A TECHNO-ECONOMIC ANALYSIS OF THERMOCHEMICAL CONVERSION OF SOLID WASTES FOR BIOFUEL PRODUCTION IN MALAYSIA

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ABSTRACT

Municipal solid waste (MSW) has long been used around the world for the production of biofuel and electricity. Malaysia, on the other hand, falls behind other countries in using MSW as a source of energy or biofuels, despite relying largely on landfills for MSW disposal. More efficient waste management is desperately needed in Malaysia because of worries about greenhouse gas emissions and scarce land. By applying waste-to-energy (WTE) techniques to MSW management, the study aims to assess the tecno-economic component of the energy, economic, and environmental (3E) impact of creating biofuels and renewable energy generation. The 3E assessment demonstrates that incineration is the superior choice considering both electricity and heat production. However, AD is more favourable when electricity production is the primary consideration. According to the findings, incineration (Scenario II) has the capacity to recover 1200 MWh per day, whereas AD (Scenario III) and gasification (Scenario IV) recover around 1050 MWh and 1000 MWh per day, respectively. The landfill gas recovery system (LFGRS) (Scenario I) technology produced the least quantity of recovered energy, approximately 275 MWh per day. Furthermore, the environmental analysis revealed that incineration has the potential to save approximately 1611 tCO2 per day, while anaerobic digestion and gasification have the potential to save approximately 1805 tCO2 per day and 1969 tCO2 per day, respectively, while LFGRS has the potential to save approximately 1729 tCO2 daily. The potential total costs related to each WTE technology were reviewed. The results of the total cost exhibited that AD had the lowest total cost of USD 93575 per day, while incineration and gasification had total cost of USD 147900 and USD 250400 per day respectively. The overall costs associated with each technology were also calculated. The study also revealed that the integrated WTE scenarios have demonstrated potential favourable results, where the combination of AD and incineration (Scenario V) provides potential energy output of 1110MWh per day of electricity, and 1105 MWh per day of heat generation, under a potential lower total cost per day of USD115,305, with a low carbon emission value of 1728 tCO_2 per day.

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APPROVAL SHEET

This dissertation entitled **"A TECHNO-ECONOMIC ANALYSIS OF THERMOCHEMICAL CONVERSION OF SOLID WASTES FOR BIOFUEL PRODUCTION IN MALAYSIA"** was prepared by **CHIN CHING CHEON** and submitted as partial fulfilment of the requirements for the award of Master in Environmental Technology (MET) degree at Universiti Tunku Abdul Rahman.

Approved by,

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Date: November 2023.

SUBMISSION OF DISSERTATION

It is hereby certified that Chin Ching Cheon (ID No: 2200AGM75) has completed this dissertation entitled **"A TECHNO-ECONOMIC ANALYSIS OF THERMOCHEMICAL CONVERSION OF SOLID WASTES FOR BIOFUEL PRODUCTION IN MALAYSIA"** under the supervision of Professor Dr Mohammed JK Bashir (Supervisor) from the Department of Environmental Engineering, Faculty of Engineering and Green Technology.

I understand that University will upload softcopy of my dissertation in pdf format into UTAR Institutional Repository, which may be made accessible to UTAR community and public.

Yours truly,

____

Chin Ching Cheon

DECLARATION

I thus declare that this project report is entirely my own work, with the exception of citations and quotations that have been properly acknowledged. I further declare that it has not been submitted for any other degree or award at UTAR or other institutions earlier or concurrently.

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Date : 21 December 2023

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LIST OF SYMBOLS / ABBREVIATIONS

C_{iorgj}	Fraction of anthropogenic carbon, j
ERP_{AD}	Energy Recovery Potential of Anaerobic Digestion, KWh/m^3
ERP_G	Energy Potential of Gasification, KWh/m^3
ERP_{LG}	Energy Recovery Potential of Landfill Gas, KWh/day
Elec	Overall electricity generated by WTE technology, KWh/t of MSW
EF_{elec}	Carbon avoidance factor, 0.000619 t of CO_2/KWh
F	Organic Fraction of Solid Waste, %
G	Daily Tonnage processed, ton/day
j	Component of Malaysia MSW
LCV_{biogas}	Low Calorific Value of Biogas, KWh/m^3
LCV_{MSW}	*Energy Recovery Potential of Incineration, KWh/m³*
M	Total Mass of Dirty Solid Waste, ton/day
M_{OFSW}	Methane Generation per ton of Organic Fraction of Solid Waste, m^3/ton
OF_j	Oxidation factor
P	Number of Population, Capita
Q	Low Calorific Value of Biogas due to Methane, KWh/m^3
Q_{CH4}	Methane Generation, m^3/day
R_{AC}	Amount of Waste Produced per Capita, %
Rf	Ratio of Excluded after Mechanical Handling, %
WF_j	Waste factor for component j, %
Z	Conversion factor for C to CO_2
γ	Efficiency of Biogas Recovery System, %

η	Electrical Efficiency, %

η	Efficiency of Process, %
3E	Energy, Economic, Environment
AD	Anaerobic Digestion
FiT	Feed in Tariff
GHG	Green House Gases
JICA	Japan International Cooperation Agency
JSL	Jeram Sanitary Landfill
LFG	Landfill Gas
LFGRS	Landfill Gas Recovery System
MIDA	Malaysian Investment Development Authority
MSW	Municipal Solid Waste
NMOC	Non-Methane Organic Compounds
NREPAP	Malaysia National Renewable Energy Policy and Action Plan
RE	Renewable Energy
RDF	Refuse Derived Fuel
SEDA	Sustainable Energy Development Authority
SWM	Solid Waste Management
WTE	Waste to Energy
WLP	Worldwide Landfill Park

CHAPTER 1

INTRODUCTION

1.1 Background

Malaysia, a country amid development, is witnessing swift urbanization and population expansion. This results in a surge and creation of municipal solid waste (MSW), given its direct correlation to population increase. It is projected to escalate to 49,670 tons daily by 2030. MSW comprises waste from various sectors including households, businesses, institutions, and parks. The average daily per person waste production in Malaysia is 1.17kg/capita/day, varying based on the developmental stage of different states (MIDA, December 2021).

Yet, the country's waste management leaves much to be desired, hindered by technological shortcomings, a lack of trained workforce, and inadequate facilities equipped to effectively address the problem. Compounding the issue, changes in public lifestyle over recent years have complicated the nature of MSW. Public lack of understanding and indifferent attitudes towards recycling, coupled with limited participation, led to merely 1% of organic and 5.5% of recyclable goods being utilized out of a waste stream composed of 45% and 35% respectively, as of 2006. The majority of MSW is discarded in unhygienic open field and dumpsites with no additional treatment. This presents significant environmental risks, including contamination of soil and groundwater from leachate migration, greenhouse gas (GHG) releases that may impact global warming and climate change, air pollution, and the occurrence of fires and explosions.

There are three types of solid wastes, namely municipal, industrial, and agricultural wastes. Municipal waste refers to the waste generated by human domestic activities, which account for about 80% of the solid waste dumped in landfills. Interestingly, a significant portion of this is recyclable material primarily from residences, as observed Tang et al (2021). It is forecasted that the volume of recyclable waste, such as paper and glass, will continue to increase, with landfills being the predominant disposal method. Furthermore, as depicted in Figure 1.1 by Chen et al. in 2020, organic waste is expected to consistently make up huge part of waste in most countries, with landfills being a preferred disposal technique. It is anticipated that landfilling will continue to be the most favoured method for the disposal of both organic and other recyclable solid wastes in the future, especially in developing countries.

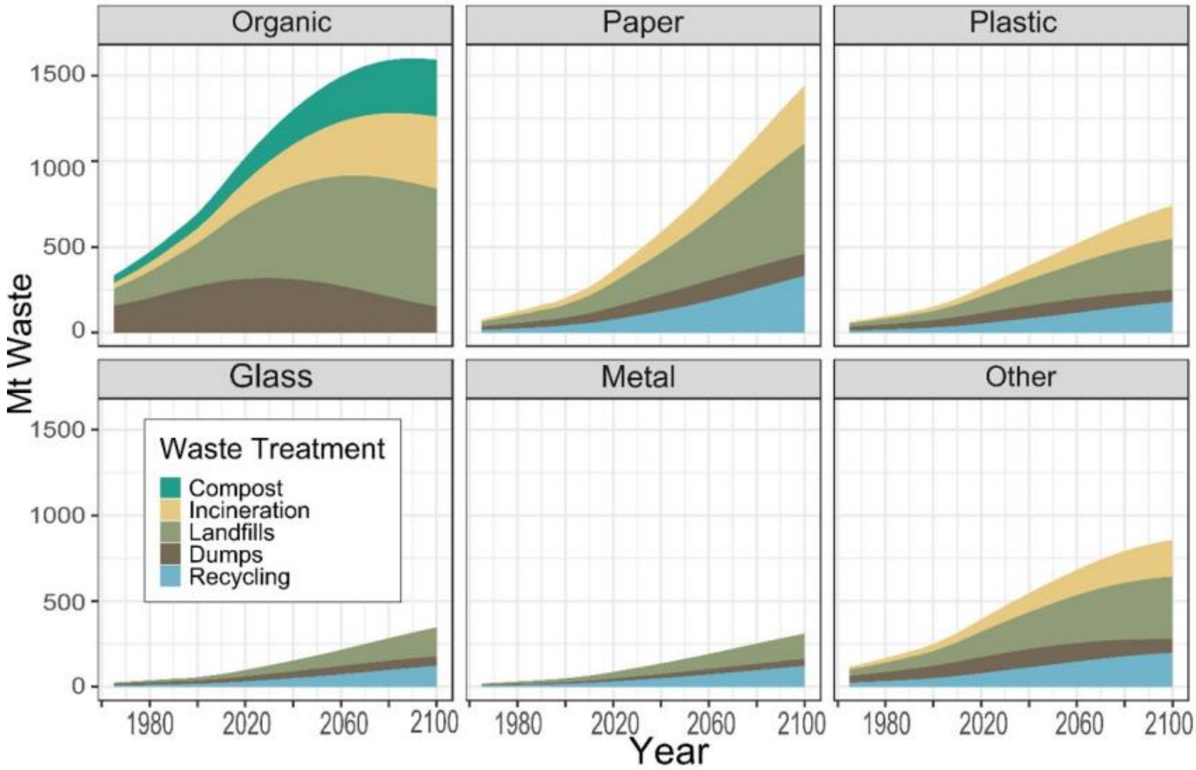


Figure 1.1: Forecast of potential waste production by types and treatment globally. (Chen *et al*., 2020)

Simultaneously, Malaysia's energy needs are escalating quickly due to the growth in population, rising a projected 4.7% yearly, with electricity consumption growing at an annual rate of 8.1%, as shown in Figure 1.2 (Energy Commission Malaysia, 2023). This is especially being experienced in Selangor, as the most populated, industrialized, and urbanized state in the country. Malaysia's main energy sources are derived from the burning of fuels derived from fossil fuels. However, these energy sources, which are rich in carbon content, contribute significantly to the phenomenon of global warming. According to projections outlined in Figure 1.3 by The World Bank (2023), it is anticipated that global GHG resulting from the combustion of fossil fuels will escalate to 70 gigatons of CO_2 equivalent by the year 2050. In response to this concern, numerous countries are exploring renewable energy as a viable alternative to fossil fuels in order to meet their energy requirements. In Malaysia, a substantial portion of greenhouse gas emissions, specifically 80% and 9%, is attributed to the energy and waste sectors, respectively.

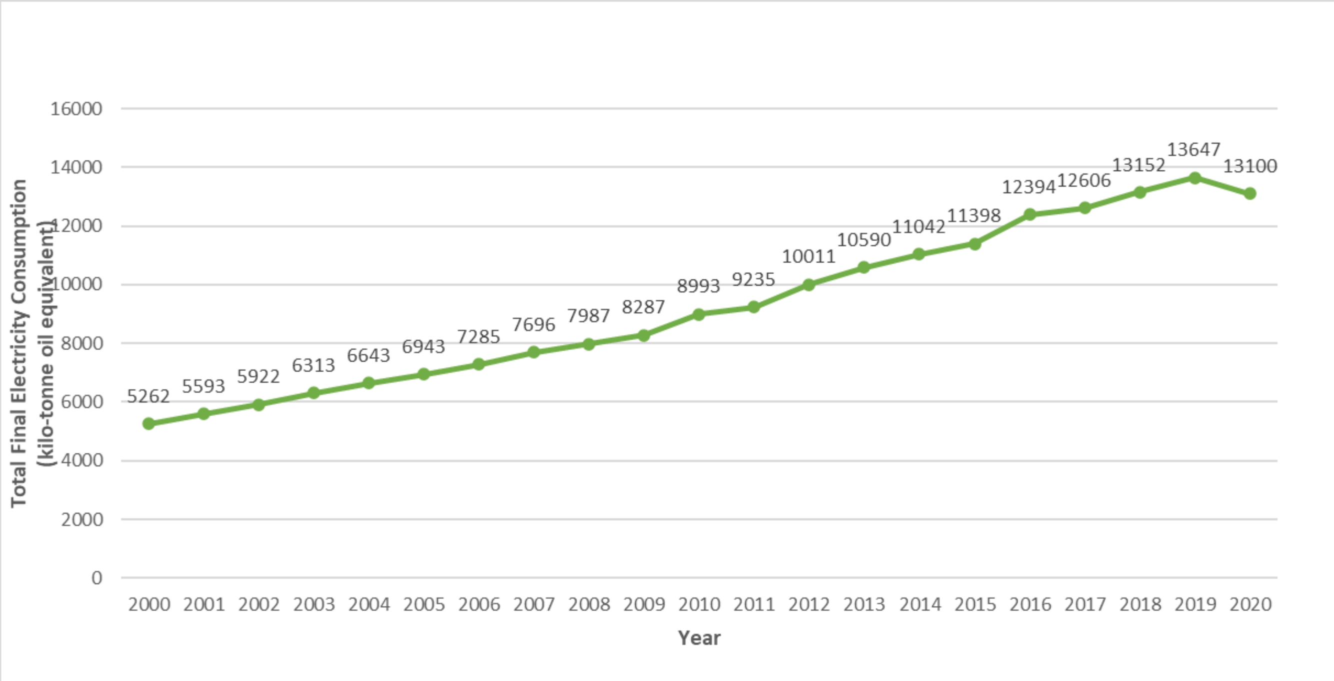


Figure 1.2: Electricity usage in Malaysia, measured in kilo-tonne oil equivalent (Ktoe), from the year 2000 to 2020**.** (Energy Commission Malaysia, 2023).

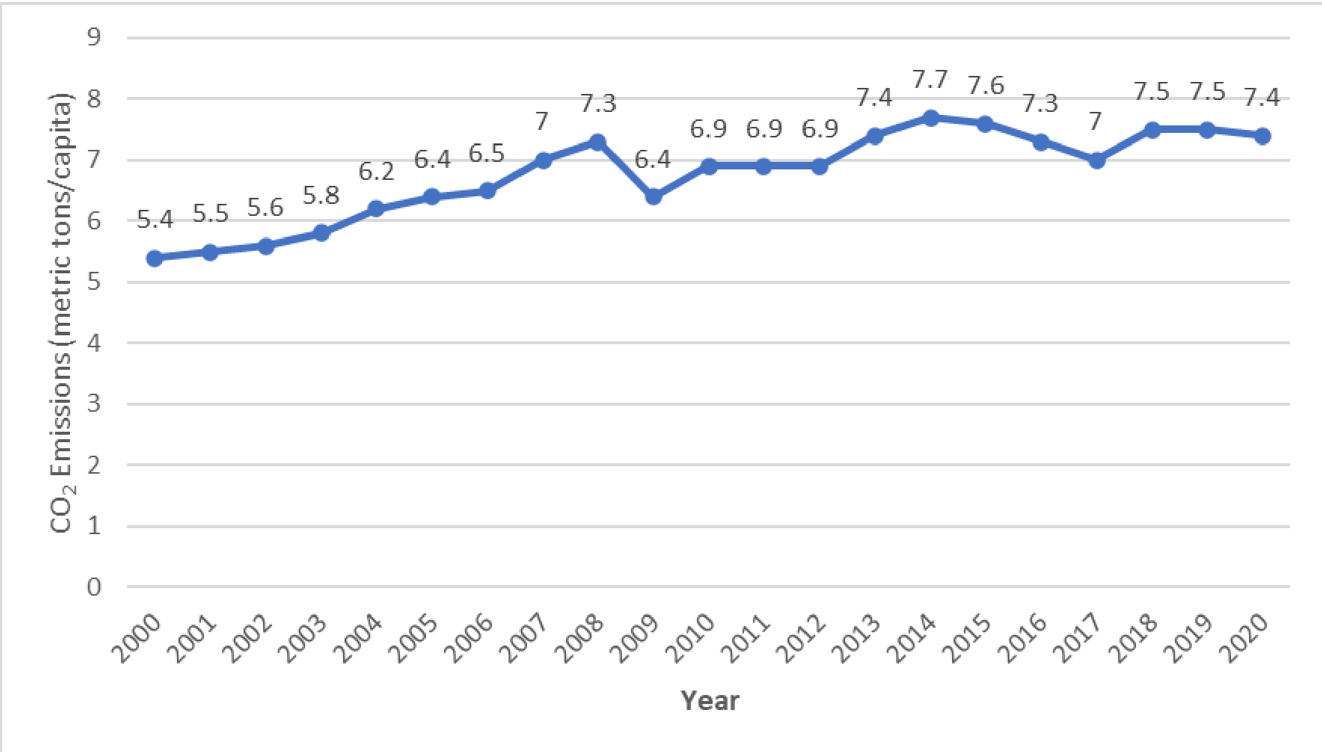


Figure 1.3: The rising pattern of per capita CO_2 emissions in Malaysia spanning the years 2000 to 2020. (The World Bank, 2023).

Taking into account both waste and energy concerns, utilizing technology from waste to energy (WTE) process emerges as the optimal approach to solve these problems concurrently, promoting sustainable MSW management. The WTE method entails diminishing the organic fraction of MSW, producing significant electrical, thermal energy and biofuels from MSW that are non-recyclable, thereby transforming MSW into a potential renewable energy source. As a consequence, this may result to a decrease in the amount of MSW disposed of in landfills, a diminished dependence on fossil fuels and other non-renewable energy resources, ultimately resulting in decreased GHG emissions.

In an effort to adopt a systematic solid waste management strategy and address the growing requirement for renewable energy (RE) sources, the Malaysian government is advocating for the adoption of WTE technology to harness RE from MSW. This innovative approach transforms MSW into a new and sustainable source of RE. WTE technology involves a process that extracts energy by converting the chemical compounds present in waste residues into usable forms such as electricity, heat, and biofuels.

In response to the prevailing environmental issues, the Malaysian government has option to implement these sustainable alternatives, moving away from the traditional practice of unsanitary landfills and open dumpsites. Currently, limited number of landfills in Malaysia employs WTE methods in recovering biofuels and renewable energy.

1.2 Problem Statement

In Malaysia, the population has experienced rapid growth, reaching 32.8 million in 2021, leading to a substantial raise in MSW production. The estimated daily amount of solid waste reached about 39,000 tonnes in 2021, averaging 1.17 kg per capita per day. A significant portion, about 83 percent, has been discarded in landfills. It is projected by 2022, the annual collection of MSW is anticipated to reach almost 14 million tonnes (MIDA, December 2021). Hence this will surpasses the rate proposed by the Japan International Cooperation Agency (JICA) study, set at 30,000 metric tonnes per day for Malaysia in 2020 (MIDA, December 2021).

This escalating situation calls for urgent attention, prompting the need for new treatment facilities. The predominant MSW management method in Malaysia involves landfilling and burial at designated sites, resulting in environmental challenges such as GHG emissions and leachate generation, causing a dilemma for the authority in selecting a viable and effective system to manage MSW. In response to related challenges and with the aim of minimizing environmental impacts, the Malaysian government is actively exploring WTE as a favorable solution.

WTE favors the change to a circular economy from the conventional linear economy, by aiming to reduce waste and environmental pollution. According to the Malaysian Department of National Solid Waste Management (MIDA, 2021), as of 2021, 137 landfills are still operating in Malaysia which 174 have ceased operation, and only 21 and sanitary landfills. This shows that most cities in this country currently practice the traditional linear model instead of an eco-friendlier secure circular city model, where energy and new products like biofuels are derived from wastes. The prevalent use of open space dumping and non-sanitary landfills as the primary methods of MSW disposal is due to their low operational costs and convenience, despite the significant harmful impacts on the environment, economy, and community health. RE and biofuel production have been advocated in most studies from landfill gas recovery, however it is still lacking for a further study on the viability of WTE technology strategies in effective management of MSW, and evaluate the RE recovery potential in Malaysia, through WTE technology by using MSW as the main feedstock source.

1.3 Objectives

This study had three main objectives:

1. To evaluate the possibility of RE recovery and biofuel harnessing from MSW through the exploration of different WTE scenarios.
2. To evaluate the economic feasibility of these WTE scenarios.
3. To evaluate the environmental impact arising from the chosen WTE scenarios.

1.4 Scope of the Study

The selected four WTE technology include incineration, anaerobic digestion (AD), gasification and landfill gas recovery system (LFGRS). The study is focused on the state of Selangor, the most densely populated Malaysian state.

The potential of the RE recovery is studied by applying WTE technologies in numerous scenarios for the purpose of power generation as electricity, thermal energy, and biofuel production by utilizing MSW as the feedstock source. The recovered energy benefits via WTE technology is investigated through the data collected from Jeram sanitary landfill (JSL) in Selangor to evaluate the energy potential.

As a supporting reference, the study intends to address the limitations of previous studies conducted on MSW management strategy in Malaysia and specifically in the state of Selangor. The study aims to assess various waste management alternatives in Selangor considering the impacts on the energy sector, economy, public health, and environment. Several scenarios are explored to examine the feasibility of applying MSW as a reliable and environmentally friendly source of RE. The study calculates and discusses the potential performance of each scenario.

Moreover, this study examines the economic and technological hurdles faced by Malaysia in its energy demand and investigates the prospective utilization of MSW as a sustainable and viable source for RE.

1.5 Thesis Content

The study will discuss the current challenges in the renewable energy recovery using MSW as source in chapter 1, followed by the literature review on the progress and development of RE recovery using MSW as source and understanding better the advantages and disadvantages of the various WTE technologies. Chapter 3 covers the methodology and framework of the study and setting the WTE scenarios with identification of the calculation methods for the respective WTE method and evaluating its impact on energy, economy and environment. Chapter 4 discusses the study result and engage in discussion of the 3E evaluation outcome. Chapter 5 provides the conclusion and recommendation of this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Municipal Waste Practice in Malaysia

Malaysia heavily relies on landfilling as a method of waste disposal, despite it being considered the least preferable option. Rather than just dumping of garbage in landfills, the optimum waste management strategy should comprises submitting it to physical, chemical, and biological treatment and separation. In the 1970s, local authorities in Malaysia dumped municipal solid waste (MSW) into assigned open dumpsites, leading to the majority of landfills in the country becoming overloaded open dumpsites. Research indicates that approximately 83% of the waste ends up in landfills, while the remaining portion undergoes intermediate treatment, is incinerated, recycled, reprocessed, or illegally dumped. Because of lack of suitable and cost-efficient waste treatment methods, many overloaded landfill sites have extended their operation times, resulting in significant environmental challenges. Moreover, some rural areas lack proper waste collection services, forcing community to resort to open burning and burying of their garbage, contributing to illegal waste dumping. Due to growing inhabitants and increased waste production, landfill sites are currently facing challenges in managing large quantities of waste. However, establishing new landfills is complicated by issues such as land scarcity, high land prices, and high demand. Table 1 shows the different levels of landfill classification in Malaysia.

Table 1: Different levels of landfill classification in Malaysia (Tang et al. 2021).

Level	Description	Available facilities
0	Open garbage dump	None
1	Supervised tipping	With fence and boundary drains
2	Sanitary landfill supplied with daily cover and bund.	Class 1 facilities with distinct unloading and working areas, daily cover, and enclosing bund. Elimination of informal scavenging and establishment of environmental protection infrastructure.
3	Sanitary landfill and leachate are circulated	Leachate recirculation system in Class 2 facilities.
4	Sanitary landfill and leachate are treated	Leachate treatment system in Class 3 facilities.

2.2 Municipal Solid Waste Characterisation in Malaysia

Noor et al. (2013) explained why MSW classification is used to establish the best waste treatment approach. This process not only allows the measurement of biodegradable organic carbon but also facilitates tracking the effectiveness of programs for landfills by rerouting eco-friendly and compostable substances . A description of MSW from Malaysia, presented by various authors, is presented in Table 2.

While paper and plastic waste have generally seen significant reductions, Manaf et al. (2001) reported a high volume of wastepaper. The considerable amount of food waste and paper provides an ideal setting for the production of landfill gas as well as composting. The reasons for the increase in MSW production include rapid population growth, swift urban development, an increasingly urbanized populace, a relatively youthful demographic, fast-paced economic progress, and a diverse racial mix in society.

Table 2: Typical description of Malaysian MSW (%) as reported by various researchers (Noor et al. 2013).

Material	Kamarudin (2008)	Eusuf et al. (2007)	Manaf et al. (2009)	Hassan et al. (2001)	ATSDR. Landfill gas primer (2001)	Nasir AA (2007)
Organic (Food)	59.0	36.6	37.43	68.67	57.0	45.0
Waste Plastic	12.8	30.7	18.92	11.45	15.0	24.0
Wastepaper	8.2	8.9	16.78	6.43	17.0	7.0
Textile waste	1.2	1.0	8.48	1.5	1.0	-
Wood waste	2.6	0.3	3.78	0.7	-	-
Yard waste	7.3	6.7	3.18	-	5.0	-
Rubber waste	0.9	-	1.32	-	1.0	-
Glass	1.4	2.8	2.68	1.41	1.0	3.0
Organic fines	3.8	-	4.37	-	1.0	-
Aluminum/metals	2.6	12.1	3.40	2.71	2.0	6.0
Others	-	0.9	7.16	7.13	-	15.0
Total amount (%)	100	100	100	100	100	100

2.3 Waste to Energy Technologies

As per the Energy Commission Malaysia's 2019 report, Malaysia heavily relies on fossil fuels for electricity production, with approximately 23,518 MW or 77% of power capacity installed, coming from coal, natural gas and diesel . Renewable major hydro power constitutes a relatively smaller share at 18.78%, equivalent to 5716 MW. Contrastingly, a small part of about %, accounting for 1205 MW, is derived from other RE sources such as solar, biomass, biogas, and geothermal, but excluding major hydro, as depicted in Figure 2.1 (Energy Commission Malaysia, 2019). Furthermore, the RE capacity installed through the Feed-in Tariff (FiT) incentives, operational only in West Malaysia and Sabah, regulated by the Malaysian Sustainable Energy Development Authority (SEDA), is notably lower than that of neighbouring countries, as shown in Figure 2.2. Joshi (2018) stated that the power capacity installed as RE in Malaysia, not including Sarawak, is at 446 MW, which is 45% short from the targeted 975 MW defined by the Malaysian National Renewable Energy Policy and Action Plan 2015 (NREPAP). Also in 2015, the proportion of power sourced through RE and integrated into the grid was less than 3%. As of the end of December 2020, Malaysia's total commissioned renewable energy installations reached 8450 MW, constituting 6.2% of the nation's total energy requirement. (SEDA, MyRER, 2021)

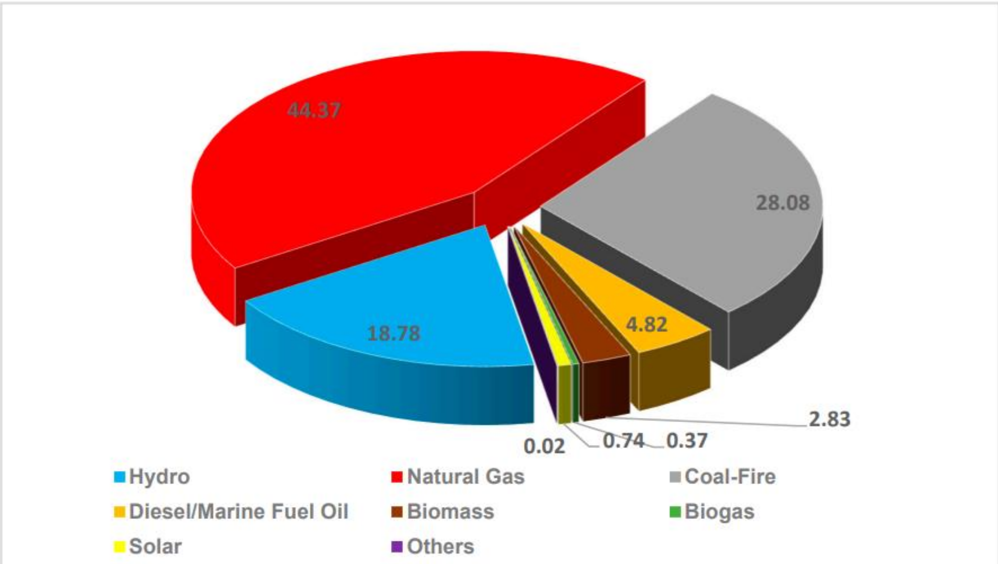


Figure 2.1: The distribution (%) of installed capacity among various energy resources in electricity production in Malaysia**.** (Energy Commission Malaysia, 2019).

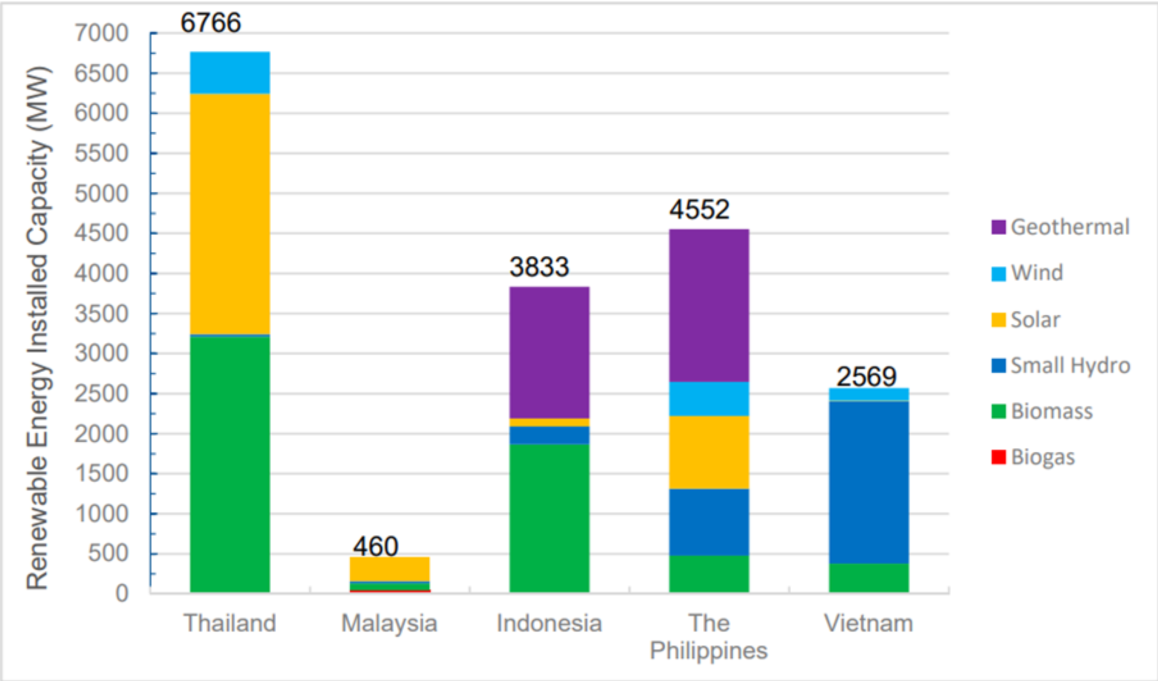


Figure 2.2: As of March 31, 2017, the renewable energy (RE) installed in Megawatts (MW) in five Southeast Asian countries. (Rohatgi, 2017).

Hence, it is unavoidable that WTE technologies are recognized as methods for recovering RE. According to Finnveden et al. (2005), WTE involves recovery of energy from waste materials into usable forms like electricity, heat, thermal energy, and biofuel. Positioned in the hierarchy for solid waste management, as depicted in Figure 2.3 just before final disposal, it emphasizes its limitations in terms of economy and environment benefits. While waste minimization is emphasized, recycling and reuse in the hierarchy requires behavioural changes at individual and societal levels, introducing uncertainties. Moreover, waste generation is an unavoidable activity. Therefore, following efforts to minimize, reuse, and recycle, the remaining waste necessitates treatment to mitigate environmental impacts. WTE emerges as a sustainable solution in the effective management of waste, addressing the challenge of the generation of solid waste and serving as a promising source of RE.

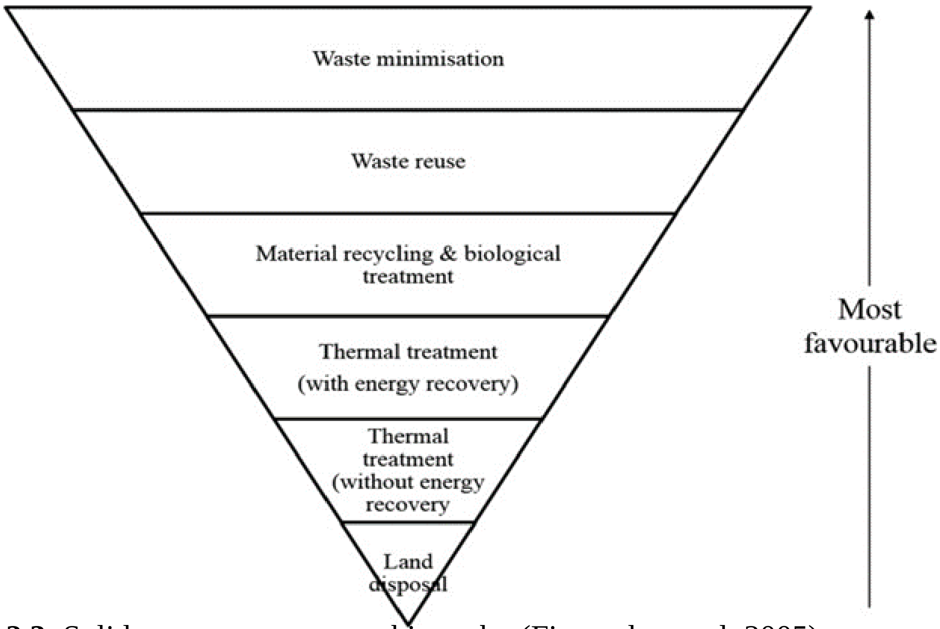


Figure 2.3: Solid waste management hierarchy (Finnveden et al. 2005)

According to Kumar and Samadder (2017), the objectives of any waste management system focus around energy and material recovery, followed by waste disposal. They emphasised that the best waste treating system is decided by criteria other than economics, energy recovery, and waste eradication capacity. It is also influenced by the imperative to comply with environmental regulations specific to the region. As a result, as highlighted by Ali et al (2010), it is critical to select the most appropriate waste treating technology that meets all of the necessary parameters for an effective operation.

As stated by Kalyani and Pandey (2014), there exist various methods for converting waste, with the following three technologies widely practiced:

(i) Thermochemical treatment, which include incineration, gasification, pyrolysis and the refuse-derived fuel (RDF) energy generation.

(ii) Biological treatment methods, such as anaerobic digestion (AD) and composting.

(iii) Landfill gas recovery system.

Figure 2.4 illustrates the techniques for treating municipal solid waste (MSW) along with their typical reaction byproducts, as demonstrated by Kumar and Samadder (2017).

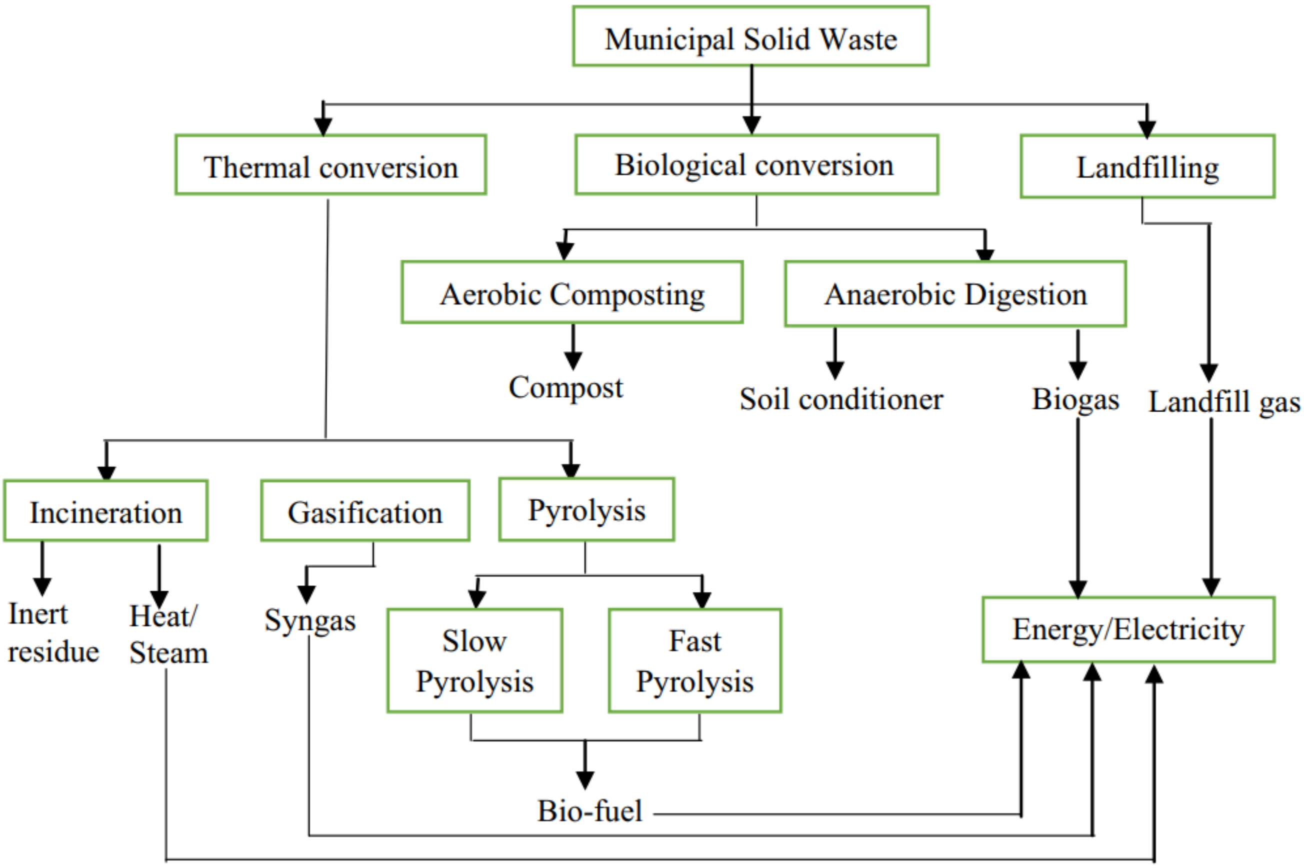


Figure 2.4. Methods and products of municipal solid waste treatment (Kumar and Samadder, 2017).

2.3.1 Landfill Gas Recovery System

Landfill gas (LFG) originates from the aerobic and anaerobic decomposition of organic matter within MSW. LFG formation take place in five stages, as depicted in Figure 2.5 (Tang et al., 2021), These stages are aerobic degradation, hydrolysis, and fermentation, acetogenesis, methanogenesis, and oxidation. Essentially, complicated organic properties undergo breakdown by microbes that are hydrolytic, producing compounds that are soluble and creating CO_2, H_2O, and heat, which are primary by-products. These soluble organic molecules are then converted by facultative bacteria into organic acids, alcohols, CO_2, H_2, and NH_3. Aerobic bacteria then help to convert these organic acids into acetic, lactic, and formic acids, as well as alcohols, H_2, and CO_2. In the fourth stage, methanogenic bacteria employ the CO_2 and acetate produced from the previous stage's products to make a substantial volume of LFG, which is largely composed of methane (CH_4) and CO_2, with minor amounts of hydrogen sulphide (H_2S), nitrous oxide (N_2O), and carbon monoxide (CO). Finally, methane undergoes oxidation to turn into H_2O and CO_2. The majority of LFG is made up of 55%-65% CH_4, 35%-45% CO_2, with the remaining percentages divided among nitrogen (N_2), oxygen (O_2), H_2S, H_2, and NH_3 (Yong et al.,2021). Therefore, electricity can be generated through LFG combustion, offering an alternative to fossil fuels given its cost-efficiency and cleanliness.

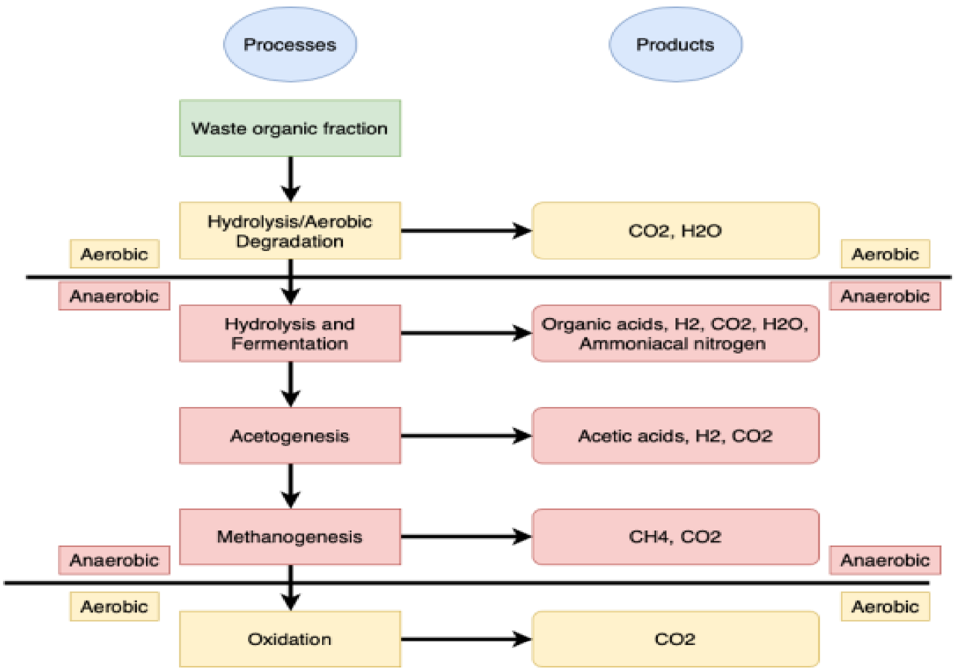


Figure 2.5: Major stages of waste degradation in landfills (Tang et al. 2021)

Tang et al. (2021) examined the diagram illustrated in Figure 2.6, outlining the process of landfill gas (LFG) extraction.

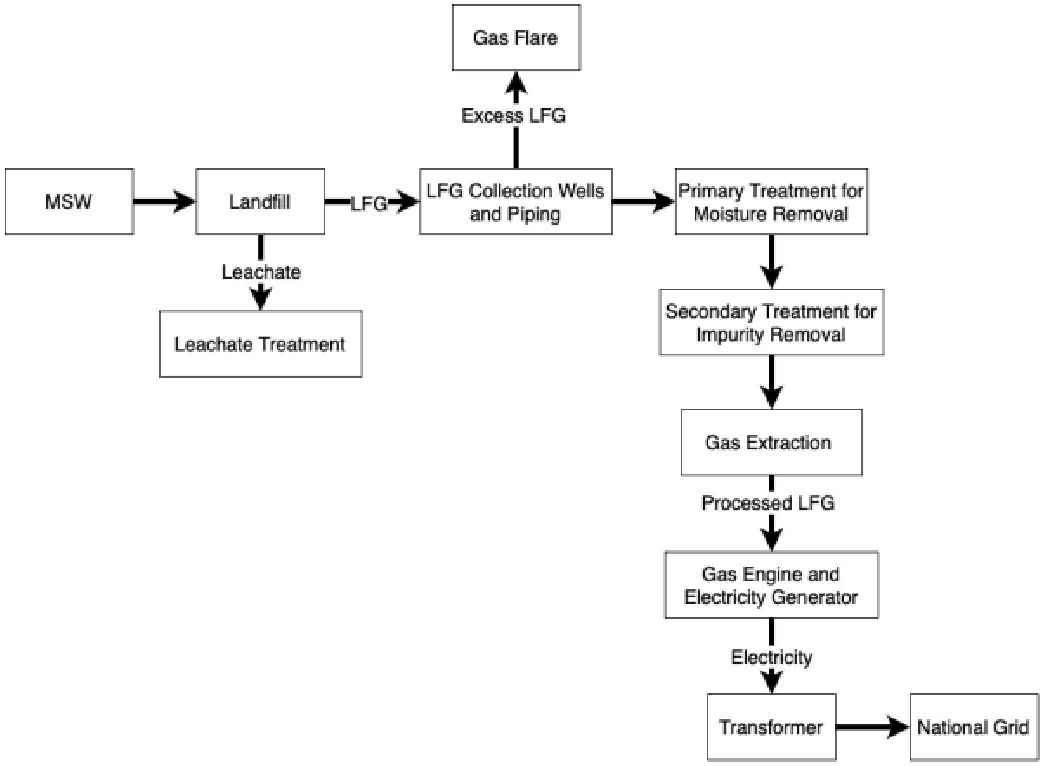


Figure 2.6: Landfill gas recovery treatment flowchart (Tang et al. 2021).

As outlined by Tang et al. (2021), although the landfill gas (LFG) recovery system represents a theoretically optimal solution for Malaysia due to the country's reliance on landfills for waste management, it encounters several practical limitations. A significant number of landfills in Malaysia are open dumpsites or unsanitary landfills that lack the necessary infrastructure for LFG and leachate collection. According to Omar and Rohani (2016), methane (CH4), a major component of LFG, is primarily generated early in a landfill's lifecycle when extraction can be most effective. Consequently, a considerable amount of LFG from closed or expired landfills may escape into the environment through openings within the waste cells. The production of LFG can be inconsistent, influenced by various factors such as waste composition and age, pH levels, moisture content, temperature, oxygen presence, as well as the type of landfill and its operational practices (Manheim et al., 2021). Additionally, the absence of robust source separation and recycling habits results in municipal solid waste (MSW) containing a high volume of non-degradable material, potentially reducing energy production and negatively impacting the economic viability of the process (Kathirvale et al., 2004).

2.3.2 Modelling Landfill Gas Generation

Sanitary landfilling, as described by Kumar and Samadder (2017), is the regulated dumping of waste on empty land with the goal of minimising environmental effect through biogas recovery and leachate treatment (see Figure 2.7). However, non-sanitary landfilling offers a simpler and low-cost answer to the increasing waste volumes and remains the predominant method in developing countries, posing a significant environmental hazard. Wang and Geng (2015) cited earlier studies that found landfilling to have the greatest environmental effect when evaluated with other waste management options.

According to reports, waste is placed in low-lying areas on the fringes of many towns in developing countries. When environmental and health consequences, land degradation, and groundwater contamination are considered, landfilling becomes the least attractive choice (Kumar and Chakrabarti, 2010). Developed countries, on the other hand, have begun to discourage waste landfilling through severe legislation, waste reduction campaigns, and greater reuse and recycling.

Leachate produced in landfills, is a substantial contaminant and is characterised by a dark discharge with a highly varied composition containing persistent chemicals. It pollutes neighbouring surface water bodies as well as groundwater aquifers. According to experts, only 10-15% of total waste produced should be designated for landfilling, and it should be regarded a last alternative in cities with limited land area (Muller et al., 2015).

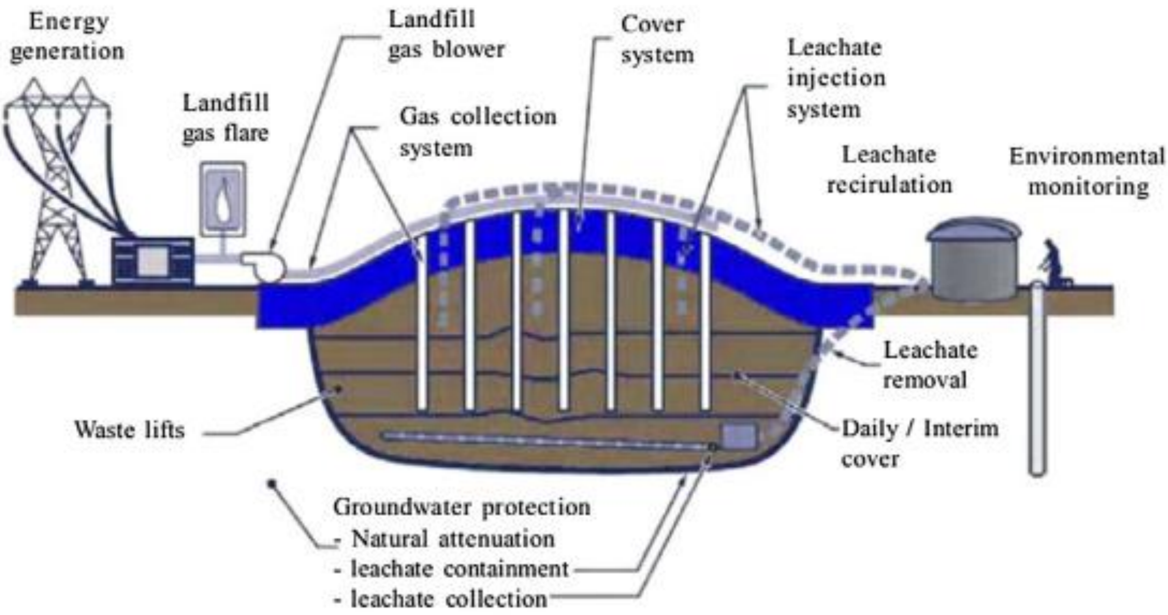


Figure 2.7: A landfill designed with a gas recovery system (Kumar and Samadder, 2017).

Kumar and Samadder (2017) underscored that the rate of landfill gas (LFG) production is subject to various influencing factors, including the landfill type, waste composition, climate conditions (temperature and precipitation), moisture content, and the age of the waste. Comprising approximately 50% to 60% methane, LFG stands as a significant contributor to human-induced methane emissions. The annual emission of 30-70 million tonnes of methane gas from waste landfills is estimated (Johari et al., 2012). Therefore, the recovery of methane from landfills for electricity generation or other purposes is crucial to minimize emissions. In cases where LFG recovery is technically unfeasible, on-site flaring of LFG is employed. However, accurate estimates of trapped LFG within a landfill are essential, necessitating the modeling of LFG generation.

2.3.3 Incinerator

Figure 2.8 provides a schematic diagram illustrating the process of incineration MSW(Tang et al. 2019). Incineration, a type of thermal WTE technology, has the capacity to significantly reduce the volume of MSW by up to 90%, and mitigate the pollution caused by hazardous waste, and simultaneously produce electricity. The typical procedure of incineration occurs in a furnace or boiler, subject to elevated pressure and temperatures of 850 °C and 1100 °C. This results in the creation of high-temperature combustion gases, including N_2, CO_2, H_2O, flue gas, O_2, and a non-combustible residue. Subsequently, these heated flue gases flow through a heat exchanger, where water is converted into steam. Finally, power is generated in the steam turbine via the Rankine cycle.

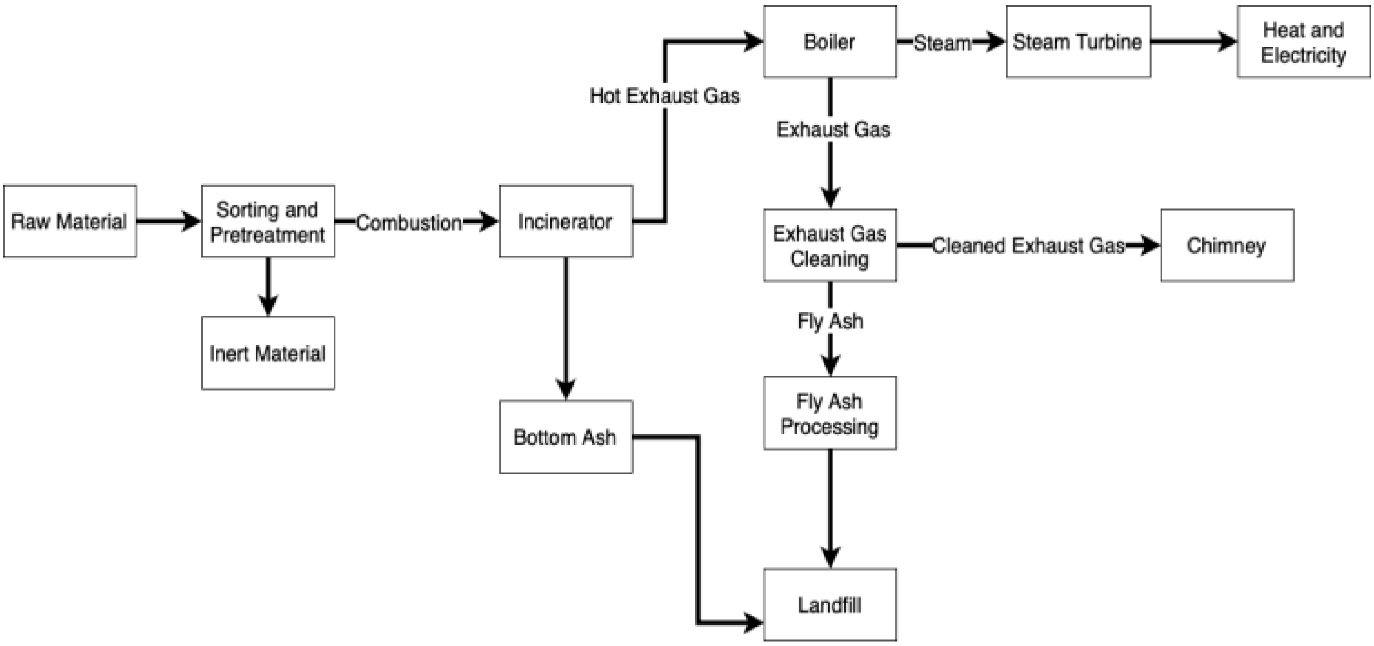


Figure 2.8. The schematic flowchart of MSW incineration process (Tang et al. 2021)

As per Kathirvale et al. (2004), the calorific value of MSW in Malaysia falls within the range of 1540 to 2640 kcal/kg, with the moisture content averaging at 55%. Incineration proves most effective for MSW characterized by low moisture levels and non-biodegradable components. Given the substantial presence of organic compounds in Malaysia's MSW, leading to elevated moisture content, a pre-drying process is necessary before introducing it into the combustion chamber. This pre-drying step aims to reduce the moisture content, as high levels negatively impact the MSW's combustibility by diminishing the calorific value through the latent heat of vaporization.

According to Salah et al. (2023), while being one of the most effective WTE methods, incineration might contribute to environmental contamination. Bottom and fly ashes, as well as flue gas containing hazardous chemicals, are produced during the incineration process. Notably, heavy metals, incapable of degradation or destruction, can transfer from MSW to incineration residues. These heavy metals not only pollute land and water, but it also endangers public health. Furthermore, the flue gas produced by incineration contains particulate matter, nitrogen oxides, sulphur oxides, dioxins, and furans, all of which contribute significantly to air pollution, acid rain, and smog. Dioxins, such as polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans, and polychlorinated biphenyls, are extremely carcinogenic and have been related to a variety of cancers. As a result, it is advised that air pollution control equipment, such as an electrostatic precipitator, be installed in incineration plants to reduce air pollutant emissions into the atmosphere.

2.3.4 Gasification

Kumar and Samadder (2017) conducted a review emphasizing gasification as a thermal conversion method wherein organic compounds undergo transformation into synthesis gas or syngas in controlled oxygen conditions at elevated temperatures. The primary output, syngas, can be applied for energy production through combustion or serve as a raw material for the production of chemicals and liquid fuels. Traditionally, gasification research has focused on the continuous flow of solid fuels such as coal, wood, and specific types of MSW. Although gasification has been widely used in the coal industry, it has recently gained attention as a potential energy recovery solution for MSW.

As per Salah et al. (2023), gasification stands as one of the primary methods for thermochemical conversion, alongside pyrolysis and incineration. This technique is employed to harness energy from biomass and waste materials. The process entails exposing biomass to high temperatures (exceeding 1000 ˚C) with limited oxygen support, leading to the generation of a gas mixture known as syngas. Syngas comprises CO_2, CO, and H_2. The combustible constituents of syngas, specifically H_2 and CO, can be used as fuel in gas engines, contributing to both electricity and heat generation. Furthermore, these elements play an important role in chemical manufacturing, enabling the Fischer-Tropsch process to produce organic acids, alcohols, methanol, and ammonia.

Gasification has the potential to reduce 95% of waste volume, necessitating fewer rigorous flue gas cleansing compared to incineration, as noted by Kumar and Samadder (2017). This method outperforms other WTE alternatives with respect to environmental emissions and energy recovery effectiveness. However, despite its advantages, widespread adoption, particularly in developing countries, is hindered by factors such as the high costs of investment and maintenance, inefficiencies in gas cleaning systems and gasifiers, variations in MSW content and particle size, and elevated moisture content, which pose challenges for stakeholders.

An illustrated schematic of the gasification process describing feedstock versatility and the generation of a diverse array of products as shown in Figure 2.9.

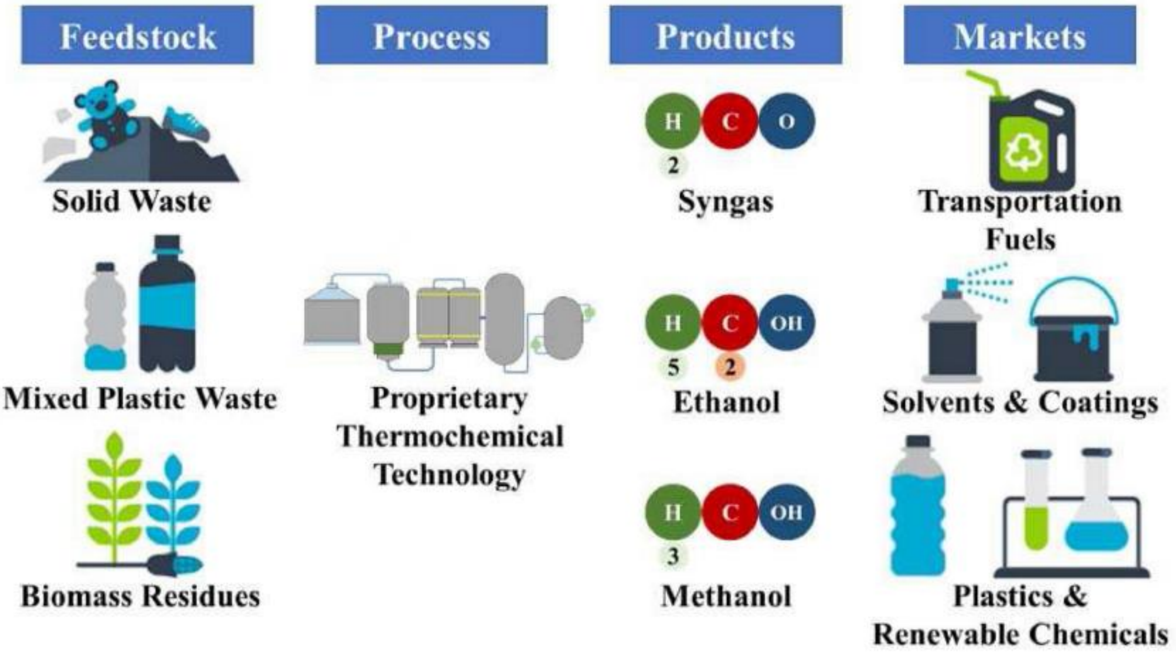


Figure 2.9: Depiction of the gasification process for MSW (Wang et al. 2023)

2.3.5 Anaerobic Digestion (AD)

Kumar and Sammader (2017) have emphasized that anaerobic digestion (AD) , or biomethanation, is a microbic method that decomposes organic matter without oxygen, producing biogas in the process and generates sludge. The composition of the produced biogas, typically containing up to 75% of CH_4, 50% of CO_2, and about 15% of other gases such as water vapor, NH_3, H_2S, etc. The slurry can be applied as a soil conditioner in agricultural fields. Ali et al. (2016) states that AD has the capacity to extract both nutrients and energy from biodegradable waste. The value of the solid AD products as a fertilizer is primarily determined by the quality of the feedstock, including its protein, mineral, and vitamin content.

Within the process of AD, the organic component of biodegradable MSW undergoes degradation and conversion into methane through sequential stages. In the initial stage, hydrolysis, complex organic compounds in MSW are converted into soluble organic substances. Subsequently, in the fermentation stage, these organic fragments are further converted to become acetic acid, H_2, and CO_2. The concluding stage, methanogenesis, leads to the generation of methane.

As outlined by Luning et al. (2003), Figure 2.10 illustrates the transformation of organic substance into CH_4. AD is classified into "wet" processes, characterized by 10% to 15% dry matter content, and "dry" processes, with 24% to 40% dry matter content. Wet processes generate more liquid waste and less solid product, requiring a smaller reactor volume compared to dry processes. The choice of reactors, processes, and methane yield is contingent on factors such as the region, feedstock quality, and specific product requirements.

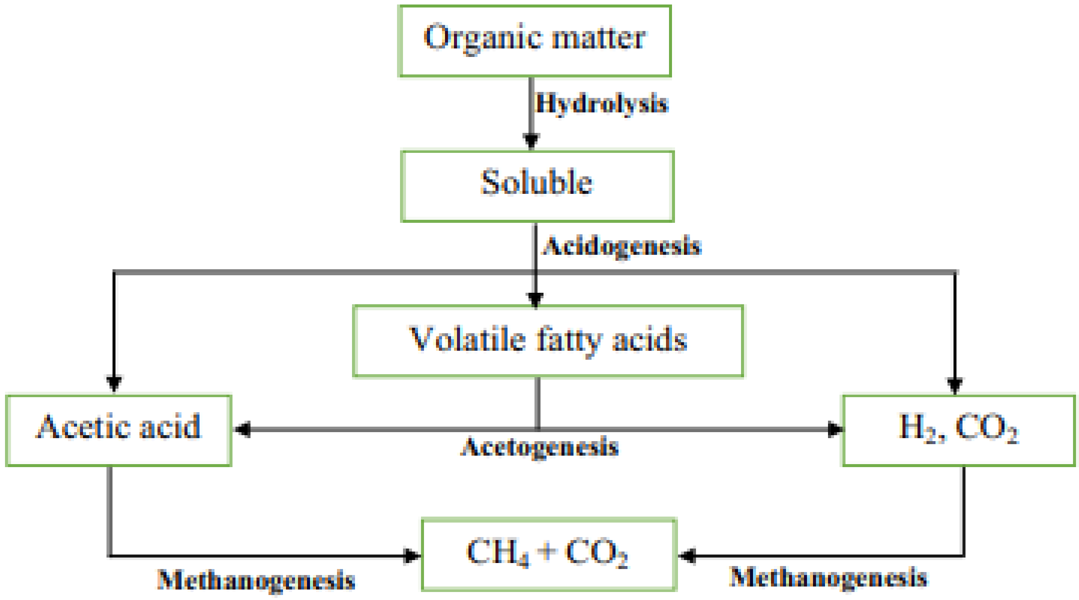


Figure 2.10: Stages in anaerobic digestion process (Luning et al., 2003)

According to Saxena et al. (2009), AD can release 2 to 4 times more methane gas per tonne of MSW in three weeks than a landfill is capable to produce in 7 years. It is observed that 1 m3 of AD-generated biogas can create 2.04 kWh of energy, assuming a 35% conversion efficiency. According to Scalet et al. (2015), an AD process per tonne of MSW, with a composition of 60:40 for organic matter moisture content, can yield approximately 150 kg of methane. However, a significant limitation of the treatment is the extended period of 20 to 40 days of the microbic reaction. Nitrogen-rich elements and cations, such as sodium, potassium, and calcium, might cause high ammonia and salt concentrations in the waste stream, rendering the process hazardous for methanogenic activities (Fountoulakis et al., 2008). While AD was previously used to treat domestic sewage, agricultural waste, organic waste, and animal manure, it is now commonly used for energy recovery from MSW, particularly in developing countries with high moisture content waste (Yap and Nixon, 2015). According to research by Abbas et al. (2017) the biogas retrieved from AD technology is sustainable both economically and environmentally.

2.3.6 Advantages and Disadvantages

In addressing the Malaysian challenges related to MSW management, Tang et al. (2021) proposed the implementation of WTE technology serves as an optimal choice. This technology contributes to sustainable MSW management by efficiently reducing the organic fraction of MSW and generating significant power and thermal heat from untreatable waste. Therefore, MSW is viewed as a reliable renewable energy recovery source. As a result, this approach leads to a MSW volume reduction directed to landfills, hence diminishing reliance on fossil fuels and other non-renewable energy sources, and ultimately, a reduction in greenhouse gas emissions (Devadoss et al., 2021).

Tang et al. (2021) further underscored the importance of assessing both advantages and disadvantages of WTE technologies to make an informed decision in selecting the most practical and beneficial method for managing MSW as a renewable energy recovery source, as outlined in Table 3.

Table 3: Advantages and disadvantages of WTE technologies (Tang et al. 2023).

WTE Technology	**Landfill Gas Recovery System**	**Incineration**	**Anaerobic Digestion**	**Gasification**
Advantages	-Reduce GHG release. -Landfill gas used as fuel. - Power can be produced.	-Reduce overall waste volume. -On-site incineration. -Minimize air emission when using pollution control system. -Less space requirement.	- Suitable for the treatment of organic waste. -Wider treatment range of organic substance. -minimum impact on the environment. -Massive potential to recover energy.	-Efficiency higher than incineration. -Treatment of inorganic waste with higher quality -Minimum emission. -Generates various biofuels.
Disadvantages	-Produces foul smell. -Fire hazard. -Landfill gas production influenced by the waste temperature and moisture content.	-Excessive investment cost. -Expert labor is needed. -Combustibility influenced by excessive moisture content in waste. -Improper treatment of flue gas causes environmental problems. -Human wellbeing threat from air pollution.	-Long duration of microbial reaction. -Require sufficient waste for operation. - Waste stream contains high nitrogen rich substances and cations.	- Excessive investment cost. - Expert labor is needed for operation. -Minimum emission. -Effectiveness influenced by excessive moisture content in waste, hence leading to high energy consumption for operation. -Fuel quality is impacted by the waste contents.

2.4 Waste to Energy Scenario in Malaysia

2.4.1 Landfills

Johari et al. (2012) stated that MSW is a widely recognized biomass resource. It is anticipated that MSW generation by 2020 may exceed 30,000 tonnes daily, with roughly 45% of the MSW undergoing processing at sanitary landfills. The breakdown of biodegradable components within MSW leads to the production of approximately 55% methane (CH_4), 35% carbon dioxide (CO_2), 3% nitrogen (N_2), 2% oxygen (O_2), and 1% hydrogen sulphide (H_2S), hydrogen (H_2), and ammonia (NH_3).

They also determined that landfills represent the predominant source of methane emissions, constituting 53% of the total volume, with 38% from palm oil mill effluent, 6% from animal manure, and roughly 3% from industrial effluent. Figure 3.0 offers an overview of methane gas generation from Malaysian landfills (tonnes/year). Given the substantial volume of methane gas potentially produced, there is a significant opportunity to harness this resource in Malaysia for renewable energy (RE) recovery purposes.

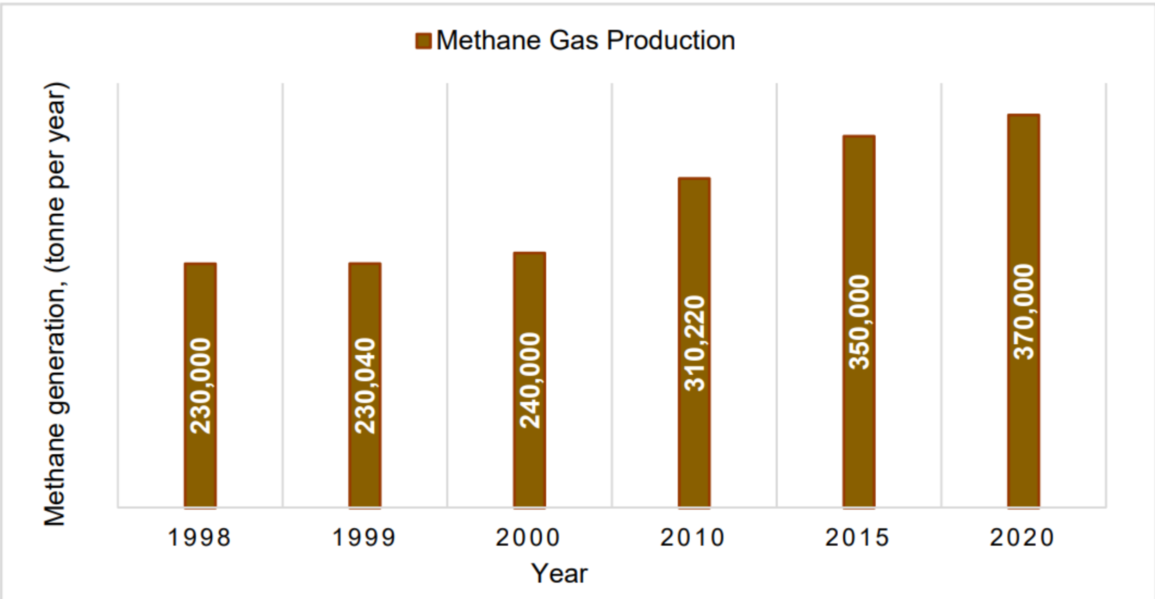


Figure 3.0. Methane gas production from 1998 to 2015, with a projection for 2020 (Johari et al. 2012).

Yong et al. (2019) carried out a review highlighting the Bukit Tagar Sanitary Landfill (BTSL) as an illustrative case. Situated in Hulu Selangor, it encompasses 18 distinct waste cells over a 700-ha area, capable of managing 120 million metric tonnes waste capacity. Presently, BTSL handles approximately 2500 tonnes of MSW daily, with the capability to manage 5000 tonnes MSW collected from Selangor. This landfill is estimated to have a 130-year lifespan. Methane gas generated from the cells is captured and utilized, producing around 3600 m^3 of landfill gas (LFG) per hour with a 60% methane content, ultimately generating electrical power of at least 6MW. Gas power engine of 1.2MW is in place to collect methane gas and generate electricity, though some of the gas is still flared. In its entirety, BTSL is one of the biggest WTE projects, featuring about 10.5MW gas engine capacity in total, supplying electricity back to the national power grid through the Feed-in Tariff (FiT) incentive.

Another example is the Puchong-based Air Hitam sanitary landfill, currently known as Worldwide Landfill Park (WLP). Because of the decomposition of organic waste accumulated over the last decade, this landfill produces landfill gas (LFG) with a high methane content. It presently generates 2 MW of electricity each month, enough to power around 2000 homes. The landfill was rehabilitated and rebranded in 2006, with Worldwide Landfills Sdn Bhd managing the renewable energy project. It is predicted to continue providing 2 MW of electrical power every day for at least another 16 years, owing to the saturation 6.2 million metric tonnes of MSW accumulated over the preceding decade. Food waste accounts for a significant component of Malaysia's MSW content. According to Yong et al (2019), an average of 7600 metric tonnes per day were generated in 2010, accounting for around 45% of total MSW generated in 2016.

2.4.2 Incineration

The application of incineration as a WTE strategy is limited in Malaysia and has been implemented on a small scale. Incineration has the potential to reduce 80% to 95% of the volume of MSW. In 2011, the Ministry of Local Government and Housing (MHLG) initiated several incineration projects, investing RM 187.74 million in five tourism spots, namely in Pulau Langkawi (100 tons/day), Pulau Labuan (60 tons/day), Cameron Highlands (40 tons/day), Pulau Pangkor (20 tons/day), and Pulau Tioman (10 tons/day) (Bashir et al. 2019).

Bashir et al. (2019) also highlighted the incineration plant in Pulau Langkawi as the most complete and the first to implement WTE technology in Malaysia. Construction cost for this facility was RM68 million, and it treats 100 tons of MSW per day to produce 1 MW of electricity. Two units of mini-incinerators with the model Hoval GG42 were installed, overseen by the Langkawi Town Council. The Langkawi plant practices on-site solid waste segregation before treating the waste stream in the incinerator. The WTE plant in Kajang, which includes a refuse-derived fuel (RDF) facility, is one of Malaysia's most advanced incinerators, emphasising RE recovery in solid waste management. It was completed in 2008 and processes roughly 1100 tonnes of MSW per day into RDF, providing approximately 8 MW of electricity per day. Three megawatts (MW) power the plant, while the remaining five megawatts (MW) are provided and sold to the national grid via the Feed-in-Tariff (FiT) system. The export capacity of power generation is being increased from 5 to 6 MW. RDF technology currently recovers 77% of the energy stored in MSW as fuel, with attempts underway to boost this to 83% by adding biogas produced from organic waste via anaerobic digestion (AD) for increased efficiency. With MSW generation predicted to increase from 6.37 to 13.38 million tonnes between 2010 and 2030, the opportunity for WTE application expands dramatically. Based on the calorific value of MSW in Malaysia, which ranges from 1500 to 2600 kcal/kg, incineration plants might possibly yield 640 kW/day.

2.5 Landfill Gas Estimation Models

According to Kumar and Kumar. (2014), different predictive models such as the Intergovernmental Panel on Climate Change (IPCC) (1997, 2006) models, the Shell Canyon model, and LandGem (US EPA, 2005) are routinely used to forecast the yearly methane generation from a landfill. Nonetheless, these landfill gas models have been criticised for their poor accuracy and lack of validation, with most results lacking verification against actual methane recovery data. Although some studies have matched methane recovery data to model-generated predictions for a small number of landfills, different countries still use different methodologies for collecting and reporting methane production from landfill sites. Despite efforts by the Intergovernmental Panel on Climate Change (IPCC) to develop a common methodology, there is still a lack of standardisation. Thomson et al. (2009) conducted a comparative analysis and found that the LandGem model generated more accurate estimates of methane emissions than other models, as shown in Table 6. Consequently, the author opted to estimate methane gas emissions from Malaysian landfill sites by using the LandGem model. Originally developed by US EPA researchers for incorporating major US landfills into air quality regulatory programs and regional emission inventories under Clean Air Act amendments, LandGem is based on two critical factors: landfill waste methane potential (L_0) and degradation rate (k) (Cho et al., 2012). Variables such as the amount of biodegradable waste, segregation levels, microbial application rates, volatile solids, and meteorological parameters such as temperature and humidity all influence methane potential (Xiaoli et al., 2010; Xi et al., 2012). LandGem was specifically designed for the weather conditions and waste characteristics of the United States.

Table 4. Assessment of various models for methane gas emission projection (Thomson et al. 2009)

Model Type	***Mean absolute error and standard error (%)***	***Error median***	***Correlation (r)***	***Mean relative error (%)***
LandGem model	81 + 17	-86	0.92	-81
German EPER model	589 + 666	238	0.85	312
TNO model	376 + 356	322	0.87	289
Belgium model	171 + 177	125	0.86	111
Scholl Canyon model	115 + 152	43	0.91	111

CHAPTER 3

METHODOLOGY

3.1 Overview

This study intends to propose a strategy to support the Malaysian government's commitment to sustainability and decrease its carbon footprint by effective management and transforming MSW into RE and biofuel source. The initial stage involves analysing the state of Selangor, which is the most urbanized and populated state in Malaysia, to understand its waste management practices and energy needs, thereby establishing a reference point for assessing the effectiveness of the proposed approach. Data collection from previous research work and from the case study is crucial in determining the volume and makeup of the MSW, predicting potential energy generation, and quantifying reductions in CO_2 emissions. By converting MSW into renewable energy source using WTE technologies, not only is solid waste are reduced and diverted from landfills but RE is also generated to fuel city and utility services. The approach may further reduce GHG emissions by enhancing MSW collection methods which can lead to cost efficiencies by reducing MSW dumping expenses while lessening reliance on landfill disposal and traditional fossil fuel energy sources.

3.2 Project Design

Figure 3.1 summarizes the implementation process of the methodology, demonstrating key procedures such as energy, economic and environmental evaluation, data collection, energy and CO_2 cost estimation, and other potential cost impacts.

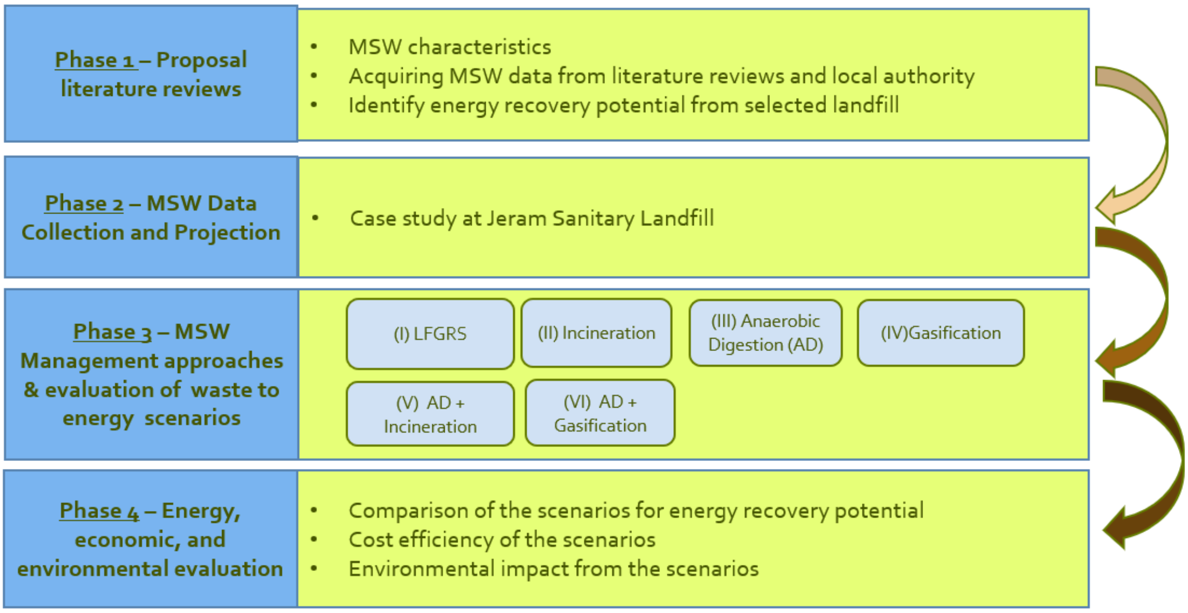


Figure 3.1: Research methodology

From the research methodology, Phase 4 involves conducting a comprehensive 3E evaluation of the four selected WTE methods, as described in Figure 3.2.

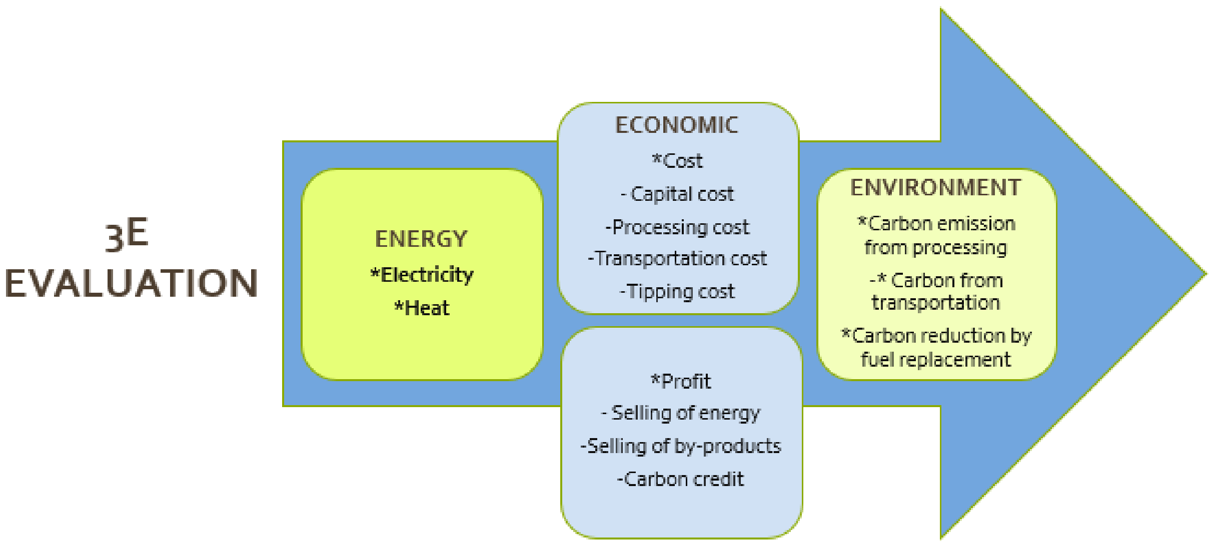


Figure 3.2: 3E evaluation framework for WTE technologies application.

3.3 Jeram Sanitary Landfill

The study area is in the state of Selangor, which is highly populated, industrialized, and developed state in Malaysia. The state is governed by 10 municipal councils. The study area covers 8,104 km^2 with total approximate population of 7 million residents (Wikipedia, 2020), focusing on the Jeram Sanitary Landfill facility, as illustrated in Figure 3.3.

The Jeram Sanitary Landfill (JSL) is situated in Mukim Jeram, Selangor, positioned 20 km to the Northwest of Kuala Lumpur. It is precisely at coordinates 3110 2000 N and 101210 5000 E. The landfill spans a total area of approximately 200 acres, comprising six phases designated for waste disposal. Its design accommodates the reception of around 2,500 tons of waste daily, and the operational lifespan, commencing in 2007, is projected to last 35 years.

JSL receives MSW from seven prominent districts in Kuala Lumpur and Selangor. The received MSW includes household waste, industrial bulky waste, and garden waste exclusively. Averagely 2500 tonnes of MSW, originating from approximately 470 compactors, is deposited daily at JSL.

Selangor's state government is developing an integrated waste management system that will investigate WTE technologies such as incineration, anaerobic digestion (AD), gasification, and landfill gas recovery system (LFGRS) in order to reduce global warming potential and generate revenue from byproducts such as electricity, thermal energy, biofuels, and fertiliser.

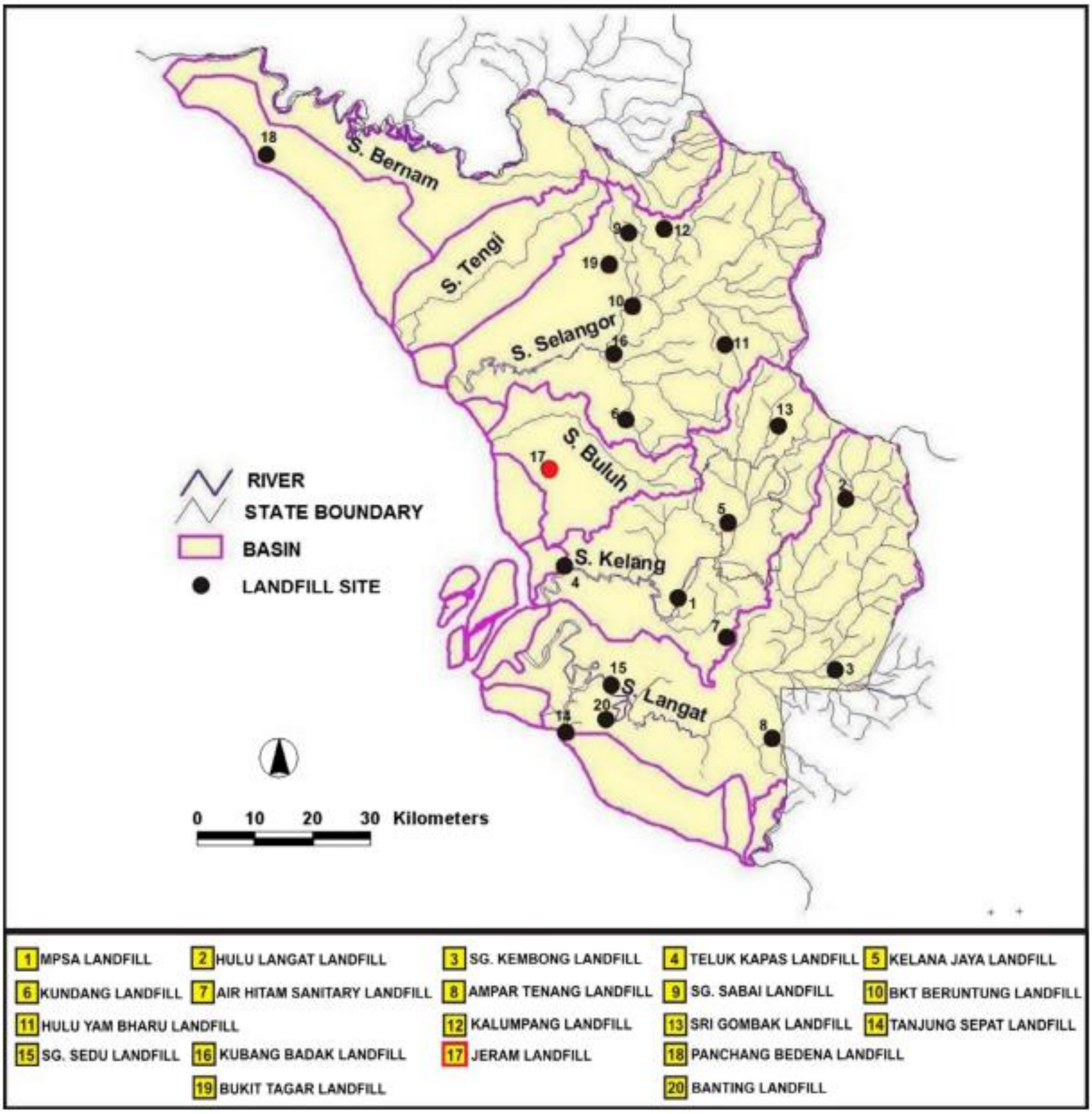


Figure 3.3: Jeram Sanitary Landfill location in state of Selangor (Abushammala et al. 2014).

3.4 Data collection and scenarios setting

From the visit by the author to the JSL site office in June 2023, the technical officer confirmed that the existing landfill has already been upgraded with a methane gas (CH_4) or landfill gas recovery system (LFGRS) since 2015, with a total of 5.8 MWh per day electricity production capacity as of January 2023, while closer to the waste transfer station, a new integrated WTE facility is being proposed to be build and operated by 2026. Figure 3.4 shows the current landfill layering activity, while Figure 3.5 and Figure 3.6 describe the leachate treatment facility and power generators respectively.

The study's seven scenarios, outlined in Table 5, encompass a baseline scenario where MSW from JSL is landfilled without energy recovery. The studied WTE scenarios fall into two categories: individual WTE system which is LFGRS, incineration, AD, and gasification depicted by scenarios I, II, III, and IV, and integrated WTE systems combining incineration with AD, and gasification with AD, describe as scenarios V and VI.

The integrated Waste-to-Energy (WTE) strategy proposes the adoption of two distinct WTE methods to alleviate the waste load on the landfill. Within this strategy, Anaerobic Digestion (AD) is paired with two different WTE processes: incineration for scenario V and gasification for scenario VI. In each scenario, 1500 tonnes per day of MSW comprising the organic portion will be directed to AD, while approximately 1000 tonnes per day of MSW (comprising the inorganic portion) will undergo the respective WTE process, as outlined in Table 6.


Figure 3.4: JSL dumpsite layering activity.

Figure 3.5: JSL compound with the leachate treatment facility.


Figure 3.6: JSL methane gas operated power generators.

Table 5: Detailed descriptions of each individual scenario, and the proposed integrated scenario waste management solutions in the Jeram Sanitary landfill using WTE technologies.

WTE Method	**Scenario**	**Technologies**	**Description (MSW Volume)**
	Baseline	Landfill only	Sanitary landfill (2500 t/day).
Individual	**I**	Landfill gas recovery system	Energy recovery for electricity and heat from sanitary landfill (2500 t/day).
	II	Incineration	Electricity and heat production from incineration(2500 t/day)
	III	Anaerobic Digester	Biogas production to generate electricity and heat (2500 t/day). Slurry will be sold as fertilizer.
	IV	Gasification	Electricity is generated from gasification (2500 t/day).
Integrated	**V**	Anaerobic Digester (AD) and Incineration	Utilizing AD for 1500 tonnes per day, combined with incineration processing 1000 tonnes per day, aims to generate biogas, electricity, and heat. In this process, Fly ash produced during incineration shall be directed to the landfill, while the slurry, a byproduct of AD, will be sold as fertilizer.
	VI	Anaerobic Digester (AD) and Gasification	Production of biogas, electricity and heat with AD (1500 t/day) and Gasification (1000 t/day) The slurry by-product shall be sold as fertilizer.

Table 6: Factors for the different technologies under consideration for the management of solid waste at Jeram Sanitary Landfill.

Parameter	**WTE Technologies**				
	Landfill	**LFGRS**	**Incineration**	**AD**	**Gasification**
*1Case study data					
Waste stream to individual option (t/d)	2500	2500	2500	2500	2500
Waste stream to integrated option (t/d)	0	0	1000	1500	1000
Transfer station to hub average distance (km)	60	60	5	5	5
Tipping fee (USD/t)	60				
Truck size (t/vehicle)	50				
*2 Conversion factor for MSW					
Electricity generation (MWh/tMSW: MWh/m^3)		0.0021	0.48	0.0021	0.40
Heat generation (MWh/tMSW: MWh/m^3)		0.0025	1.43	0.0025	
Biogas generation (m^3/t MSW)		47.7		203.6	
Ash generation from incineration (t/t MSW)			0.1		
Slurry generation from AD (t/t MSW)				0.3	
*3 Costs					
Capacity cost (USD/t waste)		0.78	2.18	1.08	3.2
Processing cost (USD/t)	18	24.02	67	35.45	96.06
Transportation cost (USD/t-km)	9				
*4 Product price					
Carbon credit (USD/t CO_2)	15.38				
Electricity (USD/MWh)	380				
District heating (USD/MWh)	50				
Fertilizer (USD/t)	100				
Emission factor					
*5 CO_2 emission from transportation (tCO_2/km)	0.012	0.012	0.114	0.114	0.114
*2,4 CO_2 emission from processing (tCO_2/t MSW)	1.11	0.35	0.28	0.253	0.2
*4 Carbon avoidance (tCO_2/kWh)	0.000619				

Note *: 1 From the study; 2 Tan et al (2013).; 3 Tolis et al and Tsilemou et al. (2010); 4 Tan et al. (2014); 5 EPA (2019).

As seen in Table 7, biomass components such as paper, food and yard wastes, wood, leather and textiles account for 62% of MSW. The remainder is made up of inorganic materials such as metals, glass, and gypsum/asbestos from building, as well as other minerals. The statistics show that organic garbage, primarily kitchen waste, accounts for 32.4% of the waste disposed of in JSL.

Table 7: MSW data characterization from Jeram Sanitary Landfill (Worldwide Holdings, 2023).

Type of MSW	**MSW sampling amount (Tonne/day)**	**MSW Composition (% wet weight basis)**
Organic waste	52	32.4
Paper	21.4	13
Soft plastic	19	11.5
Hard plastic	14	8.5
Soft paper	12	7.2
Debris	10	6.2
Glass	10	6
Wood	9	5.6
Textile	6	3.7
Tin / Alloy	4	2.4
Polystyrene	2	1.2
Aluminium cans	2	1
Electronics (Wires)	0.5	0.3
Metal	0.4	0.3
Sanitary waste (diapers etc)	0.7	0.7
TOTAL:	**163**	**100**

3.4.1 Characteristic of MSW

Assessing alternative processes and recovery options relies significantly on information regarding the characteristics of MSW. The MSW physical qualities include waste composition fraction, moisture content, and dry weight fraction. (Tan et al. 2014). Meanwhile, the chemical properties involve molecular composition, represented by parameters like C_{org} (organic carbon), C_{iorg} (inorganic carbon), H (hydrogen), O (oxygen), N (nitrogen), S (sulphur), and ash. The properties specific to the Malaysian MSW are detailed in Table 8. Establishing the genuine chemical properties of MSW relies on understanding the dry weight composition of the waste, a crucial aspect expressed through Equation (1).

Dry weight fraction (%) = Wet weight fraction (%) X (100 - Moisture content (%)) ----- (1)

The major molecular composition of the waste is determined through ultimate analysis by Tan et al. (2014), which uses the dry weight fraction of MSW, as presented in Table 8.

Table 8: MSW Properties in Malaysia (Tan et al. 2014).

	Food	Yard	Paper	Plastic	Glass	Metal	Textile	Total/average
Physical Properties								
Wet weight fraction (%)	41.06	2.45	20.93	22.23	3.63	1.96	7.74	100
Moisture content (%)	37.23	0.885	14.65	0.68	0	0	0.085	53.53
Dry weight fraction (%)	25.77	2.43	17.86	22.08	3.63	1.96	7.73	46.47
Chemical properties - ultimate analysis (Wet basis)								
C_{org} (%)	48	47.8	43.5	0	0	0	55	27.76
C_{iorg} (%)	0	0	0	60	0.5	4.5	0	9.29
H (%)	6.4	6	6	22.8	0.1	0.6	6.6	6.93
O (%)	37.6	38	44	7.2	0.4	4.3	31.2	23.24
N (%)	0.4	0.3	0.2	0.1	0	0	0.1	0.16
S (%)	2.6	3.4	0.3	0	0.1	0	90.5	13.86
Ash (%)	5	4.5	6	10	98.9	0.46	2.5	18.19

3.5 Energy Evaluation

The methods of LFGR, incineration, AD, and gasification all possess the capacity to reclaim energy. The MSW generated can be evaluated in the context of these technologies to discern which provides the most compelling argument for Jeram Sanitary Landfill's energy production. The following equations are referred from the research of Salah et al (2023).

3.5.1 Landfill Gas Recovery

Understanding methane emissions from landfills is facilitated mostly by a first-order decay (FOD) model, which evaluates the rate of methane generation relative to waste input. There are several models available for carrying out this procedure, one of which is the Landfill Gas Emissions Model (LandGEM), which includes interaction with a Microsoft Excel interface. Equation (2) was used to calculate the potential yearly electricity generated by the determined methane generation rate, as determined by LandGEM.

$$ERP_{LG} = LCV_{biogas}.Q_{CH4}.\boldsymbol{\gamma}.\ \boldsymbol{\eta} \qquad (2)$$

Table 9 details the parameters used in the landfill scenario. Although LFG is not a key WTE technology, it has become critical for communities who operate sanitary landfills and have no other options. Instead of starting from scratch with new WTE initiatives, LFG collection is seen as a viable alternative for existing landfills.

Table 9. Parameters applied in the landfill gas recovery technology.

Parameters		Value of the Parameters	Units
Biogas Low Calorific Value	$\mathbf{LCV_{Biogas}}$	**5.56**	**$\mathbf{KWh/m^3}$**
Methane Production	$\mathbf{Q_{CH4}}$	**119,250**	**$\mathbf{m^3/day}$**
Biogas Recovery System Efficiency	$\boldsymbol{\gamma}$	**80**	**%**
Electrical Efficiency	$\boldsymbol{\eta}$	**33**	**%**

3.5.2 Anaerobic Digestion (AD)

Equation (3) was used to calculate the potential energy recovery from the AD process of MSW. Table 10 summarizes the information used in the AD scenario.

$ERP_{AD}=P.R_{AC}.f.M_{OFSW}.Q.\eta$ (3)

To ignite methane gas or biogas, a liquid fuel is required, and diesel fuel can be blended with biogas for power generation. The successful application of AD at greater scale is dependent on the appropriate separation of the organic waste part. However, in many developing nations, organic waste is commonly mixed with other chemicals, which could jeopardize the success of WTE AD systems.

Table 10. The parameters applied in the AD technology.

Parameters		**Value of the Parameters**	**Units**
Biogas LCV (Methane)	Q	5.56	KWh/m^3
Population	P	2,500,000	Capita
Solid Waste Organic Portion	F	32.4	%
Process Efficiency	η	26	%
per Capita amount of Waste Produced	R_{AC}	0.85	Kg/capita.d
Methane production per ton of Organic Fraction of Solid Waste	M_{OFSW}	120	m^3/ton

3.5.3 Incineration

Equation (4) was used to compute potential energy recovery from the incineration approach, with Table 11 displaying the values used in the incineration scenario.

$$ERP_i = \eta . M . LCV_{MSW} \qquad (4)$$

Despite the favourable outlook for the waste incineration sector, various challenges have emerged due to the rapid expansion of waste incineration facilities. These issues encompass inappropriate site selection, an excessive generation of fly ash, air pollution, and adverse Environmental Impact Assessments (EIA). Therefore, ensuring the environmental safety of the waste incineration process is crucial to prevent harm to the public.

Table 11. The parameters used in MSW incinerator technology.

Parameters		Value of the Parameters	Units
Lower Calorific Value of Waste	LCV_{MSW}	480	KWh/m^3
Total Mass of Dry Solid Waste	M	2500	ton/day
Efficiency of Process	η	18	%

3.5.4 Gasification

Equation (5) was used to compute potential energy recovery from the gasification procedure, and the values employed in this scenario are shown in Table 12.

$ERP_G = 0.28.\ G.Rf.\boldsymbol{\eta}.LCV_{MSW}$ (5)

Fixed-bed gasifiers, fluidized-bed gasifiers, and entrained-flow gasifiers are the three basic types of gasifiers. Although gasification technology has the potential to recover energy from MSW materials, the choice of gasification systems (such as fixed-bed, fluidized-bed, or entrained-flow reactors) for MSW conversion is limited by a number of technical and economic constraints.

Table 12. The parameters used in gasification technology.

Parameters		Value of the Parameters	Units
Waste LCV	LCV_{MSW}	500	KWh/m³
Daily Processed Waste Volume	G	1175	ton/day
Ratio of Excluded after Mechanical Handling	R_f	46	%
Process Efficiency	$\boldsymbol{\eta}$	23	%

3.6 Economic Evaluation

The economics examined in this study were developed from a global review and customised to the Malaysian environment. Tolis et al. (2010) and Tsilemou and Panagiotakopoulos (2006) provided information on investment costs for WTE projects, including capital, processing, and transportation costs. Due to the removal of pre-treatment activities from the study scope, the study excludes pre-treatment expenditures. Furthermore, the investment cost does not apply to the existing landfill, which acts as the baseline scenario in the analysis. However, a tipping cost is included. This fee is the cost of waste disposal at the landfill. Revenue, on the other hand, is created by a variety of products, including power, heat, and fertiliser, as well as carbon credits. These credits represent the tradable profit generated by verifiable reductions in GHG emissions. Table 13 summarised the strategy.

Table 13: Economic Evaluation for WTE Technologies

Economic Value (USD/Day)	**Items**	**Remarks**
Costing	Capital cost. Processing cost. Tipping cost. Transportation cost.	This study's expenses were generated from a national review and then modified to the Malaysian environment. Tolis et al. and Tsilemou and Panagiotakopoulos provided primary information on investment costs for WTE projects in Malaysia, including capital charges, processing costs, and transportation costs.
Profit	Electricity. Heat (Thermal Energy). Fertilizer. Carbon credit.	Income is earned via the production of various commodities such as power, heat, fertilizer, and carbon credits. The carbon credit is the tradable benefit received from demonstrable GHG emission reductions.

3.7 Environmental Evaluation

An evaluation of the environmental impact took into account: (1) direct emissions arising from fugitive emissions from Landfill Gas (LFG) and Anaerobic Digestion (AD) technologies, as well as stack emissions from an incinerator, and (2) emission reduction achieved through electricity substitution. It is worth noting that coal-fired power plants generate 28% of Malaysia's electricity (Energy Commission Malaysia, 2019). As a result, the focus of this research was on replacing electricity generated from this traditional source.

3.7.1 Emissions Reduction by Fossil Fuel Displacement

Utilizing Municipal Solid Waste (MSW) in processes such as incineration, Anaerobic Digestion (AD), gasification, or the conversion of landfill gas into electricity or thermal energy helps diminish dependence on fossil fuels, consequently reducing CO_2 emissions. Equation (6) can be used to compute the quantification of CO_2 avoidance due to the displacement of fossil fuels, with coal serving as the reference. The assumption is that all MSW-generated electricity will be used to replace coal-generated electricity.

CO_2 avoidance by fossil fuel replacement = Elec x EF_{elec} ----- (6)

Elec denotes the total amount of electricity generated by WTE technology (kWh/t of MSW), and EF_{elec} denotes the carbon avoidance factor for each unit of power generation. Tan et al. (2014) provided the value of EF_{elec} for this experiment, which is 0.000619 t CO_2/kWh.

3.7.2 Emissions and Combustion

At temperatures reaching 800 °C, waste incineration turns chemical energy into thermal energy of combustion gas. This process produces carbon emissions, however WTE created from MSW serves as an alternative to fossil fuels while also reducing methane (CH_4) emissions at disposal sites. Despite its carbon footprint, this combustion process qualifies for carbon credits since it turns both the fossil carbon in the fuel and the biogenic carbon in MSW into carbon dioxide (CO_2). Trace amounts of nitrous oxide (N_2O) and methane (CH_4) are also emitted during burning (Tan et al., 2014). As a result, the total GHG emissions from WTE include the sum of anthropogenic CO_2 emissions, which are quantified in Equation (7) as an equivalent amount of CO_2.

CO_2 emissions from waste combustion

$$= \sum_j (\mathrm{WF}_j \mathrm{C}_{\mathrm{iorg}_j} \times \mathrm{OF}_j) \times Z \qquad \text{------ (7)}$$

CO2 emissions are represented as t CO_2/t MSW in this case. WF_j denotes the waste fraction for component j in terms of dry mass; C_{iorgj} denotes the proportion of anthropogenic carbon in terms of component j's dry mass (as defined in Table 7); and OF_j denotes the oxidation factor, with a default value of 1 for MSW. Z, the conversion factor from C to CO_2, whose value in this situation is 44/12; and j, the component of Malaysian MSW exposed to incineration.

CHAPTER 4

RESULT AND DISCUSSION

This section will examine and discuss the findings of the study. The LandGEM tool serves as the benchmark for evaluating biofuel such as biogas production. Subsequently, the analysis includes estimations of energy recovery potential, along with economic and environmental assessments for each scenario.

4.1 Biogas Calculation

According to the LandGEM analysis, with k (the decay constant) set at 0.03 $year^{-1}$ and L (the CH_4 production potential) at 120 m^3/Mg, the yearly landfill gas emission rates, methane (CH_4), carbon dioxide (CO_2), and non-methane organic compounds (NMOCs) were studied and displayed in Figure 4.1. The LandGEM generated result spanned a period of 36 years, from 2007 to 2043 for Jeram Sanitary Landfill (JSL).

The landfill gas recovery potential calculation results are :

- Landfill gas generation maximum rate is projected to reach 2.351 x 10^8 Mg / year in 2043.
- CO_2 emission highest rates are estimated to be 1.723 x 10^8 Mg /year in 2043.
- CH_4 generation peak rate is expected to be 6.28 x10^7 Mg / year in 2043.

During the power-generation phase, no NMOC creation is observed, which can be attributed to the exponential relationship of the first-order decay equation.

Based on the results, it is calculated that after the first 17 years, that is by 2022, a total of 3.95 x 10^{11} m^3 of methane gas will have been generated in Jeram Sanitary Landfill, which are substantial source for energy recovery as a baseline requirement.

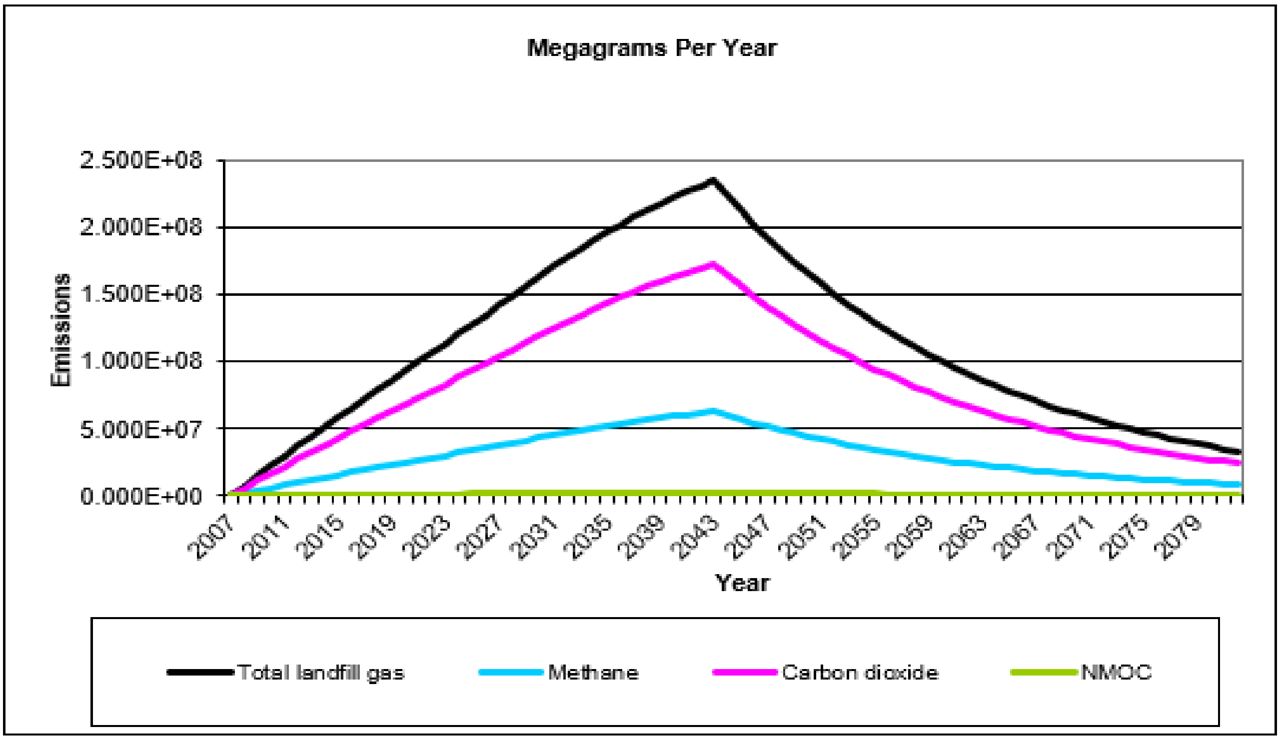


Figure 4.1. Yearly emission rates (Mg / year) of LFG, CH_4, CO_2, and NMOC for the Jeram Sanitary Landfill (2007–2043).

4.2 Energy, Economic, Environment (3E) Evaluation

The purpose of this study was to assess the potential benefits of various WTE technology applications for energy recovery from MSW in the Jeram Sanitary Landfill (JSL).

The outcomes for the baseline and individual scenarios (I, II, III, and IV) are detailed in Figures 4.2, 4.3, 4.4, and 4.5 based on the results listed in Table 14. While the computation results for the integrated scenarios (V and VI) are shown in Figures 4.6, 4.7, 4.8, and 4.9.

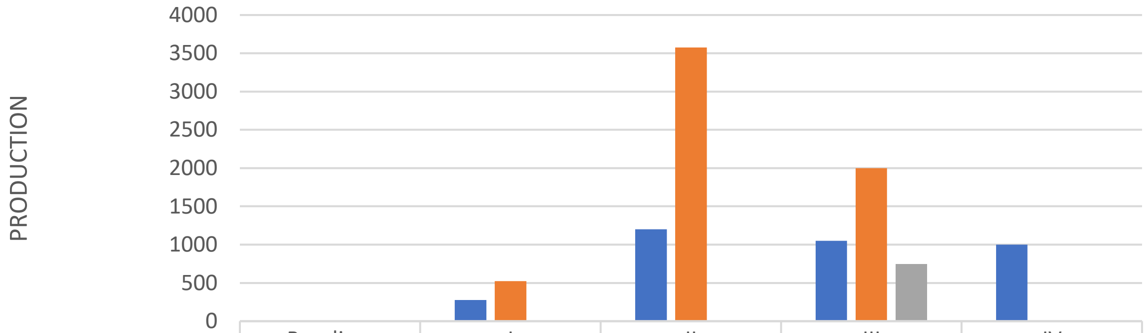
Table 14: Results for each WTE scenario.

Result	**Scenarios**	**Individual**				**Integrated**	
	Baseline	**I**	**II**	**III**	**IV**	**V**	**VI**
Production							
Biogas (m^3 /d)		119250		500000		300000	300000
Electricity (MWh/d)		275	1200	1050	1000	1110	1030
Heat (MWh/d)		525	3575	2000		1105	1200
Digestate (t/d)				750		450	450
Costing (USD/d)							
Capital cost		2145	5450	2700	8000	3800	4820
Processing cost	45000	66055	137500	88625	240150	108175	149235
Tipping cost	150000						
Transportation cost	27000	27000	4950	2250	2250	3330	2250
Total cost	222000	95200	147900	93575	250400	115305	156305
Profit (USD/d)							

Electricity		104677	456000	399000	380000	421800	391400
Heat		30432	207350	116000	0	152540	69600
Fertilizer				75000		45000	45000
Carbon credit		30498	47633.4	47769.51	49331.35	47715.066	48394.246
Total profit		165609	710983	637769.5	429331.4	667055.07	509394.25
Net profit	-222000	70409	563083	544194.5	178931.4	551750.07	353089.25
Net profit (without heat sale)	-222000	3997	355733	428194.5	178931.4	399210.07	283489.25
Emission (t CO_2/d)							
Processing emission	2775	875	700	633	500	660	580
Transportation emission	342	342	63	29	29	42	29
Total Emission	3117	1217	763	662	529	702	608
Carbon avoidance by fuel displacement		171	743	650	619	687	638
Net carbon emission	3117	1729	1,611	1805	1969	1728	1871
Net carbon emission (%)		-45%	-49%	-42%	-37%	-45%	-40%

4.2.1 Energy Potential

Figure 4.2 shows that among the WTE individual scenario, incineration (scenario II) stands out as the most attractive choice for energy generation, producing 1200 MWh/d of power and 3575 MWh/d of thermal energy. Following incineration, in terms of decreasing energy production, are anaerobic digestion, AD (scenario III), gasification (scenario IV), and landfill gas recovery system, LFGRS (scenario I). AD (scenario III) has added value since it produces digestate that can be used and sold commercially as fertilizer to the agricultural industry.



	Baseline	I	II	III	IV
Electricity (MWh/d)	0	275.47	1200	1050	1000
Heat (MWh/d)	0	524.7	3575	2000	0
Digestate (t/d)	0	0	0	750	0

Figure 4.2: Potential energy generation from various individual waste management scenario in Jeram Sanitary Landfill.

4.2.2 Economic Potential

The baseline scenario involves landfilling waste without energy generation, incurring a daily cost impact of 222,000 USD due to transportation, tipping fees, operation, and maintenance, and emitting 3117 tCO_2/d. Despite high operational costs, incineration (Scenario II) generates the highest net profit (assuming complete energy sales) at 563,083.40 USD/day, trailed by AD, gasification, and LFGRS, as shown in Figure 4.3.

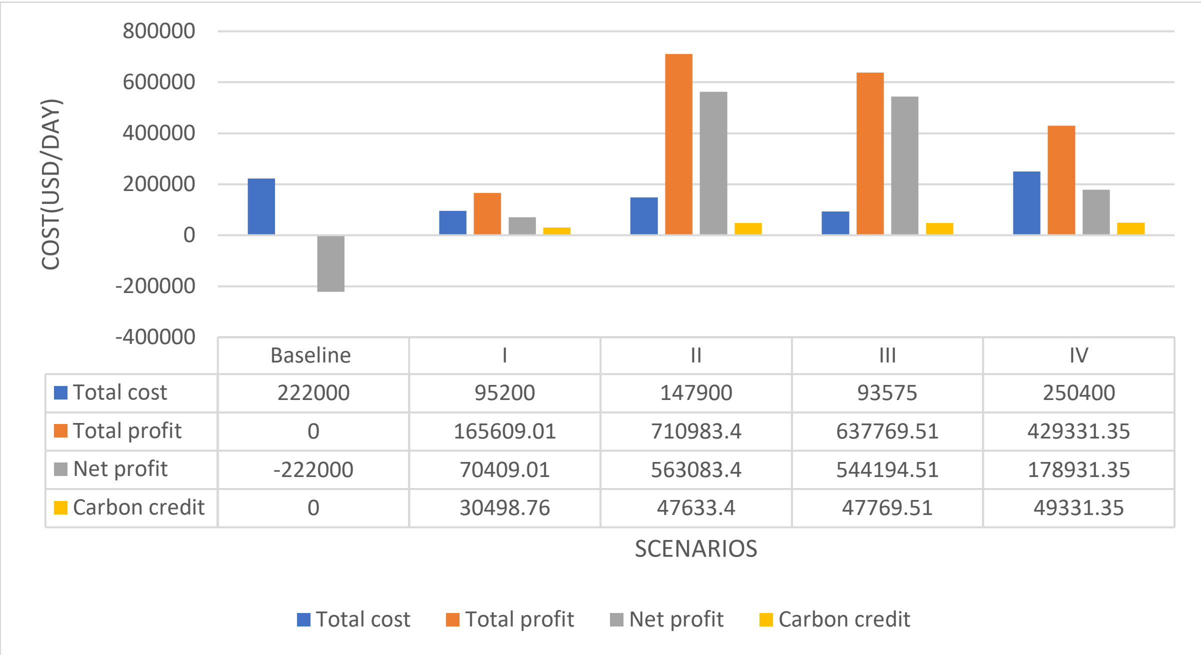


Figure 4.3: Economic potential analysis for different individual scenario in Jeram Sanitary Landfill.

However, for Jeram Sanitary Landfill, if selling the heat or thermal energy is not economically viable, then the profit from selling the electricity alone through the fit-in tariff (FiT) program to the Malaysian national energy company (Tenaga Nasional Berhad) may continue to generate substantial profit, through the AD (Scenario III) operation, as described in Figure 4.4. Gasification (Scenario IV) presents itself to be a high-cost investment and potentially low profit generator due to higher operational and maintenance costs.

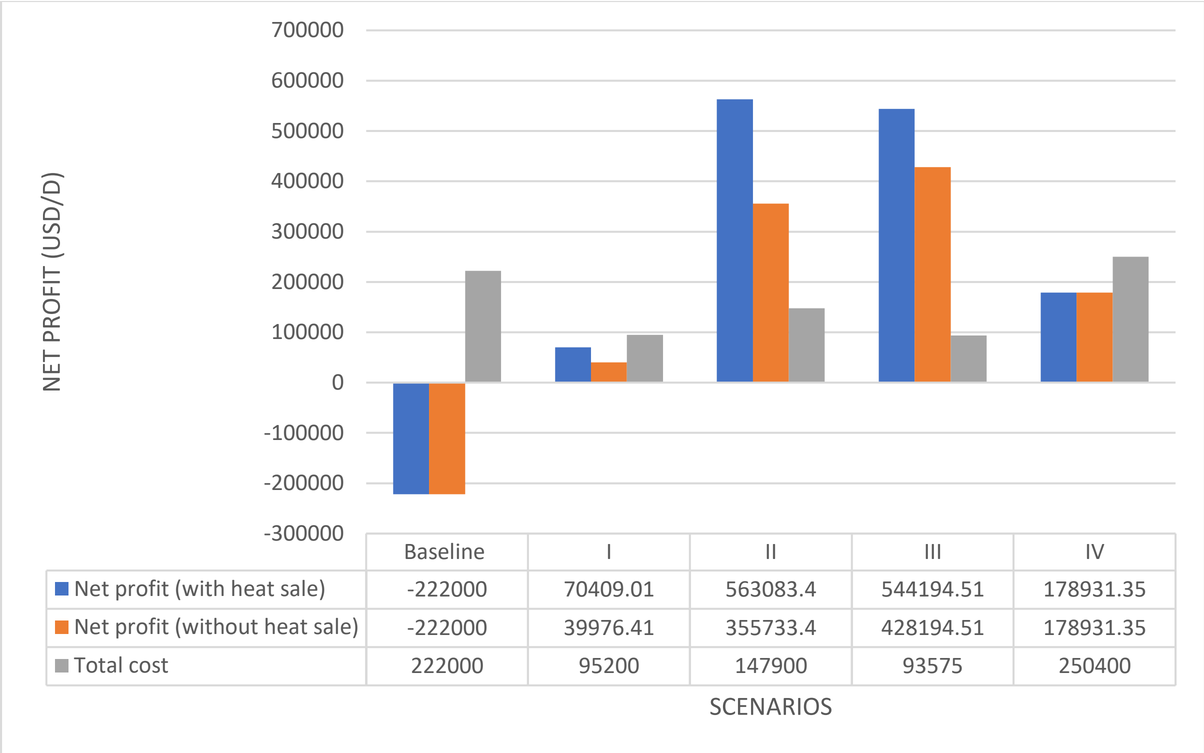


Figure 4.4: Profit potential analysis for different individual scenario in Jeram Sanitary Landfill.

4.2.3 Environmental Benefits

From an environmental perspective, Figure 4.5 illustrated incineration (Scenario II) technology stand out in carbon mitigation, reducing up to 1611 tCO_2/d, followed by LFGRS, AD and gasification.

Notably, gasification technology is less attractive due to its high capital and operating cost, marginal carbon reduction compared to incineration and AD, coupled with lower profits. Therefore, the balance between carbon emissions and profit does not favour gasification. LFGRS, although not as potent as other options, serves as an interim solution to address energy scarcity, waste management, and global warming issues. Given the current operation of landfill sites such as Jeram Sanitary Landfill in Malaysia, an immediate shift to other WTE technologies may be unfeasible due to the substantial capital required for initial investments.

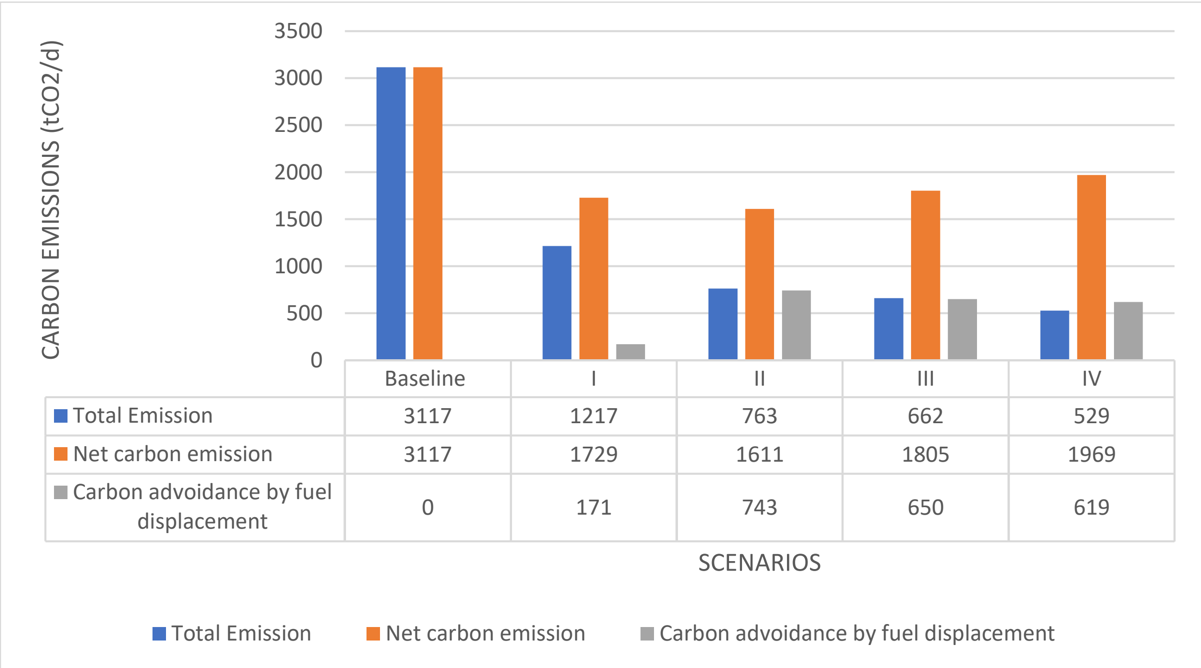


Figure 4.5: Environmental potential analysis for different individual scenario in Jeram Sanitary Landfill.

4.2.4 Integrated WTE Scenarios

The evaluation on the individual scenario has shown that incinerator and AD WTE technologies are favourable due the energy, economic and environmental benefits each offered. At the same time, integrated system, representing an additional phase for JSL's long term waste management plan, outlined in scenarios V (AD and incineration) and VI (AD and gasification). It is observed that the integrated scenario V has greater potentials in the 3E benefits, compared to scenario VI as the cost impact for the initial investment and operating cost is still higher than the incineration method when combined with AD. It is proposed that the segregation of the solid waste for the integrated method is based on 1500 ton per day of organic waste to be treated through AD, and 1000 ton per day of inorganic waste will be treated through incineration and gasification in the respective integrated scenario.

4.2.4.1 Energy Potential

Among the WTE integrated scenario, scenario V (AD and incineration) showed higher capacity in terms of energy generation, producing 1100 MWh/d of electricity and 1105 GJ/d of heat. Scenario VI (AD and gasification) showed lower electricity generation but higher heat generation. Both scenarios offer the digestate production which can be sold as fertilizer to the agricultural sector as shown in Figure 4.6.

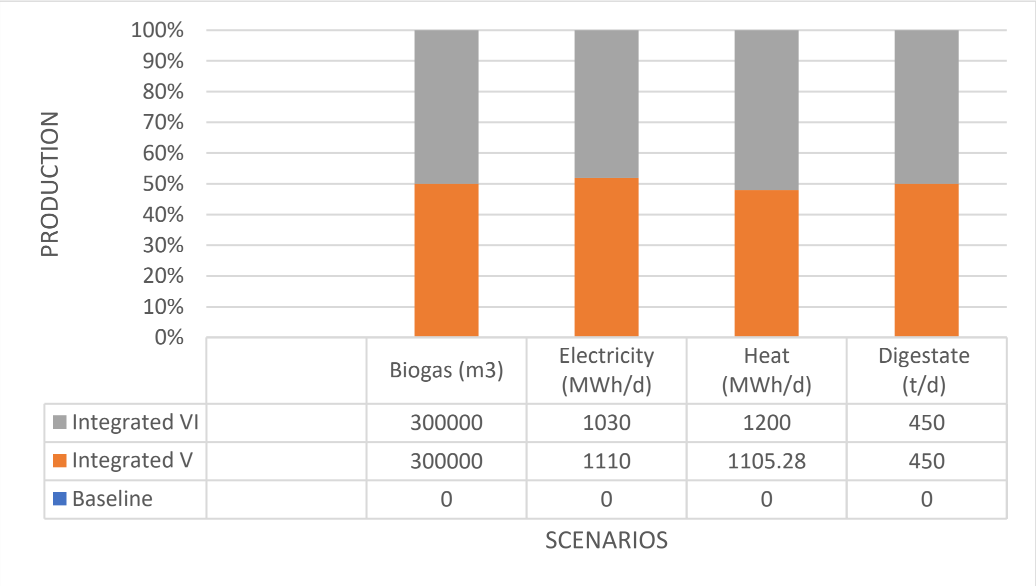


Figure 4.6: Energy potential analysis for different integrated scenarios in Jeram Sanitary Landfill.

4.2.4.2 Economic Potential

As shown in Figure 4.7, the economic potential for utilizing scenario V (AD and incineration) demonstrated greater profitability, while both scenarios shared similar income for the carbon credit incentive.

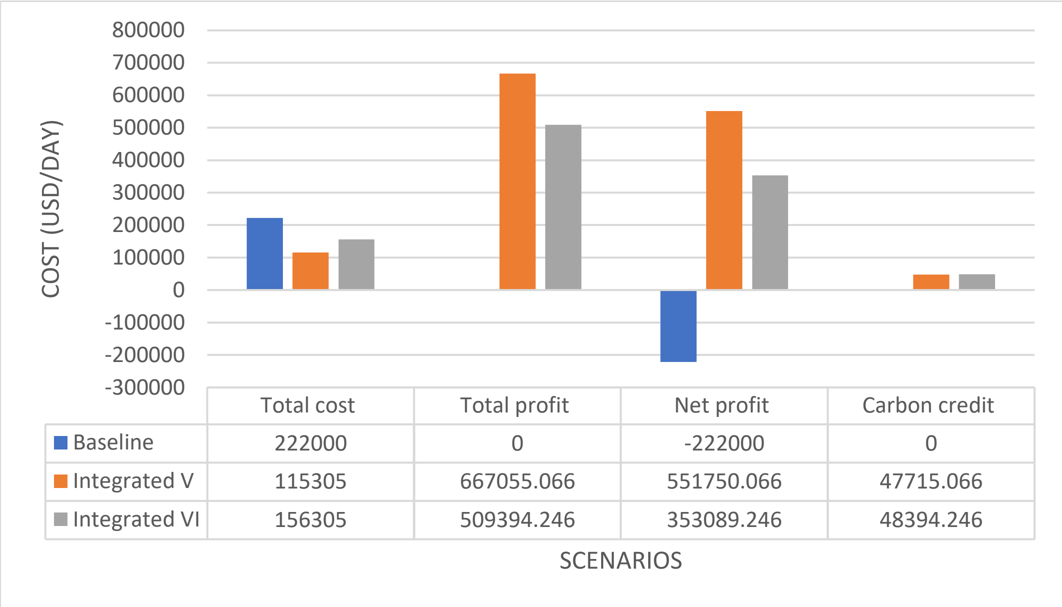


Figure 4.7: Economic potential analysis for various integrated scenario in Jeram Sanitary Landfill.

Figure 4.8 illustrated similar enhanced profitability for scenario V when heat is fully utilized and not sold commercially.

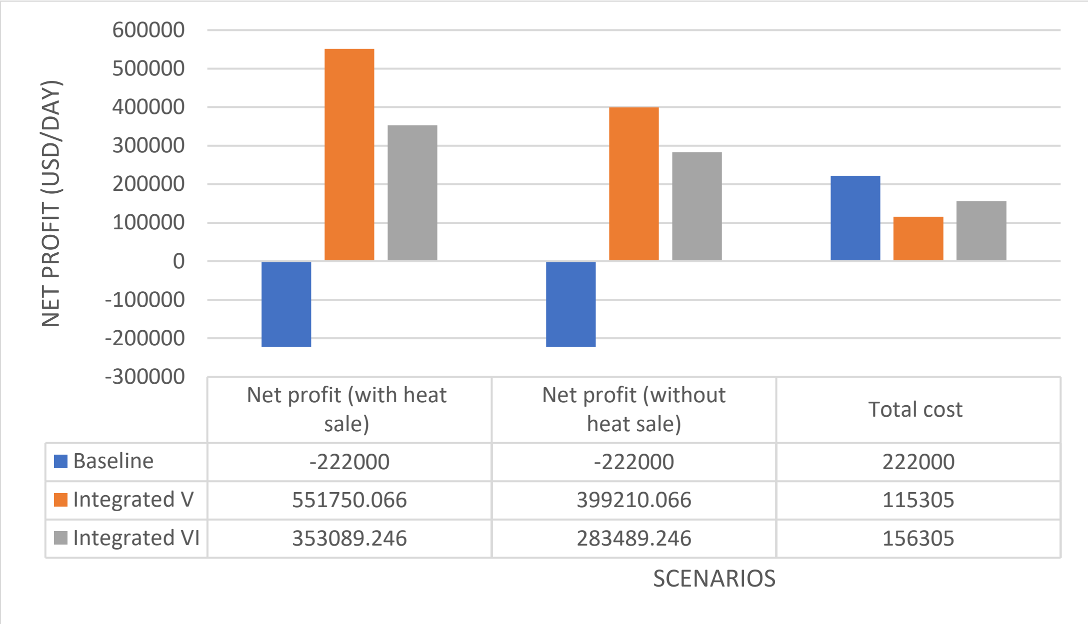
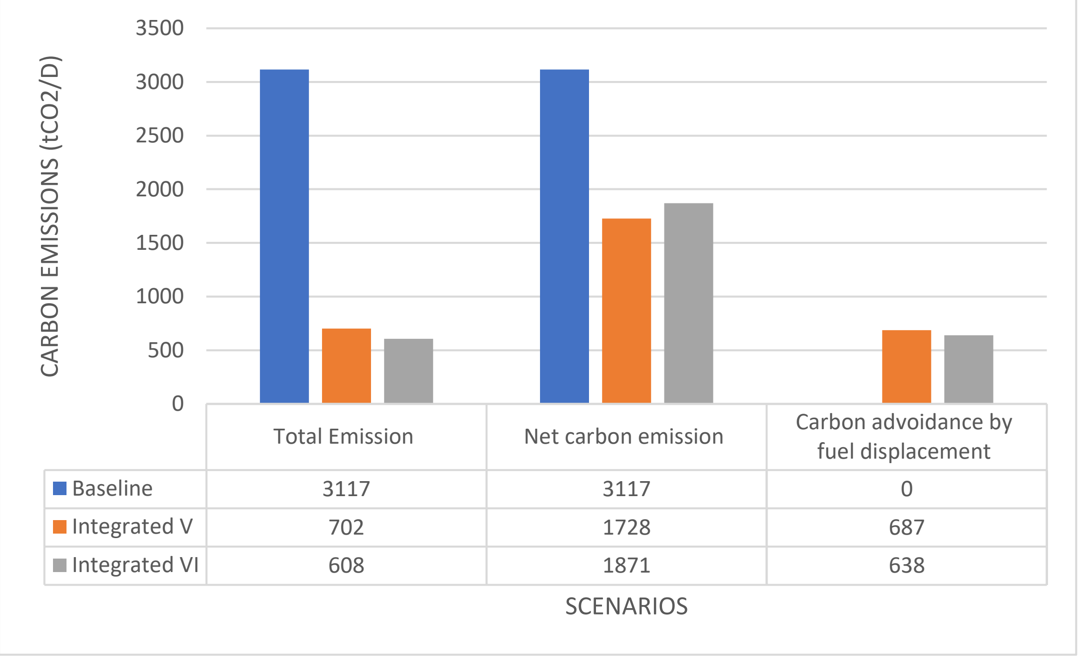


Figure 4.8: Profit potential analysis for different integrated scenario in Jeram Sanitary Landfill.

4.2.4.3 Environmental Benefits

Figure 4.9 shows the environmental benefit of applying both scenarios V and VI, where the carbon total emissions (tCO_2/day) volume are relatively lower than the landfill method, while the carbon avoidance (to replace fossil fuel such as coal) display similar amount per day as well from both scenarios. This has further enhanced the environmental benefit of the integrated system in mitigating carbon emission and reducing the impact of climate change.



	Total Emission	Net carbon emission	Carbon advoidance by fuel displacement
Baseline	3117	3117	0
Integrated V	702	1728	687
Integrated VI	608	1871	638

Figure 4.9: Environmental potential analysis for different integrated scenario in Jeram Sanitary Landfill.

4.3 Comparison of the WTE Scenarios

From the study results, several factors require further review, including pre-treatment requirements, waste characteristics, waste availability, market demand, and non-CO_2 pollutants. Therefore, a comparison of the potential implementation of the incineration, AD and the integrated systems in Jeram Sanitary landfill is presented in the subsequent discussion.

4.3.1 MSW Characteristics

The features of MSW are crucial factors influencing the performance of WTE technologies, particularly for the waste composition and moisture content. In Malaysia's tropical environment, waste typically exhibits elevated moisture levels, ranging from 52.65% to 66.2%. This high moisture content significantly affects the efficiency of incineration and gasification processes by diminishing the waste's calorific value. Conversely, for AD, water is commonly introduced into the process of digestion , addressing, and resolving moisture-related issues. Research suggests that the optimal range for methane production occurs when the input waste has a humidity level between 60% and 80%. Also, increased moisture in the waste decreases its calorific value, leading to reduced energy production, as illustrated in Fig. 4.10 (Tan et al. 2015). Additionally, waste composition is a crucial factor when choosing between incineration and AD. Incinerators can process a broader range of waste types, often not requiring segregation before treatment. AD, however, can only digest organic waste, necessitating segregation before processing. Furthermore, different types of organic waste may require distinct pre-treatment processes, impacting gas yields. Studies have shown that pre-treating MSW can enhance organic matter solubility, hasten degradation, reduce AD retention time, and increase biogas production. To improve AD biomethane generation from food waste, various pre-treatment strategies, including mechanical, thermal, chemical, and biological approaches, have been evaluated. Ensuring the sustainability of waste resources is crucial for the nonstop operation of WTE technologies. In the context of incinerators, a fluctuating waste resource, such as MSW, can significantly reduce efficiency, leading to technical and economic challenges. On the other hand, the AD system has a broader range of feedstock options.

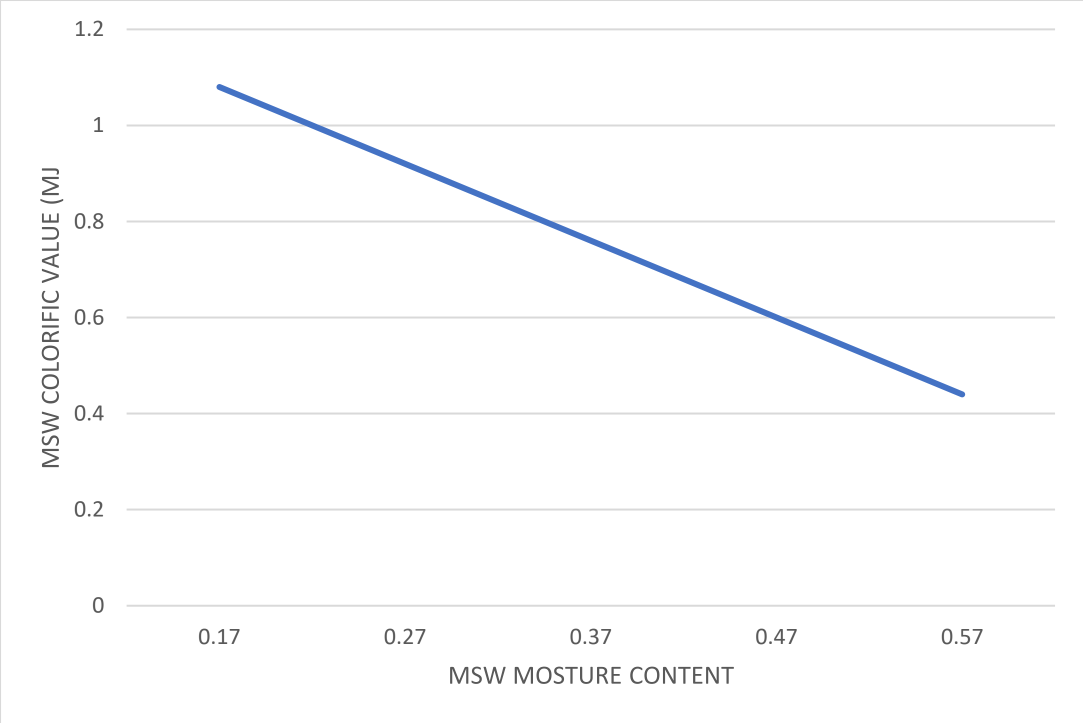


Figure 4.10: Malaysian MSW moisture content and caloric value correlation (Tan et al. 2015)

In AD scenarios (III , V and VI), implementing heat production and sales may lead to a comparable reduction in net profit, similar to cases without heat sales. This phenomenon may occur because AD is more promising for electricity production than heat generation. Additionally, purified biogas from AD can find various applications, enhancing marketability. For instance, biogas can serve as fuel for vehicles and cooking in households.

In developed countries like Sweden, biogas has been successfully utilized as fuel for public transport since 2000, with 19% of biogas production used for vehicles in 2007. Similarly, in some developing countries like China and India, biogas from MSW is commonly used for household cooking, with millions of household digesters in operation. These diverse applications enhance the market potential of AD-generated biogas beyond electricity production.

4.3.2 Environmental Pollution

Beyond carbon emissions, it is essential to take into account the release of sulfur oxides (SOx) and nitrogen oxides (NOx). In comparison to AD, incinerators typically generate elevated levels of pollutants. The possible health concerns to neighbouring residents are determined by the waste processing facility's proximity to surrounding areas.

Taking these factors into consideration, AD emerges as the preferred choice for application, primarily due to MSW higher moisture content and the lower requirement for thermal energy in locations like Malaysia. AD not only has better environmental prospects, but it also opens up more options for future growth, such as the production of biofuel for vehicles and cooking gas. While AD may not completely solve the problem of inorganic waste, the segregation methods established by the governmental ministerial project could be expanded to segregate inorganic waste. This segregated garbage might then be repurposed or recycled, potentially supporting the establishment of an industrial and commercial circular economy-focused township near the Jeram Sanitary Landfill and throughout the state of Selangor.

4.3.3 Incineration Method

Strong advocacy for the incineration approach as the best choice to address the increased power usage in Selangor and effectively resolve associated issues is warranted. This technology has the ability to generate energy at a pace that can roughly offset for the state's power demand by a factor of eight, considerably improving the state's energy security.

However, despite its promising benefits, there are certain obstacles and challenges that must be considered in adopting incineration as a main treatment option for RE recovery to meet the energy supply demand. These technical and economic hurdles require careful consideration to ensure the effective operation and utilization of this technology for sustainable energy production in Jeram Sanitary Landfill.

4.3.4 The Economic Related Issues

Thermal waste treatment technology, such as incineration and gasification, tend to be the most expensive among WTE solutions. In developing countries like Malaysia, while initial funds for establishing an incineration plant might be available from the state government and the stakeholders, operational and maintenance costs can pose challenges as they are often insufficient and difficult to obtain. Consequently, alternative financing sources need to be explored to cover both the initial construction and ongoing operational expenses of such projects. In the context of Malaysia's challenging post COVID economic circumstances and municipal budget deficits, relying solely on internal funds to cover energy costs is not feasible. Thus, seeking external investment becomes necessary, with Asian countries such as China, Japan and European investors being common sources of economic support. Considering these factors, it becomes crucial to carefully evaluate the feasibility and implications of embarking on WTE projects, considering the financial challenges and potential shifts in support from external sources. Thorough consideration and planning are essential before proceeding with such initiatives.

4.3.5 The Environmental Related Issues

The mistreatment and adverse environmental consequences associated with incineration plants raise significant concerns that have attracted attention from the press and social media. For instance, Zero Waste Europe pointed out the detrimental aspects of incineration, characterizing it as a massive carbon-intensive energy source that contributes to air pollution and poses risks as a hazardous system. These negative effects create a challenging situation for governments and communities, hindering efforts to promote reducing waste and repurposing. Anyone who were to view incineration as an effective method for waste disposal, cannot view it as a sustainable and environmentally friendly technology. The evidence is unmistakable that incineration of solid waste has highly adverse implications for the climate. Given the relatively extensive size of the case study area, the construction of an incinerator near residential areas raises major fears about the system’s emissions impact on communities’ wellbeing. With these factors in place, incineration may not be recognized as a sustainable alternate answer from the perspective of environmental factors.

Furthermore, it is incompatible with the goal of many governments of adopting sustainable energy sources. As a result of the importance of environmental issues, incineration may be the last option on the list of approved WTE technologies.

4.3.6 The Gasification Method

Gasification, being a highly advanced technology, may not be a suitable solution for the proposed case study due to various inhibiting factors. One crucial aspect is that the gasification process demands expensive equipment with highly sophisticated techniques and technology. This not only applies to the gasifier itself but also extends to other associated systems, particularly the treatment systems, which are integral and equally sophisticated.

The intricate and advanced nature of these machines and technologies presents a significant challenge in terms of importing them from abroad, rendering the implementation of gasification projects challenging in the case study area. The necessity for specialized and high-tech equipment, encompassing both the gasifier and treatment systems, may constrain its feasibility and cost-effectiveness for the specific region of interest in Selangor.

Given these challenges, gasification will not be a suitable option for the proposed study, and alternative WTE technologies should be considered that are more feasible and align with the available resources and capabilities in the region.

4.3.7 The LFGRS and AD Method

The biological methods, namely landfill gas recovery system (LFGRS) capture and anaerobic digestion (AD), appear to be among the most viable alternatives investigated.

According to information gathered from the technical department in the case study, the intended electricity output destined for the national grid in that district, encompassing the industrial area, is projected to be 500 MWh per day. Although the prospect of recovering gas from landfills is advantageous, the method falls short of fully meeting and covering this energy deficit, accounting for less than 55% of the shortfall and potentially generating around 275 MWh per day from LFGRS. Consequently, there remains a noticeable deficit that requires attention through alternative means.

On the other hand, the anaerobic digestion (AD) option proves to be promising as it can cover the remaining potential energy deficit and with surplus. Producing about 1050 MWh per day, from municipal solid waste alone, the AD provides a sufficient amount of energy to meet the energy demand and effectively eliminate the deficit. Given this comparison, the AD approach stands out as a feasible and practical solution to address both the energy deficit and the environmental impact.

4.4 Study Limitations

As field and laboratory tests were not performed on actual MSW samples and on the respective WTE technology, following are potential limitations :

1. Availability of data: The data available for waste composition, energy recovery potential, and other factors may be incomplete or unreliable, limiting the accuracy of the analysis.
2. Case study selection bias: The selection of case study may be biased towards certain region or technology, leading to an incomplete or biased assessment of the practicability of renewable energy recovery from MSW in Malaysia.
3. Technical limitations: The analysis may not consider all technical factors that affect the feasibility and effectiveness of renewable energy recovery from MSW applying the various WTE methods, such as operational and maintenance requirements of different technologies.
4. Uncertainty: There may be uncertainty around the economy and environment impacts of RE recovery from MSW, which can affect the accuracy of the analysis and the reliability of the conclusions.
5. Generalizability: The results of the study may not be standardized to other nations or regions with different waste characteristics, energy policies, or economic conditions.

CHAPTER 5

CONCLUSION

This study evaluated the feasibility of recovering RE and biofuels using MSW as feedstock source, analysing the techno-economic aspect in terms of energy, economy and environment (3E) impacts from various WTE methods, such as landfill gas recovery system (LFGRS), incineration, anaerobic digester (AD), and gasification, within the context of a Malaysian case study, which is the Jeram Sanitary Landfill (JSL).

The findings of the study indicate that incineration (Scenario II) has the potential to recover 1200 MWh of electricity per day, whereas anaerobic digestion (AD) (Scenario III) and gasification (Scenario IV) yield approximately 1050 MWh and 1000 MWh per day, respectively. The technology with the least electricity recovery, approximately 275 MWh per day, is the landfill gas recovery system (LGRS) (Scenario I). In terms of environmental impact, incineration could potentially result in savings of around 1611 tCO2 per day, while anaerobic digestion and gasification could save about 1805 tCO2 per day and 1969 tCO2 per day, respectively. The landfill gas recovery system (LFGRS) could contribute to saving approximately 1729 tCO2 daily. The overall costs related with each technology were also calculated.. Results of the total cost exhibited that AD had the lowest total cost of USD 93575 per day, while incineration and gasification had total cost of USD 147900 and USD 250400 per day respectively. The study also revealed that the integrated WTE scenarios have demonstrated potential favourable results, where the combination of AD and incineration (Scenario V) provides potential energy output of 1110MWh per day of electricity, and 1105 MWh per day of heat generation, under a potential lower total cost per day of USD115,305, with a low carbon emission value of 1728 tCO_2 per day. The total cost which includes the maintenance and operation costs, related with each technology were calculated. Results of the total cost exhibited that AD had the lowest total cost requirement of USD 93575 per day, while incineration and gasification incur total cost of USD 147900 and USD 250400 per day respectively.

At the same time, the stakeholder in JSL can consider implementing the integrated WTE treatment by combining AD (to treat the organic wastes) and incineration (to treat the inorganic wastes), which are potentially economical and environmentally feasible. In Scenario V, a combination of the AD and incineration technology, the potential energy generation is 1100 MWh per day of electricity, while the profitability of combining both technology is higher compared to Scenario VI (AD and Gasification). In terms of environmental impact, Scenario V offers the potential to produce 1728 tCO_2 per day, with potential carbon displacement of 687 tCO_2 per day, which are good indication of replacing the coal-fired power generation plants carbon emission per day, hence reducing the GHG emission volume which can ultimately help in mitigation plan of the carbon neutral strategy by the JSL stakeholders, which includes the state government of Selangor. To achieve this objective, a phased approach is recommended, beginning with LFGRS (which is already in operation since 2015 in JSL) and progressively establishing improved facilities for both inorganic and organic waste recycling through an integrated new treatment centre equipped with the AD and incineration (Scenario V) systems. However, a large amount of the energy created by incineration is heat, which may not be suitable for tropical nation like Malaysia. Consequently, AD emerges as a more favourable option for JSL, offering advantages in electricity production over the heat production. Beyond electricity, AD presents additional benefits such as the production of digestate for agricultural use and biofuel for vehicles and household cooking, enhancing its prospective for commercialization.

The study further emphasizes the feasibility of applying WTE methods to recover RE and biofuels from MSW. In the future, technologies such as incineration are expected to reduce the volume of MSW disposed of in landfills. As a result, Selangor's local governments should vigorously encourage and advocate the public about the benefits of WTE technologies, proving their safety and giving thorough understanding. Despite the initial costs, WTE systems offer potential continuous returns through sales and carbon credits. It is recommended that various organizations, acting as stakeholders in Jeram Sanitary Landfill (JSL), proactively collaborate to address financial concerns. Strategies such as the feed-in tariff mechanism could be employed to alleviate investment payback periods. Additionally, close cooperation with the Selangor state government is advised to ensure adherence to national policy and secure renewable energy incentives under the current federal government management.

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