STUDY OF SEMI CONTINUOUS STIRRED BATCH PILOT-SCALE MONO-DIGESTION OF FOOD WASTE

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A project report submitted in partial fulfillment of the requirement for the award of the Master of Civil Engineering

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JUNE 2023

ACKNOWLEDGEMENT

In completing this research, I would like to express my gratitude to my supervisor Ts. Dr Roslinda Binti Seswoya for the never-ending advice, tutoring, and guidance. All the motivation and recommendations during the research journey were highly appreciated. All her suggestions and amendments from her are what helped me in writing this thesis effectively. Additionally, I want to thank the institution (Universiti Tun Hussein Onn Malaysia) for providing the tools and resources I needed to do my research and for giving me the chance to do so.

Moreover, I would like to give a million thanks to my friends (Farihah, Amir, Aina, and Khairul) who helped me during the research journey either by moral support or a helping hand. We share a common goal to complete this study. Therefore, I wish you all the best in your future endeavour.

Last but not least, I want to express my gratitude to my family, especially my loving parents, who never ceased supporting and encouraging me while I was studying. The endless support motivates me to complete this study effectively. Finally, I hope this research will be helpful for others related to this field as guidance or future reference.

ABSTRACT

Food waste can be digested anaerobically in a batch- or pilot-scale reactor. Food waste digested anaerobically in a batch-scale performed differently than in a pilot-scale reactor. However, the performance of a batch pilot-scale anaerobic digestion of food waste was less documented. Thus, this research aims to evaluate the performance of a batch pilot-scale anaerobic digester fed with food waste (slurry) and to assess the kinetics of methane production. A batch pilot-scale anaerobic digester with 84 L of working volume at an inoculum to substrate (I/S) ratio of 2.0 with semi-continuously mixed at 70 rpm for 30 minutes was operated for 26 days at ambient temperature. The kinetic analysis for the methane production was assessed using Modified Gompertz and Logistic Function models. The digester performed well throughout the study period, and no instability was observed, indicated by the volatile fatty acid to total alkalinity (VFA/TA) ratio of 0.35. The methane accumulation and ultimate methane yield were 463.25 L and 5103.6 mL CH_4/gVS, respectively. The difference in ultimate methane yield between the laboratory and modellings was less than 10%, indicating that both models were acceptable. The Modified Gompertz model obtains a coefficient of determination (r^2) of 0.90, which is higher than the r^2 obtained in the Logistic Function model, indicating that the Modified Gompertz model is more suitable for evaluating the methane production from the batch pilot-scale anaerobic digestion of food waste (slurry). In conclusion, the batch pilot-scale anaerobic digestion working at ambient temperature for food waste (slurry) works efficiently in producing methane which no lag phase period were observed. The methane accumulation and methane yield obtained from this study were higher compared to the other studies. The future study is to utilize the pilot plant for the multiple substrate to inoculum ratios.

ABSTRAK

Pencernaan anaerobik sisa makanan boleh dilaksanakan dalam pencerna berskala besar atau skala kecil. Sisa makanan yang dicerna secara anaerobik di dalam pencerna skala besar, mempunyai prestasi penghadaman berbeza daripada prestasi penghadaman yang berlaku di dalam pencerna skala kecil. Walau bagaimanapun, prestasi penghadaman anaerobik sisa makanan mod kelompok berskala besar kurang didokumenkan. Oleh itu, tujuan penyelidikan ini adalah untuk menilai prestasi penghadam anaerobik mod kelompok berskala besar yang diberi makan sisa makanan (buburan sisa makanan), dan menilai analisis kinetik pada pengeluaran metana. Pencerna anaerobik mod kelompok berskala besar dengan 84 L isipadu kerja pada nisbah inokulum kepada substrat (I/S) 2.0, diaduk secara separa aduk pada 70 rpm selama 30 minit telah dikendalikan selama 26 hari pada suhu ambien. Pemodelan analisis kinetik untuk pencerna anaerobik skala besar dianalisis menggunakan model Modified Gompertz dan Logistic Function. Pencerna berfungsi dengan baik sepanjang tempoh kajian dan tiada ketidakstabilan diperhatikan, seperti yang ditunjukkan oleh nisbah asid lemak meruap kepada jumlah kealkalian (VFA/TA) 0.35. Pengumpulan metana dan hasil akhir metana ialah 463.25 L dan 5103.6 mL CH_4/gVS. Perbezaan dalam hasil metana akhir antara ujikaji makmal dan pemodelan kinetik adalah kurang daripada 10%, menunjukkan bahawa kedua-dua model boleh diterima. Model Modified Gompertz memperoleh pekali penentuan (r^2) 0.90, yang lebih tinggi daripada r^2 yang diperoleh dalam model Logistic Function, menunjukkan bahawa model Modified Gompertz lebih sesuai untuk menilai pengeluaran metana daripada penghadaman anaerobik mod kelompok berskala besar sisa makanan (buburan sisa makanan). Kesimpulannya, penghadaman anaerobik mod kelompok berskala besar yang bekerja pada suhu ambien untuk buburan sisa makanan berfungsi dengan cekap dalam menghasilkan metana yang tiada tempoh penyesuaian yang diperhatikan. Pengumpulan metana dan hasil metana yang diperoleh daripada kajian ini adalah lebih tinggi berbanding dengan kajian lain. Kajian masa depan adalah untuk menggunakan digester berskala besar untuk nisbah substrat berganda kepada inokulum.

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BMP	Biomethane potential
BSA	Bovine Serum Albumin
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical oxygen demand
FW	Food waste
FWS	Food waste slurry
H_2S	Hydrogen sulphide
I/S	Inoculum to substrate ratio
KEEP	Kyoto Eco-Energy Project
LFG	Landfill gases
MSW	Municipal solid waste
N_2	Nitrogen
POME	Palm oil mill effluent
SEDA	Sustainable Energy Development Authority
TA	Total alkalinity
TS	Total solids
UPM	Universiti Putra Malaysia
UTHM	Universiti Tun Hussein Onn Malaysia
VFA	Volatile fatty acid
VS	Volatile solids

CHAPTER 1

INTRODUCTION

1.1 Background of study

In Malaysia, food waste makes up the majority of the municipal solid waste discharged in landfills (Devadoss *et al*., 2021). Most of food waste are generate from residential, commercial, institutional, and industrial establishments (Li *et al.*, 2018). Food waste dumped in landfills is often not properly segregated or separated, resulting in stench and pest infestation (Kumaran *et al.*, 2016). Because of the biochemistry process, the buildup of food waste in landfills produces many greenhouse gases. The gases produced from the landfill are referred to as landfill gases (LFG), and they comprise of trace gases, 0-1% hydrogen sulphide (H_2S), 2-5% nitrogen (N_2), 40-60% carbon dioxide (CO_2), and mostly consists of 45-60% methane (CH_4) (Tao *et al*., 2019). According to Kumaran *et al.* (2016), Malaysia generates 908.33 tonnes of food waste every day.

Also, food waste composition varies by geography, season, sample preparation method, and collection technique, resulting in varying energy production levels in methane from anaerobic digestion (Li *et al.*, 2017; Xu *et al.*, 2017). Attention has been drawn to the advantages of anaerobic digestion for food waste stabilisation, such as energy recovery and food waste diversion from landfills (Li *et al.*, 2017). Food waste has the appropriate organic, pH, and moisture for anaerobic conditions (Wijayanti *et al.*, 2018). Food waste is a good substrate for anaerobic digestion due to its high moisture, organic content, and biodegradability (Li *et al.*, 2018; Li *et al.*, 2017). Carbohydrates, fat, along with protein make up the three major elements of food waste. Food waste rich in carbohydrates has faster degradation rates than food waste rich in protein (Li *et al*., 2018). Therefore, food waste rich in carbohydrates has a higher methane potential than food waste rich in protein (Pramanik *et al*., 2019a).

Theoretical estimates of the energy and methane produced by the anaerobic digestion of food waste were reported (Khairuddin *et al*., 2016). Up to 4,282,170 tons of food waste will be created in 2020, with 1,165,849 dam^3 (cubic decameter) of methane potentially produced as a result. About 3,997 MWe/year of power might be produced using the methane gas as a fuel. Methane can be used to produce energy, reduce the impact of using fossil fuels for transportation and mechanical operation, and act as a renewable energy source. Leung & Wang (2016) and Lim *et al*. (2018) stated that an anaerobic treatment plant/digester was built to treat food waste to produce biogas and fertilisers in Hong Kong and Singapore.

Anaerobic digestion is a four-stage/phase biochemical operation that disintegrate complicated substrates (biodegradable waste) to create biogas, including methane, without oxygen (Ariunbaatar *et al*., 2014a). The four stage/phase are hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Paritosh *et al*., 2017). All four stage/phase occur simultaneously and are interdependent (Vrieze *et al*., 2015; Veluchamy & Kalamdhad, 2017). Anaerobic digestion can be implemented in various setups such as single-stage and two-stage anaerobic digestion systems. The benefits of a single-stage anaerobic digestion system are minimal costs, fewer technical issues, and a simple design. In one reactor, the anaerobic digestion processes (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) occur simultaneously. Anaerobic digestion (using food waste as substrate) operated in the single-stage and multi-stage setups were reported (Ganesh *et al*., 2014). Ganesh *et al.* (2014) discovered that the single-stage anaerobic digestion yielded higher methane and had higher volatile solids (VS) removal than the two-stage anaerobic digestion process.

Food waste can be anaerobically digested in batch-scale, pilot-scale, or full-scale anaerobic plants. (Holliger *et al*., 2017). However, anaerobic digestion on the batch-scale performs differently than anaerobic digestion on the pilot-scale (Carrere *et al*., 2016). The digestion rate in a pilot-scale digester may vary more than that in a batch-scale digester (Carrere *et al*., 2016). In a pilot-scale digester, the digestion rate plays a vital role as it can affect the methane manufacturing process (Carrere *et al*., 2016). The establishment of a pilot-scale digester necessitates a complex procedure. These factors include digester size, anaerobic system type, and several parameters that assure digester stability, substrate degradability, and increased biogas production

(Carrere *et al.*, 2016; Van *et al.*, 2019). Temperature, pH, inoculum to substrate ratio (I/S), volatile fatty acid (VFA), and alkalinity are the characteristics that must be managed to avoid digester failure and create a favourable habitat for the anaerobic bacteria (Van *et al.*, 2019).

In the setup of the pilot-scale anaerobic digestion, two system can be chosen to be implement such as batch and continuous system (Van *et al.*, 2019). The feeding mode of the batch system occurs when the substrate is fed into the digester only once, after which the digester is sealed until the digestion process is completed (Sajeena, 2015). According to Sajeena (2015), the biogas produced in the batch system shows a high peak in the center of the operation and low peaks at the beginning and end. Van *et al.* (2019) studied the anaerobic digester (35 L) under batch feeding mode and observed biogas production of 314 mL biogas/gVS of organic fraction of municipal solid waste. Meanwhile, Park *et al*. (2018) reported a methane yield of 266 mL/gVS observed in a pilot-scale anaerobic digester with a batch mode and a working volume of 75 L.

Kinetic analysis can be further utilized to assess the execution of the anaerobic digestion of food waste. Food waste decomposition and methane production can be described using kinetics analysis (Li *et al.*, 2018). The first-order kinetic model, Modified Gompertz model, and Logistic Function model are common methods employed for kinetic analysis (Veluchamy & Kalamdhad, 2017). Different types of kinetic models produces different results of kinetic parameters (Li *et al.*, 2018). In order to learn through the substrate degradation and anticipate the biological system's behaviour in an anaerobic digestion system, a simplified generalised model is derived from the first-order kinetic model (Li *et al.*, 2018). Modified Gompertz model and Logistic Function model are chosen to outline the kinetics parameter of the anaerobic digestion process. These models follow the sigmoidal function that correlates with the growth of methanogens and methane production (Veluchamy & Kalamdhad, 2017).

1.2 Problem statement

Food waste makes up the majority of municipal solid waste sent to landfills. Food waste can come from various sources, including residential, institutional, and commercial buildings (Xiao *et al.*, 2019). Landfill, incineration, along with composting were the prevalent techniques of disposing of food waste. However, all three approaches appear to be ineffective in terms of cost and cause various environmental issues (Pramanik *et al.*, 2019a). Landfill methods contain a high risk of negative effects on the environment due to the leachate produced that can emit odour and contaminate the groundwater (Girotto *et al*., 2015). Incineration methods contribute to air pollution (Lim *et al*., 2016). While composting utilises fossil fuels during transportation and machinery operations, which can have a negative effect towards the environment due to greenhouse gas emissions (Bong *et al*., 2017).

Conventional methods such as landfills and incineration are expensive methods for waste management and contradict the concept of a circular economy (Baldi *et al*., 2019). Reusing or recycling materials to significantly lower the amount of natural resources needed and environmental risks is what the term "circular economy" refers to (Baldi *et al*., 2019). Anaerobic digestion is an alternative tool used in waste management to reduce waste accumulation and for renewable gas (methane) generation (Khairuddin *et al*., 2016). Additionally, food waste was subjected to anaerobic digestion with the goal of recovering nutrients, and the end result can be applied to the agricultural production system (Banks *et al*., 2018).

Despite being a preferred substrate for anaerobic digestion, food waste still vulnerable to significant acidification, which decreases the pH level as a result of the buildup of VFA (Curry & Pillay, 2012). Food waste has high biodegradability making the organic degradation rate faster, leading to over-acidification, and becoming a limitation in a large-scale anaerobic digestion process (Muis *et al*., 2021). To offer the best circumstances for a successful anaerobic digestion system, careful design and control of system parameters are required, as is excellent monitoring of digestion performance (Van *et al.*, 2019). The essential aspect of developing an excellent anaerobic digestion process is process stability. Over-acidification and foaming can all affect the stability of the anaerobic digestion process (Li *et al.*, 2016). Food waste anaerobic digestion is mainly used in batch-scale installations rather than pilot-scale installations (Pramanik *et al.*, 2019a). Most of the previous researches studied the biogas production from the anaerobic digestion of food waste at lab-scale installation (Pramanik *et al*., 2019b). Anaerobic digestion performance in the batch scale differs from the pilot-scale (Carrere *et al.*, 2016). Therefore, this study aims to contribute knowledge on the performance of the batch pilot-scale anaerobic digestion of food waste, particularly for food waste from the Malaysian diet. The results obtained from pilot-scale application can be used to develop anaerobic digester components for scale-up versions to ensure the correct process and management before full-scale installation. Food waste has different properties based on the place, season, cooking style, and food processing method, thus it is important to study the influence of food waste generated from the Malaysian diet on the stability or efficiency of the anaerobic digestion process.

1.3 Research objectives

This study's objective is to investigate the performance of a pilot-scale anaerobic digester treating food waste. Consequently, this study embarks on the following goals:

i. To characterise the food waste (slurry) with respect to the solids and organic contents.
ii. To evaluate the performance of pilot-scale biogas digester fed by food waste (slurry) in terms of methane production at batch mode operation.
iii. To analyse the kinetic of anaerobic digestion of food waste (slurry) using Modified Gompertz and Logistic Function modelling.

1.4 Scope of research

The food waste was gathered from the cafeteria at UTHM. Impurities in food waste were separated. Food waste slurry was made using a 1:2 ratio of food waste to tap water (Lou *et al.*, 2012). The pilot-scale digester uses waste sludge taken from a full-scale anaerobic plant processing POME as inoculum. This study investigated single-stage anaerobic digestion of food waste (slurry) with an inoculum to substrate ratio (I/S) of 2.0. The total alkalinity (TA), VFA/TA ratio, pH, total solids (TS), volatile solids (VS), and chemical oxygen demand (COD) removal efficiencies were all monitored daily in the pilot-scale anaerobic digester, which was agitated at 70 rpm. A water displacement approach was used to measure methane production during the anaerobic digestion process. The Modified Gompertz model and the Logistic Function model were used to analyse the kinetic analysis of the anaerobic digestion of food waste (slurry).

1.5 Significance of study

Other researchers studying anaerobic digestion may find it useful to explore the anaerobic digestion using food waste (slurry) as substrate. This research sheds light on the potential of food waste as a methane-producing substrate. This study also contributes to the anaerobic pilot plant digester's operation and design considerations. This research provides information on the biogas recovery system, which degrades organic waste to produce methane, which can then be used for energy recovery. The Sustainable Energy Development Authority's (SEDA) vision of making sustainable energy a vital part of economic development and environmental preservation serves as the motivation for this study, which is in line with the national inspiration. Utilizing sustainable energy technologies to achieve energy security is SEDA's ultimate goal. The primary energy security issue in Malaysia was the over-dependency on fossil fuels; thus, using renewable energy other than fossil fuels was sought (Shadman *et al*., 2018). Ghafar (2017) reported that the government needs to enhance research, development, and innovation in the food waste management to develop the National Strategic Plan for Food Waste Management in Malaysia. This study also supports Strategy (4) of the Food Waste Management Development Plan for Industry, Commercial, And Institutional Sectors (2016-2026), which is the enhancement of food waste treatment at the source that involves the alteration of food waste to reusable resources, including energy (Jabatan Pengurusan Sisa Pepejal Negara, 2018). In addition, following the National Renewable Energy Policy, the Malaysian government aimed to reduce 40% of the carbon emission by the year 2030 subsequently elevate the generation of sustainable energy up to 20% along the year 2025 (Woon *et al*., 2021). Therefore, with the new carbon trading policy, the method of managing food waste with anaerobic digestion may become the future technique to address the country's climate crisis (Woon *et al*., 2021).

CHAPTER 2

LITERATURE REVIEW

2.1 Municipal solid waste (MSW)

Municipal solid waste (MSW) is the waste dumped or discarded in the household, commercial, or institutional settings (Bong *et al.*, 2017). Food waste, paper, plastic, textiles, metal, wood, glass, and other materials make up the majority of MSW (Dinie *et al.*, 2016). The composition of MSW in various nations is shown in Table 2.1, and food waste makes up the majority of MSW. Jakarta, China, and India recorded higher food waste than Malaysia; meanwhile, Western countries like the UK and USA produce less food waste. Developed countries such as UK and USA generate less food waste as they generate more metal waste meanwhile less developed countries such as Jakarta, Malaysia, China, and India generate less metal waste and higher food waste.

Table 2.1: The composition of MSW in several countries

Composition (%)	UK (Kumaran *et al.*, 2016)	USA (Kumaran *et al.*, 2016)	Jakarta (Kumaran *et al.*, 2016)	Malaysia (Kumaran *et al.*, 2016)	India (Sharma *et al.*, 2019)	China (Cudjoe *et al.*, 2020)
Food waste	34.0	28.0	65.0	38.4	52.3	52.6
Paper	23.0	27.4	12.0	17.6	13.8	6.9
Metals	4.0	8.9	1.0	3.1	1.49	0.5
Glass	6.0	4.6	1.0	4.1	0.9	1.6
Textiles/Rubbers/ Leather	17.0	8.7	2.0	5.3	-	4.7
Plastics	10.0	12.7	11.0	19.9	7.89	7.3
Wood	4.0	6.3	3.0	1.4	-	6.9
Dust/Ash	-	3.4	1.0	0.7	-	-

The waste product from household, food-processing factory, canteen, as well as restaurant are examples of food waste (Xiao *et al.*, 2018). Table 2.2 summarises the features of food waste in several Asian countries. Food waste has different properties based on the place, season, special handling, and collection technique (Li *et al.*, 2017; Xu *et al.*, 2017). The pH of food waste in the Asian region was reported to be less than 7. The VS/TS ratio shows the organic content. The VS/TS ratio of more than 0.5 indicates a higher organic content (Wang *et al.*, 2016). Therefore, the food waste in Asia can be categorised as high in organic content as indicated by VS/TS ratio higher than 0.8. Food waste in Asian countries has a chemical oxygen demand (COD) concentration exceeding 20,000 mg/L. COD indicates the amount of readily organic matter present in a feedstock (Ahn *et al*., 2020). According to Seswoya *et al.* (2019) and Xiao *et al.* (2019), food waste contains more carbohydrates than protein.

Table 2.2: The characteristic of food waste in Asian countries

Parameters	Malaysia (Pramanik *et al.*, 2019b)	Thailand (Hussaro *et al.*, 2017)	Malaysia (Seswoya *et al.*, 2019)	Singapore (Rajagopal *et al.*, 2013)	China (Xiao *et al.*, 2019)
pH	4.91	6.80	4.50	6.70	4.16
TS (g/L)	66.00	176.73	57.33	295.00	108.61
VS (g/L)	63.00	158.23	46.78	280.00	102.22
VS/TS	0.96	0.90	0.82	0.95	0.94
COD (mg/L)	110,000.00	280,00.00	753,66.67	394,000.00	161,870.00
Soluble COD (SCOD) (mg/L)	350,00.00	-	337,50.00	-	786,50.00
Carbohydrate (g/L)	-	-	13.98	-	57.07
Protein (g/L)	-	-	6.35	-	22.90

Table 2.3 tabulates the characteristics of food waste slurry (FWS) utilised as feedstock in anaerobic digestion for food waste (FW). The pH of FWS was also below 7, similar to the pH range for FW tabulated in Table 2.2. The FWS was still considered a high organic content feedstock, as indicated by the VS/TS above 80%. The COD content of FWS was also above 20,000 mg/L, similar to FW, and the FWS contains more carbohydrates than protein. Park *et al*. (2018) studied anaerobic digestion using FW and FWS. The study reported that the characteristics of the FWS slurry were slightly lower than the FW. However, the FWS was still suitable to be used in the anaerobic digestion process.

Table 2.3: The characteristics of FWS

Parameters	(Baldi *et al.*, 2019)	(Park *et al.*, 2018)	(Xiao *et al.*, 2018)	(Jiang *et al.*, 2013)
pH	3.80	-	4.18	4.59
TS (g/L)	199.00	96.99	106.90	205.30
VS (g/L)	160.40	88.48	100.60	199.50
VS/TS (%)	80.60	91.23	94.11	97.17
COD (mg/L)	-	111,240.00	151,100.00	-
Soluble COD (SCOD) (mg/L)	-	84,740.00	773,00.00	125,650.00
Carbohydrate (g/L)	74.00	-	56.85	-
Protein (g/L)	39.00	-	22.94	-

2.2 Municipal Solid Waste (MSW) Treatment/Disposal

Malaysia has trouble controlling the growth in municipal solid waste caused by a growing population and increased human activities (Kamaruddin *et al*., 2017). The improper disposal of food waste and ineffective food waste management significantly damage the environment (Kamaruddin *et al*., 2017). In Malaysia, MSW is managed through landfilling and incineration (Samad *et al*., 2017). Due to the biochemical process which is anaerobic biodegradation, the accumulation of MSW in landfills produces tremendous greenhouse gases(methane) (Johari *et al*., 2012) . MSW was mostly compose of organic waste that may undergo demposition process and produce gases such as methane and carbon dioxide (Khairuddin *et al*., 2016). The gases produced from the landfill are referred to as landfill gases (LFG), and they are made up of 50-60% methane (CH_4) and 30-40% carbon dioxide (CO_2) (Khairuddin *et al*., 2016). The growing volume of food waste in landfills, and its potential concerns, have piqued the scientific community’s interest towards food waste management (Xiao *et al*., 2018). In addition, the contamination of groundwater are brought on by the production of landfill leachate (Fan *et al*., 2018). Hence, the economic impact may be related to the cost of food wastage and the effect on farmers (Girotto *et al*., 2015). It is reported by Papargyropoulou *et al*. (2013), the avoidable food waste brings negative impact on the income of the farmers and consumers. For the small farmers who lives in suburbs with difficulties in food security, the reduction of food waste may bring positive impacts on their source of income (Papargyropoulou *et al*., 2013). Meanwhile, consumers who lives in poverty, the avoidable food waste can be utilized as a source of food products that are nutritious, safe, and affordable (Papargyropoulou *et al*., 2013).

Incineration is very high-temperature combustion of waste or material (Izzati *et al*., 2020). The incineration method is expensive and requires high technology and energy to function well (Lim *et al*., 2016). Incineration was also rarely used for food waste management because the process creates air pollution (Lim *et al*., 2016). The incineration and landfill process is the more common methods utilized for food waste disposal; however, food waste is unfit for incineration because of the moisture contain in them, which can limit the application of the method and create environmental pollution (Lim *et al*., 2016).

Composting is a process of recovering nutrients through the formation of humid substances, and composting was used to treat food waste or digestate (Girotto *et al*., 2015). Composting may have negative impacts on the environment by using fossil fuel as a energy source during transportation and machinery operation and also fugitive emission of greenhouse gases (Bong *et al*., 2017). Moreover, composting facilities have varies cost depending on the scope, operating mode, operation, and maintenance cost (Bong *et al*., 2017). In addition, for waste management, composting method is utilized in a small cope (Izzati *et al*., 2020).

2.3 Anaerobic digestion of food waste

Due to the characteristics of greater moisture content and biodegradability, biological treatment is preferable for food waste rather than other technologies (Ariunbaatar *et al.*, 2015). Two biological treatments that can be implemented for food waste are aerobic and anaerobic (Ariunbaatar *et al.*, 2015). Anaerobic digestion was preferred over aerobic digestion due to several advantages, such as producing renewable energy, less land and space required, and digestate are reused as fertiliser or soil conditioner (Ariunbaatar *et al.*, 2015). Additionally, food waste is rich in nutrients, which makes it a superior substrate for anaerobic digestion (Zhang *et al.*, 2018).

Anaerobic digestion is used worldwide to reduce food waste (Li *et al.*, 2018). Anaerobic digestion of food waste can yield up to 70m^3 of methane per year (Shi *et al.*, 2018). On the report of Paritosh *et al*. (2017), the methane yield of anaerobic digestion of food waste occurs in a 5L working volume reactor, and 10 L working volume resulted in the methane yield of 530 mL CH_4/gVS and 464 mL CH_4/gVS, respectively. In a number of nations, including Turkey, India, and Sweden, anaerobic digestion has been developed for the generation of biogas (Lora Grando *et al*., 2017). In Turkey and India, the biogas produced was used for heating the greenhouse and households. While in Sweden, a biogas-powered train was implemented (Lewis *et al*., 2017; Lora Grando *et al*., 2017). In Kyoto, anaerobic digestion of food waste was practised towards minimising the fossil fuel utilization, supporting the Kyoto Eco-Energy Project (KEEP) program. Since 2005, KEEP has been practised using food waste to generate methane that was later used for power generation (Ike *et al*., 2010).

2.4 Benefits of anaerobic digestion

Conducive to recover energy (methane) from other organic waste and manage the MSW, anaerobic digestion was adopted (Campuzano & González-Martínez, 2016). It is suggested that anaerobic digestion is a practical way to process waste that contains a lot of energy and moisture while also providing renewable energy (Xu *et al*., 2018). The methane derived from the anaerobic digestion activity could be converted into renewable/clean energy to generate electricity and reduce the impact of fossil fuels (Anukam *et al*., 2019). Furthermore, methane has a high calorific value and can be used to produce sustainable energy (Krishna & Kalamdhad, 2014). Organic waste such as manure, sewage sludge, paper waste, food waste, and also fruit, and vegetable waste were some of the waste that can be employ for anaerobic digestion for energy recovery (Lim *et al*., 2022; Pavi *et al*., 2017; Silva *et al*., 2018).

Anaerobic digestion can be performed on various types of waste and applied in small-scale and large-scale digesters and at any geographical location (Xu *et al*., 2018). The management of waste like wastewater, sewage sludge, animal manure, and food waste frequently employ anaerobic digestion (Li *et al*., 2019). In 2016, the most significant biogas production was built in Europe, followed by Asia, the Americas, Oceania, and Africa (Kumaran *et al*., 2016). While in the year 2018, the United States had about 2000 facilities for producing biogas (Meegoda *et al*., 2018). It is reported that Germany fully utilised the anaerobic digestion technology towards biogas generation in which there are about 10,000 biogas plants (Kumaran *et al*., 2016). The number of anaerobic treatment plants for organic waste was slowly increasing in Malaysia, although incineration technology was still employed (Kumaran *et al*., 2016). Majorly, the waste generated in Malaysia is suitable to be implement as substrate/feedstock for anaerobic digestion. Nevertheless, Malaysia has a 6.30 MW of working volume for anaerobic digestion plants (Kumaran *et al*., 2016).

In Malaysia, sewage sludge, food waste, animal manures, and wastewater from palm oil mills are among the organic wastes that can be utilised as feedstock for the anaerobic digestion process to produce biogas (POME). Table 2.4 tabulates the anaerobic treatment plant for various wastes in Malaysia. All the waste stated in Table 2.4 except food waste was treated at the anaerobic treatment facility; however, for food waste, there is only a pilot-scale project regulated by Universiti Putra Malaysia (UPM), the Ministry of Housing and Local Government, Subang Jaya Municipal Council and the Malaysian Agricultural Research and Development Institute at Seri Serdang Market. It is reported by Woon *et al*. (2021) that the application of a commercial-scale anaerobic digestion reactor is still growing in Malaysia.

Table 2.4: The anaerobic treatment plants in Malaysia

Waste	Amount of substrate per year (m^3/year)	Owner	Methane production (m^3/year)	Energy potential (GW.h/year)	References
Palm mill oil effluent, POME	146,000.00	FELDA Besout, Perak	3.83×10^6	40.19	(Kumaran *et al*., 2016)
Sewage sludge	1,460,000.00	Indah Water Konsortium, Pantai Dalam	401.5×10^3	0.28	
Chicken manure	200.75	QL Poultry Sdn. Bhd	10.04×10^3	4.21	
Cattle manure	2,190.00	Malaysian Veterinary Services	45.55×10^3	0.19	
Food waste	803.00	Regulated by University Putra Malaysia, the Ministry of Housing and Local Government, Subang Jaya Municipal Council and the Malaysian Agricultural Research and Development Institute	-	0.26	(Woon *et al*., 2021)

According to Kumaran *et al*. (2016), the anaerobic treatment facility in Malaysia has been implemented in palm mill oil plants, wastewater treatment plants, dairy farms, and poultry farms. Although anaerobic digestion is used widely, according to Xu *et al*. (2018) and Anukam *et al*. (2019), adopting it for food waste is still challenging because of potential issues such VFA accumulation, process instability, foaming, and expensive shipping and operation. In many countries, food waste collection and segregation have become an issue in conducting anaerobic digestion of food waste (Woon *et al*., 2021).

Based on Table 2.5, the anaerobic digestion treatment plants for food waste were employed in various China states either as a mono substrate or co-substrate (Jin *et al*., 2021). China has implemented a proper food waste segregation and collection system, enabling them to conduct anaerobic digestion of food waste at treatment facilities. The food waste is thrown in plastic bags, which are later segregated from the waste stream in a different coloured bin (Woon *et al*., 2021).

Table 2.5: Anaerobic treatment plants in China (Jin *et al*., 2021)

Waste	Capacity (tonne/day)	Biogas yield (10, 000 m^3/year)	Location
Food waste	200	438	Qingdao
Food waste	300	551	Shenzhen
Food waste + sewage sludge	65+435	612-816	Changsha
Food waste + sewage sludge	200+300	561	Zibo

2.5 Anaerobic digestion processes

A biological process operating without oxygen in converting complex organic matter into a more straightforward chemical components are known as anaerobic digestion process (Pramanik *et al.*, 2019a). Hydrolysis, acidogenesis, acetogenesis, and methanogenesis are the four steps of the anaerobic digestion process (Pramanik *et al.*, 2019a). Figure 2.1 depicts the anaerobic digestion of the complex organic matter cycle, comprises of four stages: 1) hydrolysis, 2) acidogenesis, 3) acetogenesis, and 4) methanogenesis (Pramanik *et al*., 2019a).

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APPENDIX A

LIST OF PUBLICATION

Published:

Farizah Fadzil., Farihah Fadzil., Siti Mariam Sulaiman., A'isyah Mardhiyyah Shaharoshaha, Roslinda Seswoya. (2020). Methane production from the digestion of thermally treated food waste at 80°C. *Journal of Environmental Treatment Techniques*. 8(3). pp 1017-1022.

Farihah Fadzil., Farizah Fadzil., Siti Mariam Sulaiman., A'isyah Mardhiyyah Shaharoshaha, Roslinda Seswoya. (2020). Mild Thermal pre-treatment as a method for increasing the methane potential of food waste. *International Journal of Design and Nature and Ecodynamics*. 15(3). pp 425-430.

Accepted:

Title: Hydrogen yield and kinetic of wastewater from small-scale slaughterhouse
Submitted to: AIP Conference Proceeding
Status: Accepted

Title: Characteristics of co-substrates from a mixture of domestic sewage sludge and food waste
Submitted to: AIP Conference Proceeding
Status: Accepted

Title: Assessment of specific methanogenic activity from cow dung for potential producing of an anaerobic bacteria
Submitted to: International Journal of Integrated Engineering
Status: Accepted

APPENDIX B

VITA

Farizah Binti Fadzil was born in Alor Setar, Kedah, on November 1996. She received her early education at Sekolah Kebangsaan Sultanah Asma, in year 2009. In year 2013, she continued her education at Sekolah Seri Puteri (SSP), Selangor. Later on, she attended Kolej Matrikulasi Melaka (KMM) for her matriculation study. In year 2015, she pursued for a bachelor degree programme. She graduated from Universiti Tun Hussein Onn Malaysia (UTHM) in Bachelor of Civil and Environmental Engineering with honors in year 2019. She currently enrolling in a Master of Civil Engineering (M.Eng) at UTHM, Batu Pahat, Johor. Her current research interest is on the anaerobic digestion of organic waste and she was appointed as a Graduate Research Assistant (GRA) by the Research Management Centre (RMC) to perform her research.