Food Waste Co-Digestion with Microwave Pre-Treated Sewage Sludge to Enhance Biogas Production Through Anaerobic Digestion

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***Abstract*— Malaysia has been experiencing rapid growth in population, massive development in industrialization and urbanization. It has resulted in the generation of a greater amount of wastes. Usually, the solid wastes are disposed at landfills, which are mostly saturated and overloaded with solid wastes, but, due to the scarcity of land and public complaints, making the building of new landfill almost impossible, hence the disposal of MSW is one of the major environmental issues faced by the country. Meanwhile, in the sewerage industry, sludge that is high in embedded energy is generated and it can be used to produce methane through anaerobic digestion especially in the modern mechanized sewage treatment plant (STP). However, the secondary thickened sludge (STS) is a poor substrate for anaerobic digestion. Studies have shown that the digestibility of STS can be improved my pre-treatment methods such as microwave pre-treatment prior to the anaerobic digestion. Besides that, co-digestion is an effective way to overcome the low biodegradability of STS which also promotes an environmentally and an ecologically friendly way to dispose of the food wastes. Also, it can be used to produce renewable energy which could reduce the dependency on fossil fuel for power generation. Moreover, it also can deliver beneficial synergies for the sewage industry and the MSW industry. This work elucidates the preliminary investigation of the potentials of co-digestion of microwave pre-treated STS and food waste and its effect on biodegradability and methane yield, which proposes a sustainable management of solid waste generated in urban areas while harnessing the resources to generate green electricity.**

***Index Terms*—Biomass, Renewable energy sources, Waste handling, Waste management, Waste recovery.**

I. Renewable Energy Status in Malaysia

Malaysia has been experiencing rapid growth in population, massive development in industrialization and urbanization. It is undoubtedly that Malaysia has gone through massive progress due to its abundance of fuel supplies. Malaysia, a country with 31 million populations and its gross domestic product (GDP) and Human Development Index (HDI) is among the highest in the Asian region. The HDI increased by 38% from 1980 to 57th out of 169 countries in 2000 [1]. Concurrently, the final energy demand in Malaysia has increased steadily over the past years. It has increased from 93.8 to 99.5 Mtoe from 2015 to 2016, in which 94.9 Mtoe are generated from fossil fuels like oil, natural gas, and coal [2]. Malaysia's main energy resource, the petroleum reserves, is expected to deplete by 2035 [3]. Thus, it has led to the exploration of new energy resources which are renewable, readily available and eco-friendly to minimize the environmental impact and to supplement the depleting non-renewable fossil fuel reserves. In 2000, the Fifth Fuel Policy was framed to ensure sustainable development of energy resources, both non-renewable and renewable. Renewable energy is promoted widely nationwide and Malaysia has been ambitious to increase the planned renewable energy capacity. In the 11th Malaysia Plan (2016-2020), the government has intended to increase the share of renewable energy to 2,080 MW by 2020 that contributes 7.8% of the total installed capacity and also complemented by energy efficiency (EE) measures too [4]. The total licensed capacity for renewable energy in Peninsular Malaysia has increased by 7.1% from 366 MW in 2015 to of 392 MW, whereby 235 MW fueled by solar PV, 89 MW fueled by biomass, 34 MW fueled by mini hydro and 34 MW fueled by biogas [5].

II. Malaysian Municipal Solid Waste (Food Waste) Management

Malaysia has been experiencing rapid growth in population, massive development in industrialization and urbanization. Many Asian countries including Malaysia are facing a big problem with the method of MSW disposal. It is approximated that the load of MSW generated by the year 2020 will be 49,000 tons/day or more than 12,000,000 tons/year [6] with the current population growth. Federal Government has imposed a new law (Act 672) and Ministry of Housing and Local Government and Urban Well-being (KPKT) are in-charge of the waste management issues. Act

This research is supported by Tenaga Nasional Berhad (TNB) through TNB Seed Fund.

672 makes sorting of waste at source mandatory, but the result is still not encouraging. Thus, KPKT acknowledged that more efforts and more time are required to implement the act [7]. At present, more than 90.0% of the MSW is sent to landfills which is the main disposal method. However, most of them are saturated and overloaded, but, due to the scarcity of land and public complaints, making new landfill is almost impossible [8]. Therefore, the disposal of MSW is a big problem and is one of the major environmental issues faced by the country. Failure of sorting waste from the source and the humid climate enhances the moist of co-mingled waste cause difficulties to be incinerated.

The KPKT states that 24.5 million kg per day are food wastes and 70.0% of food wastes are disposed at the landfill sites [11]. A biological process such as anaerobic digestion could provide a vital element in an integrated solid waste management system for a community in a developing country while preserving the natural ecosystem within an acceptable cost [6]. The renewable energy produced from anaerobic digestion process can be seen as a good reason for many communities to start recycling our valuable resources [12]. Food wastes can be used as substrates in anaerobic digestion to produce renewable energy which tend to solve the waste disposal problem through environmental and ecologically friendly method. In addition, implementing waste to produce renewable energy reduces the dependency on fossil fuel for power generation in the country [13].

TABLE I. ESTIMATED METHANE PRODUCTION FROM FOOD WASTE BASED ON POPULATION IN MALAYSIA IN 2016

Parameter	***Unit***	***Value***
Population	million people	31.0
Food waste generated per person per day [a]	kg/day	0.6
Total mass of food waste generated	kg/day	18,600,000
Total volume of food waste generated [b]	m^3/day	18,075.80
COD level in food waste [c]	mg/day	153,733.33
Total COD level in food waste	kg/day	2,778,850.00
Methane produced [d]	m^3/day	972,598
Energy produced [e]	TJ/day	14.69
	GWh/day	4.08
	TWh/year	1.35
Gas engine installed capacity [f]	MW	170.00

a. Assume 0.600 kg of food waste generated per day by per person [9]
b. Assume the density of food waste is 1,029 kg/m^3
c. Mean value of Chemical Oxygen Demand (COD) level of food waste is 153,733.33 mg/L (experimental value)
d. Methane conversion factor is 0.35 m^3 CH_4 per kg COD [10]
e. The energy content of CH4 is 37,750 kJ/m^3 with gas engine conversion efficiency of 40% [10]
f. Assume that gas engine is operating 330 days/year

It is expected that 18,600 tonnes food waste are generated nationwide per day. Table I summarises the methane potential in Malaysia from food waste generation of 18,075.80 m^3/day based on population in Malaysia in 2016 that has the capacity to generate 972,598 m^3 of methane daily through anaerobic digestion which can generate 1.35 TWh energy annually. Nevertheless, inhibition occurs when food waste is digested alone in the long-term operation. The inhibition is due to the imbalance of nutrients in the anaerobic digester. Additionally, the concentration of lipids of volatile fatty acid (VFA) in food waste is always higher than the optimum concentration, which leads to inhibition of methanogens and causes the digester to collapse.

III. MALAYSIAN SEWERAGE TREATMENT

The sewerage industry in Malaysia has progressed over the last half a century from the primeval method, pour flush and septic tanks to fully mechanized plant. The mechanized plant was further upgraded in late 2000's, with anaerobic digesters as pilot plants to tap the unexploited potential of energy from the sewage sludge. Prior to this, the main objective of the sewerage operator is to treat the wastewater to produce high-quality effluent that is within the stipulated DOE standard which can be safely discharged to the environment. [14]

TABLE II. ESTIMATED METHANE PRODUCTION FROM SECONDARY THICKENED SLUDGE BASED ON POPULATION IN MALAYSIA IN 2016

Parameter	***Unit***	***Value***
Population	million people	31.0
Wastewater generated per person [a]	m^3/day	0.25
Total volume of wastewater generated	million m^3/day	7.75
Total volume of STS generated [b]	m^3/day	13,950.0
COD level in STS [c]	mg/L	20,301.2
Total COD level	kg/day	283,200.0
Methane produced [d]	m^3/day	99,120.0
Energy produced [e]	TJ/day	1.49
	GWh/day	415.75
	TWh/year	137.20
Gas engine installed capacity [f]	MW	17.32

a. Assume 0.25m3 of wastewater generated per day by per person
b. 0.18 % of STS generated from wastewater inflow [15]
c. Mean value of COD of STS is 20,301.2 mg/L (experimental value)
d. Methane conversion factor is 0.35 m3 CH4 per kg COD [10]
e. The energy content of CH4 is 37,750 kJ/m3 with gas engine conversion efficiency of 40% [10]
f. Assume that gas engine is operating 330 days/year

The country's main sewerage operator, Indah Water Konsortium, is dominant in providing preliminary, primary and secondary treatment. Anaerobic digesters have been deployed in few STPs within Malaysia to stabilize the sludge prior to disposal from which biogas that is high in embedded energy is generated. Although, a STP with anaerobic digesters are designed to produce 9,174.0 m3 of biogas daily at an inflow of raw sewage 93,000.0 m3/day with a solid concentration of 270.0 mg/L at 80.0% volatile solids, the average biogas production in the STP is approximately only 1,000.8 m3 [15].

Increasing population and tremendous urbanization growth influence the wastewater generation in Malaysia. The Malaysian population has increased to 31.0 million in 2016 and the total volume of wastewater generated is approximately 7.75 million m3/day. Table II summarizes the methane potential in Malaysia from STS (sewage sludge) generation of 13,950.0 m3/day based on population in Malaysia in 2016 that has the capacity to generate 99,120.0 m3 of methane daily through anaerobic digestion which can generate 137.2 GWh energy annually.

A research undertaken to enhance the biogas generation has shown that the inevitable drawback of the anaerobic digestion of sewage sludge in STPs is the secondary thickened sludge (STS). STS is the polymer/flocculants added waste activated sludge (WAS). WAS consists of the polymeric network formed by extracellular polymeric substances (EPS) and microbial cells that are resistant to direct anaerobic digestion since cell walls and EPS present a physical and chemical barrier and it has been identified as a substrate with low biodegradability. However, due to infrastructure constraint STS have to be fed into the anaerobic digesters.

IV. Microwave Pre-treatment of Sewage Sludge

The major drawback of the anaerobic digestion of sewage sludge is the poor digestibility of STS. STS is the polymer/flocculants added waste activated sludge (WAS). WAS consists of the polymeric network formed by extracellular polymeric substances (EPS) and microbial cells that are resistant to direct anaerobic digestion since cell walls and EPS present a physical and chemical barrier and it has been identified as a substrate with low biodegradability. Thus, recent researches have focused on pre-treatment methods prior to anaerobic digestion [16]; [17].

Pre-treatment helps to disrupt the cell walls and causes lysis or disintegration of sludge cells. Different pre-treatment methods to improve anaerobic digestion have been the focus of a large number of scientific studies. Among the pre-treatment methods are ultrasonic [18], thermal [16], microwave [19] and alkaline [20] pre-treatment. Industrial use of microwave irradiation is an alternative to conventional heating and it is prevalent due to the advantages which include rapid heating, low maintenance, ease of control, cost-effective and compactness of the microwave generator [21].

Recent researchers have focused on microwave pre-treatment due to the rapid heating, acceleration of reaction rates, ease of control, energy efficiency, low maintenance, cost effective, diminished hazardous product formation and emissions and compactness of the microwave generator [21]; [22]. Thus, microwave pre-treatment should be emphasized as the subject of future research in the treatment of sludge as agreed by [22].

Batch microwave pre-treatment is commonly used to enhance the anaerobic digestion process of various substrates including sewage sludge [23]; [19]. Almost all the studies on sewage sludge are done in a lab scale microwave setup through a batch process whereby the material to be heated is placed inside the oven and removed after being heated before being fed into the anaerobic digester. Based on the findings of [24], a batch microwave pre-treatment at 80 W for 5 minutes, enhances the anaerobic digestibility and biogas production by 38.5%.

V. Co-digestion of Food Waste with Microwave Pre-treated Sewage Sludge

To counteract the inhibition and to overcome the disadvantages of single digestion of food waste, co-digestion with another low degradability substrate such as STS is an alternate method to this problem. Anaerobic co-digestion of food waste with STS improves the C/N ratio, biogas production, methane yield and overcomes the nutrient imbalance of food waste [25]. Co-digestion of food waste with sewage sludge is a promising approach for biogas and methane yield improvement, and this approach could be applied in pilot-scale and full-scale plants for a richer biogas.

Various researches on the efficiency of co-digestion of food waste with sewage sludge to enhance the methane production are on-going. For instance, [26] demonstrates that the constraints of conventional/single substrate anaerobic digestion can be resolved by the synergistic effect of co-digestion of food waste and sewage. Meanwhile [27] studied the comparison of the system stability and performance of co-digestion systems with single digestions of sewage sludge and food waste. From the results, it was known that system stability was improved with co-substrate being a diluting agent to inhibitors and enhanced volumetric biogas production.

Besides that, new plants for sewage and food wastes co-digestion have been established in Denmark, Germany, and Switzerland [28]. However, co-digestion of food waste and sewage sludge has not been exploited in Malaysia although it has high potential.

In this study, the potential co-digestion of food waste and microwave pre-treated sewage sludge will be elucidated. Table III summarizes the estimated methane production from co-digestion of food waste and pre-treated sewage sludge at 80W for 5 minutes based on population in Malaysia in 2016. The optimum co-digestion volume ratio of 50:50 based on the experimental study has been used throughout this study. The potential methane generation from the co-digestion of microwave pre-treated STS and food waste is approximately 554.94 x 103 m3/day that has the capability to generate 768.13 GWh annually.

TABLE III. ESTIMATED METHANE PRODUCTION FROM CO-DIGESTION (50:50) OF FOOD WASTE AND MICROWAVE PRE-TREATED STS BASED ON POPULATION IN MALAYSIA IN 2016

Parameter	*Unit*	*Value*
Population	million people	31.00
Volume of food waste	m^3/day	18,075.80
COD level in food waste [a]	mg/L	153,733.33
Volume of microwave pre-treated STS (80W at 5minutes)	m^3/day	17,551.02
COD level in microwave pre-treated STS[b]	mg/L	20,301.20
Total COD concentration (50% STS+ 50% food waste) [c]	kg/day	1,585,541.00
Methane produced [d]	m^3/day	554.94 x 10^3
Energy produced [e]	TJ/day	8.38
	GWh/day	2.33
Gas engine installed capacity [f]	MW	96.00

a. Mean value of Chemical Oxygen Demand (COD) level of food waste is 153,733.33 mg/L (experimental value)
b. Mean value of COD of STS is 20,301.2 mg/L (experimental value) and the increment of COD for the pre-treated STS is 38.5% (experimental value)
c. The optimum co-digestion ratio of food waste and STS is 50:50 by volume (experimental value)
d. Methane conversion factor is 0.35 m3 CH4 per kg COD [10]
e. The energy content of CH4 is 37,750 kJ/m3 with gas engine conversion efficiency of 40% [10]
f. Assume that gas engine is operating 330 days/year

VI. IMPACT OF CO-DIGESTION ON SUSTAINABILITY

The co-digestion of food waste and sewage sludge has potential impacts on sustainability as summarized in Table IV below.

TABLE IV. IMPACT OF CO-DIGESTION ON SUSTAINABILITY

Advantages	*Opportunities*
Environmental	• Reduces the amount of solid waste and land space used for landfilling (extends the life of landfill) • Reduces leachate intrusion into soil and water source • Reduces methane and CO^2 from STPs and landfills • Reduces foul odor emission • Reduces dependency on fossil sources
Society	• Increases job opportunities due to the opening of the new industry • Promotes waste recycling among public • Affordable solid waste treatment for the public • Increases energy access and energy security • Promotes holistic waste management
Economic	• Reduces operational cost of sanitary landfills • Increases the ROI of the STP by selling the increased amount of electricity generated through FiT • Creates green jobs

VII. CONCLUSION

Anaerobic digestion has proven to be feasible and economically viable for RE generation from waste. Malaysia has a wide range of industries which generates waste which is high in organic content such as MSW/food waste and sewage sludge. These wastes can be utilized to generate methane which subsequently can be used to generate energy that is a valuable potential and an economical alternative renewable fuel to be tapped for electricity generation. This industry has a great potential in Malaysia to become one of the RE sources among other RE sources. However, the quantity of biogas generated in STP is not viable to be harnessed and converted into electricity due to the low biodegradability of STS. Whereas, anaerobic digestion of food waste alone causes inhibition in the long-term operation. Thus, food waste and microwave pre-treated STS can be co-digested to enhance the biogas generation leading to the plants being energy wise self-sustaining and also at the same time able to produce profitable excess energy. It also reduces the fossil fuel dependency to meet the energy demand and also results in CO^2 emission reduction. These efforts are important and efficient in both stretching the available fossil fuel resources and reducing the dependency on fossil fuels. In conclusion, this is the best method available that is economically beneficial, technically practical and environmentally beneficial. Furthermore, biogas energy recovery and utilization in STP will contribute to sustainability too. However, implementation issues such as logistics and inter-organizational negotiation issues exist and must be tackled to harvest the above-said benefits.

ACKNOWLEDGMENT

The authors would like to extend our gratitude to Tenaga Nasional Berhad (TNB) for funding this project through TNB Seed Fund. We would like to convey our sincere gratitude to all the research assistants and laboratory staffs of the Department of Mechanical Engineering in Universiti Tenaga Nasional (UNITEN), Department of Civil Engineering in UNITEN and the management of UNITEN for their support and direct involvement in this study.

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