, and digester feed at different stalk-to-sludge ratios are shown in Table 1. Fresh stalk contained 72.6% total solids, most of which were degradable, and only 0.2% TS of organic nitrogen. In contrast, the sludge contained 12.6% total solids, with 76% ash and 1.7% TS of organic nitrogen.

Partial bio-oxidation of sorghum stalk. The use of effective microorganisms should speed up the bio-oxidation process. Heat is generated as a by-product of the breakdown of organic materials, and therefore temperature is one of the key indicators in bio-oxidation. As shown in Figure 1, the process temperature rose from 28°C to 30.5°C within 2 days. As readily decomposable organic matter became depleted, the temperature began to drop. The level of temperature elevation depends on the material's composition, moisture, and size. Given the relatively small size of the bins that were used, higher temperature rises were unlikely to occur.

Microbial activity was also indicated by a decreased pH (from 6 to 4.5) within two days. During the initial stage of decomposition, organic acids were formed, which led to acidic conditions. These acidic conditions were favorable for the growth of fungi and the breakdown of lignin and cellulose. The pH started to increase again as the organic acids became neutralized.

An analysis of the pretreated biomass showed that partial bio-oxidation did not significantly alter the TS or VS content, but did significantly reduce TKN from 0.5% to 0.2%. During bio-oxidation, organic nitrogen is decomposed to ammonium, which can be further oxidized to nitrite and nitrate, thereby decreasing TKN. Another explanation is the possibility of losing ammonia, especially at high pH. Nevertheless, the main purpose of the partial bio-oxidation was to alter the lignocellulosic structure of the biomass so that it would become more open and porous, thus allowing anaerobic bacteria to gain access to the substrate.

Effect of sorghum stalk–to–sludge ratios on digester performance. As shown in Table 1, the TKN and ash contents increased in the digesters that were fed with a higher proportion of sludge. Figure 2 shows the effect of

Table 1. Characteristics of Sorghum Stalk, Sludge, and Different Ratios of Digester Feed

	Value			
	pH	Total solids (TS) (%)	Volatile solids (VS) (%)	Total Kjeldahl nitrogen/TKN (%)
Sorghum stalk		72.6 ± 0.1	69.6 ± 0.2	0.12 ± 0.02
Sludge		12.57 ± 0.02	3.0 ± 0.2	0.21 ± 0.01
Feed ratio 100:0	7.2	14 ± 2	13 ± 2	0.04 ± 0.02
Feed ratio 80:20	7.3	13 ± 1	11 ± 1	0.04 ± 0.01
Feed ratio 60:40	7.3	13.6 ± 0.6	10.5 ± 0.1	0.05 ± 0.00
Feed ratio 40:60	7.2	13.5 ± 0.7	10.0 ± 0.3	0.05 ± 0.00

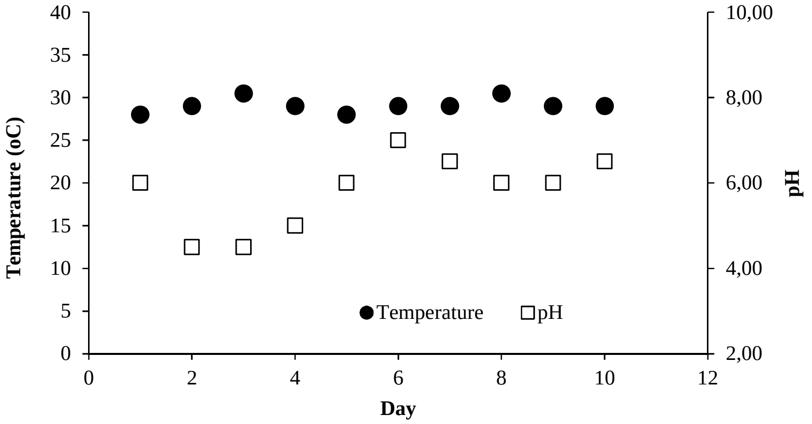


Figure 1. Temperature and pH during Bio-oxidation

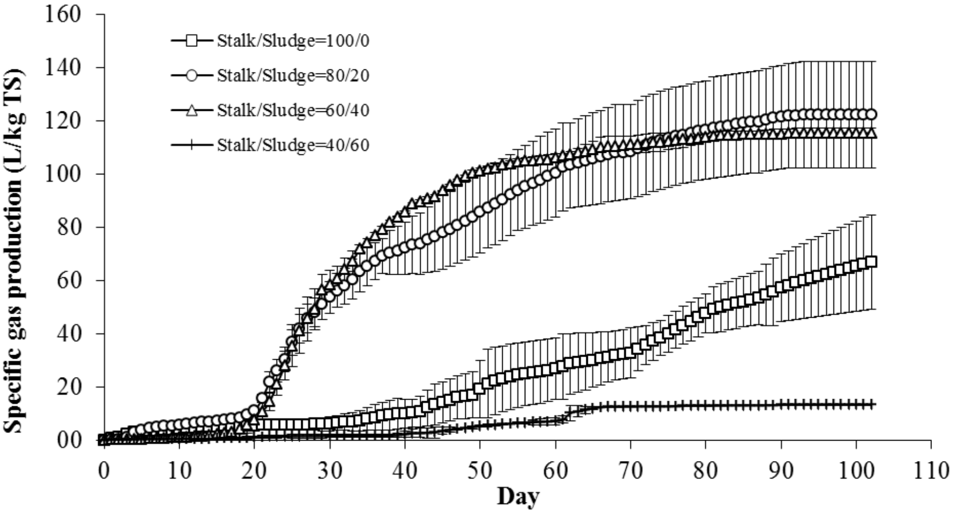


Figure 2. Effect of Co-digestion on Biogas Production

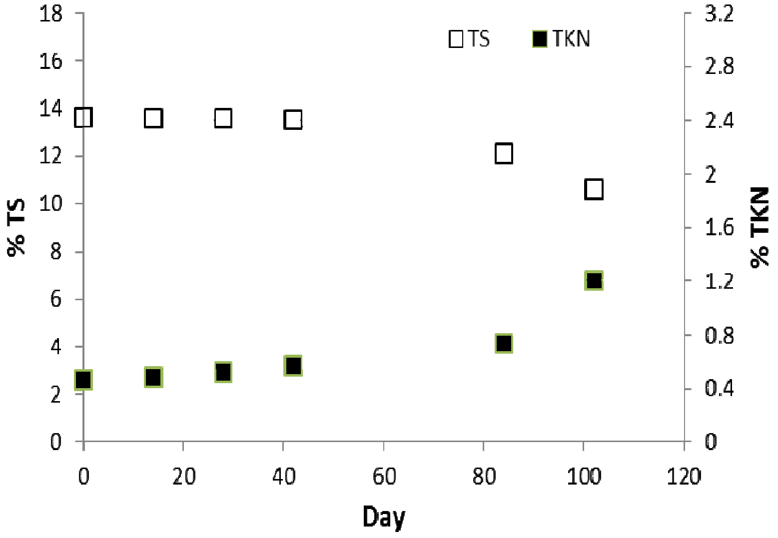
co-digestion at different stalk-to-sludge ratios on biogas production throughout the digestion period. As shown in the figure, the feed composition affected biogas production rates, as well as biogas yields. The error bar on the graph indicates the level of uncertainty, which was at the 95% confidence level.

All treatment ratios showed that lag phase existed, during which biogas generation was at a minimum. The digesters that were fed solely on stalk (ratio 100:0) showed a lag phase of around one month, later followed with gradual increases of biogas production throughout the digestion process. The cumulative specific biogas production at day 102 was 67 L/kg TS, but (as the graph indicates), higher values could be expected if the digestion period was extended. Feed ratios of 80:20 and 60:40 clearly demonstrated the significant effects of co-digestion on biogas production. The lag phase for both treatments was the shortest (about two weeks). In the case of feed ratio 80:20, the lag phase was followed by a sharp increase in biogas production, from 7 L/kg TS on day 14 to 104 L/kg TS on day 63. It continued to increase until day 90, and reached a maximum of 122 L/kg TS. The digester that was run on feed ratio 60:40 produced a similar biogas generation profile of that run at an 80:20 ratio. The biogas production increased very sharply, from 11 L/kg TS at the end of the lag phase to 108 L/kg TS on day 63. As noted, the slope of the biogas rate was even higher compared to the digester that was fed on ratio 80:20. Biogas generation continued at a slower rate until day 80, and reached a maximum of 115 L/kg TS. Although slight differences in biogas rate and maximum yield for both digesters were noted, they were not statistically significant. The digester that was run on feed ratio 40:60 resulted in poor digester performance. After a very long lag phase of 40 days, biogas was detected at 7 L/kg TS on day 56, followed by very slow development to a maximum of 13 L/kg TS on day 63.

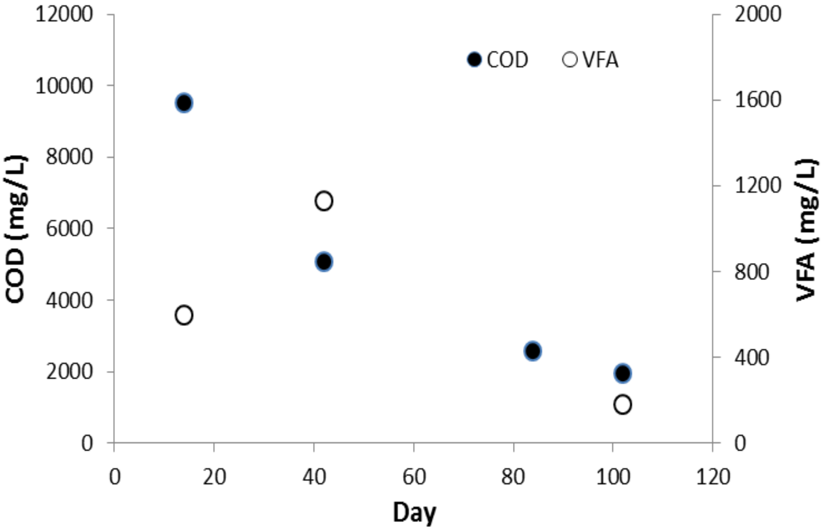
These results demonstrated that the co-digestion system of sorghum stalk with sludge affected the total production of biogas and its rate of generation. The stalk-to-sludge ratios of 80:20 and 60:40 led to improved digester performance in terms of shorter lag phase, higher biogas generation rate, and biogas yield. This improvement was primarily due to better substrate composition (especially C:N ratio), but the better supply of trace elements provided by the sludge might also have made an important contribution to the improvement.

Evaluation of digester run on stalk-to-sludge ratio 60:40. As shown in Figure 3a, TS decreased from 14% in feed to 10.6% in the final digestate. Since fermentation reduced a large amount of carbon and a lower amount of nitrogen, decreases in TS consequently led to higher TKN in the final digestate, from 0.46% to 1.2%. During anaerobic digestion, nitrogen tends to stay in digestate form. The loss of nitrogen is minor, particularly when ammonia escapes from the digester at high pH, whereas carbon removal can attain levels above 50%.

As shown in Figure 3b, the high COD of leachate (9,500 mg/L) was noted in week 2. COD then decreased to 1,100 mg/L at the end of digestion, in parallel with biogas generation. High-leachate COD in the beginning of digestion was due to the formation of soluble monomers (such as sugars and amino acids) from the hydrolysis of organic polymers, as well as the formation of acidogenesis products (such as lactic acid). This was clear, as the graph indicated that the corresponding VFA was still low. Higher concentrations of VFA were then



(a)



(b)

Figure 3. Changes in Digestate (a) and Leachate (b) Characteristics during Fermentation (Feed Ratio 60:40)

noted in week 4, thus indicating that acidogenesis and acetogenesis were starting to produce more VFA. Similarly to COD, VFA was then decreasing alongside biogas production. Table 2 shows the species of VFA that were detected in the leachate, namely acetate, propionate, butyrate, and valerate. VFA species other than acetate must first be converted to acetate in order for methanogenic bacteria to use it for methane production. As shown in the table, the value of VFA species other than acetate was thus usually at a minimum at later stages of digestion.

A decrease in pH from 7.3 to 7 was noted only in the first two weeks of digestion; a higher pH of 8 was observed throughout the rest of fermentation. Because

Table 2. VFA and pH of Leachate During Fermentation (Ratio 60:40)

	Concentration (mg/L)		
	Day 14	Day 42	Day 102
pH	8	8	8
Total VFA	599.6	1130	182.1
▪ Acetate	299.1	305.3	107.6
▪ Propionate	116	633.4	58.1
▪ iso-Butirate	20.3	13.9	1.0
▪ n-Butirate	65.6	62.2	3.5
▪ iso-Valerate	36.3	64.9	5.9

methanogens remain active within pH 6.5–8.5 [22], the digesters were still within optimum conditions for biogas production. This relatively constant pH was probably due to the high internal buffering of ammonium bicarbonate as a result of organic nitrogen decomposition.

Overall, the level of solids removal was only 25%, with maximum biogas production of 122 L/kg TS. This value of biogas production is still low compared to the reported value for similar substrates of 180–940 L/kg TS [14]. Other than feed composition, the design and configuration of the digester, as well as its operating conditions, affect digester performance. In order to improve the substrate removal efficiency, similar experiments conducted on larger-scale digesters (10 L capacity) with leachate recirculation are now being conducted.

Conclusions

The co-digestion system of sorghum stalk with sludge affected the total production of biogas and its rate of generation. The stalk-to-sludge ratios of 80:20 and 60:40 led to improved digester performance in terms of shorter lag phase, higher biogas generation rate, and biogas yield. This improvement was primarily due to better substrate composition (especially C:N ratio), but the better supply of trace elements provided by the sludge might also be an important contribution. The level of solids removal was only 25%, with a maximum biogas production of 122 L/kg TS. This value of biogas production is still low compared to the potential values. Other than feed composition, the design and configuration of the digester, as well as its operating conditions, affect digester performance. A co-digestion system with leachate recirculation is expected to improve both substrate removal efficiency and biogas yield.

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