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UTILIZATION OF FRUIT WASTE AS BIOGAS PLANT FEED AND ITS SUPERIORITY COMPARED TO LANDFILL

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ABSTRACT

Fruit waste is a part of municipal solid waste which is typically disposed of directly to a landfill site. In order to utilize this valuable renewable resource, anaerobic biological processes can be employed to convert fruit waste to biogas. This usable gas is then used to generate electricity. This paper describes a comprehensive study to set up technology for converting fruit waste to electricity via biogas production. First, the fruit waste characteristics (type and composition) were systematically evaluated, and then laboratory experiments for biogas conversion to explore gas production from the waste were carried out. The biogas plant was then designed, based on the information obtained. Finally, a comparison of biogas plant with landfill was performed using life cycle assessment (LCA) to determine environmental impacts, and economic evaluation to assess daily processing costs. The results from waste characterization in one of the biggest fruit markets in Indonesia showed that the three main component fruit types were orange (64%), mango (25%), and apple (5%). Rotten fruit contributes up to 80% of the total waste in the fruit market. Based on the experimental work, the potential gas production in the biogas plant was calculated to be approximately 1075 Nm^3/day, comprising 54% methane, based on 10 tons per day of fruit waste. The comparison demonstrates that it is a better option to utilize fruit waste in a biogas plant, in terms of LCA and daily operational costs, than to dispose of it in landfill.

Keywords: Biogas power plant; Life cycle assessment; Municipal solid waste; Waste management

1. INTRODUCTION

Increasing solid waste accumulation and diminishing non-renewable (fossil) energy sources are two major issues in sustainable development (United Nation Environment Programme, 2015). As the fourth most populous country in the world, Indonesia has been concerned to tackle the problem due to the high amount of waste discharge it produces (64 million tons annually, 2008)

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and its energy demands (210 TWh, 2016) (Rawlins et al., 2014). These issues are of interest to many parties, including government, the private sector, and higher education institutions. Each of these parties has put significant efforts into providing solutions for these issues, for example by preventing or minimizing solid waste production, and at the same time finding new resources for energy supply. Fortunately, it is already known that energy can be produced by utilizing solid waste as a raw material. Various processes and technologies have been developed for converting waste into energy, their specifics depending on the amount and characteristics of the waste used (Holmgren & Henning, 2004; Raspin, 2008; World Energy Council, 2016).

One way to utilize waste in creating energy is converting it into biogas (biomethane) through anaerobic digestion. This process provides energy and at the same time delivers benefits for the environment. Anaerobic biological treatments for methane production from the organic fraction of municipal solid waste have been commonly employed. A number of studies and field applications on have been reported utilizing fruit and/or vegetable waste to produce biogas (Ranade et al., 1987; Gunaseelan, 2004; Davidson et al., 2007; Ozmen & Aslanzadeh, 2009; Scano et al., 2014; Basaria & Priadi, 2017).

The use of methane from the biodegradation of solid waste as an important energy source has been applied in a number of countries (Holmgren & Henning, 2004; Afvall Sverige, 2014; World Energy Council, 2016). However, it is well known that the technology and processes cannot be applied directly in some other societies or countries, despite the quite lengthy experience of some countries in the utilization of waste for energy. This is mainly due to the character of waste, local habits, social structures and other differences.

This paper describes a step-by-step process for the adoption of technology to convert organic waste to energy through anaerobic digestion. The focus is on utilization of rotten fruit in Gemah Ripah traditional wholesale market located in Yogyakarta, Indonesia, for producing biogas which is then used to generate electricity. Gas and electricity production is conducted in a pilot scale biogas power plant which was set up by Universitas Gajah Mada, Indonesia and the University of Borås, Sweden. The projects involved local government and private sector partners.

Many studies have been conducted preparing, designing, and optimizing biogas plants (Nurrihardini, 2009; Cahyari & Putra, 2009; Palestine, 2010; Amelia, 2010; Widodo, 2010; Hardiyanti, 2010) and the results of these are summarized in this paper. Waste characterization, the potential of fruit waste-to-biogas processes and power plant design are described in detail. Furthermore, the advantages of the utilization of fruit waste in the biogas plant are evaluated and compared with traditional systems of disposal to landfill sites, by using LCA and economic evaluation.

2. EXPERIMENTAL METHODS

2.1. Characterization of Feed Material

The first step of the study was to identify the amount and composition of waste produced by the fruit market. The total waste produced daily was collected for a period of one year and was fractioned based on dominant types of waste. The composition was evaluated based on percent solids on wet basis. Analysis of fruit waste properties was conducted to determine moisture content, dry matter and volatile solids.

2.2. Laboratorial Experiment

Cattle dung was used as the inoculum for the biodigestion process. The feed material used for laboratory experiments was mango, which is the second most commonly found fruit in waste from the Gemah Ripah Fruit Market. In this study, the peel and flesh of the mango was chopped using an electrical blender and mixed with vegetable matter which was also chopped prior to mixing. The composition of fruit and vegetable was selected to obtain the required optimum carbon to nitrogen ratio (25:30), according to research carried out by Mshandete et al. (2006).

Experiments were conducted in a series of 150 ml digesters operated in batch mode. Each digester was filled with a measured weight of solid sample (mixture of mango and vegetable) and mixed with a measured volume of water to obtain a particular amount of volatile solids (VS) in the mixture. Other digesters were subject to the same treatment for different amounts of VS. All samples in the digesters were inoculated with material from a running biogas unit. The digesters were flashed with nitrogen gas, closed with rubber lids, and incubated at 35°C. The sample volume of gas produced from each digester was taken using a measuring syringe, and analyzed using gas chromatography to determine the gas composition.

2.3. Life Cycle Assessment (LCA) Study and Financial Aspects of the Biogas Plant

LCA was employed to study the environmental impact of fruit waste utilization in the biogas plant and the landfill for the district of Yogyakarta. The systems used in the LCA of the biogas plant are limited to the handling of the fruit in the market until it is processed in the biogas plant and the gas is converted to electricity. In the case of the landfill, the systems are restricted to collection and transportation of the fruit waste from the market to the dump site and processing in the landfill site. The system boundaries for both schemes are shown in Figure 1a (biogas plant) and Figure 1b (landfill).

A time span of two weeks was used for the study. The flow schemes include the inputs of water, energy, and raw materials and outputs released to air, land, and water. The required data for each step is gathered and applied to the correct functional unit.

The daily processing costs were calculated in order to obtain an evaluation of cost and benefits when processing fruit waste. There are two scenarios: utilizing fruit waste in the biogas plant, and dumping fruit waste in the landfill site.

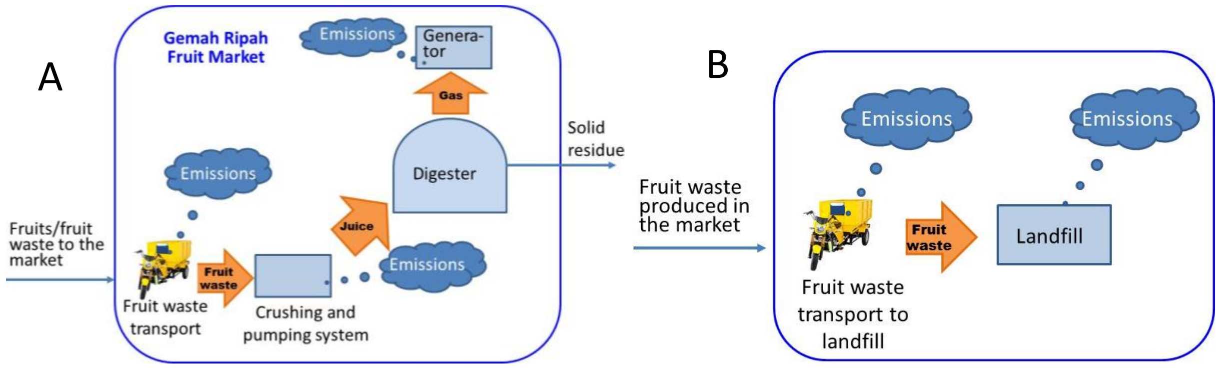

Figure 1 Graphical abstract for system boundaries of the LCA study in the case of fruit waste for the biogas plant (A) and fruit waste treated in the landfill site (B)

3. RESULTS AND DISCUSSION

3.1. Waste Characterization

Waste properties such as type of waste and its composition are important factors in determining biogas potency. Such information provides the basis for making an estimation of the amount of biogas that can be produced from a certain quantity of raw material. Based on the data provided by the legal authority of the market, waste characterization was carried out. First, the amounts and types of fruit were identified. It is suggested that the volume of incoming fruit to the market is quite changeable from month to month because of seasonal fruit production. The minimum and maximum peak volume of incoming fruit was 1000 and 11000 tons per month, respectively. The composition of fruit was evaluated from a one-year survey, and the mean values obtained (percent solids on wet basis) are summarized in Table 1.

Table 1 Composition of fruit waste in the Gemah Ripah Fruit Market

No	Waste	Average weight (kg/month)	wt%
1	Orange	3,695,000	64.70
2	Mango	1,410,000	24.70
3	Apple	288,000	5.00
4	Pineapple	114,000	2.00
5	Watermelon	70,000	1.20
6	Melon	45,000	0.78
7	Others	90,000	1.60
	Total	5,712,000	100.00

It can be observed from Table 1 that the major components are orange (65%), mango (25%), apple (5%), pineapple (2%) and watermelon (1.2%). The composition of rotten fruit was therefore assumed to be the same as the composition of incoming fruit to the market.

The waste production in the fruit market varied in the range of 4 to 20 tons per day, depending on the season. The composition of the fruit market waste is shown in Table 2 based on 10 tons per day of waste. The majority (80%) was fruit waste, with the rest being packaging materials such as rice straw, leaves, wood, fabrics, and plastics. To gain more general information about the biogas potential, characteristics of moisture, ash content and VS of the fruit were evaluated. The results showed that the fruit waste contained 88.4% moisture, 11.5% VS and very little ash content. The fact that a high moisture content is present is beneficial when processing the fruit as biogas feedstock. Based on a theoretical calculation, potential gas production based on 10 tons per day of fruit waste was approximately 1075 Nm^3/day.

Table 2 Composition of waste of the Gemah Ripah Fruit Market

No	Waste	Mass (kg/day)	wt%
1	Fruit waste	8,013	80.13
2	Rice straw	652	6.52
3	Leaves	325	3.25
4	Wood	10	0.10
5	Fabrics	735	7.35
6	Plastics	265	2.65
	Total	10,000	100.00

3.2. Biogas Conversion from Fruit Waste at Laboratory Scale

The results of the laboratory scale experiments for potential gas production are shown in Figure 2. Data presented for each percentage of VS was the product of the average of three replicates. Figure 2 shows that the experiment with VS of 1.5% resulted in the highest volume of gas production: 147 ml/g VS. Overall, significant gas production was observed until day 30, at which point it slowed down. After day 40 there was no further gas produced. This incubation period data provides important information as the basis for designing the commercial process.

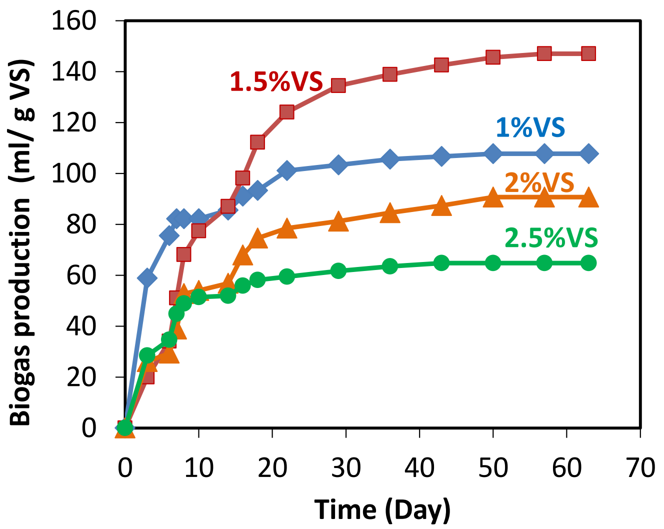

Figure 2 Production of gas from a mixture of mango fruit and vegetable with various percentages of VS

3.3. Biogas Power Plant

There is an extreme fluctuation in the amount of fruit waste production in the market, ranging from 4 to 20 tons per day. It was therefore decided that a specific amount of waste of 4 tons per day would be selected for the biogas plant design. This would result in 0.6 tons per day of dry matter from rotten fruit with a moisture content of approximately 85%. The biogas production of the biogas plant is 269 Nm^3/day VS and 0.427 Nm^3/kg VS. The biogas is converted in a generator for eight hours per day, producing 733 kWh electricity. Figure 3 shows the designed process flow diagram of the biogas plant utilizing the fruit waste.

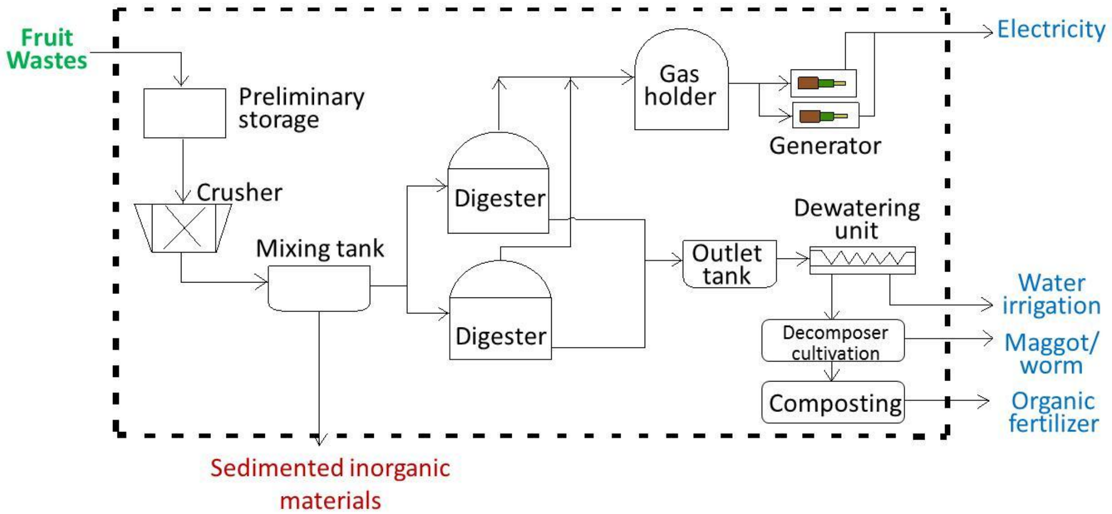

Figure 3 Process flow diagram of biogas plant

The anaerobic digestion process of the fruit market waste is carried out in a digester (150 m^3 total volume) for about 43 days with sufficient water to keep an optimum percentage of total solid (TS), to dilute volatile fatty acids and to avoid inhibition in a mesophilic condition (T=35ºC–37ºC). Once the retention has been fulfilled, biogas will be generated in the top of the digester consisting of methane (CH_4), carbon dioxide (CO_2), and small amounts of H_2S, impurities, and others. The biogas is then compressed and stored in a biogas holder and delivered to the generator for producing electricity for the market's consumption. Residual sludge may be used as organic fertilizer and/or nutrient for fish. The liquid residue, which is rich in organic matter, is conducted to irrigation systems for farming areas near the plant, or is pumped back to the biodigester if the TS concentration becomes too high.

3.4. LCA Study Comparing Fruit Waste as Biogas Feed with Dumping in a Landfill Site

LCA was conducted to evaluate and compare the impact of fruit waste on the environment when used as biogas plant feed or when dumped in a landfill site. The processes involved include collecting, transporting, and processing the rotten fruit into biogas and then into electricity. Every process has input and output flows which contribute to environmental change. In order to determine which option has less impact on the environment, the total emissions and global warming potential (GWP) of biogas production and landfill dumping were assessed. The assessment basis was 4 tons per day of rotten fruit as the designated feed capacity of the biogas plant. The total emissions of the biogas plant and the landfill are 237 kg and 565 kg, respectively. The major component of the emissions of both schemes is carbon dioxide (CO_2). While CO_2 emissions of 561 kg result from the landfill process, the biogas plant produces only 232 kg of CO_2. However, the biogas plant has a higher energy consumption (258 kWh) than landfill (162 kWh) when processing 4 tons per day of fruit waste, since the plant utilizes a variety of equipment during the preparation of the biogas feed juice. GWP quantifies the contribution of a certain amount of greenhouse gas to global warming. The biogas plant showed a lesser impact (50% with respect to landfill) in terms of global warming, with total GWP of 350.

The impact assessments were evaluated based on three categories: acidification, human health, and climate change/terrestrial. The data from the impact assessments for both schemes are provided in Table 3.

Table 3 Impact categories obtained from the LCA study

Impact category		Biogas plant	Landfill
Acidification (SO_2 eq)	NO_2	1.13×10^{-2}	3.94×10^{-1}
	Sulphur	1.88×10^{-5}	0.00
Human health (DALY)	CO_2	3.24×10^{-4}	7.86×10^{-4}
	NO_2	6.18×0^{-6}	2.16×10^{-4}
	CH_4	1.59×10^{-4}	1.02×10^{-4}
Climate change: terrestrial (PDF)	CO_2	1.8×10^{-6}	4.5×10^{-6}
	NO_2	3.5×10^{-8}	1.2×10^{-6}
	CH_4	9.0×10^{-7}	5.8×10^{-7}
	Sulphur	9.0×10^{-7}	0.00

The acidification criterion for the biogas plant (1.1×10^{-2}) is considerably lower than for landfill (3.94×10^{-1}) indicating a lesser effect on the acidification of the environment. The human health category shows the effect of climate change on human health through the disability-adjusted life year (DALY) measurement. While the total impact on human health for the biogas plant is 4.9×10^{-4} DALY, the human health impact for the landfill is a factor of 2.2 times higher, indicating a much larger impact on human health. The outcome in terms of climate change/terrestrial impact for the two options is as follows: the biogas plant shows 2.8×10^{-6} potentially disappeared fraction (PDF) and the landfill exhibits 6.3×10^{-6} PDF. This corroborates the two criteria aforementioned, showing that the biogas plant has a lesser impact than dumping in landfill.

Finally, the daily processing cost of fruit waste was evaluated. These costs were calculated by adding up all the daily costs of processing 4 tons of fruit waste per day and then dividing down the monthly and annual costs (fuel, staff costs and dumping permissions) to derive a daily equivalent and combining these two costs. In terms of these costs, the following conclusion can be drawn: the biogas plant is a better method of processing 4 tons of fruit waste because it has a daily processing cost of 246,450 IDR and can sell the produced electricity at a profit of 2,414,550 IDR. The landfill option shows higher processing costs, at 335,720 IDR for 4 tons of fruit waste. The overall conclusion is that the biogas plant is the better choice both for the environment and in terms of daily processing costs.

4. CONCLUSION

A comprehensive study to set up a biogas power plant utilizing fruit waste as feedstock was carried out. From the waste characterization, the three main components of fruit waste in Gemah Ripah Fruit Market, Yogyakarta, were orange (64%), mango (25%), and apple (5%) and these rotten fruits contribute 80% of the total waste of the market. Laboratory scale experiments utilizing fruit waste and vegetable matter for biogas production showed that the optimum production of gas was obtained with volatile solids of 1.5% of the mixture of mango and vegetable (147 ml/g VS). Based on this design and calculation, gas production for 10 tons per day of fruit waste was calculated as approximately 1075 Nm^3/day with 54% methane, which could be converted into electricity in a biogas power plant. From the LCA study, the impact of the biogas plant on the environment is found to be less than landfill disposal. Furthermore, when evaluating the financial aspects of processing waste to produce electrical energy, utilizing waste for the biogas plant is more efficient compared to the cost of processing the waste in landfill.

5. ACKNOWLEDGEMENT

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