GREENHOUSE GAS REDUCTION THROUGH MUNICIPAL SOLID WASTE MANAGEMENT AND ANAEROBIC DIGESTION SYSTEM

By

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Chairman : Mohd Zulkhairi bin Mohd Yusoff, PhD
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The challenge in municipal solid waste (MSW) management is on MSW production, which amounts to 11.2 billion tonnes annually, leading to greenhouse gas (GHG) emissions, pollutions and occupied landfills. The objective of the study proposed solution through the implementation of anaerobic digestion (AD) for conversion of food waste (FW) generated from residential area, yielding biogas and digestate. The survey on awareness and estimation of FW generation from was obtained from study area. Further, 500 L anaerobic digester system was fabricated and designed for self-operated, capable of degrading residential FW. Survey on 441 participants led to 70% of respondents ready to participate in segregation at source followed with estimation of 0.35 kg/capita/day FW generation. The study identified an organic loading rate (OLR) of 0.06 kg COD/L/day, through valuing chemical oxygen demand (COD), main parameter monitored due to the value range variability upon type of FW, performed at optimum level with yield a daily biogas production of 750 L on average, comprising mainly methane (60 – 70%) and carbon dioxide (30 – 40%) and utilized as cooking gas, while the digestate served as liquid fertilizer. Quantifying the data with SimaPro software illuminated the potential of GHG emissions reduction, registering at 0.215 kgCO_2eq. The study thus contributes insights into sustainable waste management and anaerobic digestion environmental impact, fostering informed decision-making for future waste management strategies.

Keywords: Anaerobic digestion, anaerobic digester, biogas, food waste, life cycle assessment.

SDG: GOAL 7: Affordable and clean energy

Abstrak tesis yang dikemukakan kepada Senat of Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENGURANGAN GAS RUMAH HIJAU MELALUI PENGURUSAN SISA PEPEJAL DAN SISTEM PENCERNAAN ANAEROBIK

Oleh

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Julai 2024

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Cabaran dalam pengurusan sisa pepejal adalah pada penghasilan sisa pepejal yang berjumlah 11.2 bilion tan setahun yang menjurus kepada pelepasan gas rumah hijau, pencemaran dan pemenuhan tapak pelupusan. Objekif kajian mencadangkan penyelesaian kepada isu terbabit melalui pelaksanaan pencernaan anaerobik untuk penukaran sisa makanan yang terhasil dari kawasan perumahan, menghasilkan biogas dan cecair cernaan. Prosedur bermula dengan tinjauan terhadap kesedaran dan penilaian penghasilan sisa makanan dari kawasan kajian. Seterusnya, sistem perncerna anaerobik 500 L difabrikasi dan direkabentuk untuk beroperasi-mandiri, mampu untuk menguraikan sisa makanan perumahan. Tinjauan dari 441 peserta menjurus kepada 70% maklumbalas bersedia untuk terlibat dalam pengasingan sisa dari punca dan disusuli penganggaran penghasilan sisa makanan berjumlah 0.35 kg/kapita/hari. Kajian mendapati kadar muatan organik 0.06 kgCOD/L/hari, melalaui penilaian keperluan oksigen kimia, parameter utama pantauan berikutan kepelbagaian julat nilai mengikut jenis sisa makanan, beroperasi pada tahap optima dengan menghasilkan

biogas 750L secara purata, mengandungi metana (60 – 70%) dan karbon dioksida (30-40%) dan digunakan sebagai gas memasak manakala cecair cernaan dijadikan baja cecair. Data dikuantiti dengan perisian SimaPro mendapati potensi pengurangan pelepasan gas rumah hijau, didaftarkan pada kgCO_2eq. Kajian seterusnya menyumbang dapatan pada pengurusan sisa mampan dan impak pencernaan anaerobik, memupuk perancangan berinformasi untuk strategi pengurusan sisa di masa akan datang.

Kata Kunci: Biogas, kebuk penguraian anaerobik, pencernaan anaerobik, penilaian kitar hayat, sisa makanan.

SDG: MATLAMAT 7: Tenaga bersih dan mampu milik.

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LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
APHA	American Public Health Association
CH_4	Methane
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CQI	Continuous Quality Assessment
EPA	Environment Protection Agency
Eq	Equation
FW	Food Waste
GHG	Greenhouse Gases
H_2S	Hydrogen Sulfide
HRT	Hydraulic Retention Time
kg	Kilogram
L	Litre
LCA	Life Cycle Assessment
MSW	Municipal Solid Waste
OFMSW	Organic Fraction Municipal Solid Waste
OLR	Organic Loading Rate
POME	Palm Oil Mill Effluent
SDG	Sustainable Development Goals
TS	Total Solid
UN	United Nation

UPM	Universiti Putra Malaysia
VFA	Volatile Fatty Acid
VS	Volatile Solid

CHAPTER 1

INTRODUCTION

1.1 Research Background

1.1.1 Municipal Solid Waste (MSW)

Waste production globally totalled 2.01 billion tonnes per year. This value corresponds to 0.5 kg of municipal solid waste (MSW) produced per capita across the entire human population (Das et al., 2021). In Malaysia, MSW generation per capita accounted at 0.8 - 1.2 kg/capita/day (Ghani, 2021). MSW is defined as any waste or rejected material produced daily such as food, paper and packaging materials, excluding chemicals and used medical apparatus which require a separate disposal method as translated from Malaysia Act 672 2007 (Kai, 2018). As projected, following the current trend of waste generation, it is estimated that by 2050, 3 billion tonnes of MSW will be generated per year (Selvam et al., 2021). The issues related to MSW include the availability of landfills, treatment at landfills, and environmental pollution, which encompasses air quality and human health concerns (Ng et al., 2023). The aforementioned issues may also result in the need for opening new residential areas, contamination of soil with toxins affecting agricultural activities, and pollution of clean water sources.

1.1.2 Food Waste (FW)

The problems arising from MSW become a growing concern among policymaker, authorities and waste management contractor in Malaysia, a developing country that may be facing the same problems in the near future. The increase in MSW production proportional with the increasing human population then reflected through human activities such as food preparation and consequently contribute to the generation of organic waste, which made up to 50% of total MSW generated (Mapa et al., 2019). Organic waste in general is categorised as FW, rejected food (Al-samet et al., 2021), waste generated from cooking activities and processed food that are disposed of. The organic waste term is used to describe waste gathered upon waste collection and later described as FW according to the scope of study. FW, a component of organic waste is one of the major types of wastes produced by Malaysians daily, with approximately 1.2 tonnes produced per day (SWM, 2018), and this amount doubles during the fasting month. FW is defined after segregation was made to remove any inorganic material that may disrupt the anaerobic digestion process (Choon et al., 2017b). FW which also termed as organic fractions municipal solid wastes (OFMSW) components that may utilised for the production of biogas via anaerobic digestion (AD) (Wainaina et al., 2020). It is a form of recyclable energy or green energy which is used as fuel for combustion.

1.1.3 Anaerobic Digestion (AD)

Tanah Merah landfill located in Seremban district, Negeri Sembilan is one of landfill that is still operating. The landfill estimated to reach its max capacity in less than 5 years. Though new landfilling technique implemented as intervention method to maximise land usage. Companies, institutes, municipalities, and organisations spend almost RM 1 million to dispose of the waste material (Ahmad et al., 2019). Since almost all the waste ends up in the landfill, it produces a lot of gases that may cause air pollution while the gas can be utilised as biogas that can fire up an engine and produce electricity (Abushammala et al., 2011). AD is a series of breakdown processes by microbes happening in the absence of oxygen. Bioreactor for the AD process is generally called an anaerobic digester(Uddin & Wright, 2021). Main product of AD is biogas and digestate. During anaerobic digestion process, FW undergoes four stages (hydrolysis, acidogenesis, acetogenesis and methanogenesis). Methanogens, which thrive during the methanogenesis stage, produce methane and carbon dioxide as they decompose the material (Basak et al., 2021). Several applications such as heat treatment, grinding, and addition of catalysts may speed up the reaction of AD. Through utilising the process of AD at the source of waste, it may reduce the amount of waste being sent to landfill. Thus, reducing the amount of greenhouse gases (GHG) being released to the atmosphere.

1.1.4 Biogas

Biogas is composed of methane (60% -70%), carbon dioxide (30% - 40%), small amounts of nitrogen and trace elements (less than 10%) (Harun et al., 2021). Biogas may have different composition depend on inoculum sources and feedstock such as cow dung and FW, respectively, with methane composed highest composition between 50 – 80% based on stoichiometry. A 15000 L anaerobic digester in Universiti Putra Malaysia (UPM) operated to treat FW produced from the cafeteria. The digester can treat up to 50 kg of waste per day and produces 1.5 – 2.15 m^3 biogas daily (Zulkifli et al., 2019). The potentials are projected to treat up to 100 kg of FW. AD system in UPM is considered as in-situ treatment as the FW is not transported outside of UPM compound and has great potential for implementation to premises or houses. Current project to implement the AD system starts with quantifying the amount of MSW together with the organic fraction. The anaerobic digester may be fabricated according to the amount of FW produced daily. Outreaching of currently operating AD to residents is the new direction to be parallel with emphasis on Sustainable Development Goals (SDGs) in providing sustainable cities, creating alternative green energy and reducing GHG in atmosphere (Khan et al., 2021).

1.1.5 Life Cycle Assessment (LCA)

Life cycle analysis is acknowledged as an accurate and comprehensive approach of cradle-to-grave analysis to assess the GHG emissions associated with all the stages of product or process stages (Zeller et al., 2020). In relation of the study to SDG, initiated by the United Nation (UN), recycling of waste and generation of renewable energy are related to SDG; Goal 7 Affordable and Clean Energy, Goal 11 Sustainable Cities and Communities, and Goal 13 Climate Action (Fusi et al., 2016; Walid et al., 2021). An end-to-end approach is established to identify the loophole that might exist through the AD process for a continuous quality assessment (CQI). The parameters were observed as maintenance and profiling upon application of AD process; pH, temperature, bioreactor size, mixing and aeration. Biogas and digestate are further characterised for utilization through gas chromatography and COD determination, respectively. Characterization of both outputs may aid in the GHG evaluation of the overall AD process with the baseline upon GHG emission per tonne FW. This will further complete the cycle of FW from being ended up at landfill sites in comparison to conventional waste management.

1.1.6 AD Implementation

Solid waste management generally involves the type of system and process, cost of operation, type of output, overhead cost, logistics and site of processing. Segregating the waste into its own kind such as paper, plastics and aluminium has been practised for many years (Warunasinghe & Yapa, 2016). Separated FW can be utilised to produce biogas which later can be used as cooking gas. Thus, creating a circular economy and positive waste management value of designated areas. However, there are several factors that need to be identified to prove that the system provides sustainability to the ecosystem (people and environment) consisting of the elements involved in solid waste management (Harun et al., 2021). Thus, the research aim is to quantify FW generation from study area, followed by biogas production from FW via anaerobic digestion through designated feeding regime, utilization of biogas and its impact on the environment through life cycle assessment. Empowerment of AD implementation through endpoint evaluation, critical point identification, troubleshooting and data analysis which then provide a comprehensive implementation evaluation and the impact of applying a digestion at residentials through LCA.

1.2 Problem Statement

1.2.1 FW Variability

The deficiency in accurately quantifying MSW generated from residential sources constitutes a significant impediment to the effective execution of AD initiatives. The broad spectrum of variations in chemical oxygen demand (COD) values within FW from residential origins further complicates the precise prediction of biogas volume achievable through anaerobic digestion, especially when employing custom-designed digesters. The absence of detailed data on residential waste generation and the complexities introduced by varying COD values hinders the strategic planning required for optimizing anaerobic digestion systems.

1.2.2 GHG Emission

Compounding this issue is the current estimate of greenhouse gas (GHG) emissions, which stands at 90,805 kgCO_2eq per tonne of MSW sent to landfill (Cenviro, 2022). To comprehensively evaluate the potential GHG emission reduction achievable through AD, there is an urgent need to precisely estimate the GHG emissions associated with this process and subsequently compare them with the emissions stemming from conventional landfill disposal. Addressing these challenges is imperative for assessing the environmental sustainability of diverse waste management approaches and determining the viability of AD as a more environmentally friendly alternative.

1.3 Objective

The research objectives are to quantify FW generation from study area, followed by biogas production evaluation from FW via AD through designated feeding regime, utilization of biogas and its impact on the environment through life cycle assessment.

1.3.1 Specific Objectives

1. To identify awareness level of residentials towards municipal solid waste generation.
2. To investigate the effect of increasing organic loading rates on the production of biogas from FW via anaerobic digestion, using 500 L anaerobic digester.
3. To evaluate the impact of anaerobic digestion in comparison with conventional municipal solid waste treatment system towards greenhouse gas reduction emission.

CHAPTER 2

LITERATURE REVIEW

2.1 Municipal Solid Waste (MSW)

2.1.1 MSW Generation

In the year 2020, the global volume of solid waste reached a staggering 2.24 billion tons, marking a noticeable increase from the 2.1 billion tons generated in 2019. A concerning aspect of this surge is its association with a carbon emission rate of 0.79 kilograms per individual per day (Maalouf & Mavropoulos, 2023). Equally alarming is the revelation that a substantial one-third of the total MSW remains uncollected, finding its way into open dumping sites and undergoing uncontrolled burning. Projections for the future paint a worrying picture, with expectations of 40 to 50 billion tons of total solid waste being generated globally by the year 2050 (Peces et al., 2014). Within this projection, MSW is estimated to account for 2 to 3 billion tons, reflecting a staggering increase of 30-50% in the generation of MSW (Rocamora et al., 2020). The per capita waste production statistics, ranging from 350 to 800 kilograms per year (Forbes et al., 2021), further underscore the magnitude of the waste generation challenge at a global scale and emphasise the urgency of addressing this escalating issue over the years (Mantovani et al., 2016).

2.1.2 Factors Contributing to MSW Generation

The escalation in waste generation can be attributed to a confluence of factors, prominently among them being the burgeoning human population. The efficiency of waste collection systems, the availability of segregation facilities, and the effectiveness of awareness campaigns also play pivotal roles (Ismail et al., 2020).

Furthermore, the deployment of conversion technologies, the availability of operational capital, the presence of incentives, and individual initiatives collectively contribute to the rise in waste production. Geographical location adds another layer to this complexity, with access to logistics often being contingent on the specific location (Gallardo et al., 2015). Legislative measures have the potential to curtail the quantity of waste generated by enforcing strict controls on material packaging and promoting recycling options. Notably, regions with lower economic status tend to generate a substantial amount of organic waste (Adeleke et al., 2021), shedding light on the socioeconomic dimension of waste generation dynamics. This multifaceted interplay of factors underscores the need for comprehensive strategies that address the diverse contributors to the surge in waste generation.

2.1.3 Impact of MSW

The environmental repercussions of waste mismanagement are extensive and diverse. Greenhouse gas emissions, a chief concern, contribute to climate change, while the accumulation of plastic in oceans poses a persistent threat to marine ecosystems (Yi et al., 2014). Nitrogen pollution exacerbates ecological imbalances(Wainaina et al., 2020). Haze resulting from open burning not only compromises air quality but also endangers respiratory health (Aslani & Taghipour, 2018; Zealand et al., 2017). The unpleasant odour emanating from improperly managed waste in open environments further compounds the local challenges (Shakil et al., 2023). Colourless gases released during such processes can have adverse effects on respiratory systems. On a more localised scale, health hazards, pest infestations, and spillage or overflow from main disposal bins create immediate threats. Drainage issues stemming from improper waste disposal can escalate to flash floods, compounding the environmental toll (Pheakdey et al., 2022). Additionally, the overall aesthetic value of an area diminishes with inadequate waste management practices. Recognizing these multifaceted impacts is pivotal for devising effective strategies to address and mitigate the environmental consequences of improper waste disposal (Kementerian Alam Sekitar dan Air, 2019; Omolayo et al., 2021).

2.1.4 Food Waste (FW)

MSW refers to total waste or often called garbage generated from everyday activities [cooking, gardening, cleaning] thrown away due to expired, malfunctioned and unused [packaging material, bottles, appliances] coming from home, schools, hospitals, premises and businesses (EPA, 2016). FW refers to food appropriate for human consumption being discarded, whether after it is kept beyond its expiry date or left to spoil. Often this is because food has spoiled but it can be for other reasons such as oversupply due to markets, or individual consumer shopping/eating habits (Yu & Jaenicke, 2020). Solid waste can be defined as material that is unwanted such as FW, yard waste and demolition or construction debris. In general, domestic waste generated are FW. On the other hand, commercial waste mainly consists of wood, glass, hazardous waste, e-waste whereas agricultural waste usually consists of husks, cotton-stalks, coconut-shell waste from agricultural activities (Jain, 2018). Generation of MSW in Malaysia is increasing due to human population growth, rapid urbanisation, economic growth and its multicultural society (Ren et al., 2018; Rodzi et al., 2019). Waste can be defined as any degraded materials or other unwanted surplus or rejected products that arise from human activities.

Currently, the human population contributes to the highest amount of MSW (Mantovani et al., 2016; Wainaina et al., 2020). It is reported that the composition of waste generated by Kuala Lumpur as the capital city of Malaysia with high population is FW (57%), followed by mix paper (17%) mix plastic (15%) and other (Saeed et al., 2017). Most studies in the cities of developing countries showed that the solid waste composition is high in organic material and contains less metal and plastic.

2.1.4.1 Impact of Food Waste

FW impacts directly on the environment through its disposal on landfill. It used up spaces in landfill due to clumping and its physical form change exerted by pre-landfill processing (Nasir et al., 2021). Therefore, there is a need for the digestion of the FW stems from the imperative to diminish waste, produce viable biogas, and efficiently optimise the quality of the horticultural compost-substitute product. This drive is rooted not only in waste reduction but also in the economic enhancement of the overall process (Meegoda et al., 2018). Conversely, for energy crops, the principal impetus lies in the generation of biogas as a valuable source of energy. In certain scenarios, plant biomass undergoes pre-treatment and stored, often in silage form, for subsequent utilisation as a feedstock for anaerobic digestion (Hijazi et al., 2016; Nordahl, 2018). This underscores the diverse motivations and methodologies associated with anaerobic digestion processes, reflecting both waste reduction and energy generation objectives.

2.1.5 MSW Generation in Malaysia

The amount of MSW being produced in Malaysia is 3,300 tons daily as reported by SW Corp (Abdullah et al., 2017; Sakawi et al., 2017; Rodzi et al., 2019). The amount is also increasing by year which requires authorities to provide another type of treatment specifically for organic waste. Waste management is considered as a factor to produce a sustainable environment, this goes with the fact that landfills use large areas to damp the waste and become a huge pile. There are 5 landfill that are operating in Negeri Sembilan (Anuar, 2019; Nasir et al., 2021) and one sanitary fill are located in Bukit Pelanduk and Sendayan operated by Solid Waste Management Environment (SWME) Sdn Bhd and Kualiti Alam. Without any intervention taken on FW management particularly, the lifespan of landfill is less than 5 years.

In Negeri Sembilan, it was reported approximately 500 tonnes of municipal waste are being produced daily in 2019. The amount of organic waste after segregation is minimum 50% from the total municipal waste. The total amount of organic fractions after collection are consistent with the amount of organic waste from residential areas. However, the numbers from residential are highly dependent on the activities and facilities provided by the municipalities for waste disposal (Saheri et al., 2012; Sakawi et al., 2017). There is lack of data on per house organic waste produced in Negeri Sembilan. A few reports are being done to study the behaviour of waste management by service providers and the respondent pattern of waste segregation (Budhiarta et al., 2012; Choon et al., 2017a).

2.1.5.1 MSW Generation from Residential

The amount of waste production per house ranges from 0.5 to 1.5 kg per household on average. The norm for a house with 5 people is equivalent to 0.3 kg of waste produced per individual. According to the Department of Statistics Malaysia, there are 216,000 houses in Seremban (area of studies) with an average of 4 people per house (Department of Statistics Malaysia, 2019). House to house waste collection is being done in residential areas while in village areas are centralised collection. For example, in Kampung LBJ located in the Labu area, they have 5 disposal sites. The problem of this method of collection is that the disposal tank capacity cannot load with the amount of waste which is commonly higher. Through survey, the villagers are preferred to dispose of their waste through burning and dumping either at their backyard or at designated areas in their village (Mapa et al., 2019). The development in Seremban has high chances of implementing house to house collection in every area in Seremban are much likely to be done as waste management is crucial criteria in a developing city. In relation to this study, the quantification of organic waste will be made by the assumption that every house is implementing house to house waste collection provided by the contractor that is authorised to collect the waste.

2.1.6 Waste Management Practices

Waste management practice required a collective effort from all levels of the community (Rahman, 2017). Although there are several alternatives that may generate renewable energy and reduce the amount of waste that ends up in landfill, the implementation required a definitive strategy from source to collection until the processing into renewable energy. People tend to segregate their waste by providing them the tools for them to separate. Tools such as specified bins are helping users to segregate their waste accordingly (Rangga et al., 2022).

2.1.6.1 Recycling and Waste Segregation

Recyclable waste such as bottles are easy to separate after use. Different for substances used as food packaging, it needs to be washed before being disposed of. The practices might require extra effort since the material might be contaminated before being collected (Selvam et al., 2021). As practised in most areas, recyclable material is usually being collected once a week since it needs to be accumulated before being collected (Alias et al., 2021). For organic waste which in this project includes FW, unused part of food ingredients, food leftovers and expired food materials, it can be segregated by preparing a specific bin for disposal (Lim et al., 2021). Besides segregation, another factor that is included in waste management is the frequency of waste being disposed of in collection bins which are located in front of house compounds (Abdullah et al., 2017). If the frequency is based on per week disposal, there are 4 groups of frequency which are every day, every two days, every three days and once per week. The pattern of waste disposal is important to design the size of digester and to gain an insight of daily waste production which are correlated with the pattern of human activities, lifestyle and expenditure.

2.1.6.2 Waste Management Obstacles

Financial constraints emerge as a significant challenge in waste management, impacting operational costs required to provide adequate collection and disposal services. This issue is exemplified in Negeri Sembilan, where waste management primarily involves a singular main disposal contractor without the support of other contractors in operation. Inconsistent waste collection exacerbates environmental issues, emphasising the need for streamlined and efficient waste management practices. Furthermore, the availability of facilities for proper waste disposal is crucial in encouraging individuals to dispose of their waste responsibly. Advanced waste segregation at the source is facilitated by such disposal facilities, promoting a more sustainable waste management system. Recognizing these challenges is pivotal for developing comprehensive waste management strategies that address financial, operational, and environmental concerns (Praveena & Aris, 2021)

Effecting change at the individual level necessitates periodic campaigns to instil a sense of responsibility across all strata of society. A more stringent approach involves legalising and enforcing waste management practices to ensure compliance across individuals, institutions, industries, and corporations. The current paradigms of waste management, encompassing practices like reuse, recycling, reduction, storage treatment, recovery, and disposal, need constant reassessment to address evolving environmental challenges (Pheakdey et al., 2022). Practical contingencies must be established in response to dynamic situations. For instance, during the national flood emergency in 2022, landfill facilities in Selangor became inoperable due to flooding. This underscores the importance of having alternative landfill options readily available to avert consequential damages.

2.1.6.3 Sustainable Waste Management

In 2019, the Environmental Protection Agency (EPA) reported a staggering 66 million tonnes of FW generated by food retail, food services, and residential sources. Alarmingly, 60% of this wasted food found its way to landfills. The EPA advocates for a sustainable approach to FW disposal, proposing a hierarchy that begins with prevention, followed by options such as donation or upcycling, feeding animals or leaving unharvested, and composting or anaerobic digestion. Notably, landfill disposal and application to the land are considered the least preferred methods (Rocamora et al., 2020).

Embracing sustainable waste management not only conserves resources but also contributes to a reduction in greenhouse gas emissions. Beyond environmental benefits, it has the potential to address social issues, such as providing sustenance to low-income families, fostering cleaner communities, creating job opportunities, and optimising capital expenditure by streamlining waste management practices. These comprehensive strategies (Forbes et al., 2021), showcase the multifaceted advantages of sustainable waste management in promoting both environmental and societal well-being (Sachs et al., 2022).

Components of waste management included waste collection, disposal method, type of feedstock, inoculum source, operation of digesters, pre-treatment, monitoring, utilisation of biogas, digestate management and cash flow. Waste-to-energy approach has become widely known and promisingly able to convert into products which may give return in the form of capital and benefits many parties including government and society (Noufal et al., 2020).

2.2 Anaerobic Digestion Implementation

2.2.1. Survey on Awareness

Survey is the feasible way of obtaining data of waste produced. The assessment of waste produced is based on the range of waste that is easy to choose by the participants. Survey on waste generation is crucial to understand the pattern which is affected by income capital, seasonal events and awareness level (Subhan et al., 2014). Pilot study is done to assess the suitability of the question before proceeding to mass survey. A low awareness of waste disposal may hamper poor waste disposal practices. Input on current practices and perceptions are required to make decisions on waste management strategies (Choon et al., 2017).

2.2.2. Waste Quantification

A waste management practices survey is being done to study the impressions of respondents towards the performance of service providers. MSW generation is generally related to seasonal events, festivals, ceremony, population, area density, types of building and collection. Survey found that MSW generation is typically higher than off season, although the number of populations remains the same over a short period of time. Seasonal events such as Ramadan, Deepavali and Christmas recorded an increase in MSW generation. MSW quantification is based on several methods; number of trucks, collection, truck load, waste disposal centre quantification, direct measure and self-measure. Sampling made by stratified and systematic sampling (Aslani & Taghipour, 2018).

2.2.3. Anaerobic Digestion

Anaerobic digestion, chemical process in which organic matter is broken down by microorganisms in the absence of oxygen, which results in the generation of methane, CH_4 and carbon dioxide, CO_2 (Zulkifli et al., 2019). Materials high in organic content, such as municipal wastewater, livestock waste, agricultural waste, and FWs, may all undergo anaerobic digestion (Loh et al., 2017). The methane gas produced may be collected and used directly as a fuel for cooking or heating, or it can be burned to generate electricity. Unlike the production of methane from gas wells, anaerobic digestion is a renewable source of energy (Ren et al., 2018).

The amount of methane versus carbon dioxide produced depends on the composition of the original organic substrate being broken down. Sugars, starches, and cellulose produce approximately equal amounts of methane and carbon dioxide (Steffen et al., 1998; Umar et al., 2012). As shown in Figure 2.1, when proteins and fats undergo anaerobic digestion, more methane than carbon dioxide is produced. Digested biogas typically contains a maximum concentration of 70% when fats are digested. Digested slaughter-facility wastes can produce approximately 60% methane.

Biogas production is also very dependent upon temperature. Anaerobic bacteria survive in a broad range of temperatures, but there are two broad categories of methanogens. Medium-temperature (mesophilic) bacteria thrive between 20 - 45 °C (68 - 113 °F), and anaerobic digestion using mesophilic bacteria takes place between 30 and 38 °C (86 and 100 °F). In contrast, the optimum gas-producing temperature range for high-temperature (thermophilic) bacteria is 49–57 °C (120–135 °F). Gas production can be maximised when the temperature is kept within those ranges and the feedstock is constant (Zhang et al., 2021).

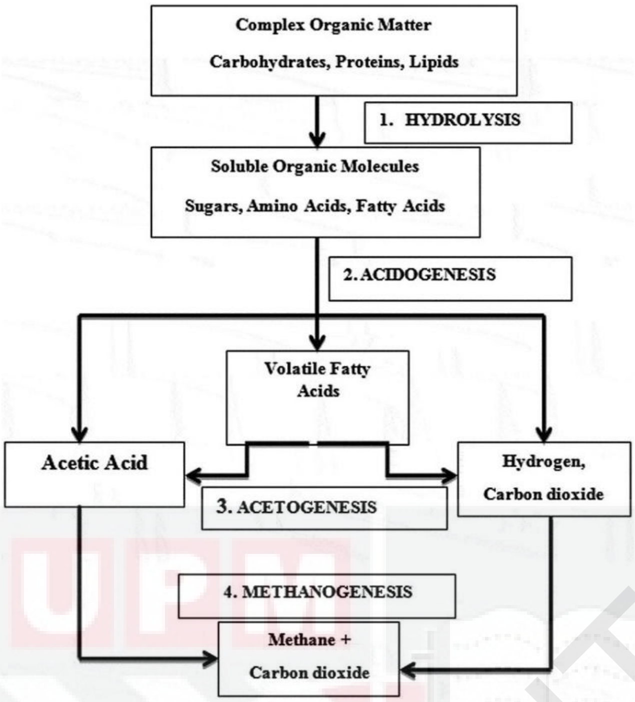


Figure 2.1: Anaerobic degradation process (Lindmark et al., 2014)

2.2.3.1 pH Effect on Anaerobic Digestion

PH value is measured upon anaerobic digestion and determined upon reading. pH 7 is the optimum value for an operational anaerobic digester. pH lower than 6 might indicate the build-up of volatile fatty acid (VFA) (A. Gao et al., 2017). Maintaining neutral pH is important in determining the digestate as the output. pH 7 is the optimal set point for ammonium release and gas production rate that acted for a reduced pollution and optimised gas production (Gonde et al., 2023). A higher pH value affects the stability of the AD process due to the rapid conversion rate of ionised ammonia nitrogen into free ammonia nitrogen which inhibits methanogenesis (Mohd et al., 2021; Sötemann et al., 2005). Besides, at pH 7 resulted in TS, VS and COD removal of 49.44 %, 50.91% and 38.92 % which is substantially higher compared to other pH values (Umar et al., 2012).

2.2.3.2 Temperature

Parameters such as temperature are essential to be monitored as it determines the optimum thriving of the microbial consortia and performance of anaerobic digestion. Two ranges of temperature for AD operation defined as mesophilic (25 – 40°C) and thermophilic (50 – 65°C). Whilst, thermophilic allows a higher loading rate, yield, substrate digestion, methane production and pathogen destruction (Babaei & Shayegan, 2020).

Temperature affects wastewater treatment processes at three different conditions; biological waste treatment, digestion processes, microbial growth and accelerated conversion process. Low temperature significantly affects the intracellular and extracellular environment of bacteria. Low temperature operation shows a decrease of biogas production after temperature dropped to 25°C. drop of temperature affects other important parameters; volatile fatty acid content, volatile solid, COD and concentration of free ammonia (Cioabla et al., 2012). Furthermore, temperature has a strong effect on the concentration of free ammonia, which is the important inhibitor rather than ammonium (NH_4^+). Free ammonia concentration increases with the increase in temperature by influencing the equilibrium (S. Gao et al., 2021).

2.2.3.3 Mixing

The homogenization of substrate within the anaerobic digester is a crucial aspect of the process, fostering a uniform environment conducive to microbial growth (Kawai et al., 2016)(Kawai et al., 2016). Achieving this homogeneity is typically executed through mixing, a fundamental operation that can employ methods such as a blade impeller or a water pump (Rocamora et al., 2020). Control measures for mixing involve parameters like pump action, flow rate, area coverage, vortex formation, and time frequency (Karlsson et al., 2014).

The choice between continuous and intermittent mixing strategies has notable implications. Continuous mixing may elevate the rate of the hydrolysis stage, leading to higher levels of volatile fatty acids (VFAs) within the digester. However, intermittent mixing, inherent in the design of semi-continuous digesters, has been demonstrated to enhance biogas production by 40-50% compared to continuous and minimal mixing modes (Babaei & Shayegan, 2020). The significance of mixing is further underscored by its role in bio flocculation formation within the digester. Maintaining adequate and optimal mixing conditions is therefore essential for achieving and sustaining optimum biogas production (Lindmark et al., 2014). This nuanced understanding of mixing dynamics contributes to the refinement of anaerobic digestion processes and the optimization of biogas yield.

2.2.3.4 Chemical Oxygen Demand (COD)

Chemical Oxygen Demand (COD) serves as a pivotal indicator, offering insights into the organic and inorganic content present within a substrate (Cel et al., 2013). In the context of anaerobic digestion, the reduction of COD is a crucial metric, serving as a reliable indicator of digester performance. Traditional methods for assessing COD involve the use of mercury as a reagent. However, contemporary alternatives in the market prioritise mercury-free options for safety considerations. Mercury plays a critical role in breaking down the material during the digestion process, and the quantification of organics oxidised by mercury becomes a key marker of organic concentration. To measure this concentration value accurately, a colouring agent such as potassium dichromate is combined with the reagent, producing a visible indication of the oxidised mercury. The unit of measurement for COD is typically expressed in milligrams per litre (mg/L). The ongoing evolution in COD measurement techniques reflects a commitment to safety, environmental consciousness, and precision in evaluating the organic dynamics within substrates undergoing anaerobic digestion (Mohd et al., 2021).

2.2.3.5 Total Solid and Volatile Solid

The investigation of feedstock characteristics constitutes a pivotal facet in comprehending the intricacies of AD performance. One salient parameter in this realm is the total solid (TS) content, (Gong et al., 2020) illuminating its impact on AD efficiency, particularly in the methanogenic pathway (Basak et al., 2021). Notably, a TS level of 20% correlates with a reduction in specific methane yield. This underscores the nuanced role of TS levels in dictating the outcomes of AD processes. Beyond methane yield reduction, the influence of TS extends to microbial communities, as demonstrated by Yi et al. (2014). Their study reveals a discernible shift in bacterial communities with an escalation in TS levels. The wet AD process, defined by TS levels below 15%, emerges as a viable and effective approach. Interestingly, when TS percentages are maintained below 20%, no significant disparities in methane yield are discerned, indicating the multifaceted role of TS, where lower levels are inversely related to moisture content.

In the domain of feedstock selection, wet AD processes, especially when employing FW, exhibit advantageous traits, showcasing elevated methane yield. An additional critical parameter, volatile solids (VS), serves as a pivotal indicator of potential methane production (Wang et al., 2020). The typical VS content of FW ranges between 73% and 98% (Pramanik et al., 2019). However, for FW sourced from canteens, a slightly lower VS content, possibly below 90% due to contamination, is observed (Yi et al., 2014).

In summation, the exploration of feedstock characteristics, notably the content of total solids and volatile solids, holds profound significance in shaping the dynamics of anaerobic digestion. Wet AD, particularly when utilising FW, surfaces as a preferred avenue, underscoring the imperative nature of comprehending and optimising these parameters for the efficient production of biogas.

2.2.3.6 Digester Design and Technology

Technology of anaerobic digestion can be distinguished into many aspects; digester scale, method of pretreatment process, type of substrate and its combination, parameter control, mixing, flow rate control and purification process. Anaerobic digestion is widely applied in treating palm oil mill effluent (POME) generated after palm oil processing (Amin et al., 2022). Companies such as FGV Berhad are having their own anaerobic digester for treating POME by reducing the COD value and generating biogas. The biogas is being utilised as electric generation at their palm oil mill plant (Aziz, Hanafiah, Gheewala, et al., 2020). Anaerobic digesters exhibit various characteristics that can be classified into different types, including inhomogeneous systems, solid phase, liquid phase, gas phase, time instability, and space instability (O. & O, 2016). This categorization provides insights into the diverse aspects and complexities of anaerobic digestion processes. (Babaei & Shayegan, 2020; Mir et al., 2016)

Geographically, the application of anaerobic digesters varies. In European contexts, a centralised digester model is prevalent, where waste is collected and transported to central facilities for processing (Connor et al., 2021). This approach optimises efficiency on a larger scale. Conversely, in Asian regions, particularly in Eastern Asia, there is a notable preference for small-scale digesters. These facilities are strategically located close to waste sources or residential areas, minimising travel distances and associated costs (Chin & Tee, 2018). The choice between centralised and small-scale digesters reflects the adaptability of anaerobic digestion strategies to the specific needs and logistical considerations of different regions.

2.2.3.7 Advantages of Anaerobic Digestion Implementation

The implementation of anaerobic digestion presents a compelling advantage in waste management by significantly decreasing the volume of waste, particularly organic waste, destined for landfills. In conventional waste disposal practices, MSW including FW, is compacted and sent to landfills, necessitating regular and rapid expansion of landfill capacity. Given that organic waste constitutes half of the MSW, landfills reach their maximum capacity swiftly. However, by opting for anaerobic digestion to treat FW, there is a substantial reduction in the quantity of organic waste directed to landfills (O.A. Adeleke, 2021).

Efficient source segregation, notably at the point of origin, enhances this reduction. As FW is diverted away from landfills through anaerobic digestion, valuable space within landfills is preserved for an extended period. This shift not only optimises landfill capacity but also mitigates challenges associated with FW liquid spillage, a common issue at central disposal areas in residential zones and during waste transportation. Consequently, the adoption of anaerobic digestion emerges as a strategic and sustainable approach to curbing the disposal of both general waste and FW to landfills, contributing to more efficient waste management practices (Abdelgadir et al., 2014).

Anaerobic digestion emerges as a pivotal and transformative solution, notably through the production of biogas—a renewable fuel. This not only resonates with the worldwide emphasis on sustainable energy but also underscores the environmental advantages inherent in the cleaner combustion of biogas compared to the direct burning of biomass. By prioritising this cleaner energy pathway, anaerobic digestion significantly mitigates environmental impact, aligning itself with the imperative for more sustainable and eco-friendly energy sources on a global scale (Whiting & Azapagic, 2014).

On another note, the AD process takes a leading role in promoting sustainable agriculture through the production of a nutrient-rich fertiliser. This not only serves as a substitute for conventional inorganic fertilisers but also plays a crucial role in enhancing soil quality. By actively addressing issues such as erosion and compaction, anaerobic digestion contributes to soil improvement. Furthermore, the application of the generated fertiliser fosters increased water retention in the soil, delivering tangible agronomic benefits. In essence, anaerobic digestion becomes a cornerstone for sustainable agricultural practices, offering a dual advantage of organic fertiliser production and soil enhancement (Harun et al., 2021).

The adoption of anaerobic digestion goes beyond mere waste treatment; it actively prioritises both public and environmental health. Through a substantial reduction in odours and pathogens, this approach not only ensures effective waste management but also contributes to the creation of a cleaner and safer environment. This underscores the broader positive impact of anaerobic digestion, extending its significance beyond the confines of waste treatment to actively enhance the well-being of communities and the ecosystems in which they reside (Feiz et al., 2020).

Anaerobic digestion goes beyond mere waste treatment by instituting a revenue-generating model. The collection of tipping fees from external sources of organic waste accentuates the economic viability of this approach, establishing a mutually beneficial scenario for both waste management and financial sustainability. This dual functionality not only ensures effective waste treatment but also underscores the economic feasibility of anaerobic digestion, positioning it as a sustainable and economically sound solution in the realm of waste management practices (Tanvir et al., 2022).

Anaerobic digestion boasts an indisputable advantage through its substantial role in reducing greenhouse gas emissions. By effectively curbing the release of methane (CH_4) and nitrous oxide gases known for their significantly higher global warming potential this method emerges as a pivotal player in the global effort to mitigate climate change. This underscores the environmental significance of anaerobic digestion, positioning it as a key solution in the broader strategy to combat the adverse effects of greenhouse gas emissions on our climate (Shakil et al., 2023).

Anaerobic digestion serves as a catalyst for fostering rural economic growth with a dual-pronged impact. Firstly, it stimulates job creation by necessitating a technically trained workforce, thereby contributing to skill development and employment opportunities in rural areas. Secondly, by creating markets for its diverse output, which includes valuable commodities like biogas and fertiliser, anaerobic digestion plays a pivotal role in fortifying a resilient and flourishing rural economy. In doing so, it not only addresses employment needs but also establishes economic sustainability by tapping into the market potential of its varied end-products (Khan et al., 2021).

2.2.3.8 Biogas

Biogas is a naturally occurring gas that is generated by the breakdown of organic matter by anaerobic bacteria and is used in energy production (Lim et al., 2021).Biogas differs from natural gas in that it is a renewable energy source produced biologically through anaerobic digestion rather than a fossil fuel produced by geological processes. Biogas is primarily composed of methane gas, carbon dioxide, and trace amounts of nitrogen, hydrogen and carbon monoxide (Slopiecka et al., 2022). It occurs naturally in compost heaps, as swamp gas, and as a result of enteric fermentation in cattle and other ruminants (Morales-polo et al., 2018). Biogas can also be produced in anaerobic digesters from plant or animal waste or collected from landfills. It is burned to generate heat or used in combustion engines to produce electricity. The use of biogas is a green technology with environmental benefits. Biogas technology enables the effective use of accumulated animal waste from food production and of MSW from urbanisation. The conversion of organic waste into biogas reduces production of the greenhouse gas methane, as efficient combustion replaces methane with carbon dioxide. Given that methane is nearly 21 times more effective in trapping heat in the atmosphere than carbon dioxide, biogas combustion results in a net reduction in greenhouse gas emissions. Additionally, biogas production on farms can reduce the odours, insects, and pathogens associated with traditional manure stockpiles (Al-samet et al., 2021). Figure 2.2 included capital, operating and other cost involved in biogas production to obtain a positive revenue through revenue channelled from sale of heat, electrical, biogas and digestate.

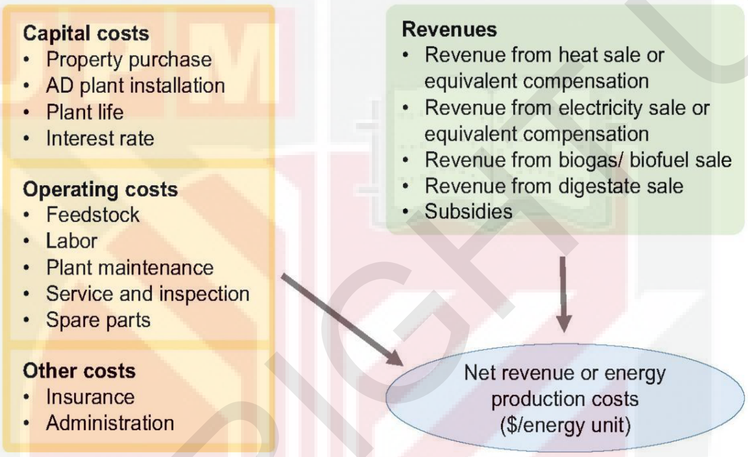


Figure 2.2: Differences of AD systems based on energy production cost and revenue.
(Source: Obileke et al., 2022)

2.2.4. Disadvantages of AD

Anaerobic digestion, a valuable waste treatment method, does come with certain drawbacks. Firstly, the process exhibits a long recovery time, requiring extended periods to regain normal operation after disruptions (Xu et al., 2015). Additionally, anaerobic digestion may not be as efficient as some other methods in removing pathogens and certain nutrients from treated waste. Its start-up period can be considerably extended, demanding patience and careful planning. Unpleasant odours can also be a concern, particularly in proximity to human habitation. The sensitivity of methanogenic bacteria to various chemical compounds poses a challenge, as significant variations can disrupt their activity, affecting overall process efficiency. Moreover, in middle- and low-income countries, the application of small- and middle-scale anaerobic technologies for solid waste treatment is relatively new. This novelty may present challenges in terms of adoption and optimization due to the lack of extensive experience and infrastructure. Recognizing these disadvantages is crucial for informed decision-making and the development of strategies to mitigate these challenges in the application of anaerobic digestion for waste treatment (Tong et al., 2018).

2.2.5. Application of AD

A prevalent industrial application of AD is the treatment of palm oil mill effluent (POME) before its discharge into rivers. In this process, POME undergoes preliminary treatment in a cooling and mixing pond before progressing to the anaerobic digester pond. This study observed the generation of approximately 16.63 kg of biogas per ton of POME, comprising 60% methane (CH_4), 36% carbon dioxide (CO_2), less than 7% nitrogen (N_2), less than 2% oxygen (O_2), less than 1% hydrogen sulphide (H_2S), and less than 1% ammonia (NH_3) (Amin et al., 2022). The produced biogas is efficient utilised by burning it in a gas engine to generate power. This power serves for internal use as electricity and contributes to electricity generation for grid connection.

Apart from biogas, the AD process yields digestate, a sludge enriched with nutrients. The liquid fraction of digestate is cycled back into the digester, promoting a closed-loop system. Meanwhile, the solid digestate is repurposed as fertiliser, benefitting agricultural practices. It is noteworthy that the final discharge into the river adheres to established environmental standards under the Environmental Quality (Industrial Effluent) Regulations 2009, part of the Environmental Quality Act 1974 (Act 127)

(Environmental Quality Act 1974, 2009). This adherence reflects a commitment to environmental responsibility and compliance within the parameters of sustainable waste management practices.

2.2.6. Feedstock

In a broad sense, any biodegradable material can serve as suitable feedstock for AD. Common examples include cow manure, agricultural residues, energy crops, and organic fractions from municipal waste, as well as industrial waste like palm oil mill effluent (POME) (Amin et al., 2022). The effectiveness of AD is heightened when dealing with feedstock exhibiting high moisture and organic content, aligning with the natural conditions of the AD process. However, it is crucial that feedstock is free from contaminants, toxic compounds, and indigestible materials, such as paper, ensuring optimal conditions for microbial nutrient provision during the AD process (Keng et al., 2020).

Anaerobic digestion is particularly renowned for treating organic and liquid waste, given its propensity for processes occurring in environments with high moisture and liquid content. Industrial wastewaters like POME, OFMSW, agricultural waste, and energy crops are examples of feedstock commonly employed in AD systems (Yi et al., 2014). Co-digestion, where different feedstocks are treated within a single digester system, is a prevalent practice. This approach is especially valuable when some organic wastes lack sufficient methanogen content to initiate the anaerobic digestion process. For instance, cow manure is frequently utilised in digester commissioning or start-up processes, and co-digestion not only streamlines treatment but may also enhance biogas production due to the increased digestible content.

2.2.7. Feeding Regime

The biological conversion capacity of a reactor is pivotal in determining the viable input of volatile solids into the anaerobic digester. Overloading this capacity can have detrimental effects, leading to the accumulation of fatty acids that act as inhibitors, consequently resulting in a diminished biogas yield. Such overloading scenarios can instigate the proliferation of acidogenesis, causing a decline in pH levels and a mass die-off of methanogenic bacteria. (Igoni et al., 2007; Ray et al., 2013). Organic Loading Rate (OLR): The OLR describes the input rate of organic material per unit volume of the digester. The OLR can be defined as,

$$OLR = \frac{(Q \times COD)}{V} \quad \text{(Equation 1)}$$

where Q is the feed flow rate in m^3/day, COD is chemical oxygen demand in (kg COD/m^3) (a measure of organic material content in any substrate), and V is the reactor volume in m^3. The OLR depends on the substrate organic matter concentration, and the optimal rate is determined experimentally. Higher than optimal OLR can cause toxicity to the digester leading to a decrease in methanogenic activity, as discussed later. On the other hand, a lower than optimal OLR reduces biogas production. (Uddin & Wright, 2021)

Extant literature, as cited by Nagao et al. (2012), sheds light on optimal OLR and hydraulic retention times (HRT) for various fermentation processes (Kawai et al., 2016). For hydrogen fermentation, an OLR of 22.65 kg VS/m^3d over a 160-hour SRT was identified as optimal, while methane fermentation exhibited optimal conditions at an OLR of 4.61 kg VS/m^3d with an SRT of 26.67 days (Mohd et al., 2021). These findings underscore the significance of carefully managing organic loading rates and solid retention times to ensure the efficiency and stability of AD processes.

HRT refers to the duration for which feedstock remains within the reactor. It serves as a metric for measuring both the COD and biological oxygen demand (BOD) of the influent and effluent materials (Westerholm et al., 2019). Achieving optimal retention time is crucial for facilitating complete biological conversion. Thermophilic digesters typically operate optimally within a range of 12 to 24 days, while mesophilic digesters show optimal results within a slightly wider range of 15 to 30 days (Man-chang et al., 2006). This time frame varies based on factors such as the type of substrate, environmental conditions, and the intended use of the digested material (Feiz et al., 2020).

Several parameters, including OLR, HRT and temperature, require meticulous monitoring to prevent the instability of the digester (Shamurad et al., 2020). Keeping a close eye on these parameters ensures the efficient functioning and stability of the anaerobic digestion process.

2.2.8. Biogas Utilisation

Household digesters produce biogas that is directly burned in stoves and lamps. On a larger scale, such as in bigger plants, the biogas undergoes a drying process, and impurities are removed before utilisation (Fei et al., 2021). While biogas can be burned for heat or steam generation in boilers, its most common application is in combined heat and power (CHP) units, where it is used for electricity and heat generation. However, it is important to note that biogas, having a lower heating value compared to natural gas (600 btu/ft^3 vs. 1,000 btu/ft^3), is primarily due to its lower methane (CH_4) content, ranging from 50–70% compared to natural gas, 81–89% (Han, 2017).

To address this disparity, biogas can be upgraded into biomethane, a gas similar to natural gas, by removing carbon dioxide (CO_2). Biomethane has versatile applications; it can be injected into the natural gas grid, enabling distribution over longer distances, or compressed and used as a transportation fuel, commonly known as bio-Compressed Natural Gas (bio-CNG), suitable for vehicles adapted to use compressed natural gas (CNG). This upgrading process not only enhances the energy content of biogas but also expands its potential applications, making it a more versatile and valuable resource in the broader energy landscape.

2.2.9. Digestate

Digestate is defined as organic liquid and nutrient rich by-product from digester organic waste through anaerobic digestion process. It is characterised by its colour, odour, pH and COD value (Gong et al., 2020; Vasco-Correa et al., 2018). Due to nutrient richness, digestate is suitable to be used as liquid fertiliser. The simplicity of usage was determined by its liquid characteristics that have the same application of organic fertiliser. However, there is limited access to the usage of digestate as fertiliser through the fact that it depends on the availability of digester. Digestate characteristics or condition is dependent on the type of feedstock or substrate, type of processing, type of anaerobic digester and processing operation. The anaerobic digestion process reduced the contamination level however, without proper management, it would lead to environmental pollution such as harmful algal blooms, eutrophication and hypoxia.

2.2.10. Impact on Environment

The management of slurry from cow farms through AD presents a noteworthy opportunity for mitigating greenhouse gas (GHG) emissions, as demonstrated by E. Maranon et al. in 2011. Their findings indicate a substantial reduction in GHG emissions, ranging from 978 to 1776 $kgCO_2eq$ per year per livestock. Moreover, Andrew Whiting (2014) study underscores the potential of AD systems to achieve a 50% reduction in global warming potential compared to conventional waste treatment methods (Andrew Whiting, 2014). However, it is essential to recognize the nuanced environmental impact. Whiting reveals that while GHG reduction is a direct and positive outcome, there are trade-offs, such as a 25-fold increase in the potential for acidification and a 12-fold increase in eutrophication. These variations are notably higher than those associated with natural gas (Loh et al., 2017). The impact on land and water, though present, is of a lower magnitude, resulting in an overall positive environmental balance for AD implementation. It is crucial to consider factors such as feedstock type, digestate management, and application methods, as these influence the comparative performance of AD systems. In essence, the literature underscores the multifaceted environmental implications of adopting anaerobic digestion for waste treatment, emphasising the need for a comprehensive evaluation of its benefits and trade-offs (Hanum et al., 2019).

2.2.11. Impact on Economy

Minimising costs associated with fossil fuel consumption in waste management, creating additional revenue streams, and decreasing expenses linked to fertiliser inputs stand out as key benefits of anaerobic digestion. The enhancement of soil fertility further adds to its merits. However, the progress and expansion of anaerobic digestion projects often hinge on governmental incentives. Tipping fees, ranging between \$30 and \$50 per ton (Alves, 2023), contribute to the economic viability of this approach. While the utilisation of biogas as a transportation fuel is a plausible prospect, it demands higher initial investment capital. The success of anaerobic digestion projects is also influenced by geographic factors, including the location of the digester and the logistics involved in transporting feedstock from its source. Notably, in Europe, a significant number of anaerobic digestion operations are subsidised by governments and benefit from various state capital incentives (Burneo et al., 2020).

2.3 Life Cycle Assessment (LCA)

Life cycle analysis provided a comprehensive data tabulation on waste management. In Europe, LCA has been done widely and provides latest info in terms of performance in waste management. The availability of the technology made the study and research can be done comprehensively. Although the technology is only available at one level, it is enough as the data can be collected to understand, improve and optimise the system (Shi et al., 2015).

The comprehensiveness of LCA made researchers able to develop a comprehensive model out of data input that include the unit factor start from upstream until downstream. It has various focuses which are mainly related to environmental perspectives such as greenhouse gas emission, land area usage, contamination level and eutrophication (Yang Li et al., 2022).

The LCA method starts with goal scope and definition. It required a directive understanding as the data needs to be compiled and consistent. The functional unit can be varied depending on common units used in previous study or being used by the industries. System boundaries are formed to designate the process outflow and identify all the elements included in from input to output and its formation of cycle between cradle-to-grave or cradle-to-cradle (Ismail, Idaty, et al., 2020).

The situation in Malaysia, most of the reported journals mention the potential outcome by applying the anaerobic digestion in waste treatment. As for existing technology is available and widely applied on POME treatment. Due to its availability, consistency, and mass amount, it is efficient in terms of cost and return on investment for the application of anaerobic digestion (Amin et al., 2022).

2.4 Sustainability

Sustainability requires an integrated approach to achieve its objectives. Main factors such as economy, social and governance (ESG) plays an important role in order to maintain and act upon any decision made by the policy maker. (Mohammad & Wasiuzzaman, 2021) In the end of 2019, novel-Coronavirus disease 2019 (Covid 19) starts infecting humans where many early cases are reported to happen in China. Since then, the virus has been infecting humans worldwide and causing all countries to enforce a lockdown, preventing human contacts to stop the transmission of the disease (Das et al., 2021). It causes low productivity, high debt and salaries lost due to the stagnant economy cycle. Eventually, a positive impact on the environment was reported due to the decrease of human activities such as driving and construction. Sustainable development means inculcating or to embed the process of maintaining human needs like farming while preserving the environment for future generations (Basir, 2016)

2.5 Sustainable Waste Management

Opting for a 100% sanitary landfill approach stands out as the preferable waste disposal method, primarily due to its minimal contributions to eutrophication, global warming, and photochemical oxidation impacts, as suggested by Saheri et al. (2012). This method, despite being the current waste disposal practice in the country, is not considered environmentally favourable. The need for a sustainable waste management approach goes beyond environmental concerns and extends to social, economic, and national dimensions. As waste management becomes an integral part of the national agenda, discussions focus on new approaches, future planning, and the positive components of such strategies.

A robust waste management system not only mitigates environmental impacts but also addresses social and economic aspects. Effective waste management contributes to the reduction of health risks, promotes cost-efficient practices, and aids in environmental conservation (Mapa et al., 2019; Banks et al., 2011). While the implementation or enhancement of such practices may necessitate new technologies, such as anaerobic digester (Figure 2.3), expertise, and operational costs, the potential return on capital investment can be effectively managed. In essence, a comprehensive waste management strategy emerges as a pivotal component in the pursuit of sustainability, touching on multiple facets crucial for the well-being of society and the environment.

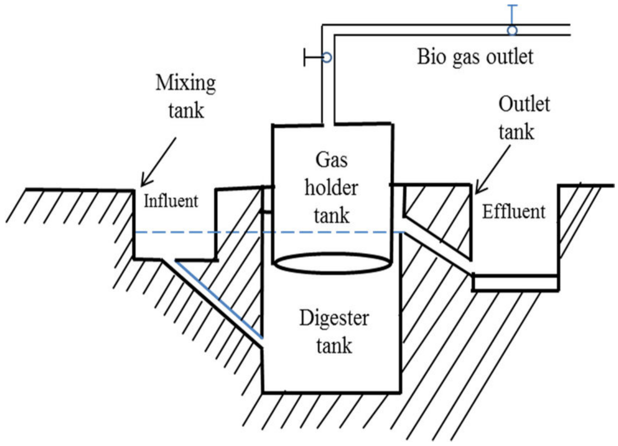


Figure 2.3: A schematic diagram of a typical pilot scale anaerobic digester for the production of biogas.
(Source: Rahman M. et. al., 2017)

2.6 Sustainability Development Goals (SDG)

Sustainable development goals (SDG), also known as Global Goals, adopted in 2015 by United Nations (UN) to organize a universal call to action with emphasis on 5Ps; People, Planet, Prosperity, Peace and Partnership. There are 17 SDGs, 169 associated targets which aim to be achieved by 2030. The idea is to integrate the 17 SDGs with action in one area which may affect outcomes to other which also may describe as development with balance on social, economic and environmental sustainability. The results for SDGs are ending of poverty, hunger, AIDS and discrimination against women and girls. Out of 17 SDGs proposed by UN, there are 3 SDG that are highly related to project on biogas from FW which are SDG 7, SDG 12 and SDG 13 (Sachs et al., 2022).

On Sustainable Development Goal 7 (SDG 7), UN have outlined a comprehensive set of objectives directed at reshaping the global energy landscape by the year 2030 (Lafortune et al., 2018). A primary focus is directed towards ensuring universal access to energy services that are not only affordable but also reliable and modern. A concurrent commitment within the SDG framework is the substantial increase in the share of renewable energy sources within the global energy mix, highlighting a significant shift towards more sustainable alternatives.

Parallel to these access and renewable energy goals, SDG 7 aims to achieve a doubling of the global rate of improvement in energy efficiency by the target year. The international dimension of these objectives is underscored by a commitment to foster enhanced cooperation, facilitating global access to clean energy research, technology, and investments. The ambition extends to making these advancements accessible to all nations, with a particular emphasis on addressing the energy needs of developing countries. This inclusive approach considers the unique challenges faced by the least developed, small island, and land-locked nations. The synthesized literature portrays a concerted effort outlined by SDG 7 to usher in a more equitable, sustainable, and resilient global energy paradigm. (United Nations, 2022)

Sustainable Development Goal 12 (SDG 12) encapsulates a holistic vision for global sustainability, centring on responsible consumption and production. This goal seeks to foster a shift towards more sustainable patterns of resource use and waste management worldwide. The primary focus is on reducing environmental impacts, SDG 12 addresses issues ranging from the management of natural resources to the minimization of FW and the environmentally sound handling of chemicals and waste. It sets ambitious targets for both developed and developing nations, promoting collaboration and leadership from those with advanced capabilities to drive positive change.

At its core, SDG 12 recognizes the pivotal role of businesses and public practices in shaping sustainable consumption and production. It advocates for the integration of environmentally conscious practices in business operations and encourages sustainable choices in public procurement. Furthermore, SDG 12 underscores the importance of information and awareness, aiming to ensure that individuals worldwide are equipped with the knowledge needed for sustainable lifestyles (Forbes et al., 2021). This comprehensive approach, balancing ecological considerations with economic and social dimensions, reflects the global commitment to a more sustainable, equitable, and responsible approach to consumption and production.

Due to human activities, development, opening of new area for industries and residentials, disposal of waste at open area and open burning, earth's temperatures have increased by 1℃ as in 2017. Assume that increase by 1.5℃ by 2025. Sea level rise has risen by more than 20 cm since 1880 which kept increasing and progressing to rise another 30-122 cm by 2100. SDG 12 embodies a comprehensive vision for global sustainability by emphasizing responsible consumption and production. The objective is to cultivate a shift towards more sustainable practices in how resources are used and waste is managed on a worldwide scale. SDG 12 is geared towards minimizing environmental impacts, addressing concerns such as the efficient management of natural resources, reduction of FW, and the environmentally sound handling of chemicals and waste. It sets ambitious targets for nations at various stages of development, calling for collaboration and leadership from those with advanced capabilities to catalyse positive change (Forbes et al., 2021; Razali et al., 2020).

Central to SDG 12 is the acknowledgment of the influential role of businesses and public practices in shaping sustainable consumption and production patterns. The goal advocates for the integration of environmentally conscious practices into business operations and urges the adoption of sustainable choices in public procurement. Additionally, SDG 12 highlights the significance of information and awareness, with the aim of equipping individuals worldwide with the knowledge needed to lead sustainable lifestyles. This comprehensive approach, which balances ecological considerations with economic and social dimensions, underscores the global commitment to fostering a more sustainable, equitable, and responsible approach to consumption and production. Although, following the SDGs may become a side line result which may be approved later for sustainability aspects. A clear objective on sustainability should become a priority for a project conduct such as including a projection, assessment, cost and return on investment (Razali et al., 2020; Sachs et al., 2022).

CHAPTER 3

MATERIALS AND METHODS

3.1 Project Concept

The big picture of the project occurred at three phases according to the objectives flow. At first phase, survey was conducted to assess three (3) factors; participants profiling, assumptions on MSW and FW generated per day and awareness. Awareness is the main priorities obtained for survey as to proceed second step of first phase; MSW collection from residentials. Characterization of MSW collected were made to fed FW into anaerobic digester. Second phase, operated AD using 500 L anaerobic digester fabricated based on previous AD project in UPM (Zulkifli et al., 2019). The design was scaled down for a real application at site. AD operation starts with digester commissioning, inoculum feeding, oxygen purging and biogas production. Phase three is the determination of environmental impact of AD implementation at residential area with targeted site used as example. As the main purpose of utilizing AD is to generate biogas, in parallel, it reduced the amount of FW sent to landfill which have become problem due to wet condition and leachate at landfill (Zeller et al., 2020).

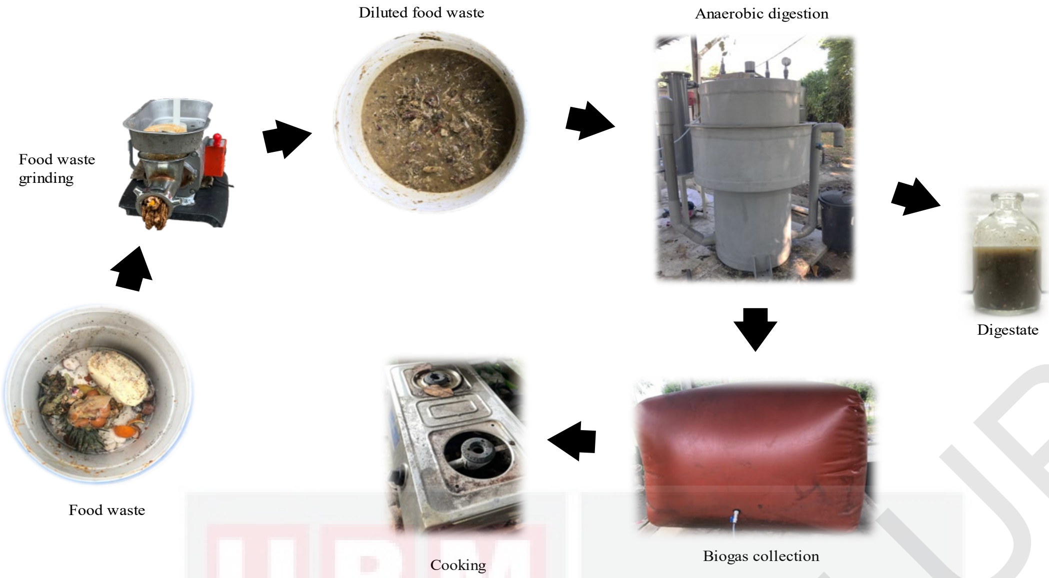


Figure 3.1: Flow of project start from collection of FW from residentials, feedstock preparation (grinding, dilution and physicochemical characterisation), anaerobic digestion, biogas collection and utilization. The awareness was done to obtain an early picture of future project implementation.

3.2 Study Location

Seremban district was chosen based on the accessibility, municipality status, population and waste management operation. Area of study comprised of four (4) area which included two (2) township, one (1) residentials area, one (1) educational complex and two (2) villages. Area listed in Table 3.1 are connected with main road, created a continuous traffic for logistics services. The coordinate for each area is as in Table 3.1.

Table 3.1: List of areas located within Seremban district and conducted study on survey and waste collection.

Area	Status	Coordinate	
Bandar Enstek	Township	2.746	101.784
Kota Seriemas	Residential	2.783	101.775
Kompleks Pendidikan Bandar Enstek	Educational	2.727	101.789
Bandar Seri Sendayan	Township	2.677	101.860

The proposed area for implementing the AD system is strategically located in the Nilai township area within the Seremban district. This region, originally developed as a plantation area and later acquired by the State Government for further development, offers an ideal setting for AD system deployment. Positioned centrally between Kuala Lumpur International Airport (KLIA) and Seremban, the area boasts excellent road access, facilitating smooth logistics and transportation. The ongoing development in Nilai enhances the potential for AD system implementation, ensuring effective waste management with minimal disruption. This prime location not only supports the efficient collection and processing of food waste but also provides a unique opportunity to gather valuable data on the systems performance in a rapidly developing urban environment.

The selection of the area as indicated in Figure 3.2 for survey and waste collection was driven by both convenience and the strong potential for implementing an AD system. This strategic choice helps to minimize unnecessary costs and logistical complications, which might otherwise arise from the need to alter plans, reassess schedules, or manage resident adaptation to new waste management practices.

Conducting the survey and waste collection in a conveniently located area within the Seremban district allowed for streamlined operations. The proximity to key infrastructure and the existing waste generation patterns made it an ideal candidate for AD system deployment. The area's accessibility and existing waste management framework reduced the need for significant changes to the current system, saving time and resources.

The areas suitability for AD implementation is underscored by its waste generation profile and the readiness of the local infrastructure to support such a system. Implementing AD in a well-chosen location ensures that the system can be integrated smoothly into the existing waste management processes, thereby enhancing efficiency and effectiveness. By selecting an area with a high potential for success, the project can avoid the pitfalls of deploying the technology in less suitable locations, where factors such as insufficient organic waste or lack of community readiness could hinder success.

By choosing an area where the AD system can be implemented with minimal modifications to the existing waste management practices, the project avoids unnecessary expenditures. There is no need for significant alterations to the current infrastructure, no drastic reassessment of waste collection schedules, and no extensive efforts to get residents accustomed to new practices. This approach ensures that resources are optimized, with funds and efforts directed towards the actual implementation and operation of the AD system rather than overcoming logistical challenges.

The choice of location also considers the likelihood of resident adaptation to the new system. Selecting a community that is already somewhat aligned with the goals of AD (e.g., familiarity with waste segregation or recycling practices) reduces the challenges associated with behaviour change. It also facilitates quicker adoption and smoother operation of the system, thereby maximizing its effectiveness from the outset.

Although the study focuses on a specific area within the Seremban district, the overall results are reflective of the district waste generation and management practices. This broader context allows for a comprehensive assessment of the potential impact of AD implementation across the district. By examining the waste generation data and AD effect on it, the study provides valuable insights that can inform wider adoption of the technology throughout the region, contributing to improved waste management and sustainability on a larger scale.

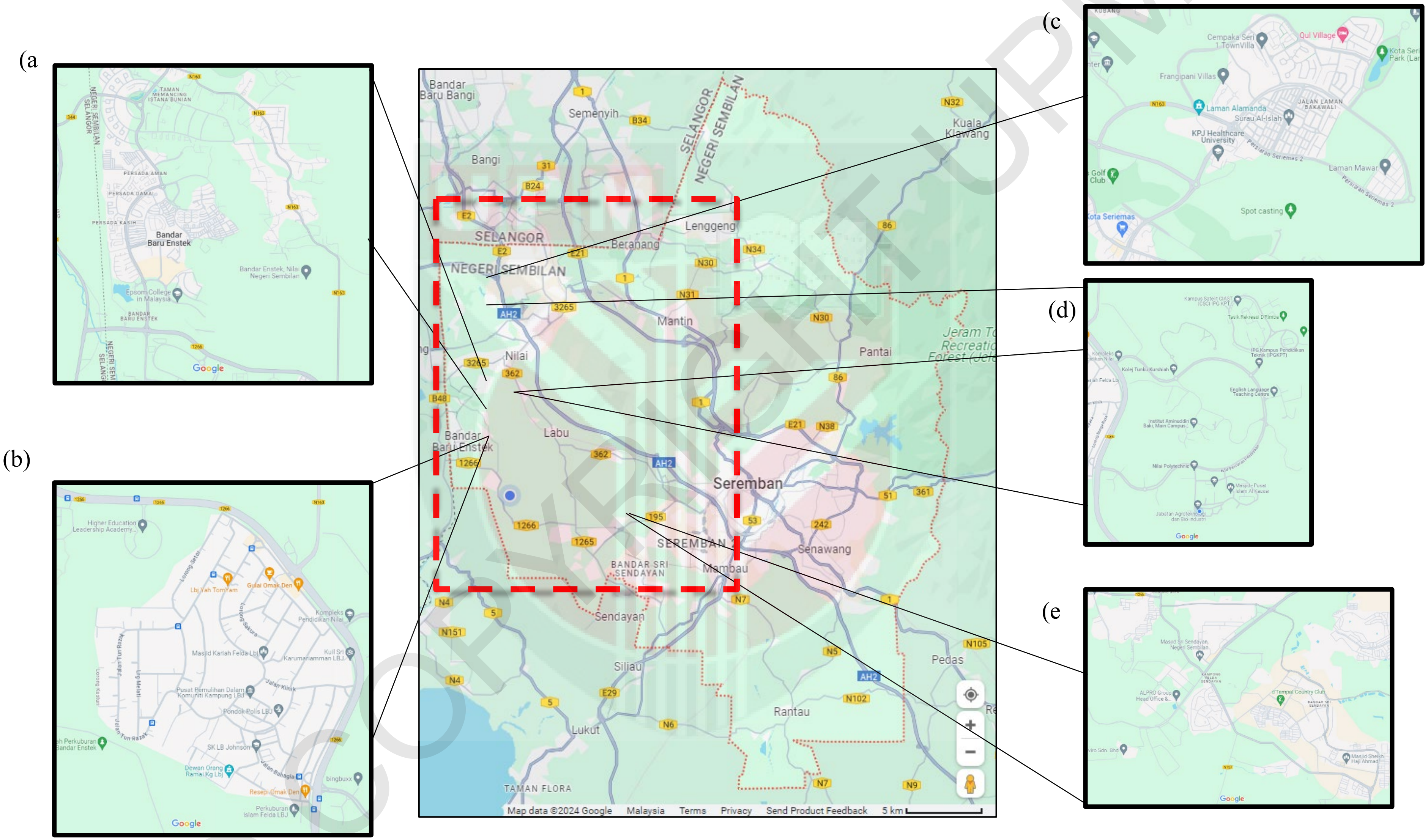


Figure 3.2: Map shown the area of study which included (a) Bandar Enstek, (b) LBJ village, (c) Kota Seriemas, (d) Bandar Enstek educational complex and (e) Bandar Seri Sendayan. (Google map)

3.3 Awareness Survey

Determination of organic waste produced from residential area in Seremban district was done through survey from March 2020 – December 2020. More than 400 samples were determined based on the table of sample size determination from a given population (Abdullah et al., 2017; Flanagan & Priyadarshini, 2021; Ouhsine et al., 2020). The survey was disseminated through two ways; face to face approach and online responds. Participants were randomly chosen from the population. Participants were being provided with a range of waste amount. The range indicated an approximate amount of waste being produced. The data was used to determine the amount of organic produced per person in a household.

3.4 Physico-Chemical Characterization of FW

3.4.1 MSW Collection

MSW was collected from residentials and food premises. The appointment was made before collection to ensure participants to dispose waste into the bin provided. A 10 L bin capacity was provided for each participant to aid in segregation and disposal procedure. MSW was collected the day after the waste was generated. MSW brought to the Biomass Technology lab site for the segregation process post-collection procedure. A total of 65 participants were involved in MSW collection and 5 food premises were identified and participated in the waste collection process.

3.4.2 Segregation

Malaysian food may be found to be gravy which have high lipid content. FW is defined as food leftover from plate, unfinished food, expired and unprocessed food. These types or conditions of FW are identified during segregation. To meet the requirement of anaerobic digester operation, indigestible material was separated and removed from FW collection (Kasmuri et al., 2023). Upon collection and segregation of FW, organic materials such as bones was separated (Feiz et al., 2020). FW was determined by the method of preparation. As in Malaysia, gravy foods are very common and it is very related to Malaysian culture. In segregating the waste, recyclable item is to be removed remaining only food related waste. The purpose is to be optimizing the performance of anaerobic digestion. The presence of fibre from woody material such as tissue are found to inhibit and slow the methanogenesis due to presence of cellulose (Connor et al., 2021; Rocamora et al., 2020). Plastic and other plastic fraction, paper box, metal was removed. Metal may rust and cause disrupt oxidation process inside digester.

3.4.3 Quantification of FW

The parameters determined are weight of organic waste, number of persons in their house, physical characters of the waste including gravy, state of waste and percentage of bones presence. The justification for gravy considering the mechanism of pre-treatments and projection of weigh before being feed into digester. Presence of bones are required as the instrument to crush down the bones are unavailable for the time being. The waste was placed in front of their house for collection prior to segregation.

Segregated FW was weighed and calculated as its generated per capita per day at study area. Below is the formula used to calculate the average FW generated per day (Mantovani et al., 2016).

$$\text{Average (kg/capita/day)} = \frac{\text{Total FW (kg)}}{\text{Household individuals (capita)}/\text{Day (d)}} \quad \text{(Equation 2)}$$

Averaging of FW production is one of important part in considering the strategy for waste collection, life cycle assessment and determination of anaerobic digester capacity (Rodzi et al., 2019). The amount of waste was correlated to the capacity of anaerobic digester (Atmika et al., 2019). Anaerobic digestion is a process with a long period of retention time. Although, digester used in this project was fabricated to cater HRT of 30 days. Therefore, the feedstock needed to be feed into the system daily for at minimum 30 days. Other factors to be considered are human activities in one month are varies and to have the monthly data will enable to assess the actual operational cost and output in one month.

3.4.4 pH, Total Solid (TS) And Volatile Solid (VS)

The pH of food waste (FW) was measured using a pH meter, with samples taken in falcon tubes before being fed into the anaerobic digester. This measurement was conducted for every batch to ensure optimal conditions for microbial activity during anaerobic digestion production (Jayaraj et al., 2014). Both the influent (before digestion) and effluent (digestate) pH levels were recorded to monitor the stability of biogas production. A stable pH is crucial as it indicates the acidity level of FW, directly influencing the anaerobic digestion process. While low pH can inhibit digestion, some reports suggest that methanogenesis can still occur under acidic conditions (Ajibade et al., 2015). Monitoring pH daily in both pre-treatment and post-feeding stages helps maintain optimal conditions within the digester for efficient biogas production (Tanvir et al., 2022).

Determination of total solid (TS) and volatile solid (VS) of FW was performed as characterization procedure. The TS level should be below 25% (Li et al., 2013; Lin et al., 2016). The crucible was cleaned, heated inside muffle furnace and dried overnight inside a desiccator chamber. The crucible was weighed using an analytical balance. A ground sample weighed 5 g was pipetted into the pre-weighed crucible. The crucible with the sample was placed inside the drying oven for 24 hours at 103-105℃. The crucible was cooled down in the desiccator chamber and weighed using analytical balance. The heating, weighing and cooling process was repeated to ensure a weight change less than 4%. The value of total solid was measured using Equation 3 (Franson, 1998).

The VS was continued using dried sample from TS procedure. The crucible with dried sample was placed inside muffle furnace for 2 hours at 550℃. The procedure was conducted according to appropriate safety measures; heating inside functioning fume hood and labelled usage. The muffle furnace was turned off and the sample was cooled down to room temperature before contained inside desiccator chamber and weighed to measure the percentage of VS using Equation 4. The procedure was repeated for determination of VS of digestate flow out from digester to compare the reduction percentages. All of the analysis was referred to the Standard Methods for the Examination of Water and Wastewater, American Public Health Association (APHA) (Franson, 1998) as per Equation 3 and 4 below.

Total solid defined as weight of dried residue per wet sample,

$$\%\ \text{Total solids} = \frac{(A-B)\times 100}{C-B} \quad \text{(Equation 3)}$$

Volatile solid defined as weight of residue after ignition per weight of dried residue,

$$\% \text{ Volatile solids} = \frac{(A\text{-}D) \times 100}{A\text{-}B} \text{ (Equation 4)}$$

A - weight of dried residue + crucible, mg,

B - weight of crucible,

C - weight of wet sample + crucible, mg, and

D - weight of residue + crucible after ignition, mg.

3.4.5 Chemical Oxygen Demand (COD)

The prepared food waste (FW) sample was diluted 1000 times using distilled water by pipetting 2 mL of the sample into 1000 mL of distilled water. From this diluted solution, 2 mL were pipetted into HACH HR digestion vials, suitable for a chemical oxygen demand (COD) range of 20 – 1500 mg/L. The samples were digested on a heating block at 180°C for 2 hours. The COD measurement was carried out using the standard method provided by the kit supplier, which included sample dilution to match the reagent range of 0 – 15,000 ppm. The COD level of the sample was then analysed using a HACH DR2900 spectrophotometer at a wavelength of 620 nm, with the COD values recorded in mg/L (Zulkifli et al., 2019). The COD value and COD removal percentage (%) were calculated using Equation 5 and Equation 6.

COD defined as amount of digested sample per liter solvent,

$$\text{COD (g/L)} = \frac{\text{Sample, mg}}{\text{Solvent, L}} \times 1000 \quad \text{(Equation 5)}$$

COD removal defined as difference on COD of influent and effluent per COD influent,

$$\% \text{ COD removal} = \frac{COD_{influent} - COD_{effluent}}{COD_{influent}} \times 100 \quad \text{(Equation 6)}$$

3.5 Biogas Production from FW using 500 L AD

3.5.1 Site Designation

Site designation played an important role in determining the logistics and efficiency of daily process. Waste segregation, processing, storage, anaerobic digester and digestate flow are main component in an AD process flow (Zulkifli et al., 2019). Current project site situated at lab facilities as pilot test but has comparable parameters for actual operation. The site for experiment is determined based on four (4) factors; population, traffic area, activities and main spot of attraction (Feiz et al., 2020). The determination of factor was done through survey and observation of the area. Previously, food premises were measured for its waste generation per day. This may give information on the size of the digester that to be fabricated (Kuo & Dow, 2017). This is to prepare the flow of process for people to dispose their organic waste properly. It is to ensure the waste did not attract pest and cause diseases. Besides to highlight to the residents that the site of operation is not a landfill. Project site also was setup with electrical and water source.

3.5.2 FW Preparation

Highly potential site to run the project are food court, apartments or flats, market and restaurant. In relation to the studies, the observations were made upon the rate of segregation of waste, daily volume of waste, activities that gave impact to production of FW and total carbon footprint. The method follows procedure on FW quantification as describe by Ismail, Ghazi, et al., 2020; Meegoda et al., 2018 and Zulkifli et al., 2019. The 10 L bin size was placed to the designated location and houses around the site of the study area (Figure 4) 65 participants were agreed to participate in the MSW sampling. The sampling was done every three days according to local garbage collection system. The collected samples were undergone pre-treatment which are inorganic composition such as plastic, can, paper, boxes and large bones size were segregated. Undigestible material was removed for prior to AD process. Grinding of FW will increase the surface area for digestion by microbes. This action assimilates human digestive system. The process can be done through grinding using food grinder, food crusher or industrial blender. A journals did mention the advantages of grinding (Tong et al., 2018) about biogas production. The meat mincer used to ground the FW brand Berjaya Steel Product, model BJY – MM12/S, Malaysia has a wattage of 650 W, a capacity to operate at 120 kg/hour, a dimension of 375x210x405 mm and weight of 26 kg. The grounded FW was diluted using water at 1:1 ratio to the respective OLR based on the COD of the FW. Initial COD was measured prior to the storage. The FW was stored in close container inside cold room before use in the following days with maximum of 5 days to avoid over storage inside cold room and lowered organic content.

3.5.3 Inoculum Source

Cow dung was collected from cow farm located at Ladang Pertanian, Fakulti Pertanian Universiti Putra Malaysia. Cow dung was used as it enables direct utilization and available at time for usage. Cow dung was ensured to be fresh; moist, mesophilic temperature (20 - 45°C), dark brown colour and has mild pungent smell. Stored inside a clamp type tank and immediately poured into digester for activation. Cow dung was diluted with tap water at 1:1 ratio. In this digester, inoculum was poured until reached full capacity of digester volume to ensure the commissioning process happened uninterrupted. The biogas generated was flushed out for three cycles to acclimatize the inoculum and ensure the digester's anaerobic condition. After the acclimatization process completed, the reactor was fed with organic waste as the main substrate. The procedure happened for 20 – 30 days where oxygen was removed totally.

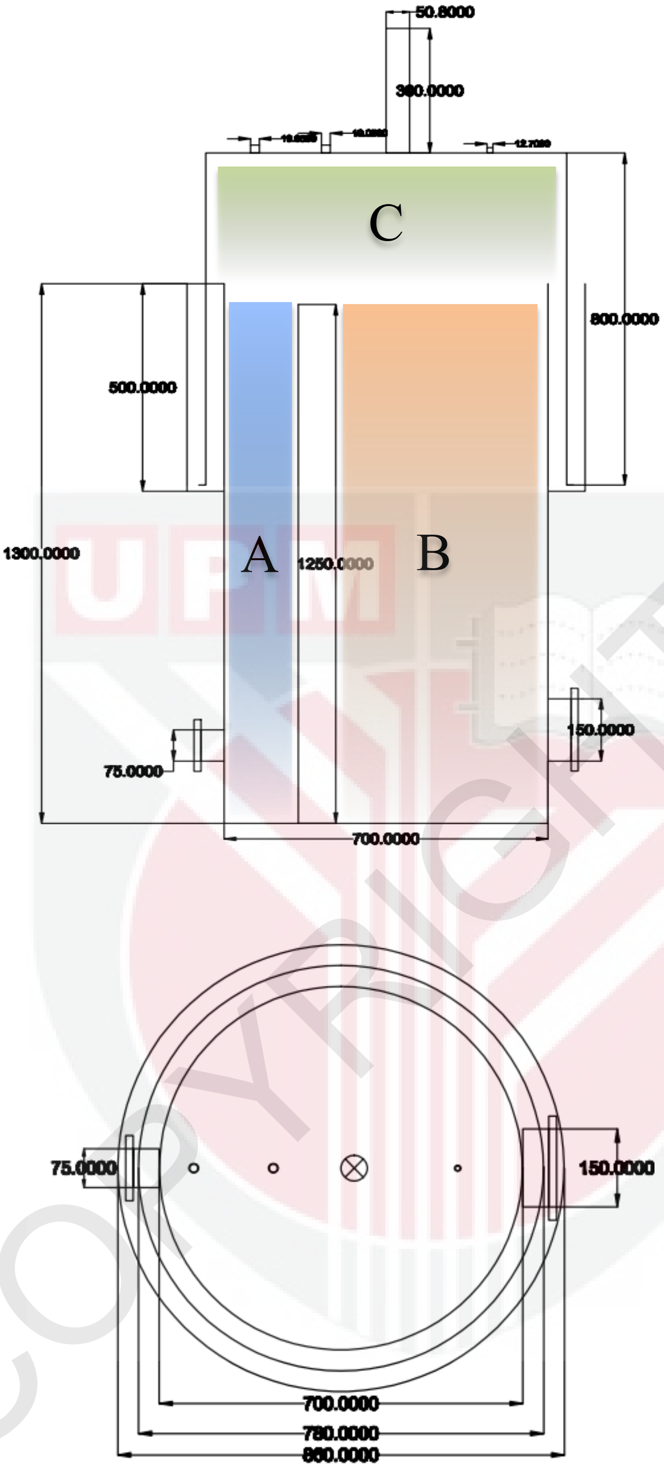
3.5.4 Anaerobic Digester

Anaerobic digester chamber divided into two partitions: digestion and liquid phase, divided by a wall of one inch drop from outflow height. The working volume of digestion chamber is approximately 350 L in volume, another 150 L designated to contained finished organic solution, the digestate. Digestion occurred in digestion phase partition as liquid phase partition and solids was filtered from flow out of the digester. FW fed through 50 mm inlet and effluent flow through outlet attached at the sides of digester. Biogas capture happened at the floating tank resided at topside of digester. The height increased when the gas produced as it trapped inside the floating tank. The valve released daily to flow biogas produced into biogas bag. Volume of biogas is measured using gas flow meter attached at gas pipeline. The collected MSW (procedure 3.4.2) from study was segregated into organic and inorganic fractions. Subsequently, organic fraction grounded into slurry form by mixing with water. The slurry organic fraction then fed into the anaerobic digester for the anaerobic fermentation process. The biogas was channelled through a piping system into the flow gas meter to measure the volume generated. The biogas was stored in a gas storage balloon for further application.

3.5.5 Anaerobic Digester Setup and Commissioning

The anaerobic digester was fabricated and maintained its operation by ensuring one way substrate flow and segregating newly fed food waste with finished digestate as depicted in Figure 3.3. The digester dimensions, as illustrated in Figure 3.3 (a), are crucially outlined. The digester boasts a height of 1.3 meters from the bottom to the chamber surface, with an internal diameter of 0.7 meters, resulting in a total volume of 500 litres. A separator wall, positioned at approximately 2/3 of the total volume, effectively divides the digester chamber into two distinct sections: the working chamber (designated as B) and the finished chamber (designated as A). Notably, the inlet measures 0.15 meters in size, while the outlet is slightly smaller at 0.075 meters, both serving to halve the inlet size and promote a one-way flow pressure from the working chamber. The designated area labelled as C in Figure 3.3 (a) serves as a disengagement zone, facilitating gas exchange, stabilizing pressure, and preventing substrate entry into the gas pipeline attached to the floating tank within this zone. The floating tank upward movement signifies gas production, generating the necessary pressure to propel biogas into the biogas bag. The site area was ensured to be gated to avoid any disruption from humans or animals. Any mismatched fittings were replaced with tensile material that may operate for long period. Initially, the digester is filled with tap water. The air pump is placed inside the digester to replicate the biogas produced when using the FW sample. The air pump is switched on until the gas balloon became inflated. Leakage was identified during the process indicated by low pressure reading and deflated gas balloon (Brambilla et al., 2012). The anaerobic digester may also classify as mesophilic anaerobic digester and anaerobic sequencing batch reactor type, which directed to the determination of temperatures, feedstock, volume of substrate and the retention period.

(a



(b)

Figure 3.3 (a)(b): Schematic diagram of anaerobic digester used to convert FW into biogas and effluent. The flow starts from inlet into A) the chamber where anaerobic digestion activities occurred, overflown into B) second chamber for a finishing step before flowing out of the digester every time feeding cycle conducted to fed feedstock into digester. C) Component is the headspace or disengagement zone, which act as buffer between substrate with top tank that covered the chamber top surface.

3.5.6 Biogas Startup Production under Different Hydraulic Retention Time (HRT) Feeding Regime.

Hydraulic retention time is used as baseline formation for anaerobic digestion (AD) process. Provided timeline of decided feeding regime to operate digester and biogas production. A range of biogas production are developed to obtain a guideline on operational digester employed on field in the next phase of project (Isni et al., 2016). Determination of HRT was made based on stability of digester which emphasized with volume of biogas produced, period duration, control.

HRT is defined as amount of volume, V, per volume of substrate flow, Q. Formula for HRT is as below:

$$HRT = \frac{V}{Q} \quad \text{(Equation 7)}$$

HRT - Day, d

V - Volume of reactor, L

Q - Flow of substrate, L/day

Two HRT value was set for this procedure, 100 days and 50 days with feeding value 1 kg and 5 kg, respectively. The FW was fed immediately after inoculum startup stage end. Each set was setup upon long period of time for a stability observation. The fluctuation of biogas production indicated the disruption of process and may be observed from the influent and effluent flow into and out of digester and low pH value.

3.5.7 Biogas production under increased Organic Loading Rate, OLR feeding regime.

Organic loading rate feeding regime is introduced to control the amount of organic content load into digester (Shamurad et al., 2020). Organic loading rate is efficient to determine an optimum range of AD operation (Atmika et al., 2019; Karlsson et al., 2014; Tanvir et al., 2022). OLR is defined as the amount of organic, COD, of substrate flow into the system, Q, per volume of the system, V. Formula to calculate OLR is as below:

$$OLR = \frac{[COD \times Q]}{V} \quad \text{(Equation 8)}$$

OLR	- Organic loading rate, kg COD / L / day
COD	- Chemical Oxygen Demand, kg/L
Q	- Substrate flow, L/day
V	- Volume of reactor, L

The value of OLR was manipulate in increasing order at five ranges with each value independent of each other. 0.02, 0.03, 0.04, 0.06, 0.1 and 0.12 kg COD/L/day. OLR value was determined based on baseline from HRT feeding. COD value of HRT feeding based was used to as reference determining the range of OLR. COD value, high and low, fluctuated biogas production.

3.5.8 Theoretical Methane Composition per 1 kg Food Waste

To estimate the theoretical biogas yield from food waste, the biochemical methane potential (BMP) method was employed. The food waste composition was first analyzed, assuming an average distribution of 50% carbohydrates, 30% proteins, and 20% fats (Mohamed Abdulrahman Al-samet, 2021).

$$\text{Theoretical Biogas Yield} = \left(\frac{A_1 \times A_2}{100} + \frac{B_1 \times B_2}{100} + \frac{C_1 \times C_2}{100}\right) \times \frac{1}{\text{D}} \times \text{E} \qquad \text{(Equation 9)}$$

A_1 - CH_4 Yield per Carbohydrate

A_2 - Carbohydrate Fraction

B_1 - CH_4 Yield per Protein

B_2 - Protein Fraction

C_1 - CH_4 Yield per Fat

C_2 - Fat Fraction

D - Methane content in Biogas

E - Process Efficiency

The theoretical methane yields for each component were considered as 415 L CH_4/kg for carbohydrates, 496 L CH_4/kg for proteins, and 1014 L CH_4/kg for fats. These values were then multiplied by their respective proportions in 1 kg of food waste to calculate the potential methane production for each component. The sum of these values provided the total theoretical methane production, which was converted to biogas production by assuming a methane content of 60% in the biogas. Practical biogas production was then adjusted for an estimated process efficiency of 70%, yielding an estimated practical biogas production value for 1 kg of food waste at 932 L biogas/kg food waste.

$$\text{Theoretical Biogas Yield} = \left(\frac{415 \times 50}{100} + \frac{496 \text{ x } 30}{100} + \frac{1014 \times 20}{100}\right) \times \frac{1}{0.60} \times 0.70$$

$$= 652 \text{ L biogas/kg food waste}$$

3.5.9 Chemical Oxygen Demand (COD)

The COD determination during anaerobic digestion procedure followed COD protocol in procedure 3.3.5. The COD determination was made prior to FW characterization AD and OLR calculation. Percentage % of COD removal was calculated using Equation 6.

3.5.10 pH and Temperature

pH was measured by sampling upon feeding at the inlet and outlet. A Falcon tube was used to store the sample. The sample was brought to lab and measured for its pH using pH meter model Sartorius, Germany. pH was measured daily to prevent any disruption on the process using specific instruments. The data will be recorded to check for any significant details to be considered as factors determining biogas production (Ajibade et al., 2015). Temperature was measured using a glass thermometer at the inlet and outlet.

3.5.11 Biogas Measurement and Collection

Biogas produced was measured using a gas flow rate meter, model JBD.5-SA, max flow rate of 4 m^3 per hour and a minimum flow rate of 0.025 m^3 per hour. Biogas is collected inside a 6 m^3 biogas bag attached through a pipeline. Biogas was sampled using a sampling gas bag per week based on the feeding regime and analysed for CH_4 and CO_2 percentage using a gas-spectrophotometer.

Gas chromatography (GC) model GC-8A brand Shimadzu, Japan, was used to measure the percentage of CH_4 and CO_2 from the total biogas produced. The peak measured the percentage of CH_4 and CO_2 formed using standard gas for CH_4 and CO_2, respectively.

The standard for CH_4 was tabulated in Appendix 1. The results were tabulated in Chapter 4 Table 2 below and a comparison was made for every feeding regime. Statistical analysis was made upon different feeding regime using Microsoft Excel Statistical Analysis Toolpak.

3.5.12 British Thermal Unit (BTU) and cooking time measurement calculation of biogas produced

BTU was calculated to estimate the amount of heat energy generated per feeding batch. The formula to calculate of BTU is multiply the volume of biogas generated with the biogas heating value (BHV), 24367 Btu/m^3. The formula is as follows:

$$\text{BTU} = \text{Volume of biogas (L)} \times \text{BHV} \quad \text{(Equation 10)}$$

$$\text{Cooking Time} = \text{Volume of biogas } (m^3) \times \text{BHV} \times \text{BTU} \quad \text{(Equation 11)}$$

3.5.13 AD implementation and biogas cost

In Table 3.2 outlined costs and benefits represent a detailed financial overview of implementing a 400-liter anaerobic digester system. This system is designed to convert food waste into biogas, a renewable energy source, and requires an initial and ongoing financial commitment to ensure its successful operation.

The primary component of the investment is the 400-liter anaerobic digester, which incurs a one-time cost of RM 30,000. This digester is the core of the system, responsible for processing food waste anaerobically (without oxygen) to produce biogas. In addition to the digester, there is an accessories cost of RM 10,000, which covers essential supplementary equipment. This includes a grinder for breaking down food waste into manageable sizes, a cement-based structure to house the digester securely, and a roof to protect the entire system from environmental elements. Together, these one-off costs total RM 40,000, which represent the major upfront investment needed to set up the system.

To ensure the digester operates efficiently and has a long lifespan, annual preventive maintenance is required. This is estimated to cost RM 1,000 per year and covers regular check-ups, minor repairs, and any necessary adjustments to keep the system running smoothly. Additionally, there is a labour cost associated with operating the system, calculated at RM 150 per month. This totals RM 1,800 annually and accounts for the salaries of workers responsible for daily operations, monitoring, and maintenance of the digester.

The cumulative cost, including both the initial setup and ongoing expenses, amounts to RM 31,600. The return on investment (ROI) is projected to be within 5 to 6 years. This means that the financial benefits derived from the system—primarily through savings on energy costs by using biogas as a substitute for traditional energy sources and reduced waste management expenses—are expected to offset the initial and recurring costs within this timeframe. After the ROI period, the system is anticipated to provide net financial benefits, making it a sustainable and economically viable investment in the long term.

Table 3.2: Summary of tangible and intangible costs upon AD implementation.

	Benefit	Cost (RM)
1	400 L anaerobic digester - one-off	30 000
2	Accessories - grinder, cement based and roof one-off	10 000
3	Annual preventive maintenance	1000
4	Cost for labour workers, RM 150/month	1800
Total		31600
Return of investment		5-6 years

Another method for calculation on the number of digesters required is as follows:

$$N = \frac{[M * COD]}{[V_R * K * OLR]} \quad \text{(Equation 11)}$$

Where N = number of anaerobic reactors; M = FW produced per day; COD = COD of FW; V_R = volume of reactor for FW digestion; K = the utilization rate of V_R; OLR = organic loading rate. From this formula, the number of digesters required in study area is estimated at 10000 unit.

3.6 Life Cycle Assessment and Impact Determination

3.6.1 Goal and Scope of FW Management

This project generally compares cradle-to-cradle of in-situ anaerobic digestion of FW with conventional cradle-to-grave approach of landfill treatment. The aspects to be assessed through LCA approach are the amount of FW generated, type of pre-treatment, electrical usage, fossil fuel usage, land usage, digestate and leachate treatment, biogas production, and biogas usage (De Menna et al., 2020; Omolayo et al., 2021).

The goals and scope of life cycle assessment onto this project are 1) To evaluate the environmental impact difference between in-situ AD of FW and the production GHG at landfill area, 2) To provide data on efficiency of in-situ AD and 3) To identify the impact of segregate and treating FW at. source on waste management with regards community, environment and economy in general (De Menna et al., 2020; Kuo & Dow, 2017; Razali et al., 2020). As a baseline, 1 tonne of FW is the basis for environmental impact analysis. Assuming that feedstock supplies might have disruption in the future, an optional method are to be prepared such as made networking with waste management contractors.

Environmental impact studies of anaerobic digestion treatment cause less impact to environment compared to landfill with the emphasize on: Greenhouse gas emission to atmosphere, release of leachate to land, land usage and electricity usage. Other aspects studied in this part of the project are cost of operation and operation management. Considering the elements of sustainability is the ability of this project to operate at long period of time with expansion that are directly affected by the amount of population of designated area. In this case, Seremban district which also may reflect on other peri-urban area worldwide.

The objective was determined using guidelines imprinted from ISO 14040 (Brancoli et al., 2017; Guan, 2016; Yang Li et al., 2022). Generally, the method emphasized on 4 stages of life cycle assessment: goal and scope, inventory analysis, impact analysis and interpretation (Ain et al., 2022). Production of biogas are the main scope in the studies of LCA for this project. The objectives were stated as purposely on life cycle analysis process in objectifying and determining the environmental impact which focuses on greenhouse gas emission (Fei et al., 2021). The main objective for this LCA studies is to compare the performance of anaerobic digestion treatment of FW from household and premise in reducing environmental impact with landfill disposal method. Three main scenarios are created based on data from previous objectives which also recorded the source of FW that has the potential of implementation of AD treatment system.

3.6.2 System Boundaries

System boundaries included 4 aspects regarding anaerobic digestion operation; FW characteristics, treatment process, end products and the environmental impacts. Two set of process as shown in Figure 3.4, anaerobic digestion and conventional waste management, started from waste generation from residentials. Boundary was limited in regard of waste movement from residential into each system. AD process bounded within the cycle started with FW, grinding, flow into 500 L anaerobic digester with the output of biogas and digestate which both indicated as output using Simapro. FW in Figure 3.4 indicate a segregation has occurred from residentials and the process of recyclable item is not included within anaerobic digestion system boundary. Utilization from anaerobic digestion cycle was indicated as recycling process which may show a reduction in environmental impact results. Current landfill treatment was bounded within operation as per mentioned by Cenviro and SWM in their annual report. The flow bounded within waste generation which then become MSW, transported to landfill using truck assigned by the contractor. The process become a cradle to grave as no recycling, recycling and utilization was available after dumped into landfill.

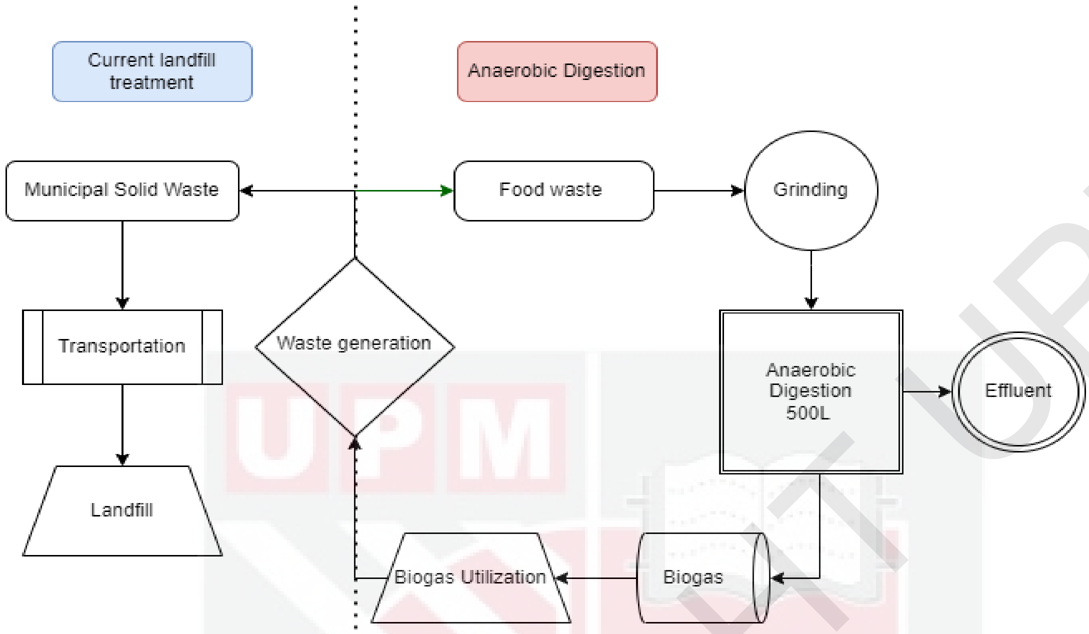


Figure 3.4: Flow of FW from the point of generation to two distinct processes. The right block, denoted by the label "Anaerobic digestion," denotes the proposed process pathway for AD in Seremban, as laid out in this effort. As the waste management provider in Seremban, SWM Environment and Cenviro implement the present landfill treatment process path.

3.6.3 Database and Analysis Methods

SimaPro software are commonly used in several report regarding LCA studies. Aziz et.al., (2020), reported that the software has been used to monitor the sustainability performance of a products or services (Aziz, Hanafiah, & Izzah, 2020; Tong et al., 2018b). Software is widely use as the enable researchers to tabulate the data and performed the analysis thoroughly. Several methods are used for studies of life cycle; ReCiPe, IMPACT 2002+ and Ecoinvent database (Ain et al., 2022; Harun et al., 2021; Yang Li et al., 2022).

In this study, three key tools were utilized for the Life Cycle Assessment (LCA): the ReCiPe method, Impact 2002+, and the Ecoinvent database. The ReCiPe method was applied to assess environmental impacts at both midpoint and endpoint levels, offering a broad analysis of potential damages across human health, ecosystems, and resource availability. Impact 2002+ was used to focus on specific impact pathways, condensing various midpoint indicators into key endpoint categories. The Ecoinvent database provided the foundational Life Cycle Inventory (LCI) data, ensuring accurate and comprehensive inputs for the assessment models. These tools collectively enabled a detailed and reliable evaluation of the environmental impacts associated with the processes under study.

3.6.4 Life Cycle Inventory

Life cycle inventory for this project is to identify the elements that involved in landfill treatment start from waste production until it reaches landfill and being treated. The inventories included transportation, type of vehicles, fuel consumption, energy used for treatment, and land area usage (Cenviro, 2021; Timonen et al., 2019; Vasco-Correa et al., 2018). In addition, the costing for AD operation was calculated to identify the possibility of economic sustainability through creation of circular economy (Burneo et al., 2020; Das et al., 2021; Maalouf & Mavropoulos, 2023). The component of costing included; cost of anaerobic digester, overhead cost, storing, and delivery. However, the parameter included were limited to costing of current operational.

3.6.5 Impact Assessment

Impact assessment was calculated using three methods that are available on Simapro which are ReCiPe, IMPACT 2002+ and Ecoinvent database (Harun et al., 2021; Saheri et al., 2012; Shi et al., 2015). Impact was solely focus on attribute of each AD process and conventional waste management toward GHG emission or climate change impact. The data obtained from experimental results and literature survey were input into the Simapro software. The input for each process integrated between raw materials, processes which included the amount of energy consumed and usage, water usage, product generated, disposal and recycling activities as per stated in life cycle inventories.

3.6.6 LCA Analysis Interpretation

Interpretation was made based on environmental impact, comparison between anaerobic digestion processes and conventional landfilling disposal methods, cost impact and management. Interpretation was made attribution for each type of processes was acquired from this study and literature survey. Consequently, comparison between system, the benefits, advantages are parts of discussion which are particularly required for implementation, future planning, policy making, job employment and environmental (Feiz et al., 2020; Lim et al., 2021; Tong et al., 2018a).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Awareness Survey Analysis

Awareness level was obtained to visualise the potential behaviour of residents on implementation of FW segregation in targeted area. These factors indicate the awareness level of residential which could translate into the possibilities of AD implementation. The survey result in Figure 4.1, 60% of respondent was not practicing segregation and 40% are currently practicing segregation. The response depends on factors such as availability of bin and benefits to household, although segregation is a crucial factor to increase the successes of implementing anaerobic digestion. Campaign conducted by waste operator happened regularly to increase the participant of segregation at source through monthly campaign. The activities may contribute to the increase in knowledge of residents' waste management. Capitalization, credit and token may embed to increase the segregation effort upon resident as it possibly could benefit both contributors and management.

To enhance the possibilities obtaining FW for AD, participants were asked for their readiness in doing segregation from their household. Average 78% respondents are shown their interest in practicing segregation. Figure 4.1 shows an increment of 21% agreed to perform segregation at source (SAS) which indicate a positive situation imposed by the residents upon implementation of SAS in Seremban district. Respondent may agree upon positive impact that might they obtain through practicing segregation. Increase in awareness should come with an emphasis on the need of segregation and contribution that may be made from the effort of segregation. Besides, the situation might aid in the process of FW collection in future. The big percentage also may indicate the participants to contribute by preparing necessary items to practice segregation. The sustainability of segregation process might be improved by providing special bin to discard the waste according to their types. Common segregation practices are separation between organic waste and recyclable materials.

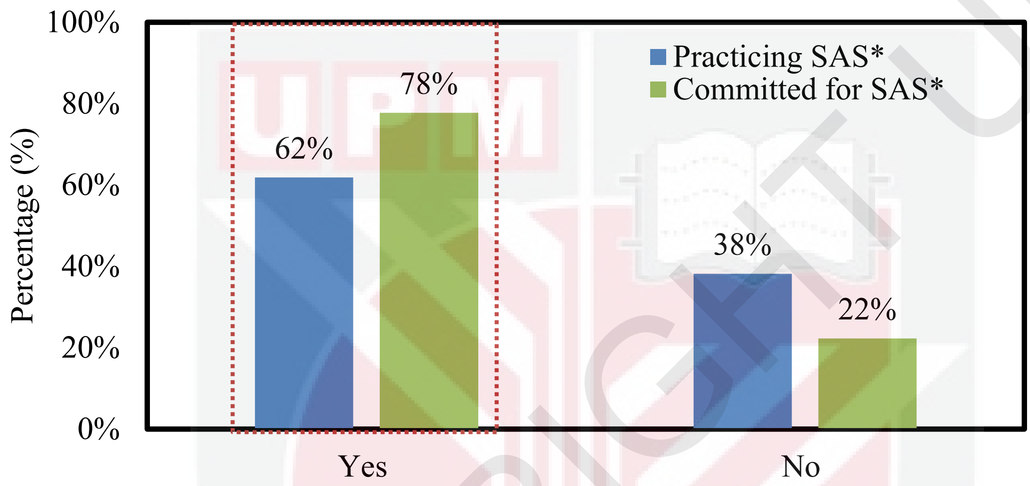


Figure 4.1: Pattern of practicing and committed to SAS* from total 441 survey respondents. Positive respond from respondents towards the practicing SAS* (red box), shown through increment of respondent chosen 'Yes' towards participation in SAS*, to which may enable the implementation of AD.
***SAS – segregation at source**

Disposal frequency is dependent on waste collection schedule, cooking activities and individual practices. The factors contribute toward the setup of AD system by assigning the collection time from houses. The importance of collection time is to avoid the FW expose to environment in prolonged period as to avoid infestation by pest, degradation and pollution as this would beat the purpose of implementing AD. The highest percentage of disposal frequency is everyday disposal, 35%, followed by 3-4 times per week which accounted for 29% of total respondent. Following the respondent answer in Figure 4.2, everyday collection is the most favourable practice by residents. In addition, possibilities of implementing AD system have a positive potential through continuous supply of food waste. The high waste disposal frequency indicates a steady supply of feedstocks over the course of the week, which is critical for maintaining the functionality of an AD system. Of particular note, the convenience of depositing waste in a central bin situated near residences may have contributed to the observed data. Furthermore, the waste collection by contractors also contribute to the answer by respondent.

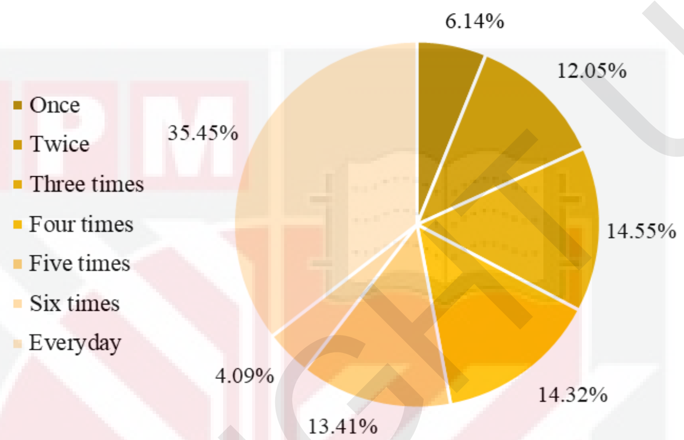


Figure 4.2: Weekly disposal frequency distribution by respondent from Seremban district. The frequency determined per week with everyday disposal is the highest frequency disposal followed by four and five times per week.

Figure 4.3 further clarifies a significant discovery derived from the survey on the spectrum of MSW and food waste produced by individual households. Regardless of family size or household membership, 64% of the respondents indicated that their MSW weight was below 2 kg (Figure 4.3). The maximum proportion of MSW, comprising 33% of the entire sample, lies within the category of 1.1 to 2 kg. This finding is in line with Choon et al. (2017), where the mean daily MSW generated per capita is 1.17 kg (Ng, Yeoh, Iacovidou, Ghani, & Yamaguchi, 2023). As stated, insight on awareness may gained through responses which in overall, most participants are unaware of the amount of MSW generated per day. Assumed that, residents do not own a measuring scale at home, besides, measuring MSW might be tedious for those who are already preoccupied with other commitments and works. Another factor is the pattern of disposal which related to the facilities provided at respondent's household. Fundamental issues are how to encourage people to reduce, recycle and reuse. Besides to adapt segregation practices by improvising facilities and services regarding segregation at source. Thus, a focusing studies on fundamentals issues are required to improve waste management in Malaysia.

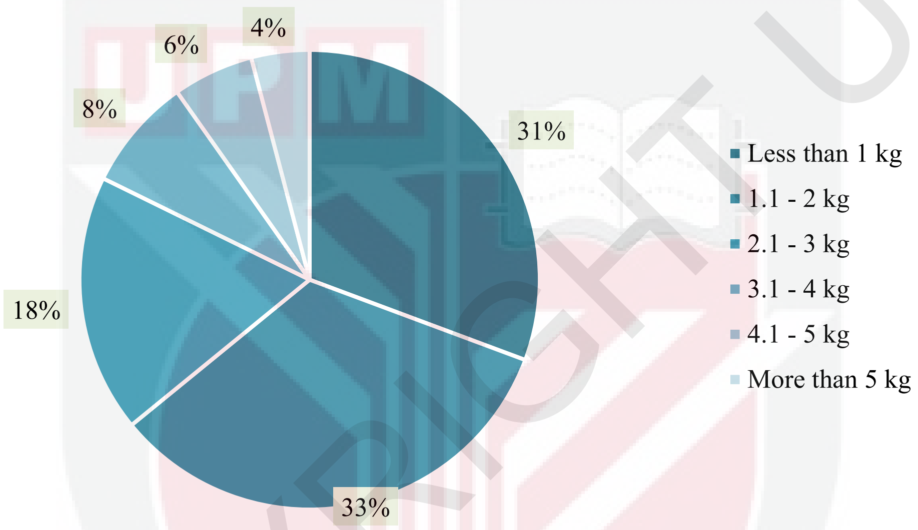


Figure 4.3: Percentage of respondents on range of MSW weight generated daily. Option of less than 2 kg of total MSW has the highest response by respondent. Factors such as availability of measuring scale might affect the response.

The operational viability of an AD system is greatly determined by the volume of organic fraction of the MSW collected, as this metric dictates the system's required capacity. Nevertheless, the organic fraction (food waste) is generally acknowledged to make up the largest portion of the overall MSW (40% to 55%) (Rodzi et al., 2019). Following up from total MSW generated by residents, the survey led to estimation of organic fraction percentages from total MSW (Figure 4.4). About 50% of respondents believe less than 10% of organic fraction constitutes meanwhile 33% answered the organic fraction around 11 – 20%. Although the numbers opposed to national statistics

(45% organic), the potential organic fraction content is formidable for implementation of anaerobic digestion system. One possible explanation for this is that individuals usually do not track the weight of their MSW (Kasmuri et al., 2023). Awareness may be considered on a good level with a good waste management practice at house such as practicing segregation, maintain cleanliness of disposal area and involvement in local waste management campaign which expose residential with common and latest practices in waste management at house, therefore, may giving out a different outcome on survey responses. Such a huge deficit compared to the reported quantity suggests a lack of awareness regarding actual weight. These findings also evidenced that the data from survey are limited to demographic studies as it does not depict the actual amount of MSW generated.

Study found that household income have relation with organic content (Adeleke et al., 2021), low income area generated higher organic waste compared to higher income area. Lack of knowledge on waste including waste management, types of waste and disposal contribute to respondent answer. Therefore, implementing the AD comes with a strategy to enhance the waste management of areas with low household income. A campaign that focuses on enlighten the people on type of waste, the effect of waste to environment, positive impact of segregation and best segregation practice could be done beforehand AD implementation.

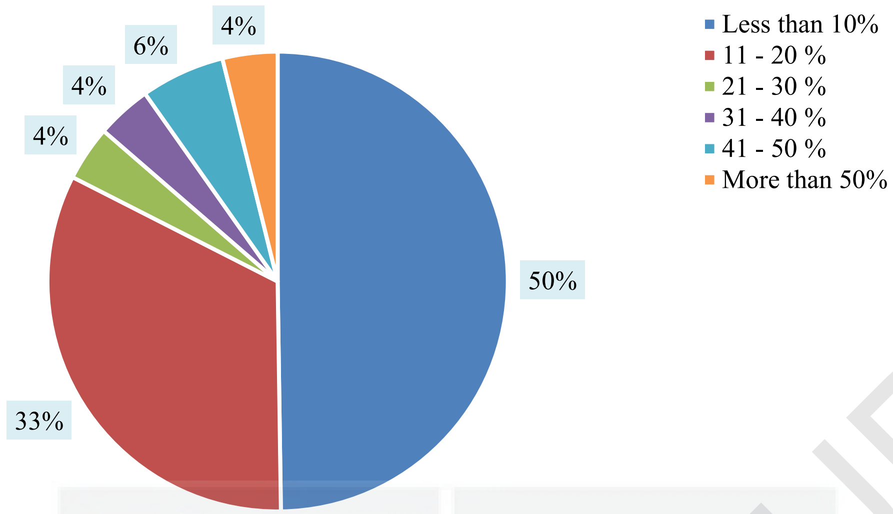


Figure 4.4: Summary of estimation on organic fraction percentages obtained from MSW survey regarding total MSW generated by residents.

Figure 4.5 elaborate the respondents' disposal practices comprise of; 1) waste segregation followed by disposal at designated sites, 2) burning MSW at designated sites, 3) engaging in decomposition activities and 4) deliberate disposal. These practices are identified as common utilized household techniques for the management of MSW. For households to dispose of waste in an organized manner based on its category, effective segregation requires the use of specialized bins. In contrast, composting requires space either surrounding the residence or within its compound; inhabitants of landed homes are afforded more advantageous opportunities to engage in such activities.

According to the survey results, a mere 65% of respondents do not participate in waste segregation, whereas 23.41% of respondents actively engage in this practice, as illustrated in Figure 4.5. This huge discrepancy may be resolved by highlighting the significance of designated bins in influencing the adoption of segregation practices by residents. Such practice is ascribed to the mandatory enforcement in Germany in residential zones, strategically placed and positioned to prompt residents to comply with segregation protocols (Igini, 2022). In the context of Malaysia, as of now, to ensure effective waste management, the presence of suitable facilities that facilitate the segregation process is essential. The production of biogas can be considerably affected by the presence of extraneous materials, due to the rigorous criteria of anaerobic digestion. As a result, source segregation becomes an essential procedure that improves the effectiveness of everything from waste collection to biogas production, a matter in which Malaysia has a long way to go to improve.

Additional efforts to elevate the proportion of upcycling of waste would require detailed studies examining variables that impact the knowledge integration, awareness, and segregation practices of local inhabitants. The survey findings shed light on the feasibility of gathering FW for AD operations in Seremban, accentuating the criticality of waste source separation preceding the installation of AD systems on residential properties. This present work also has found correlations between awareness and a variety of factors, including living conditions, cost implications, and the availability of instruments.

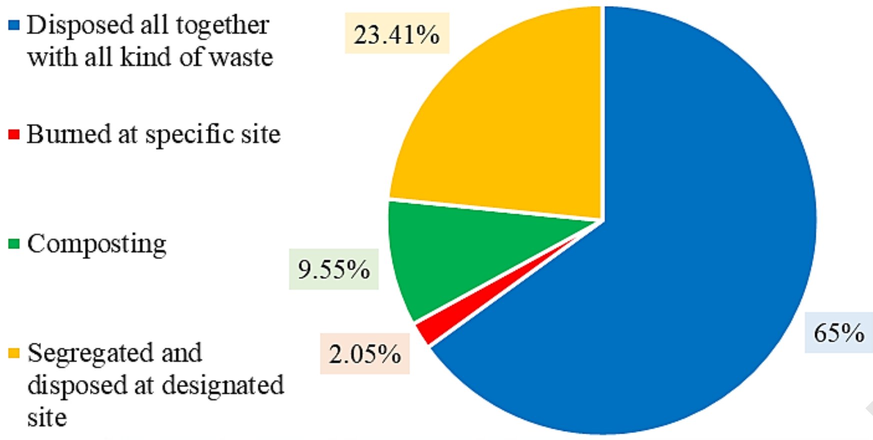


Figure 4.5: Disposal method practiced by residents. Every disposal method is defined based on the availability of facilities, knowledge of disposal method, and ability to practice

4.2 MSW On-Site Collection Data

The amount of waste generated by residents at the designated area is 0.55 kg. Organic fraction made up to 55% of the total MSW as in Figure 4.6. A study in Shah Alam shown 0.43 kg/capita/day of solid waste generated per day (Eeda et al., 2018) while in Sarawak is 0.88 kg/capita/day (Kai, 2018). On the individual basis, 0.35 kg of organic waste was generated/individual/day. However, this amount comes with a loophole where the amount of FW generated was not included with the waste generated from food premises and office facilities. Although, the calculations on waste generated per individual to give an initial data on waste generated per individual from household. Therefore, the scope from now on is focusing on the waste from household where the anaerobic digestion process is obtaining the feeding source.

Accessibility to the waste does require a specified bin for collection. The collection is enhanced through providing tools and equipment, provided along with the collection services (Fadhullah et al., 2022; Yu & Jaenicke, 2020). Waste was collected and segregated to identify the possibilities of implementing AD system in Seremban district. The estimated total population in study area is 70,000 individual, thus total organic waste at which is called as FW in the next part, may totalled up at 24.5 tonnes kg per day. Alternatively, 0.35 kg of FW per individual are potentially prevented from disposed to the landfill at which became a centre in this study.

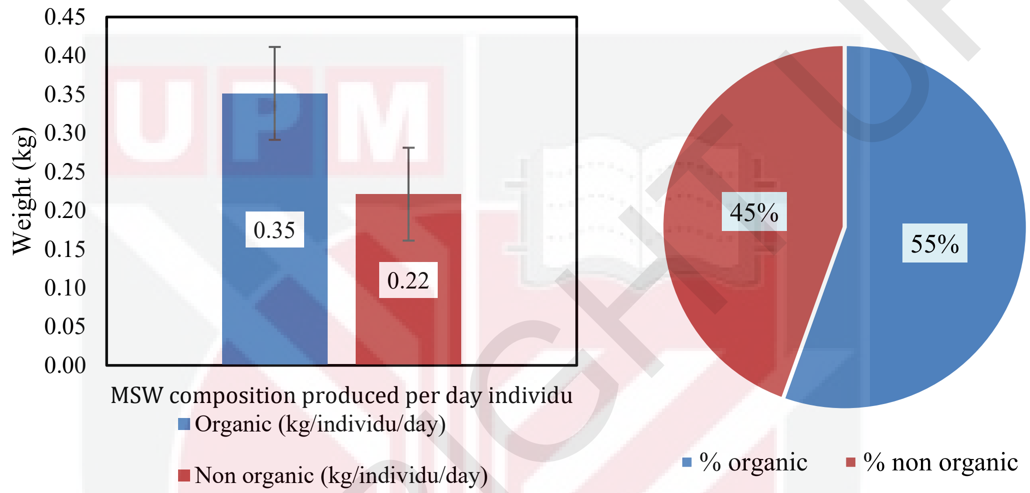


Figure 4.6: Table of MSW weight composition per individual per day. The MSW total up to 0.57 kg/individual/day.

Figure 4.7 comprised data of MSW generated by food premises that volunteered to participate in waste collection. Food waste accounted for 50% of total waste generated. Thus, food waste generated averaged at 60 kg/day/premise and signify the potential of AD implementation at premise. In addition, there exists a gap on food waste generation with the exclusion of waste generation at premises.

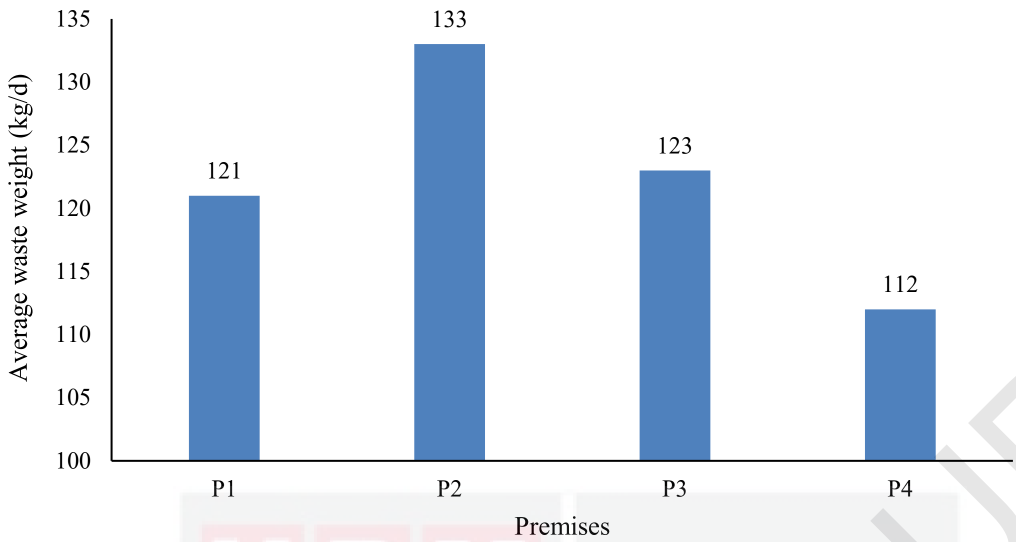


Figure 4.7: Bar graph shown the amount of waste generated from food premises. P1, P2, P3 and P4 are restaurants. Each food premises was volunteered to participate in waste determination. The value indicated the total mass of both organic and inorganic waste.

Generally, FW collected can be specified into fruits, rice, gravy, flour based and protein. Rotten and expired food contained together with the FW. From Table 4.1, a wide range of COD, pH, TS and VS values were recorded. FW was collected fresh, although some of the material had rotten and give out pungent smell. Due to the varies types of FW, the material was wet, saturated and slimy. Physical characters are the main reason for anaerobic digestion process due to its capability on degrading wet and high moisture material into biogas and digestate (Uddin & Wright, 2021). COD is the main parameters characterised upon FW to be used as feedstock. COD of FW collected shown a wide range from as low as 0.16 mg/L up to 14.6 mg/L which are out of range from reference. The high value of COD comes from gravy and protein block (fish, chicken and meat). The COD value averaged at 3.2 kg/L. COD value indicated a potentially high amount of organic supply may fed into digester for AD and a high conversion rate into biogas in return. In other terms, type of FW collect was not able to be controlled since it was contributed by the participants, therefore the COD value need to control upon feedstock preparation and feeding into digester. TS has a value ranging from 6.34 – 54.4% shown a wide range value in comparison with references. VS value shown a range from 5.47 – 50.41%, indicate a potential biogas conversion from FW. Hypothetically, the FW collected from targeted area allowed to utilize as feedstock for AD. Controlled COD is effective method to avoid digester shock regardless the type of waste obtained.

Table 4.1: Physicochemical properties of FW collected from area of study. Five parameters were deducted from the FW which are required for anaerobic digestion operation.

Parameters	Value Range	Referenced values	References
COD (kg/L)	0.16 – 14.6	0.3 – 0.5	Kuo & Dow, 2017
pH (pH)	4 – 6	4 – 6	S. Gao et al., 2021
TS (%)	6.34 - 54.4	15 – 35	Zulkifli et al., 2019
VS (%)	5.47 - 50.41	70 – 85	Zulkifli et al., 2019
TKN (%)	1.11 - 48.8	1 – 25	Slopiecka et al., 2022; Zulkifli et al., 2019
Moisture (%)	50 - 70	70	Hafid et al., 2017

4.3 Biogas Production From FW

4.3.1 Initial phase

In this study, cow dung is used as an inoculum to kick-start the anaerobic digestion process. Cow dung is effective because it is rich in anaerobic bacteria, particularly methanogens, which are essential for converting organic material into biogas. Using cow dung helps establish a stable microbial community quickly, reducing startup time and ensuring consistent biogas production. It is also a cost-effective option, especially in rural areas where it is readily available.

Compared to other inoculum sources like sewage sludge or commercial microbial cultures, cow dung is more accessible and economical. Sewage sludge is another common inoculum with a high microbial content, but it may require more treatment to ensure safety and effectiveness. Commercial cultures are specifically designed for biogas production and can offer a faster startup, but they are often more expensive and not as readily available as cow dung. Overall, cow dung is a practical and efficient choice for initiating anaerobic digestion, particularly in settings where cost and availability are key considerations. In another practices, inoculum was fed into digester ranged from 30 – 50 % (Yirong et al., 2017).

The choice of food waste to be processed in the anaerobic digester is based on the digester's hydraulic retention time (HRT), which is set at 30 days and remains constant. A key reason for this is that the breakdown rates and biochemical compositions of various organic materials might affect the extent to which they digest in a certain HRT. Hence, the criterion for food waste selection is its capacity to endure efficient digestion and generate biogas during the designated 15 to 30-day retention period (Anaya Menacho et al., 2022).

The feeding process of the anaerobic digester commenced with an initial input of 1 kg of food waste as a controlled start to the digestion process, often done to establish microbial activity and initiate gas production. At this feeding rate, no instances of digester shock were noticed throughout the feeding process. This speaks well for the digester ability to manage the expected waste load.

4.3.2 Biogas production under increased feeding regime and HRT

By increasing the daily volume of food waste introduced into the digester to 5 kg, the HRT (60 days) was prolonged. In many cases, increase in HRT is necessary to keep digestion and biogas generation stable and at their best. More organic matter enters the digester as the feeding rate rises. The microbial community has more time to break down the extra organic material when the HRT is increased. There has to be enough time for the microorganisms to completely metabolize the additional load; otherwise, digestion would be partial and biogas production efficiency will be lowered (Bi et al., 2020). Digester pH and other environmental factors are susceptible to change when feeding rates are excessive. The microbial population is better equipped to adjust to changes in feedstock composition and keep digesting conditions steady when the HRT is longer because it offers more buffering capacity (Uddin & Wright, 2021). This helps in avoiding potentially harmful consequences, such as sharp decreases in pH, which might impede microbial activity.

The system was in stable condition during 1 kg feeding rate per day, indicated by a small range of biogas produced, 40 – 250 L. The feeding input of 1 kg did not affect the system due to high HRT value and the stability of pH value of FW. Biogas volume may fluctuated because of high COD value, nitrogen, fat or volume of FW (Lindmark et al., 2014; Purwanto et al., 2022; Yirong et al., 2017). High COD obtained from gravy and lipid-based FW. Fluctuation that occurred (day 37, 41, 47 and 56) did not affected the overall biogas production. Organic content may reside for 500 days from 1 kg per day feeding rate which take up only 0.2% of total digester volume. The summary was tabulated in Table 4.2.

In Figure 4.8, 5 kg feeding started at days 65. A consistent generation of biogas was observed with daily feeding in both regimens, except an anomaly that came about on day 55 under the 5 kg feeding regime, characterized by an increase in COD to 14 kg/L. Fluctuations of biogas production during 5 kg feeding due to high COD value of FW accumulated inside the system. As a result, biogas production increased to 900 L per day for a few days before resuming the range of 200-300 L/day. It indicates that the biogas production is susceptible to COD variation. Indicators of digester condition stability include the volume and consistency of effluent and biogas.

Biogas produced daily is directly proportional to the amount of FW fed into digester. An average of 92 L/day and 262 L/day were generated for 1 kg and 5 kg feeding rate, respectively. In comparison with similar AD procedure, 1 kg of FW able to convert into 22 - 100 L/day on average. Nevertheless, the CH_4 content in biogas is consistent across different input amounts, with values between 78 and 93%. The efficacy of the anaerobic digestion process in pollutant removal from the waste stream is measured by effluent removal rates. The marginally improved removal rate observed for the 1 kg input (51.76 %) in contrast to the 5 kg input (48.64 %) implies that reduced input amounts could result in relatively more effective treatment, potentially attributable to better substrate-to-microorganism ratios. The achieved efficacy of COD removal is similar to that of a 5000 L AD system that we previously investigated, which ranged from 60% to 70% (Zulkifli et al., 2019).

Hypothetically, the fabricated digester used in this project was able to generate biogas from FW under provided condition. The system was stable as overall. However, in order to achieve its full capacity, a high volume of FW is required to feed into system.

Due to its small capacity in regard with the volume and COD value intake, OLR is measured against biogas produced. System stability became a main concern as to implement the system at residentials. Although the biogas was generated as high as 900 L per day from a high COD value, the system might disrupt due to high COD value of FW. Therefore, optimization was done by controlling the OLR value of FW. As opposed to current disposal method, 5 kg of FW can be reduced from residentials to landfill daily through operating one 500 L anaerobic digester.

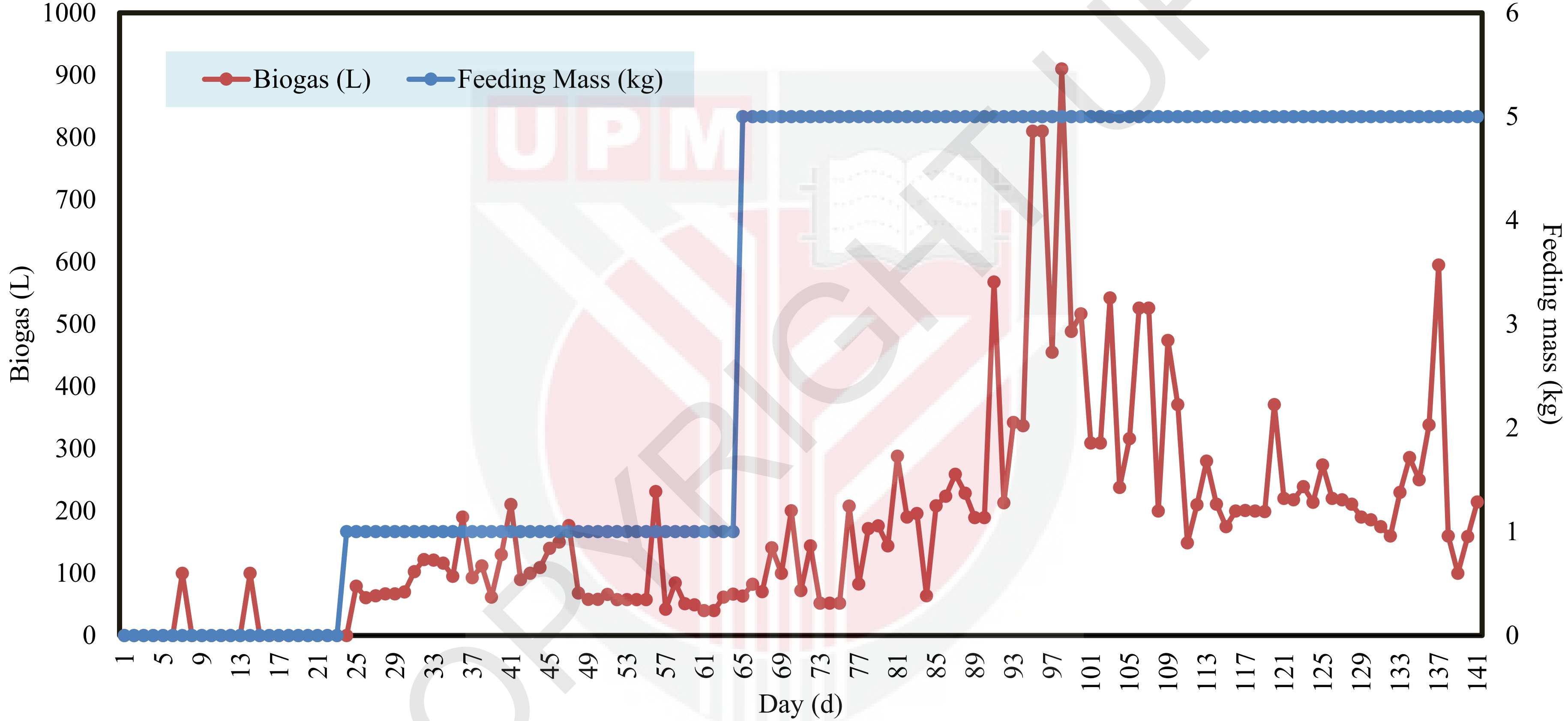


Figure 4.8: Graph shown pattern of biogas production during base feeding start with commissioning (day 1 – 23), 1 kg feeding (day 24 – 64) and 5 kg feeding (day 65 – 141).

4.3.3 Biogas production under increased OLR

The performance of digester was measured through OLR feeding base. A stable biogas production was observed at 0.06 kg COD/L/day. Stable AD process indicated through stable biogas production and effluent properties. The trend was stable until the feeding rate reach 0.12 kg COD/L/day. Fluctuations occurred due to instability of pH, high COD value and accumulation of organic compounds inside digester. Technical problems occurred during this period which identified through drawback of feeding materials, dissipation of substances through water jacket wall, drop of pH at outlet and no digestate flowing out from outlet. At OLR 0.1, biogas production at similar range with 0.06 kg COD/L/day recorded at 741 L/day. Thus, it signifies the same pattern of biogas production after OLR 0.06. At OLR 0.12, Despite the small difference percentages, a higher OLR value causing technical problems toward AD system. Although biogas production was stable, the inflow and outflow were disrupted due to clogging at the internal digester surface.

OLR value range was determined based on the capability of digester to and inoculum to digest COD ranging up to 14 mg/L. As in accordance with the OLR range increment, the study was made to ensure the digester adhere to current performance by maintain a same outflow and inflow volume, biogas production daily, neutral effluent pH value. OLR range was followed mesophilic type anaerobic digester operation with temperature ranging from 30 - 50°C that occurred to have standard OLR up to 2 kgCOD/L/day (Yirong et al., 2017). The volume of feedstock fed, Q, into digester is indirectly proportional to the COD value. Thus, the steps required to identify the COD value of FW to measure the amount of flow, Q. As the volume limit is 20 L, the FW needs to be diluted to reduce the COD value. Q value more than 20 L may disrupt the system, causing shock due to flushing of microflora or biofilm disruption (Abdelgadir et al., 2014).

Reactivity depends on size of digester which applies at smaller scale digester. Volume of FW fed into digester from OLR 0.02 – 0.1 is 10 L on average, 2 % of total digester volume. Though, the methanogenesis process has a high rate due to digester size and design. The height of the digester enables the microbe to digest to convert the organic content into biogas at for at least 35 days at constant feeding volume of 10L. The estimation is based on working volume, 350 L. The surface area of working chamber, 0.26 m^2, enable the biogas developed able to flow up and collected in floating tank. Thus, the digester design is technically effective to operate for biogas production followed with collection at smaller scale. Identifying optimum OLR is beneficial in reducing the capital cost involved, as an example : maintenance, improving the biogas yield, and ensuring stability in operation (Jiang et al., 2020)

Technical problems occurred due to presence of undigested cellulose fibre which take up space, trapped fat and grease, accumulated at digester wall. Although fibre was not the cause of the problem, but fibres aid the fat accumulation which clogged the surface area and disable digestate movement from working zone to settlement zone. PH value of digestate decrease and biogas volume was dropped followed by dropped methane percentage. The system collapsed start from day 91. No feeding was made into the system. Gas produced was recorded as to observe the consequences and as stated in graph, volume of gas produced dropped followed by methane percentage drop.

No drawback mechanism equipped to the digester to remove fat and grease. Therefore, the substrate was flushed to remove and degrease the digester internal surface. Determination of organic content gave the ability to measure the OLR. Though the lipid percentage was not measured, the control of OLR gave a concise tabulation on performance of anaerobic digester. As should AD operated for biogas production, the limitations can be observed and standardised for further optimisation. Correlation between feeding volume and biogas produced under OLR regime. On a similar capacity basis, biogas produced at 51.7 L/day.

In summary, for technical operations, FW is ensured to be grounded thoroughly by grinder mould and fibres are removed during segregation. It may be inserted if the fibres can be torn into small pieces. Kickback of influent and dissipation of substrate through the water jacket wall are indicators for clogging inside the digester. The pH of digestate is 7, the maximum feeding volume is 10 kg, and digestate flow out has the same value as influent. The optimum operation for the digester is tabulated in Table 4.2.

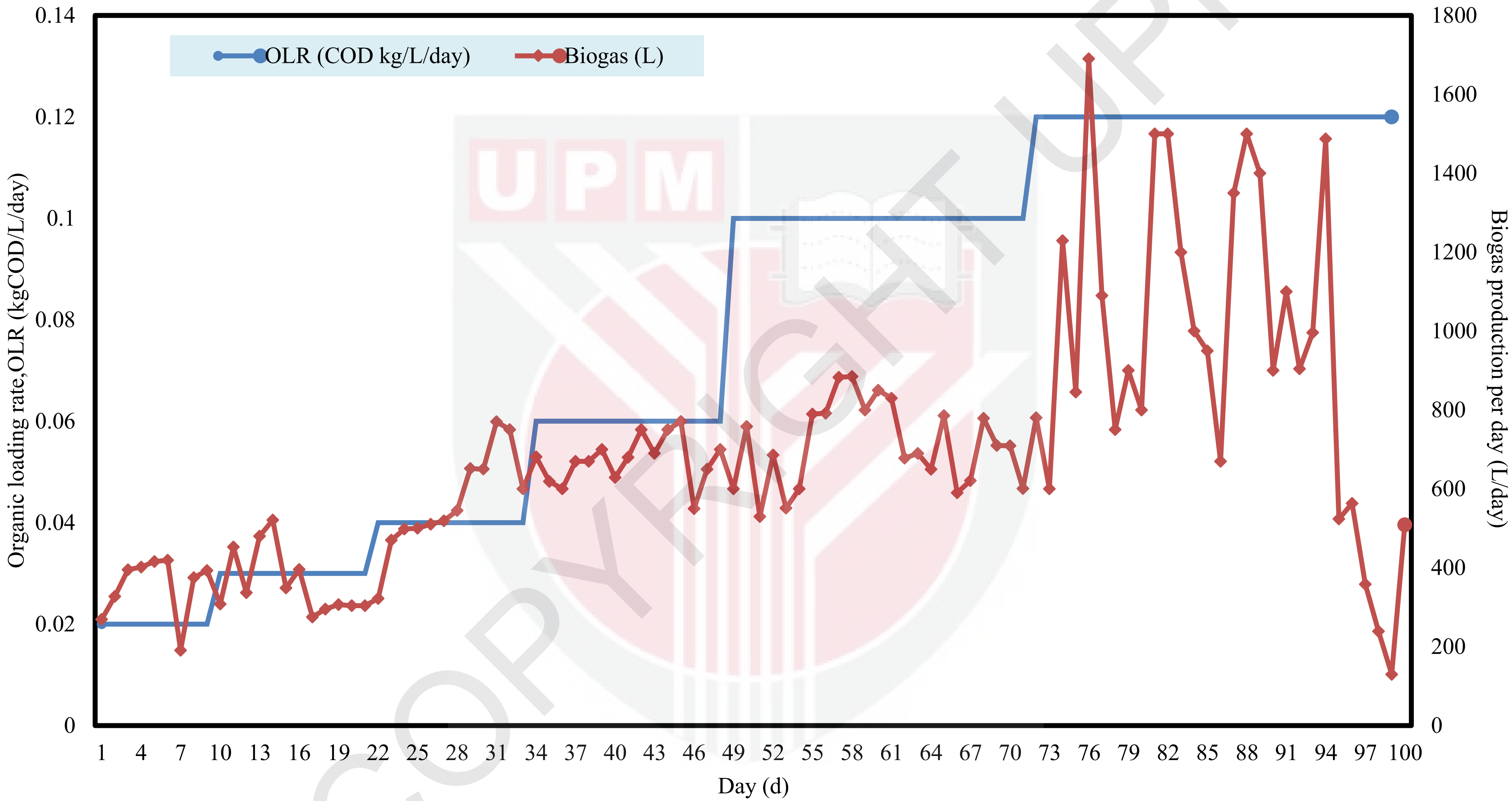


Figure 4.9: Graph of biogas production per OLR set range from 0.02, 0.03, 0.04, 0.06, 0.1 and 0.12 kgCOD/L/day. Stable production observable at 0.06 kgCOD/L/day (day 31 – 49). Production remains stable at 0.1 kgCOD/L/day (day 49 – 71) and unstable after OLR value increased to 0.12 (day 73 onward).

4.3.4 Summary on Biogas Production

Organic loading rate feeding at 0.06 kg COD/L/day shown an optimum biogas production. Mean biogas production per batch OLR shown an increasing trend as shown in Table 4.2. Feeding prior to OLR hint a depth insight on biogas production from food waste which varies in COD value.

The observed relationship between OLR and biogas production (Figure 4.10) reveals important insights into the operational efficiency of the anaerobic digestion process. The scatter plot data demonstrate a clear positive correlation, where biogas production consistently increases with the rise in OLR, highlighting the potential of higher OLRs to enhance biogas yield. Notably, the production rate remains steady and stable up to an OLR of 0.06 kg COD/L/day, suggesting that this range represents a sweet spot for the process—where biogas output is maximized without risking system performance.

However, as the OLR surpasses 0.06 kg COD/L/day, particularly around 0.1 kg COD/L/day, the data indicate significant fluctuations in biogas production. This variability points to potential challenges such as microbial stress or overload within the system, which could lead to operational instability or even system failure. The erratic biogas production at these higher OLRs suggests that while they can theoretically increase output, they may also compromise the long-term reliability of the digestion process.

Therefore, while pushing the OLR to higher values might seem advantageous for boosting biogas yield, it is crucial to consider the trade-offs in terms of process stability. An OLR of 0.06 kg COD/L/day emerges as the most favourable operational condition, balancing consistent biogas production with the stability of the anaerobic digestion system. This finding is critical for optimizing the design and operation of anaerobic digesters, particularly in settings where reliability and consistent output are paramount.

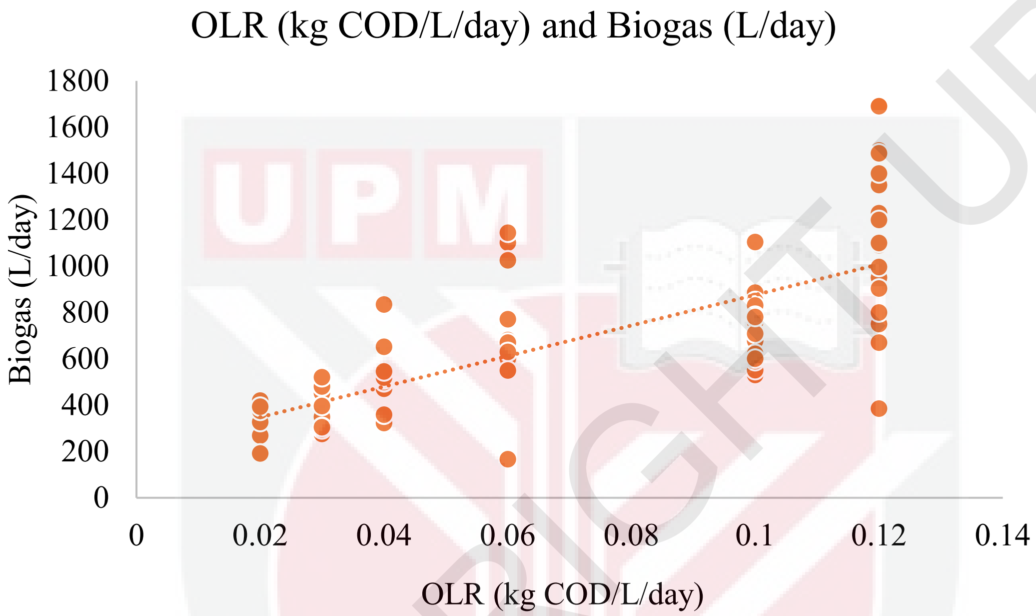


Figure 4.10: Correlation between OLR value and biogas production shown through spreading value of biogas production.

The highest percentage of COD removal was observed during OLR 0.06 regime. On an important note, COD removal indicated the safety level of digestate being remove to environment. As suggested for agriculture or plant usage, the digestate is considered safe if it met the condition of did not cause harm to plant. Direct flow into water source is unrecommended, besides, in a life cycle assessment, the disposal might increase the percentage of greenhouse gas emissions from AD process. Biogas produced per OLR fed regime is independent of each group.

Studies conducted on overloaded grease waste digesters found that rapid shocks in the loading rates were able to cause shifts in microbial populations, with methane yields returning to normal levels after developing a tolerance to higher loading rates. It has been hypothesized that improved digester performance and resistance to overloading after an initial instance of overloading is due to an increased diversification of methanogenic microorganisms (Basak et al., 2021; Kuo & Dow, 2017).

In the application of anaerobic digestion, methane makes up a substantial part, making up 60% of the total biogas produced, the practical implications relate to everyday considerations of how we use energy. The heating value of the biogas, a critical measure of its energy content, is at 24367 Btu/m³. This measure becomes particularly important before utilization upon common household appliances. Think about a regular household stove, a typical appliance that can produce heat at 7000 Btu per hour. Understanding the numbers interact helps on to see the application of biogas at homes.

The comparison between the actual biogas production at an OLR of 0.06 kg COD/L/day and the theoretical biogas yield per kilogram of COD reveals that the system was performed efficiently. The theoretical biogas yield was estimated to be approximately 652 L per kg of food waste, assuming that methane constitutes about 60% of the biogas. Given the actual biogas production of 763 L/day at 0.06 OLR, it is evident that the anaerobic digestion process is yielding higher-than-expected biogas volumes. This suggests that the digestion process is operating under optimal conditions, potentially due to effective microbial activity, well-maintained pH balance, and other favourable factors. The higher yield could also reflect the effectiveness of the inoculum used, ensuring thorough and rapid degradation of the food waste. Overall, the system performance at this OLR level indicates a highly efficient conversion of organic material into biogas, making it a promising condition for maximizing biogas production. However, ongoing monitoring would be essential to ensure the process remains stable and sustainable over time.

Table 4.2: Table of summary on overall biogas production under two feeding regimes.; Mass feeding and OLR feeding. Mass feeding undergoes two consequent feeding regimes; 1 kg and 5 kg. OLR was measured using COD value of FW available and operated consequently.

Feeding regime	**Mass Feeding**		**OLR Feeding (kg COD/L/day)**					
	1 kg	5 kg	0.02	0.03	0.04	0.06	0.1	0.12
COD range (kg/L)	0.2 - 14.6	0.17 - 5.79	0.49 - 3.61	2- 6.52	2.5 - 3.3	1.79 - 5.98	1.49 - 5.52	1.94 - 7.61
Mean COD (kg/L)	2.61	1.74	2.17	2.76	2.97	4.11	3.83	3.36
Range Biogas Production (L)	40.2 - 231	52 - 910	191 - 419	275 - 521	322 - 834	550 - 1144	530 - 1104	130 - 1690
Mean Biogas/day (L/day)	91.85	261.84	354.06	360.75	545.00	762.73	741.50	953.00
CH_4 %	79 - 87	78 - 87	78 - 85	78 - 82	78 - 82	79 - 82	79 - 87	28 - 82
HRT	500	100	50	71	63	50	50	31
Average daily feeding mass (kg/day)	1	5	8.78	6.58	8.05	9.64	9.27	16.32
Yield per kg COD	35.22	150.10	163.23	130.83	183.54	185.51	193.83	283.61
Yield per kg feeding	91.85	52.37	40.34	54.80	67.70	79.15	79.97	58.39
COD Removal (%)	51.76%	48.64%	54%	64%	66%	76%	74%	70%

Table 4.3 tabulated and summarised the potential of biogas utilization for cooking gas. It signified the potential of biogas utilization to complete the food waste cycle. As OLR increases, biogas production also increases, with the highest production observed at an OLR of 0.12 kg COD/L/day, a heating value of 23,222 Btu, and 199 minutes of cooking time may be obtained. The data indicates that OLR feeding is more efficient than mass feeding, particularly at higher OLRs (0.04 to 0.12 kg COD/L/day), which results in higher biogas output, greater methane volume, and longer cooking times. At OLR of 0.06 kg COD/L/day, biogas production reaches an optimal balance with 762 L/day, providing substantial methane (457 L) and a high heating value (18,568 Btu) with 159 minutes of cooking time. Higher OLR feeding offers greater heating value and extended cooking time, making it preferable over mass feeding to optimize anaerobic digestion. However, while the highest OLR (0.12 kg COD/L/day) yields the most biogas and methane, the optimal OLR for consistent and stable operation without risking system instability may still be 0.06 kg COD/L/day.

Table 4.3: Summary on biogas production per feeding regime vs heating value and cooking time.

Feeding regime	Feedstock	Avg. Biogas Production (litre/day)	Methane Volume (litre)*	Heating Value (Btu)**	Cooking Time (minutes)***
Mass feeding	**1**	91	55	2072	18
	5	261	157	7447	64
OLR feeding	**0.02**	354	212	8626	74
	0.03	360	216	8772	75
	0.04	545	327	13280	114
	0.06	762	457	18568	159
	0.1	742	445	18080	155
	0.12	953	572	23222	199

Note:
***Taking methane is 60% from total biogas produced.**
****Biogas heating value is 24367 Btu/m^3.**
*****Using a regular household stove that has a capacity of 7000 Btu/hour.**

In this scenario, the calculated heating value of biogas is a crucial factor in figuring out if it can be a useful energy source for households. When we compare the attributes of biogas with the energy needs of a standard stove, we get a clearer picture of how this renewable energy source could be practically used at home. Such considerations contribute not only to the technical discussions about anaerobic digestion but also have real-world implications for using sustainable energy at home, aligning with broader goals of using more renewable energy and relying less on traditional fossil fuels.

4.3.5 Effluent generated from anaerobic digestion.

Digestate is one of important parameters observed. Same as in wastewater treatment, the COD value was taken and valued when digestate flow out of the system. The digestate is dark brown in colour. It has a cow dung odour. Visually, the digestate resembles diluted cow dung. The COD value, however, 1.12 g/L is higher compared to previous study, 0.04 g/L, a difference at 90%, although using a similar technical operation digester. The value is doubled the COD value of permitted effluent, 0.5 g/L (Water Services Industry (Prohibited Effluent) Regulations 2021, 2021). Thus, the digestate is not suitable and prohibited to be released into water stream. The digestate produced could be potentially utilized as a liquid fertilizer for fertigation, as it is still rich in nutrients, such as nitrogen and phosphorus (Sötemann et al., 2005). pH value 7 indicates the digestate is suitable for soil application followed by VS % which resides at 0.0266 %. Hydrothermal application might be applied to lowered the contamination level (Purwanto et al., 2022). From table 4.4, each parameter measured upon feeding of feedstock shown a reduction in value.

Table 4.4: Summary on digestate characteristics indicated by COD, pH, TS and VS.

Parameters	Average Value	Unit
COD	1.12	kg/L
pH	7.00	
TS	0.03	%
VS	0.0266	%

Figure 4.11: Sample of digestate collected at the outlet of digester. The condition of digestate collected indicates a healthy microbial growth and anaerobic digestion process showed through dark-greenish colour, pH neutral, same volume flowing out of digester and pungent smell.

The digestate from anaerobic digestion shows good potential as a biofertilizer. The COD of 1.12 kg/L indicates leftover organic material that could enrich soil, though it may need further treatment to prevent environmental issues like water pollution. The neutral pH of 7.00 is ideal for most plants and ensures efficient nutrient uptake without altering soil pH.

The TS content of 0.03% suggests the digestate is highly diluted and better suited as a liquid fertilizer, though additional nutrients may be needed to meet crop demands. On the positive side, it is easy to apply, especially in large irrigation systems. Finally, the low VS content of 0.0266% means the digestate is well-digested and stable, reducing the risk of odours or harm to plants, making it safe for immediate use in agriculture.

In summary, the digestate shows promising characteristics for use as a biofertilizer. Its neutral pH, low volatile solids content, and manageable organic load make it a stable and beneficial addition to soil. Nevertheless, the high COD may require monitoring or treatment, and the low total solids content suggests that the digestate may need to be applied in large volumes or supplemented with additional nutrients to fully meet agricultural needs. Overall, the digestate can be considered a viable option for improving soil fertility, particularly when applied as a liquid fertilizer in controlled agricultural systems.

4.3.6 Anaerobic digestion performance

Digester fabricated in this project was designed to being able to self-operated. It is planned to reduce human intervention for operation and error due to misfeeding and environment factor. First measurement on performance is on feeding capacity of digester reached 10 kg. Following the procedure for FW preparation, 5 kg FW was used to prepare 10 kg of feedstock.

Temperature as responded variables shown that no fluctuations and digester may operate as usual. Temperature recorded between 30-45°C. Indirectly, on a raining season, biogas production remains stable although rain may affect digester temperature due to cooling down effect. However, no identified temperature dropped due to rain as environmental factors.

As of pH, indicator on digester performance may obtained from digestate. pH of substrate inside digester was not able to obtain due to technicalities of digester. On a performance wise, pH is the terminal results which determined the AD operation. Slight change on digestate pH from 7 to 6 indicated that the microbial flora has been disrupted. While this applied on this digester, it is due to the dimensions and capacity of this digester which are limited to over 15 days of HRT catering at 10 kg of feedstock.

COD reduction ranging at 50 – 70 % with mean value of digestate recorded at 1.12 mg/L. COD reduction indicated the microbial activities which converted the organic content into biogas. Digester has a stable technical operation until OLR 0.06 which recorded COD reduction at 76%. At 0.1 and 0.12 kg COD/day, the reduction percentages retain at 70% although organic input has been increased. therefore, the limit of this digester is at 0.06 kg COD/day. Conversion of organic into biogas ranging from 160 – 280 L per kg COD organic load.

The system was designed to supply biogas as cooking gas. Besides to be self-operated, the system also connected from biogas storage bag to vacuum pump and direct to cooking stove. In table 4, the minimum period of cooking time is 74 minutes from 200 L of biogas produced. The cooking time are dependent on the methane composition as methane is the combustible gas and can be converted into heat energy. Ideally, the solution to organic waste that are abundant in landfill is through conversion into biogas through 500L anaerobic digester used in this project, the utilization of biogas as cooking gas is analysed on environmental impact through life cycle analysis. Digestate was also included on impact toward environment. Typical AD process utilized digestate as liquid fertilizer due to its low contaminant level indicated by many factors such as organic content, heavy metal content and microbial level. As per this project, digestate were recycled as fertilizer as option from flow into drainage to avoid from further environmental damage due to anaerobic digestion.

On the current operation, the mass of feeding reached 20 kg/d on average. In comparison with AD operation using 15 m^3 digester from Zulkifli et al. (2019), the feeding reached 15 kg/day during start-up and projected to reach 50 kg/d. The biogas produced from 500 L digester, 0.55 – 1.144 m^3 per day, 30 – 50% from biogas produced via 15 m^3 digester, 1.5 – 2.15 m^3 per day. Thus, the performance of the system has a similar performance in biogas production.

As per discussed on digester performance, the factors that applied towards environmental impact studies included the overall process from feedstock collection, preparation, anaerobic digester operation until biogas and digestate production. Those are factors which are included into life cycle analysis with highlighted on OLR 0.06 feeding regime as per operated in future.

4.3.7 Cost estimation for anaerobic digestion system

In the pursuit of sustainable energy generation through biogas production, a meticulous examination of the associated costs is imperative for financial viability and strategic decision-making. The daily feeding rate of 10 kg establishes the operational scale of the anaerobic digestion system. The consequential biogas production, quantified at 600 L per day, becomes a pivotal metric in evaluating the system efficiency. Intangible costs, amounting to RM 30,000.00 over a span of 5 years, represent a substantial upfront investment that encapsulates elements beyond direct monetary transactions, such as operational expertise, system optimization, and potential regulatory compliance. In contrast, tangible costs estimated at RM 8,000.00 per month, constituting a recurring operational expense. This financial outlay covers essential aspects such as maintenance, labour, and routine system checks, contributing to the sustained functionality of the biogas production facility. The unit cost for biogas is quantified at RM 2.50 per Litre, encapsulating the monetary valuation of the produced biogas. The price of biogas from another project using composite material cost the biogas at USD 1.50 (Obileke et al., 2022), a difference at 50% which prior to the material use to fabricate the digester. In another project using pig slurry, the price of biogas amounted RM 1.90 per m^3. Thus conclude that price are based on the amount of biogas produced, type of digester material and incentives from government (Cappannelli et al., 2020; Wu et al., 2016).

This metric is integral in assessing the economic feasibility of the anaerobic digestion system, providing insights into the cost-effectiveness of biogas as an energy source. Cumulatively, this financial landscape underscores the multifaceted nature of costs associated with biogas production. The balance between tangible and intangible costs, coupled with the unit cost of biogas, forms a comprehensive financial framework (Feiz et al., 2022; Mohammad & Wasiuzzaman, 2021; Rangga et al., 2022). This framework not only elucidates the monetary considerations of daily operations, also to ensure the ability of the implementation to sustain. Providing the same operation to every site of current 500 L AD implementation. Thus ensure the continuity of the project to divert food waste from sent to landfill.

4.4 Life Cycle Assessment (LCA)

The input inventory for this process highlights key elements essential for efficient anaerobic digestion in Table 4.5. Food waste (5 kg) is the main organic material that gets broken down to produce biogas and digestate. Water (5 L) is added to ensure the right moisture content, which helps the microorganism's function effectively. Biogas utilization (300 L) shows that the produced biogas is used for cooking, reducing the need for other energy sources and making the system more sustainable. Effluent (10 kg), which is the digestate, can be used as a biofertilizer, contributing to the circular use of resources. Finally, electricity consumption (0.65 KWh) for the food grinder is relatively low and helps prepare the waste for more efficient digestion. Overall, the inputs ensure a smooth and eco-friendly process, with biogas and digestate as valuable outputs.

Table 4.5: Inventory list for treatment of FW using 500 L anaerobic digester tabulated according to input and output as per anaerobic digestion operation.

	Inventories	Value	Unit	Remarks
Input	FW	5	Kg	-
	Water Usage	5	L	-
	Biogas Utilization	300	L	-
	Effluent Utilization	10	Kg	-
	Electricity Consumption	0.65	KWh	Food grinder (meat mincer)
Output	Biogas	300	L	Used for Cooking
	Digestate	10	Kg	-

Table 4.6 details the inputs for the life cycle inventory, which correspond to the operational parameters of anaerobic digestion at present. The environmental impact assessment (EIA) covers the complete system boundary, which includes processes that are critical for the in-situ AD method used to remediate organic waste. As a result of cooking activities constituting the recycling or utilization of biogas, the cycle is closed and FW is diverted away from landfills. The inventories included the time taken for feedstock preparation which required the usage of meat mincer. On average, the process took over 1 hour time per operations which cater the amount of 10 kg of FW or per batch. Although, the amount of FW here 5 kg which is related to feeding regime chose for life cycle analysis. Anaerobic digestion is considered as process whereas, no technical inventories registered because of no presence of element that contributed to

emission were found. Different from treatment of other feedstock or biomass such as POME where the comparison was made between types of treatment (Harun et al., 2021). Therefore, input and output identified as the whole process of anaerobic digestion within comparison to conventional treatment. The outcome in Table 4.6 highlighted that ReCiPe midpoint method has the on-point discussion as moving forward as it provide the broadest set of midpoint impact categories with a database of global scope within the scope boundary prior to inventory list.

Table 4.6: Life cycle inventories of conventional municipal solid waste (MSW) treatment in study area. MSW generated included both from residentials and food premises. SWM Environment is the sole operator of waste collector in Negeri Sembilan that manage MSW generated.

Inventories				Amount	Unit	Remarks
Upstream	Waste Collection SWME Sdn Bhd	Truck	Loading Capacity	17,000	kg	-
			Leachate	500	liter	-
			Distance Travelled Daily	24	km	Return Trip
			Number of Truck Operated	170	Unit	Negeri Sembilan Record
		Average Daily Collection		3500	kg	Wilayah Selatan Record
		Weekly Trip		7	Day	-
Downstream	Landfill Cenviro Sdn Bhd	Leachate Treatment Plant		-	-	-
		Landfilling		550000	kg	Sustainability Report 2022

Three method was used to quantify environment impact; IPCC, IMPACT 2002+ and ReCiPe with the value of GHG emission is 0.203 $kgCO_2$ eq, 0.204 $kgCO_2$ eq and 0.215 $kgCO_2$ eq, respectively. The terms used from each method are different, for example IPCC used global warming potential which indicate for the impact of GHG towards climate change, although, it refers to the same impact as IMPACT 2002+ and ReCiPe. As such, ReCiPe used the term climate change to indicate for GHG emission from process. From those three methods, ReCiPe midpoint give out a much more comprehensive value of environmental impact specifically on climate change impact which indicated the GHG emission. Net value of these three methods shown difference at 5%, the background details of process and info on impact are much highlighted from ReCiPe compared to IPCC and IMPACT 2002+. The equivalence is much dependent on the stages on process which give out different impact start from its sources, for example, electricity and water. Therefore, it is important to determine the process used to produce both electricity and water.

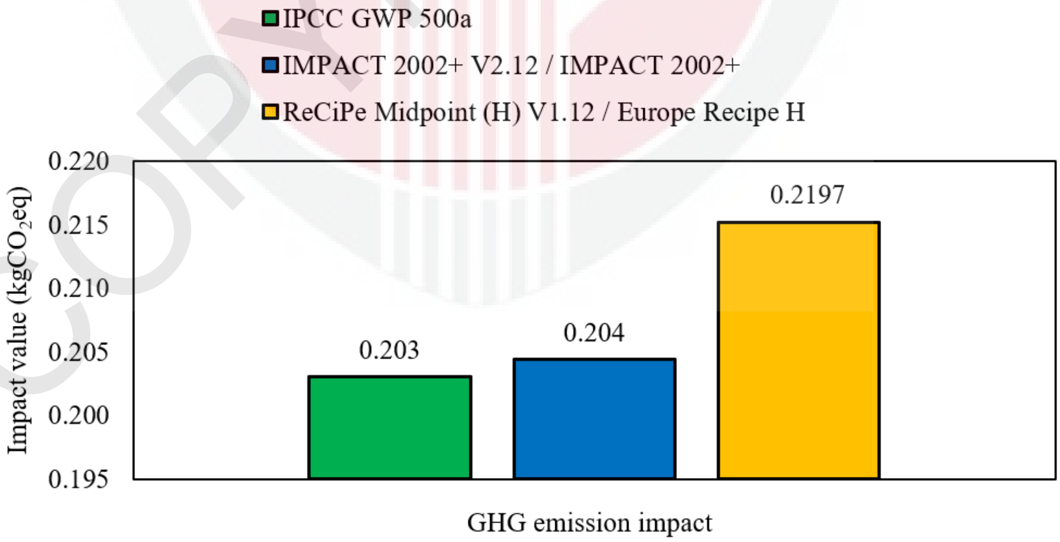


Figure 4.12: GHG emission impact contribution calculated using three different method, ReCiPe Midpoint, Impact 2002+ and IPCC.

Figure 4.13 shown the range of impact that are identified using ReCiPe midpoint method. The chart shown the impact that are potentially or currently progressing upon implementation of process. Climate change have the highest value of emission followed by fossil depletion, human toxicity, metal depletion, freshwater ecotoxicity, marine toxicity and water depletion with value of 0.215, 0.067 and 0.024, respectively. Details on value of other environmental impact indicated in Figure 4.13. Mentioned there are 18 impact categories in total. Negative value from ionising radiation and agricultural land occupation shows a reduction of impact or feedback output by implementing AD for FW reduction. On a net value, the negative value will reduce the amount of impact which indicate for a positive impact on the implementation of anaerobic digestion. Noted that the value is prior to feeding volume of 10 kg via AD. This gives insight on the positive impact of implementing AD in a long run. Although, interpretation might made through single implementation or a batch operation of AD in Seremban district, a cumulative value of FW generated throughout Seremban might have a potential of giving out a positive result in comparisons with conventional waste management in terms of GHG emission.

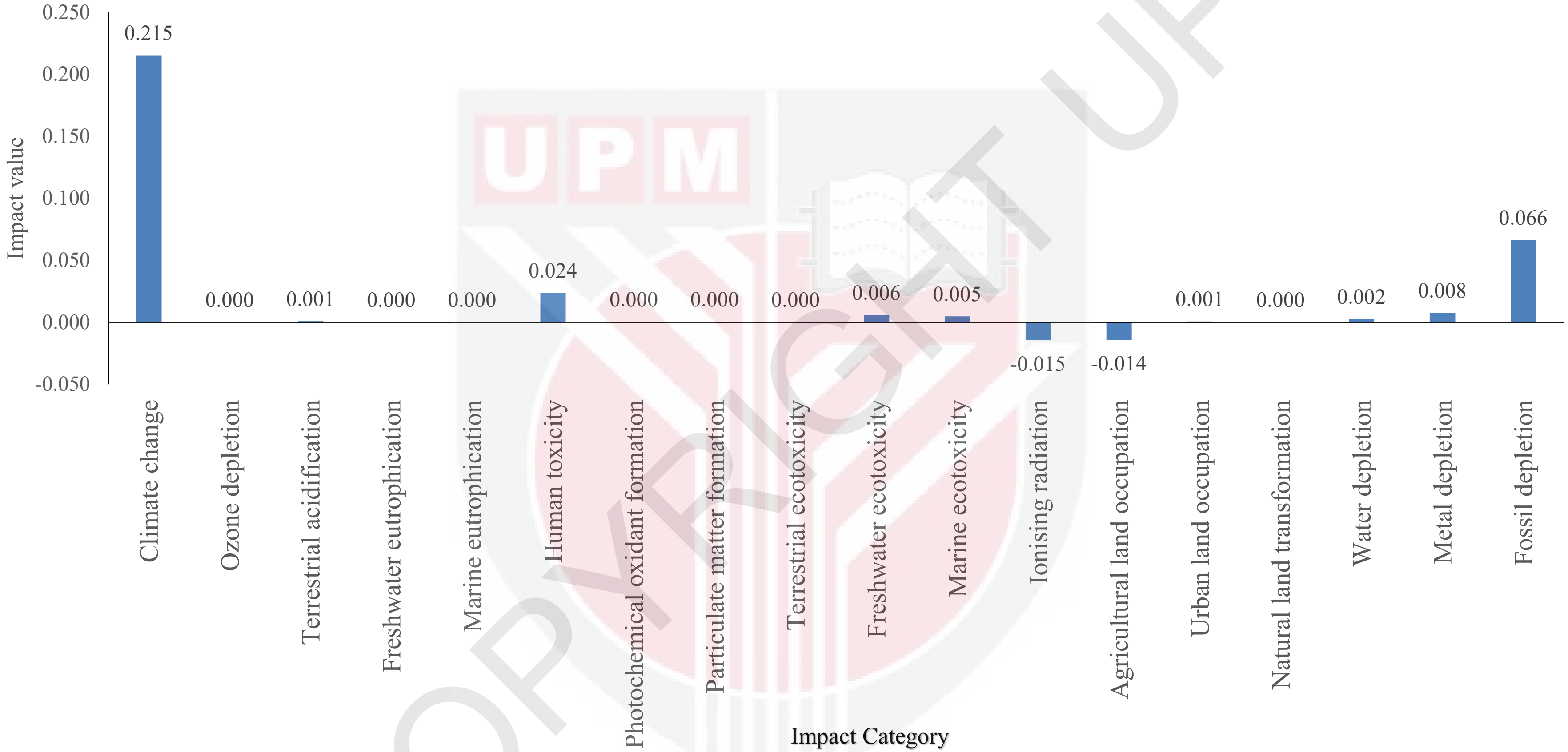


Figure 4.13: Chart state the summary of environmental impact through implementation of anaerobic digestion system. There are 18 impact categories with each category are valued through the input from AD operations. Climate change impact has the highest impact value followed by fossil depletion and human toxicity.

Figure 4.13 summarize the contribution of each element involved in anaerobic digestion summarizes into biogas, electricity, water and leachate with each contributed for 2%, 80%, less than 1% and -18% respectively. Concerning GHG emissions, the combined emissions of all GHG categories amount to 0.2197 kgCO_2 eq. The largest contributor was electricity, which contributed 0.2662 kgCO_2 eq. The regulated flow of biogas that is directed into the gas balloon contributes to the relatively low GHG emissions of the remaining processes involved in biogas production. Even though biogas is repurposed for cookery applications, the emission of CO_2 during biogas combustion is negligible in comparison to the overall emissions. The negative values assigned to leachate indicate that the utilization of leachate as fertilizer, in which carbon is assimilated by the plants, facilitates a carbon mitigation effect.

The negative value of leachate indicates the recycling process which takes up the emission instead of releasing it into the atmosphere which occurs to another component. Electricity has the highest percentage of contribution due to the amount of energy used that comes from electricity generation and during the grinding process. Electricity generation in Malaysia is generated from coal burning, therefore, the potential of GHG emission is much higher as compared to biogas which become the second highest following electricity, which is due to biogas that are burnt for cooking gas might has potential of releasing GHG into atmosphere. However, net outcome of GHG emission is 0.215 kg CO_2 eq, indicating that climate change impact of anaerobic digestion has lower value as compared to conventional. The AD process has reduced emission due to exclusion of transportation which for real application, the digestion process occurred in-situ.

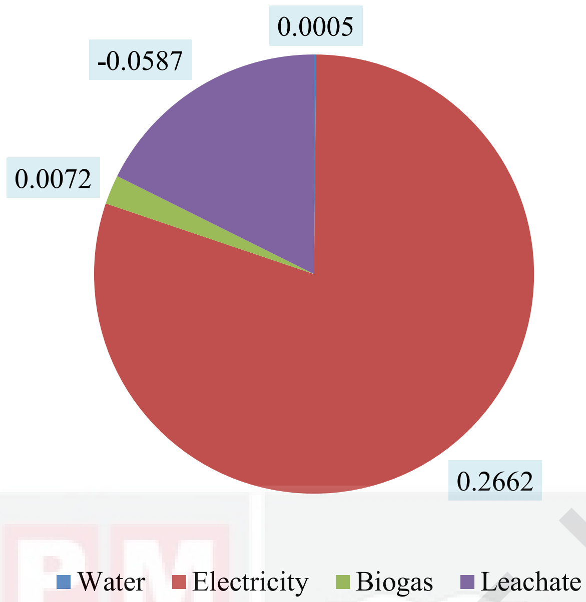


Figure 4.14: Component of anaerobic digestion that contribute to the climate change potential. 4 main components indicated which are water, electricity, biogas and digestate.

Significantly, the consumption of electricity throughout the grinding process is identified as the primary source of GHG emissions. Because of technical difficulties encountered during operation, operational complexities require the grinding process to continue for one hour. Illustrative instances encompass fibrous substances that desiccate and obstruct the outflow of the grinder; animal lipids that adhere to other components in the FW mélange and restrict the functionality of the blades; and the segregation of animal bones that hinder the operation of the grinder. The application of industrial-grade grinders, which are distinguished by their increased capacity, demonstrates sustained operational life for a maximum of one hour, devoid of any technical malfunctions. Consequently, it is indisputable that there is a critical need to develop more effective approaches to reduce electricity usage and resulting GHG emissions.

In the comprehensive evaluation of GHG emissions within the waste management sector, the utilisation of SimaPro software has been instrumental in calculating the environmental impact of both AD and conventional treatment, namely landfilling. The conventional waste processing, conducted in three distinct stages at waste processing sites, involves waste management centre total treatment, solidification, and physical and chemical treatment of liquid waste. The associated emissions for these stages are quantified at 0.442 tonne CO_2 eq, 0.37 tonne CO_2 eq, and 0.218 tonne CO_2 eq, respectively. The assessment highlights the intricate stages involved in conventional waste treatment and the associated carbon footprint.

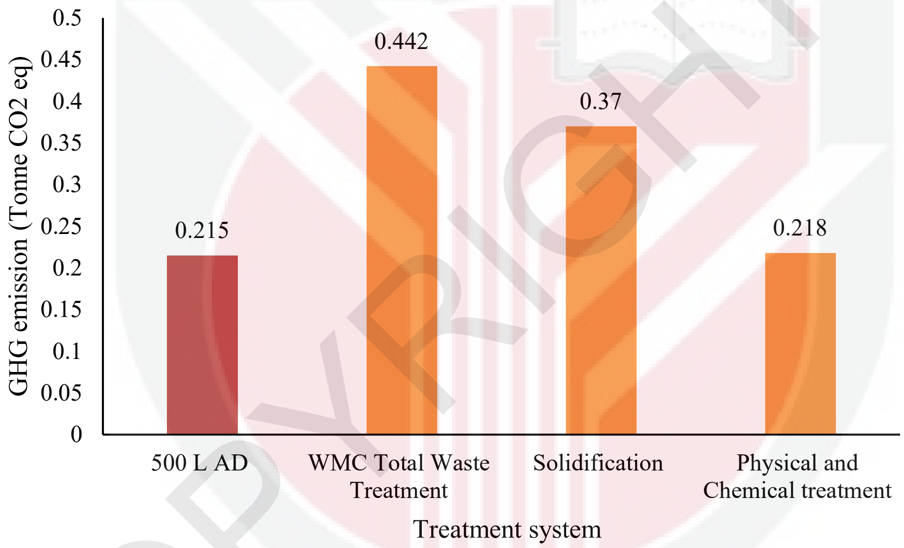


Figure 4.15: Potential GHG emission from 500L Anaerobic digestion process and conventional process/landfilling which consist of WMC total waste treatment, solidification and physical/chemical treatment.

In delineating the management of MSW, it is imperative to recognise the roles of two key authorities, SWM Environment and Cenviro. SWM Environment oversees the crucial aspects of collection and logistics, forming a pivotal part of the waste management process. Figure 4.15 visualise the culmination of GHG emissions per tonne of MSW, revealing a total of 1.03 tonne CO2 eq. Notably, assuming that FW constitutes 50 – 70 % of the total MSW, the estimated contribution from unsegregated

FW disposed in landfills is approximated at 0.5 – 0.7 tonne CO2 eq. Cenviro (2022) reported total emission of 0.37 tonne CO_2 eq per tonne FW. A difference of 80% between KAWMC and AD which indicate a positive impact due to implementation of AD. While these calculations are approximate and do not include logistics considerations, they spotlight the substantial disparity in emissions between conventional treatment and anaerobic digestion. Crucially, these findings prompt consideration of emission reduction strategies, particularly regarding FW sent to landfills. A discerning reduction of 50 % from landfills could potentially be achieved by curtailing the amount of FW, representing a substantial 250% reduction compared to anaerobic digestion treatment alone. This insight underscores the environmental implications of waste management choices and the potential for emission mitigation through strategic interventions in waste disposal practices. Going through the environmental impact, there are 18 impact included as per mentioned in Table 4.7. The impact remarked the land, air and water pollution that are caused by the system upon implementation. The amount of impact is varied based on the emission.

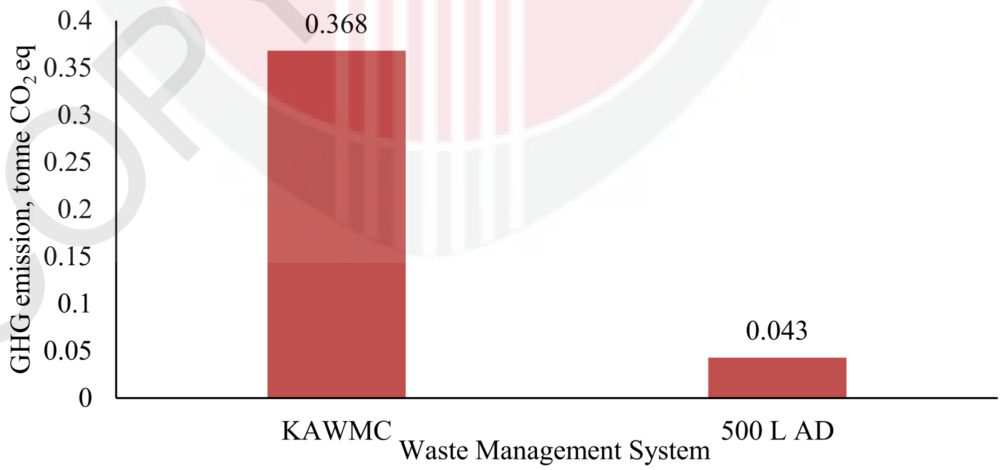


Figure 4.16: Comparison of GHG emissions between Kualiti Alam Waste Management Centre (KAWMC) and 500 L AD. More than 80% difference between KAWMC and 500 L AD which indicates a positive impact upon implementation of AD in study area to cater 1 tonne FW per day.

Table 4.7: Summary of Impact category from ReCiPe midpoint on anaerobic digestion implementation. 18 categories available for comparison from the 500 L anaerobic digester with other life cycle items.

Impact category	Unit	Total	Water	Electricity	Biogas	Leachate	Total
Climate change	(kg CO_2 eq)	2.15e-01	4.99e-04	2.66e-01	7.15e-03	-5.87e-02	2.15e-01
Ozone depletion	kg CFC^{-11} eq	5.68e-09	2.98e-11	6.42e-09	2.88e-10	-1.05e-09	5.68e-09
Terrestrial acidification	kg SO_2 eq	9.08e-04	3.14e-06	1.04e-03	1.32e-04	-2.65e-04	9.08e-04
Freshwater eutrophication	kg P eq	7.01e-06	1.76e-07	8.36e-05	1.61e-06	-7.84e-05	7.01e-06
Marine eutrophication	kg N eq	2.55e-05	2.93e-07	4.38e-05	4.85e-06	-2.35e-05	2.55e-05
Human toxicity	kg 1,4-DB eq	2.38e-02	1.50e-04	7.20e-02	2.49e-03	-5.09e-02	2.38e-02
Photochemical oxidant formation	kg NMVOC	3.93e-04	1.57e-06	4.72e-04	8.33e-05	-1.64e-04	3.93e-04
Particulate matter formation	kg PM10 eq	4.39e-04	1.20e-06	5.17e-04	3.55e-05	-1.15e-04	4.39e-04
Terrestrial ecotoxicity	kg 1,4-DB eq	8.67e-06	2.81e-08	1.20e-05	2.53e-07	-3.61e-06	8.67e-06
Freshwater ecotoxicity	kg 1,4-DB eq	5.94e-03	5.73e-06	7.13e-03	8.34e-05	-1.28e-03	5.94e-03
Marine ecotoxicity	kg 1,4-DB eq	4.83e-03	5.14e-06	6.00e-03	7.88e-05	-1.25e-03	4.83e-03
Ionising radiation	kBq U235 eq	-1.46e-02	9.13e-05	1.78e-03	3.02e-04	-1.67e-02	-1.46e-02
Agricultural land occupation	m^2	-1.41e-02	1.82e-05	1.86e-03	1.90e-04	-1.62e-02	-1.41e-02
Urban land occupation	m^2	7.62e-04	4.64e-06	1.25e-03	2.56e-05	-5.13e-04	7.62e-04
Natural land transformation	m^2	2.96e-05	6.19e-08	3.02e-05	5.00e-07	-1.16e-06	2.96e-05
Water depletion	m^3	2.49e-03	1.50e-03	1.26e-03	1.74e-05	-2.98e-04	2.49e-03
Metal depletion	kg Fe eq	7.53e-03	9.46e-06	5.42e-03	1.58e-03	5.17e-04	7.53e-03
Fossil depletion	kg oil eq	6.65e-02	1.28e-04	7.94e-02	7.82e-04	-1.38e-02	6.65e-02

4.5 Impact Interpretation

4.5.1 Environment

potential of climate change is context as GHG emission from landfill ranging from to 1323 - 2383 Mt CO_2 eq globally (Chen et al., 2020). The environmental impact from this study enabling the identification of loophole that can be optimize and improve in further study. In anaerobic digestion treatment, electricity usage can be reduced, however it is not practical due to requirement of industrial or heavy-duty grade to operate over a period of 1 hour. Feedstock stuck is commonly happen during pre-treatment due to hard substance and heterogenous of FW. An electricity efficient might reduce the operation time and it may become more efficient if further segregation of FW was practiced (Lim et al., 2021).

Current operation use rainwater contained. The utilization of rainwater was possible due to availability of facility for rainwater collection. On real application, setup of rainwater harvester might increase the start-up facilities cost. In terms of recycling, it may reduce usage of tap water where it is due to environmental impact because of the water filtration system operated to supply the tap water (Opatokun et al., 2017) .

Digestate resulted in positive impact as it reduced the amount of GHG emission by 18%. Through recycling as fertilizer, it diverted the lifecycle of digestate from being disposed into drain and uncontrolled released to environment (Timonen et al., 2019). Digestate characters enable for direct application as fertilizer. On an ideal situation, a small farm is suggester to be developed near anaerobic digester facilities.

In the intricate landscape of municipal waste management, the quantification of individual waste generation, averaging at 0.57 kg/d, provides a baseline for understanding the considerable scale of the environmental challenge faced by the city of Seremban. With an overall daily waste generation reaching 540 tonnes, the focus on the organic fraction, amounting to 270 tonnes per day, becomes particularly salient. This organic component holds significant potential for sustainable waste management practices, especially in the reduction of FW disposed in landfills. The shift towards waste reduction strategies has tangible effects on logistics, notably exemplified by a decrease in the required waste truck operation. The calculated demand for waste trucks, standing at 21 trucks operating daily, underscores the logistical intricacies of waste collection and transportation (Warunasinghe & Yapa, 2016). This nuanced relationship between individual waste contributions, overall waste generation, the significance of the organic fraction, and the consequential reduction in waste truck operations paints a comprehensive picture of the evolving waste management dynamics in Seremban. This narrative establishes a foundation for strategic planning and underscores the potential impact of waste reduction initiatives on logistical efficiency and overall sustainability.

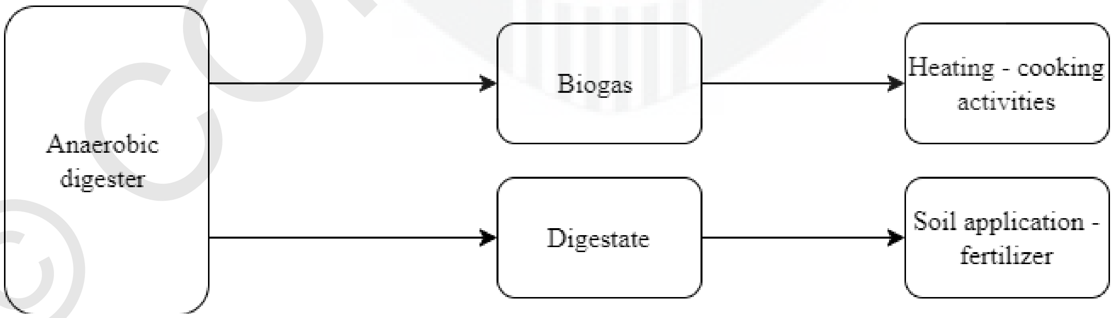


Figure 4.17: Process flow of biogas and digestate. Biogas is required to direct cooking applications as it is in the form of gas while digestate may have longer retention times before application on soil. Ideally, nearby farm is a better option to reduce logistics cost and environmental impacts.

4.5.2 Implementation of AD in Study Area

In the context of waste management and AD operations, the application of a specific OLR at 0.06 kg COD/L/day has been undertaken. This AD process is executed at a rate of 10 kg per day, constituting a composite input of 5 kg of FW and an equivalent volume of 5 kg of water. To contextualize the waste composition, it is noteworthy that the 5 kg of FW represents the daily accumulation from approximately 15 individuals. In light of the demographic factors, the population of Bandar Enstek is recorded at 40,371 individuals.

Considering the waste management flow and the application of AD technology, the estimation of the number of digesters required is calculated at 897 units. This estimation is based on a comprehensive evaluation that considers the waste generation rate, OLR, and the specific input from each residential unit.
The number of digesters required in study area is estimated at 10000 unit. In comparison, the number of digesters is double the value of digester required in China, which estimated at 4677 unit (Jiang et al., 2020). The value indeed is dependent on the size of reactor which depend on the volume and OLR of FW generated and higher number of AD may contribute to higher energy consumption. Although, the value may be a threshold for implementation of pilot scale AD, an in stages application is applicable prior to financial condition (Wu et al., 2016).

Moreover, the estimation of biogas produced is contingent upon the frequency of waste disposal per week per residential unit. This intricately links the operational aspects of AD with waste management practices. The frequency of waste disposal has a direct impact on the efficiency and productivity of the AD process, influencing the quantity of biogas generated. This comprehensive analysis not only delves into the technical aspects of AD operation but also underscores the interplay between waste management strategies, demographic considerations, and the potential impact on sustainable energy production. The data presented forms a crucial foundation for understanding the operational dynamics of AD within the specific context of study area, providing valuable insights for further research and policy considerations in the realm of waste-to-energy initiatives.

In the current operational paradigms, operators confront three prominent limitations that bear substantial relevance to their concerns, particularly in the context of restaurant ownership. These limitations encompass the implementation cost, labour requirements for efficient digester operation and the requisite sophistication in overseeing the digesters functionality. These concerns, though intertwined, distinctly revolve around the nuanced concept of hidden costs that can significantly impact the operational dynamics of a business which occurred in UKs upon farm-fed AD implementation (Wu et al., 2016). Under typical business-as-usual practices, the feasibility of AD implementation hinges on the capacity of a solitary operator to engage in full-time operational responsibilities. However, budgetary constraints often necessitate the recruitment of additional labour for digester operation (Selvam et al., 2021). This introduces a pivotal decision point for premises owners, who must deliberate on either hiring new personnel or augmenting the responsibilities of existing staff, potentially leading to task overload or performance discrepancies due to disparate job scopes. Furthermore, the sophistication inherent in digester operation compounds the challenge, demanding operators to possess a profound understanding of the system to facilitate troubleshooting in the event of disruptions. These collective limitations underscore the intricacies involved in on-site AD implementation and prompt a nuanced examination of the associated costs and operational dynamics within the realm of restaurant ownership.

Figure 4.18: Setup of 500 L AD system at food premises for the project purpose.

4.5.3 Digester Standard Operation Procedure (SOP)

The establishment of a Standard Operating Procedure (SOP) serves as a foundational guide for operational protocols within the anaerobic digestion system, prioritizing safety for operators, the system itself, pedestrians, and the environment. This comprehensive guideline aims to mitigate, prevent, and control potential hazards and accidents that may arise during operations. An essential aspect of this SOP is the meticulous collection and segregation of waste, emphasizing the use of designated containers to ensure appropriate waste segregation. This not only minimizes errors in segregation but also enables operators to identify hazardous materials within the waste stream.

The grinding phase, recognized as a hazardous step due to the involvement of rotating machinery, demands heightened awareness and caution to prevent accidents. Segregation measures are underscored to specifically avoid the grinding of fibrous, hard, and large materials in the meat mincer, minimizing potential risks. In the subsequent AD process, adherence to a feedstock size of less than 3 cm^3 is mandated to enhance the surface area for microbial digestion. Operators are directed to employ gloves during the procedure, with a strict directive to keep hands away from the grinding inlet to avert accidents.

To further ensure operational safety, the mixing of feedstock and water at a specified 1:1 ratio is recommended, primarily to prevent overfeeding of organic load. Key parameters such as Chemical Oxygen Demand (COD) and pH levels are prescribed for measurement during preparation. Proper feeding into the digester is emphasized to prevent the flushing of microbes and disruption of the biofilm. The collection or directed flow of digestate into a closed container is specified. Rigorous checks on biogas volume, biogas bag, pipeline connections, floating tank, and pressure are outlined. Additionally, a cleanliness protocol is mandated before leaving the operational area to mitigate the attraction of pests or animals. This SOP encapsulates a meticulous framework for operational safety and protocol adherence within the anaerobic digestion system.

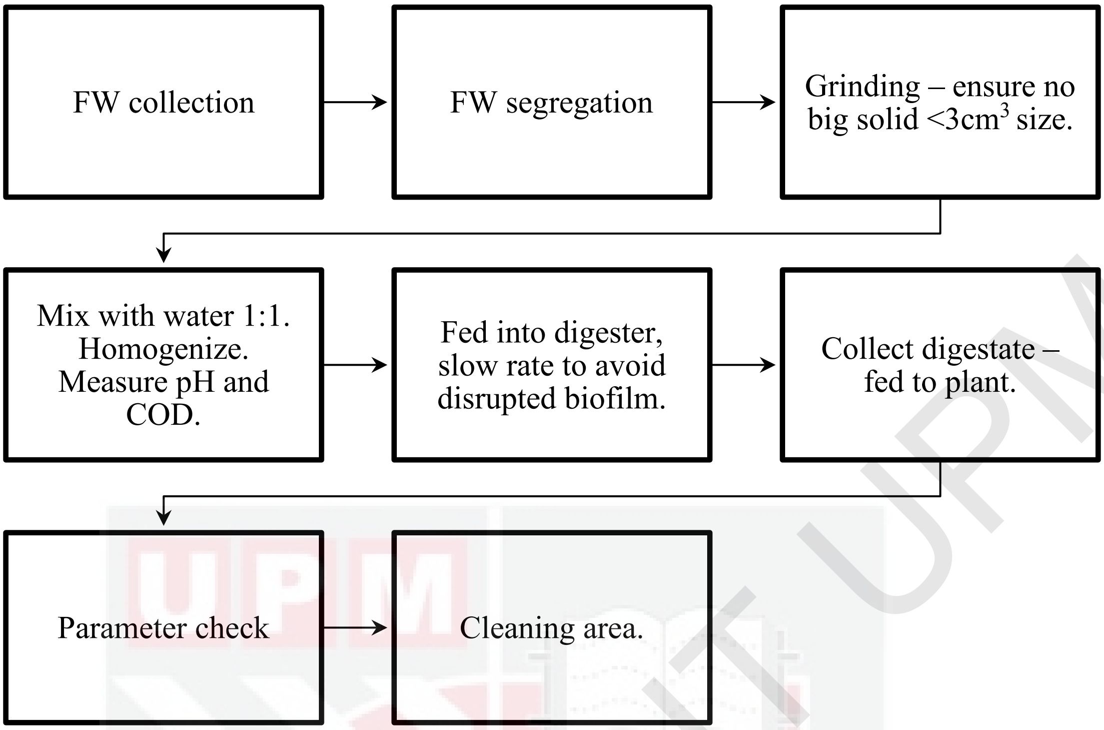


Figure 4.19: Standard operation procedure for 500 L anaerobic digester implementation. The chart provided act as major guideline for operation. A detail is advised to be provided upon operation.

4.5.4 General Financial Evaluation upon AD Implementation

The comprehensive evaluation of net cost-profit dynamics within the implementation of AD underscores a synergistic relationship among key facets, presenting a holistic sustainability paradigm. The reduction in logistics expenses, achieved through optimized waste collection strategies, serves as a pivotal financial lever. These saved resources are intelligently redirected toward the operation and developmental enhancements of the AD site, forging a self-sustaining cycle that amplifies overall efficiency. Concurrently, this logistical optimization translates into a tangible reduction in GHG emissions, aligning with paramount environmental sustainability goals and manifesting as a tangible contribution to a diminished carbon footprint.

The paradigm shift embedded in the direct treatment of waste via AD signifies a departure from conventional linear waste management models, paving the way for a circular economy ethos. In this transformative process, organic waste metamorphoses into valuable resources, such as biogas and nutrient-rich digestate, thereby reducing reliance on external inputs and championing the principles of sustainability. Furthermore, the cultivation of employment opportunities emerges as a consequential outcome of AD operations, offering diverse roles ranging from facility management to skilled positions. This job creation not only fulfils socio-economic imperatives but also positions AD as a catalyst for local economic development.

The multifaceted advantages of AD extend to the generation of digestate, a by-product endowed with the potential to serve as a valuable soil amendment. Abundant in nutrients, this organic material elevates soil fertility and structure, echoing the ethos of sustainable agriculture (Feiz et al., 2022). Collectively, these interconnected elements form a cohesive framework wherein cost savings, circular economy principles, employment generation, and soil enhancement collectively underscore the holistic benefits of AD, transcending the binary realms of economic and environmental considerations.

CHAPTER 5

CONCLUSION

On the verge of total modernisation of the whole country, waste management play an important role in maintain the environment to be suitable for living. Data on current waste generation in the Seremban district might stand out as one value on AD implementation. The urgency of AD implementation is on top priorities by comparing current data with trend on waste management at 5 years back which shown an increasing value directly proportional to human population. 500L anaerobic digester fabricated able for implementation nearby FW generation premises such as residentials and restaurants. On average, 0.57 kg/capita/day of FW is generated by populations in study area. The probability of AD implementation may increase due to total waste generated may increase due to continuous development. The volume of biogas produced may reach 600L/day on average per system applied at optimum OLR of 0.06 kg COD/day. SOP must be followed accordingly to avoid misfunction and system shock due to overload which incurs to other problem and stop the process. With proper implementation and management, the system may operate at optimum phase by producing biogas continuously at which in return, reducing the amount of MSW sent to landfill. Reduction on GHG emission from AD up to 80% compared to landfill. Thus, performance of AD implementation shown a positive impact towards environment by generating 0.215 kg CO_2 eq of GHG compared to landfill, 1 kg CO_2 eq. in addition, benefiting population in general followed by environment. Financially, the return on investment may achieve supplying of biogas as cooking gas at reasonable price and benefited both producer and consumer, indirectly to waste management operator.

FUTURE RECOMMENDATIONS

Waste management require a systematic planning from collecting until processing. After the by-product were obtained, it needs a proper storage before being converted into electrical energy. After the biomass in conserved into other form of energy, the waste will be considered reduced. In this context, the formation of biogas must be plan in a way that no other waste will be created hence the waste reduction is a success. Therefore, the significance of this study is to reduce and identify another potential by-product that will be produced to achieve green technology. The issues on digester clogging may avoided by segregating; fibrous materials, fat components from gravy and animals, control COD uptake into digester. Digester size may be apprehended to certain requirements such as MSW availability; thus, COD value needs to be verified upon feeding procedure.

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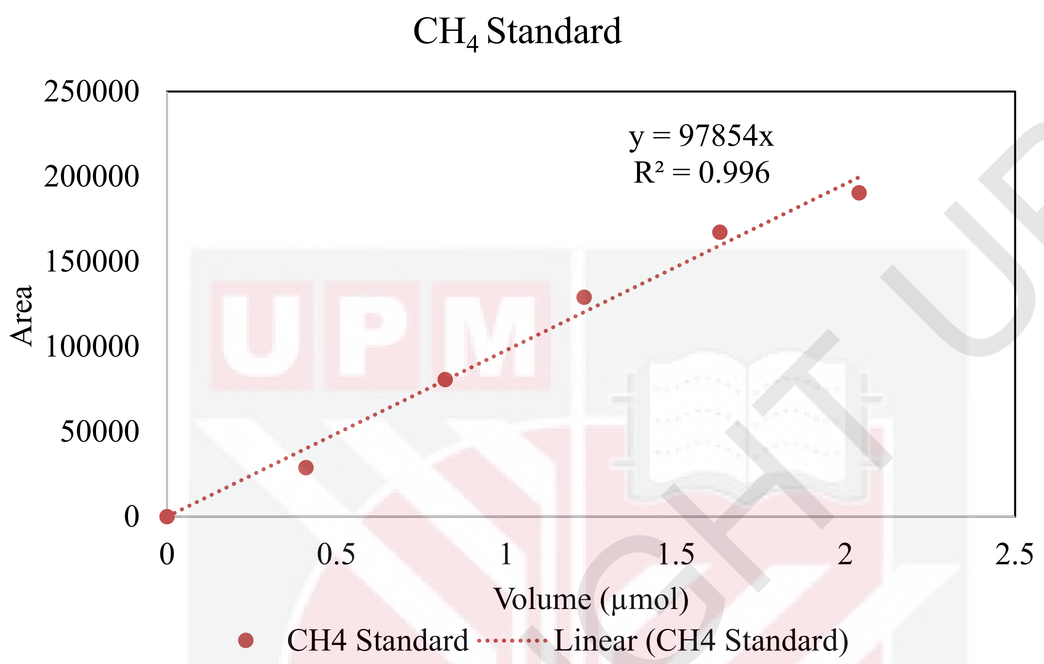
APPENDICES

A.1 Appendix I

The standard curve of CH_4 was performed using Shimadzu Gas Chromatography.



A.2 Appendix II

Krejcie and Morgan table for sample size determination

Table 1: Krejcie and Morgan Table

N	S	N	S	N	S
10	10	220	140	1200	291
15	14	230	144	1300	297
20	19	240	148	1400	302
25	24	250	152	1500	306
30	28	260	155	1600	310
35	32	270	159	1700	313
40	36	280	162	1800	317
45	40	290	165	1900	320
50	44	300	169	2000	322
55	48	320	175	2200	327
60	52	340	181	2400	331
65	56	360	186	2600	335
70	59	380	191	2800	338
75	63	400	196	3000	341
80	66	420	201	3500	346
85	70	440	205	4000	351
90	73	460	210	4500	354
95	76	480	214	5000	357
100	80	500	217	6000	361
110	86	550	226	7000	364
120	92	600	234	8000	367
130	97	650	242	9000	368
140	103	700	248	10000	370
150	108	750	254	15000	375
160	113	800	260	20000	377
170	118	850	265	30000	379
180	123	900	269	40000	380
190	127	950	274	50000	381
200	132	1000	278	75000	382
210	136	1100	285	1000000	384

Note.—*N* is population size. *S* is sample size.

Source: Krejcie & Morgan, 1970

A.3 Appendix III

Survey questions

BAHAGIAN I : Maklumat Am

1. Peringkat umur

□ 20 tahun dan ke bawah □ 21 - 40 tahun □ 41 - 60 tahun □ 61 tahun ke atas

BAHAGIAN 2 : Sumber dan Penghasilan Sisa

Sisa pepejal perbandaran (MSW) adalah di hasilkan di rumah mengandungi pelbagai bahan organik dan tidak organik. Bahan organik dalam MSW adalah kebiasaanya sisa makanan. Definisi bagi sampah organik adalah sisa makanan, lebihan masakan, bahan dah tamat tempoh(expired), sayuran yang tidak digunakan (akar, batang), kuah-kuah lebih dan isi ikan/ayam. Penghasilan sisa adalah MSW yang di buang ke luar rumah untuk pelupusan.

2. Bilangan isi rumah

□ 1 orang □ 2 orang □ 3orang □ 4 orang □ 5 orang □ 6 orang □ Lebih dari 6 orang

3. Berapa kali dalam seminggu anda membuang sampah ke luar rumah?

□ 1kali seminggu □ 2 kali seminggu □ 3 kali seminggu □ 4 kali seminggu □ 5 kali seminggu □ 6 kali seminggu □ 7 kali seminggu

4. Setiap kali sampah di buang ke luar rumah, berapakah anggaran berat keseluruhan sampah berkenaan?

□ 0.1 kg - 0.5 kg □ 0.6 kg - 1.0 kg □ 1.1 kg - 1.5 kg □ 1.6 kg - 2.0 kg □ 2.1 kg - 2.5 kg □ 2.6 kg - 3.0 kg □ 3.1 g - 3.5 kg □ 3.6 kg - 4.0 kg □ 4.1 kg - 4.5 kg □ 4.6 kg - 5.0 kg □ lebih dari 5 kg

5. Daripada keseluruhan sampah yang di buang, berapa peratuskah anggaran bahan organik?

□ kurang dari 5% □ 11% - 15% □ 16% - 20% □ 21% - 25% □ 26% - 30%

□ 31% - 35% □ 36% - 40% □ 41% - 45% □ 46% -50% □ Lebih 50%

BAHAGIAN 3 : Pengurusan Sisa dan Kesedaran

Mengenalpasti kaedah pengurusan sisa pepejal di kawasan anda dan tahap kesedaran ke arah pengurusan sisa yang lebih baik.

6. Kaedah yang anda amalkan bagi melupus sisa organik

☐ Buang di dalam bekas bersama sampah lain dalam tong sampah

☐ Membuat pengasingan dan di buang di tempat khas

☐ Dijadikan baja kompos

☐ Dibakar di kawasan khas atau sedia ada

7. Adakah anda bersedia untuk mengasingkan sisa organik di rumah?

☐ Ya ☐ Tidak

8. Apakah cabaran untuk anda mengasingkan sisa organik di rumah?

☐ Tiada kemudahan tong yang sesuai

☐ Ruang yang terhad

☐ Berbau

☐ Rumit dan susah dilakukan

☐ Kekangan masa

☐ Tiada pengetahuan

☐ Tidak berminat

9. Adakah anda menjalankan pengasingan sampah di rumah mengikut jenis sampah?

☐ Ya ☐ Tidak

A.3 Appendix IV

Anova: Single Factor of Biogas Production per day

SUMMARY

Groups	Count	Sum	Average	Variance
OLR (COD kg/L/day)	99	7.58	0.076565657	0.001432983
Biogas (L)	99	67735.5	684.1969697	98479.96826

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	23167026	1	23167026	470.4921431	5.48469E-54	3.889340998
Within Groups	9651037.03	196	49239.98484			
Total	32818063.03	197	Independence between each OLR set upon feeding batch.			

A.4 Appendix V

Cost analysis of AD plants using different types of feedstocks.

Feedstock	Product	Feedstock cost*	Plant Size	Capital cost*	Operational cost*	Product cost*	Study region
Animal manure	Electricity	0	32,000–37,000-ton feedstock / year	–	–	0.06–0.19 / kWh	Turkey, U.S.
	Heat	0	–	–	–	0.04 / kWh	Turkey
	Solid fertilizer	0	–	–	–	122 / ton fertilizer	Turkey
	Liquid fertilizer	0	–	–	–	34 / ton fertilizer	Turkey
Animal manure and energy crops	Electricity	+59 / ton feedstock	–	408–544 / ton feedstock	31–82 / ton feedstock	0.11–0.19 / kWh	Germany, U.S., Canada, Italy

Energy crops	Electricity	26–31 / ton feedstock	–	–	–	0.17–0.23 / kWh	Turkey, Germany, Ireland
Food waste	Electricity	+61 / ton feedstock	11,000–44,000-ton feedstock/ year	455–608 / ton feedstock	34–91 / ton feedstock	–	U.S., Canada
Municipal solid waste	Electricity	+44–53 / ton feedstock	5,500–110,000-ton feedstock/ year	222–571 / ton feedstock	18–101 / ton feedstock	–	Ireland, U.K, Canada, Spain, Denmark
	Biogas	–	1,100–11,000-ton feedstock/ year	122,550	68 / ton feedstock	333 / ton biogas	Thailand

*Costs are in USD. When feedstock cost is shown as positive (+), it refers to the revenue obtained by tipping fees. Adapted from Vasco-Correa et al. [10].

BIODATA OF STUDENT

My name is Is Aizat bin Samsuri, graduated from UPM with a Bachelor of Science in Biotechnology in 2014. Currently pursuing Master of Science in Environmental Biotechnology under the supervision Assoc. Prof. Dr. Mohd Zulkhairi Mohd Yusoff with project focusing on converting food waste into biogas through anaerobic digestion. I have been a lecturer at Politeknik Nilai teaching Biotechnology program since 2015 with the scheme Pegawai Pendidikan Pengajian Tinggi (PPPT) under KPT. Been teaching bioprocess technology which is related to my current degree subject taken at UPM. My studies are being sponsored by KPT under the HLP scheme.