Assessment of environmental, energy and economic prospective of anaerobic digestion of organic municipal solid waste in Malaysia

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Abstract. The continuous increase in population, higher living standards and economic development resulted in the inevitable increase of waste generation, energy consumption, carbon emissions and environmental degradation. The current average operating expenditure (OPEX) of a landfill is RM148/tonne/day for disposing municipal solid waste (MSW) which is an economic burden to the government. Thus, this study investigates the feasibility of biogas production from organic MSW as a renewable source of energy via anaerobic digestion. The economic and environmental benefits including the sales of electricity and fertilizer were investigated. Organic fraction municipal solid waste (OFMSW) was collected at Sahom landfill, Kampar. Waste composition was analyzed to determine the percentage of organic waste. Approximate and ultimate analysis were conducted to characterize the organic samples and to measure the calorific value. The biogas and bio-fertilizer yield were estimated. It was found that OFMSW consists 45% of the total MSW. Conversion of OFMSW to electricity and fertilizer via anaerobic digestion (AD) resulted in 3,274,812.51 m³/day of biogas which consists of 56.62% CH₄ and 43.38% carbon dioxide. This can be resulted in 7,494.08 MWh/day of electrical energy and a daily yield of 13,013.73 tonnes of bio-fertilizer. This transforms the economic burden of solid waste management expenditures into an income generating movement.

Keywords: Organic Waste, Anaerobic Digestion, Bio-energy, Bio-fertilizer, Environment, Feed-in-Tariff (FiT).

1. Introduction
The “Anthropocene” is a term introduced by Crutzen and colleagues since 2000 in the Global Change Newsletter, implies that “The Earth as Modified by Human Action” [1]. According to Wilson, [2], the global population will increase to 9 billion and perhaps 11 billion by the end of the 21st century compare to the current population of 7.74 billion people. Therefore, “Anthropocene” means human population and activities have become so profound and pervasive that able to overcome the greater forces of nature by exceeding the nature’s capacity to replenish the damages done [3]. The continuous economic development in Malaysia with increasing population and rising living standard had resulted in the inevitable increase of waste generation, energy consumption, carbon emissions and other environmental degradation. Municipal solid waste management in Malaysia was identified as one of the three most important urban environment
challenges as the country progresses. In 2015, 38,563 tonne/day of waste is generated in Malaysia and is expected to increase to 49,670 tonne/day in year 2020 which is a 5.19% increase compared to levels in 2015 [4]. At present, 89% of the Malaysian solid waste is being disposed into non-sanitary landfill and open dumping sites with minimal treatment. This brings various negative environmental impacts [5]. The annual carbon dioxide (CO₂) emission in Malaysia has increased from 5.42 metric tons (MT) in 2000 to 8.53 MT in 2016 which indicates an increase of 57.38% [6] while the final electricity consumption increased from 7,665 kilo-tonne oil equivalent, ktoe/person/year in 2007 to 12,517 ktoe/person/year [7]. In Malaysia, organic fraction municipal solid waste (OFMSW) accounts for the largest chunk of waste composition at 45%, followed by 13% of plastics, 12% of diapers, 9% of paper, 6% of garden wastes and others [4]. Therefore, by diverting OFMSW from landfills by converting them into electricity and organic fertilizer via anaerobic digestion; this can bring about a paradigm shift in environmental, energy and economic aspects in Malaysia. Selling of electricity generated from OFMSW back to the national electrical grid via the Feed-in-Tariff (FiT) mechanism and the sales of fertilizer back to domestic market can greatly bring additional revenue to the local authority at the same time reduce the current RM148/tonne of MSW [4] of landfill operating expenditure (OPEX). It is necessary to evaluate the potential benefits of energy and fertilizer recovery from organic Municipal waste in Malaysia. Consequently, this study aimed to investigate the feasibility of biogas production from organic MSW as a renewable source of energy via anaerobic digestion. Moreover, the economic and environmental benefits including the sales of electricity and fertilizer were investigated.

2. Materials and Methods

2.1 Collection of organic municipal solid waste
The OFMSW samples were collected at Sahom Landfill at Jeram, Kampar (Coordinate: 4.392594, 101.179842) in Malaysia. In order to determine the consistency of OFMSW quality, samples were collected 3 times during the study period from 14th July 2019 – 2nd September 2019. The purpose of multiple collection is to determine the fluctuation and test of consistency of the characteristics of organic waste samples.

2.2 Sample preparation and homogenization
The procedure to prepare and homogenize the OFMSW samples was done according to the methods described by Esteves and Devlin. [8] where sample stored at 5 °C in a laboratory fridge for a maximum of 24 hrs. Large pieces of samples were chopped using knives and shredded using food processor.

2.3 Characterization of organic municipal solid waste
Laboratory chemical characterization of organic waste samples from landfill was carried out. The characterization including both approximate analysis (pH, Moisture Content, Dry Matter, Total Solids-TS, Volatile Solids-VS Calorific Value, Chemical Oxygen Demand-COD and Total Organic Carbon-TOC) and ultimate analysis (Weight Percentage, % of Carbon, Hydrogen, Nitrogen, Sulphur and Oxygen) were conducted to obtain the full characterization of organic waste samples.

3. Determination of Energy production and cost saving

3.1 Biogas Yield
In this study, Buswell and Mueller (1952) formula which uses the inputs from ultimate analysis together with the use of TS and VS obtained from proximate analysis as inputs respectively to theoretical estimate the biogas composition (Methane to Carbon Dioxide) and biogas yield.

3.2 Carbon dioxide, CO₂ Avoidance
The carbon dioxide avoidance is based on the 2014 baseline of CO₂ in Peninsular Malaysia is 0.694tonne CO₂/MWh [9]. Generating electricity from organic MSW as a source of energy can displace the carbon...
emissions of generating electricity from fossil fuel resources namely coal, natural gas and diesel. Therefore, the estimated CO₂ avoidance was calculated by Eq. (1):

\[ \text{CO}_2 \text{ avoidance (tonne)} = 0.694 \text{tonne/MWh} \times \text{electrical energy generated from waste (MWh)} \]  

(1)

3.3 Electricity Generation
The energy from biogas comes purely from methane, CH₄ which is a combustible gas with an energy density of 55.5MJ/kg. By definition, 1m³ of methane contains 36MJ of energy and 1 kWh of electrical energy contains 3.6 MJ of energy therefore 1m³ of methane is equivalent to 10kWh of electrical energy [10]. However, a typical biogas engine available in today’s market is having an average electrical efficiency of 40%. Hence, 1 m³ of methane is effectively to be converted into 4kWh of electrical energy. Therefore, the electrical energy generation was calculated based on the amount of methane gas generated, m³ using Eq. (2):

\[ \text{Electrical energy yield (kWh)} = \text{methane (m³)} \times 4 \text{ kWh} \]  

(2)

3.4 Bio fertilizer Yield
The theoretical calculation of biofertilizer yield from the anaerobic digestion process is based on the Dublien and Steinhauser formula [11], where 75% of VS is the actual fraction used for biogas yield for organic fraction of MSW. Therefore, only 25% of the fraction is left for bio fertilizer yield. The formula used to estimate the bio fertilizer yield is by using Eq (3):

\[ \text{Biofertilizer yield} = (\text{DM} - \text{VS}) + (25\% \text{ of VS}) \]  

(3)

Where, DM (kg/tonne) = Dry Mass, mass of solid components of organic waste; VS (kg/tonne) = Volatile Solids, portion of DM that can be potentially converted to biogas.

3.5 Economic Revenue
In Malaysia, the electricity generated from organic MSW can be sold back to the electricity grid based on the Feed-in-Tariff (FiT) mechanism which is authorized and governed by Sustainable Energy Development Authority (SEDA) Malaysia. The sales of electricity generated is based on the category of “biogas (landfill/agriculture waste)” with a FiT rate of RM 0.3997/kWh [12]. Hence the potential revenue of selling electricity is based on the Eq (4). The sales of organic fertilizer in Malaysia has an average cost of RM 515/tonne based on the average market value ranging from a minimum of RM 480/tonne to a maximum of RM 550/tonne [13]. Hence, the cost benefit of selling organic fertilizer is based on the Eq (5):

\[ \text{Revenue}_{\text{electricity}} (\text{RM}) = \text{RM 0.3997/kWh} \times \text{Electricity Energy Generated (kWh)} \]  

(4)

\[ \text{Revenue}_{\text{fertilizer}} (\text{RM}) = \text{RM 515/tonne} \times \text{fertilizer generated (tonne)} \]  

(5)

4. Results and Discussions
4.1 Quantity and Characteristics of Organic Municipal Solid Waste
In Malaysia, it was found that 47,218 tonne/day of municipal solid waste is generated in 2019 and the amount is expected to increase to 49,670 tonne/day by 2020 [4]. In year 2019 and 2020, there will be a grand total of 7,755,557 tonnes and 8,158,298 tonnes of organic waste from the total 17,234,570 tonnes and 18,129,550 tonnes of MSW respectively. The organic MSW characterizations are shown in Table 1.
Table 1: The results of the characteristics of organic municipal solid waste.

| Analysis          | Parameters                          | Unit       | Value (Min – Max)       |
|-------------------|-------------------------------------|------------|-------------------------|
|                   |                                     |            |                         |
|                   | Physical Properties                 |            |                         |
|                   | Temperature                         | °C         | 26.4 - 27.4             |
|                   | pH                                  | -          | 4.47 - 4.81             |
|                   | Oxidation Reduction Potential (ORP) | mV         | 141.83 - 146.80         |
|                   | Moisture Content (MC)               | %          | 48.18 - 60.08 (Wet basis) |
|                   | Dry Matter (DM)                     | %          | 39.92 - 51.82           |
|                   | Total Solids (TS)                   | %          | 20.90 – 43.95           |
|                   | Volatile Solids (VS)                | %          | 20.29 – 43.05           |
|                   |                                     |            |                         |
|                   | Chemical Properties                 |            |                         |
|                   | Calorific Value                     | kJ/g       | 19.97 – 22.31           |
|                   | Chemical Oxygen Demand (COD)        | mg/L       | 290,608.9 – 301,979.4   |
|                   | Ammoniacal-Nitrogen (NH3-N)         | mg/L       | 239.05 – 478.44         |
|                   | Total Organic Carbon (TOC)          | mg/L       | 34,210.2                |
|                   |                                     |            |                         |
|                   | Ultimate                            |            |                         |
|                   | Carbon (C), Oxygen (O), Hydrogen (H), Nitrogen (N) and Sulphur (S) | % | C=47.03%  |
|                   |                                     |            | O=32.7%                 |
|                   |                                     |            | H=6.75%                 |
|                   |                                     |            | N=2.58%                 |
|                   |                                     |            | S=0.52%                 |

4.2 Bio-Energy and Bio-Fertilizer Potential

The anaerobic digestion process can transform organic MSW into biogas and digestate (bio fertilizer), hence the process itself fully utilize the waste into useful means of energy and resources. Biogas consists mainly methane, CH₄ and carbon dioxide, CO₂ where these two gases are greenhouse gases. Therefore, landfilling and open dumping of organic MSW releases tremendous amount of biogas into the atmosphere which contribute to global warming where methane has 21 times of global warming potential to carbon dioxide. By harnessing biogas as a source of energy for electricity production, this would convert methane into carbon dioxide via combustion process in the biogas engine to produce electricity hence reducing the global warming effect. Table 2 shows the results regarding the total biogas yield, biofertilizer yield, electrical energy and capacity output from the recovery of organic MSW for power generation. It can be seen from Table 2 that with total organic MSW generation of 21,248.1 tonnes/day and 22,351.5 tonnes/day in 2019 and 2020 respectively, there will be a potential generation of 7,494.08 MWh/day and 7,883.24 MWh/day of renewable electrical energy. The digestate which is the left-over solids after the anaerobic digestion process can be used as organic fertilizer. The bio-fertilizer yield was 13,013.73 tonne/day in 2019.
**Table 2:** The biogas, bio-fertilizer and potential electrical energy and power generated from organic municipal solid waste in Malaysia. (Estimated for Year 2020*)

| Parameter                              | Unit          | 2019            | 2020*           |
|----------------------------------------|---------------|-----------------|-----------------|
| Mass of MSW                            | tonne/day     | 47,218          | 49,670          |
| Organic Fraction from MSW              | %             | 45              | 45              |
| Mass of Organic MSW                    | tonne/day     | 21,248.1        | 22,351.5        |
| Biofertilizer Output                   | tonne/day     | 13,013.73       | 13,689.53       |
| Biogas Output (CH4: CO2 = 56.62%:43.38%) | m³/day        | 3,274,812.51    | 3,444,871.39    |
| Pure Methane Output                    | m³/day        | 1,873,520.24    | 1,970,810.92    |
| Energy Value                           | MJ/day        | 443.66          | 466.70          |
| Electricity Energy                     | MWh/day       | 7,494.08        | 7,883.24        |
| Electrical Capacity                    | MW            | 312.25          | 328.47          |

4.3 *Revenue Generated from the Sales of Electricity and Fertilizer*

The anaerobic digestion has two useful outputs from digesting organic MSW as feedstock mainly energy (electricity) and digestate (fertilizer). As presented in Table 3, the estimated revenue from selling both electricity and organic fertilizer was RM 9.7 million/day in year 2019.

**Table 3:** The estimated net revenue generated from the sales of electricity though the Feed-in-Tariff (FiT) mechanism, sales of organic fertilizer in Malaysia. (Estimated for Year 2020*)

| Parameter                              | Unit          | Price per Unit | 2019 | 2020* |
|----------------------------------------|---------------|----------------|------|-------|
| Revenue from Electricity               | RM Million/day| RM 0.3997/kWh  | 3.00 | 3.15  |
| Revenue from Fertilizer                | RM Million/day| RM 515/tonne   | 6.70 | 7.05  |
| Total Revenue from Electricity and Fertilizer | RM Million/day | -              | 9.70 | 10.20 |

5. Conclusion

Energy recovery from organic waste can bring contributions to sustainable development and economic growth. Based on the characteristics of the current Malaysian organic MSW (21,248.1 tonne/day); the bioenergy potential of 1,892,945.4 m³/day of pure methane gas which can be converted into 7,494.08 MWh of electricity. Moreover, a generation of 13,013.73 tonne/day of digestate which can be used as organic fertilizer for domestic agriculture applications. This can lead to several environmental benefits including the avoidance of carbon dioxide, CO₂ emissions and leachate. By applying anaerobic digestion in Malaysia to convert all organic MSW into energy, the national renewable energy shares in the electricity grid will be increased to 25% of renewable energy by 2025 in the electricity grid. The current cost of solid waste management from collection, transport to landfilling at RM 148/tonne of MSW can be overcome by selling the electricity and fertilizer generated from anaerobic digestion. The electricity generated from organic MSW can be sold back to the utility company at a rate of RM 0.3997/KWh via the Feed-in-Tariff (FiT) mechanism while organic fertilizer generated can be sold back at an average price of RM 515/tonne. By doing so, solid waste management in Malaysia will no longer be a burden to the local authority.
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