# Waste-to-Energy in Malaysia: Technologies, Biomass Resources, Municipal Solid Waste Management, Techno-Economic Feasibility, Environmental Impacts and Future Prospects

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## ABSTRACT

Waste-to-energy (WtE) technology has emerged as an important alternative for addressing the growing challenges of solid waste management while supporting the transition towards renewable and sustainable energy systems. In Malaysia, rapid urbanisation, population growth, industrial development and increasing consumption have contributed to rising municipal solid waste (MSW) generation, placing considerable pressure on existing landfill-based disposal systems. At the same time, Malaysia possesses substantial energy recovery potential from various waste streams, including food waste, agricultural residues, oil palm biomass, industrial waste and municipal solid waste. This paper presents a comprehensive review of waste-to-energy technologies, with particular emphasis on their suitability, performance, implementation challenges and future prospects in Malaysia. The review examines major WtE conversion pathways, including incineration, anaerobic digestion, landfill gas recovery, gasification, pyrolysis and hydrothermal carbonisation, together with emerging opportunities for biogas, biofuel and hydrogen production. Particular attention is given to the availability and characteristics of Malaysian waste feedstocks, especially organic municipal solid waste, food waste and oil palm residues. The paper further evaluates the technical, economic, environmental, institutional and social considerations influencing WtE implementation, including energy recovery efficiency, greenhouse gas emissions, investment requirements, waste segregation, feedstock sustainability, public acceptance and regulatory support. International experiences are incorporated to identify relevant technological approaches and implementation strategies that may be adapted to Malaysian conditions. The review highlights the importance of integrating waste-to-energy development with circular economy principles, effective source separation, resource recovery and sustainable waste management policies. It also identifies key research gaps concerning technology selection, commercialisation, operational performance and long-term environmental sustainability. An integrated framework is proposed to connect waste resource availability, conversion technologies, energy recovery, economic feasibility, environmental performance and policy development. The paper concludes that WtE technologies offer significant opportunities to strengthen Malaysia's waste management system and diversify its renewable energy portfolio, provided that technology selection, institutional coordination and economic viability are addressed through an integrated national approach.

**Keywords**: Waste-to-energy; Malaysia; municipal solid waste; circular economy; renewable energy

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# INTRODUCTION

The management of solid waste has become an increasingly important environmental and energy challenge for Malaysia. Population growth, urbanisation, industrial development and changing consumption patterns have contributed to increasing waste generation and placed pressure on existing waste collection, treatment and disposal systems. Landfilling remains an important component of municipal solid waste (MSW) management; however, reliance on landfill disposal raises concerns about land availability, environmental pollution, greenhouse gas emissions and the loss of potentially recoverable materials and energy. These challenges have encouraged greater interest in waste-to-energy (WtE) as an approach that can connect waste management with renewable energy production and resource recovery.

WtE refers to a group of processes through which the energy contained in waste materials is recovered in useful forms, including electricity, heat, biogas, biofuels and other energy carriers. The available technologies include direct combustion or incineration, anaerobic digestion, landfill gas recovery, gasification, pyrolysis and hydrothermal conversion. The suitability of each process depends on the physical and chemical characteristics of the feedstock, moisture content, organic fraction, contamination level, required pre-treatment and intended energy product. Consequently, WtE should not be treated as a single technology. It is a collection of conversion pathways that must be matched to the type and quality of waste available.

Malaysia has several waste streams that may provide feedstock for energy recovery. These include household and commercial waste, food waste, agricultural residues, oil palm biomass and selected industrial wastes. The organic fraction of MSW and food waste may be suitable for biological treatment, particularly anaerobic digestion, which can produce biogas. Meanwhile, suitable dry and combustible waste fractions may be considered for thermal conversion technologies. Malaysia's oil palm industry also generates substantial biomass residues that have been examined as potential sources of renewable energy and value-added products. The availability of these different feedstocks creates opportunities for a diversified WtE sector, although their practical potential depends on collection systems, consistency of supply, pre-treatment requirements and competing uses.

This review synthesises literature on Malaysian waste-management practices, feedstock availability, conversion technologies, energy recovery, economic feasibility and environmental performance. Studies conducted in Malaysia provide the principal evidence base for assessing local resources and implementation conditions. International studies are included where they clarify process performance, technology design or evaluation methods that may be relevant to Malaysia. Their findings are not treated as directly transferable because feedstock composition, climate, infrastructure, energy prices, regulatory requirements and institutional arrangements differ between countries.

The review provides a Malaysia-focused critical assessment of waste resources and energy-recovery options. It evaluates the principal conversion pathways and synthesises evidence on technical performance, investment and operating costs, environmental impacts, policy conditions and implementation barriers. Particular attention is given to distinguishing Malaysian measurements and deployments from pilot studies, modelled scenarios and international comparisons. Where the available evidence is insufficient for a reliable numerical comparison, the limitation is explicitly acknowledged.

Despite the potential benefits, the implementation of WtE projects involves technical, economic, environmental and social considerations. The performance of a facility is influenced by the quantity and composition of available feedstock, the efficiency of conversion processes, the reliability of operations and the ability to use or sell the energy produced. High capital and operating costs, waste-separation limitations, feedstock contamination, public concerns and uncertainty in project revenues may also affect project feasibility. In addition, energy recovery must be assessed alongside emissions control, ash and digestate management, resource conservation and the wider waste-management hierarchy. WtE should therefore complement waste prevention, reuse and recycling rather than undermine these priorities.

This paper reviews the selected literature on WtE, focusing on its relevance to Malaysia. It considers the country's waste resources and energy-recovery opportunities, evaluates the main conversion technologies, and discusses technical performance, economic considerations, environmental impacts, policy conditions and implementation barriers. It also draws on relevant international studies to identify approaches that may be considered in the Malaysian context, while distinguishing comparative evidence from findings specifically reported for Malaysia.

The objectives of this paper are to:

1. Examine the major waste streams in Malaysia that may serve as feedstock for energy recovery.
2. Review the principal WtE technologies and their suitability for different waste characteristics.
3. Assess the technical, economic and environmental factors affecting WtE implementation.
4. Identify policy, institutional, infrastructure and public-acceptance challenges.
5. Highlight research gaps and propose an integrated direction for sustainable WtE development in Malaysia.

The paper is organised to move from the Malaysian waste-resource context to technology options and their applications, followed by assessments of performance, feasibility and sustainability. It then considers the policy environment and barriers to implementation before discussing future research priorities and an integrated framework for WtE development.

# 1. WASTE GENERATION AND ENERGY RESOURCES IN MALAYSIA

### 2.1 Municipal Solid Waste Generation and Management

Municipal solid waste (MSW) is an important potential feedstock for WtE development in Malaysia. It consists of waste generated from households, commercial premises, institutions and other urban activities. Its composition may include food residues, paper, plastics, textiles, garden waste, metals, glass and other discarded materials. The proportion of each component is important because it influences the selection of treatment technologies and the amount of energy that can be recovered.

The selected literature examines Malaysia's MSW management system from several perspectives, including waste generation trends, technology adoption, policy-driven management, economic incentives and optimisation of waste-treatment systems. These studies indicate that effective MSW management requires more than the provision of disposal facilities. It also depends on waste collection, segregation, recycling, treatment capacity and coordination between the institutions responsible for waste management [2, 10, 24, 60, 61].

For WtE applications, the composition and characteristics of waste are particularly important. Organic waste with high moisture content may be more appropriate for biological treatment, whereas relatively dry and combustible materials may be considered for thermal conversion. Mixed waste can require additional sorting and pre-treatment before it is suitable for a particular conversion process. Therefore, the assessment of Malaysian MSW resources should consider not only the total quantity generated but also the recoverable fraction, material quality and consistency of supply.

The literature also highlights the relationship between recycling and the sustainability of WtE feedstock. Recycling can reduce the quantity of recoverable combustible material available to an energy-recovery facility, but it also supports material conservation and reduces the demand for virgin resources. Consequently, the objective should not be to maximise the amount of waste burned. Instead, WtE facilities should be integrated

into a waste-management system that prioritises waste reduction, reuse and recycling before recovering energy from residual waste [16, 27, 47].

### 2.2 Food Waste as a Renewable Energy Resource

Food waste is a significant organic waste stream with potential for energy recovery. It can originate from households, restaurants, food services, markets, food-processing activities and other commercial operations. Its organic content makes it a potential feedstock for anaerobic digestion, through which microorganisms break down biodegradable materials in the absence of oxygen and produce biogas.

The selected Malaysian literature gives particular attention to food waste management and biogas production. Research on food waste-based biogas identifies both opportunities and implementation challenges, while studies on organic fractions of MSW examine the combined production of biogas and biofertiliser [29, 32]. Research on restaurant food waste-to-electricity conversion in Malaysia and Singapore also considers the relationship between energy recovery, economic performance and life-cycle impacts [42].

Food waste management is not solely a technological issue. Collection arrangements, source separation, contamination, transportation and the reliability of feedstock supply can influence the performance of an anaerobic digestion facility. Policy coordination is also important, particularly where responsibilities for food waste prevention, collection and treatment are distributed across different stakeholders. The selected study on urban food-waste governance in Malaysia specifically examines policy-mix challenges, highlighting the importance of institutional arrangements alongside technical solutions [8].

Anaerobic digestion may be particularly relevant where organic waste can be collected separately and delivered consistently to treatment facilities. The resulting biogas can be used for heat or electricity generation, subject to appropriate gas treatment and system design. The remaining digestate may also have potential for further use, depending on its quality and applicable environmental requirements. These possibilities support the integration of organic waste treatment with resource recovery and circular-economy objectives.

### 2.3 Oil Palm Biomass and Agricultural Residues

Malaysia's agricultural and agro-industrial activities provide another important resource base for WtE development. Oil palm processing generates several types of biomass residues, including empty fruit bunches, palm kernel shells, mesocarp fibres, palm trunks, palm fronds and palm oil mill effluent. These materials differ in their physical and chemical characteristics and therefore require different handling and conversion approaches.

The selected literature examines oil palm waste conversion, biomass supply chains, commercialisation challenges and the development of biofuels from palm-based residues. These studies identify the potential of oil palm biomass for sustainable energy production while also recognising that technical availability does not automatically translate into commercial viability [35, 36, 65, 67]. The Malaysian biomass resource literature further describes the country's wider resource base, including forestry residues, rice residues and other agricultural and agro-industrial materials [70].

Oil palm biomass can be considered for several conversion routes. Depending on its characteristics and processing requirements, it may be used in direct combustion, gasification, pyrolysis, torrefaction or other biomass-conversion processes. Some residues may also be suitable for the production of upgraded solid biofuels or higher-value products. The choice of process depends on moisture content, particle size, energy content, ash characteristics, transportation distance and the intended final product.

Despite its potential, biomass utilisation faces supply-chain challenges. Residues may be dispersed across different locations, and their availability can vary according to agricultural and processing schedules. Collection, storage, drying and transportation can add to the cost of energy production. Commercialisation

therefore requires coordination between biomass producers, processing facilities, energy developers and relevant government institutions. The selected Malaysian research on oil palm waste conversion specifically identifies commercialisation as an important consideration in the development of sustainable energy production [36].

### 2.4 Other Waste Streams and Emerging Feedstock Opportunities

Beyond MSW, food waste and oil palm residues, the selected literature considers several other waste streams that may contribute to resource recovery. These include industrial organic waste, sludge, construction and demolition waste, electronic waste, photovoltaic waste and hazardous waste. Their potential for energy recovery varies considerably, and not all of these materials are appropriate for direct conversion into energy.

Sludge, for example, has been examined as a potential resource for biofuel production and circular-economy applications [68]. However, its composition, contamination levels and treatment requirements must be evaluated before selecting a conversion pathway. Similarly, studies on electronic waste and photovoltaic waste focus substantially on material recovery and sustainable waste management rather than direct energy generation [12, 14, 23, 64].

Construction and demolition waste and hazardous waste also require careful consideration. Their management is influenced by material composition, contamination risks and regulatory requirements [5, 15]. These waste streams should not be grouped indiscriminately with biodegradable or combustible MSW because their treatment requirements and environmental risks are different.

The broader literature on waste-derived hydrogen also identifies waste resources as potential feedstocks for emerging energy pathways [48]. Nevertheless, hydrogen production from waste depends on the selected conversion process, feedstock quality, energy inputs and overall system efficiency. Its potential in Malaysia therefore requires further assessment rather than an assumption that all waste streams can be converted economically into hydrogen.

### 2.5 Summary of Malaysian Waste Resources for Energy Recovery

Table 1 summarises the main waste streams identified in the selected literature and their potential relevance to WtE development. The technology options shown are indicative pathways for further assessment, not confirmation that every waste stream is commercially suitable for each process.

Table 1. Major waste streams and potential energy-recovery pathways in Malaysia

| Waste stream | Examples | Potential conversion pathways | Key considerations | References |
|---|---|---|---|---|
| Municipal solid waste | Residual household and commercial waste | Incineration, gasification, landfill gas recovery | Waste composition, segregation, moisture content and emissions control | [16, 24, 27, 47, 60, 61] |
| Food waste | Household, restaurant and market waste | Anaerobic digestion, hydrothermal treatment | Collection, contamination, moisture content and consistent supply | [8, 29, 32, 42] |
| Oil palm biomass | Empty fruit bunches, fibres, shells, trunks and fronds | Combustion, gasification, pyrolysis, torrefaction | Logistics, moisture content, pre-treatment and commercialisation | [35, 36, 65, 67, 70] |
| Industrial organic waste | Organic processing residues and effluent | Anaerobic digestion and selected thermal processes | Feedstock characteristics and treatment requirements | [32, 48, 68] |

| | | | | |
|---|---|---|---|---|
| Sewage and organic sludge | Wastewater-treatment sludge | Anaerobic digestion and biofuel conversion | Contaminants, process requirements and residual management | [68] |
| Landfill waste | Biodegradable material decomposing in landfills | Landfill gas recovery | Gas collection efficiency and landfill conditions | [24, 60, 61] |
| Electronic and photovoltaic waste | Discarded electronic equipment and solar panels | Primarily material recovery and recycling | Hazardous components and recovery of valuable materials | [12, 14, 23, 64] |
| Construction and demolition waste | Concrete, wood, metals and other building materials | Selective material recovery; limited energy recovery for suitable fractions | Material separation, contamination and competing recycling uses | [5, 15] |

### 2.6 Implications for WtE Development in Malaysia

The reviewed literature suggests that Malaysia has a diverse range of potential waste resources for energy recovery. However, the availability of waste alone is insufficient to establish the feasibility of a WtE project. Each resource must be assessed according to its quantity, composition, location, collection arrangements, competing uses and suitability for conversion.

Three broad feedstock groups are particularly relevant to the Malaysian context:

1. Organic municipal waste, especially food waste, which may support anaerobic digestion and biogas production.
2. Residual municipal waste, which may provide opportunities for thermal treatment after appropriate segregation and material recovery.
3. Agricultural and oil palm biomass, which may support several thermochemical and biochemical conversion pathways.

An integrated approach is therefore necessary. Waste prevention and recycling should remain central to waste management, while WtE should focus on suitable residual materials and organic resources that can be recovered efficiently. This approach can help align energy recovery with resource conservation, environmental protection and Malaysia's wider circular-economy objectives.

## 2. WASTE-TO-ENERGY TECHNOLOGIES AND CONVERSION PROCESSES

Waste-to-energy (WtE) technologies convert suitable waste materials into useful energy products, including electricity, heat, biogas, biofuels and hydrogen. The selection of an appropriate technology depends on several factors, particularly waste composition, moisture content, organic content, heating value, contamination, feedstock availability and the intended energy output. The selected literature discusses both biological and thermochemical conversion technologies, highlighting the importance of matching conversion processes to the characteristics of individual waste streams [9, 20, 38, 50, 53, 59].

For Malaysia, this consideration is particularly important because the country's waste resources include food waste, municipal solid waste, oil palm biomass and other agricultural and industrial residues. These materials have different physical and chemical properties and therefore require different treatment approaches. This section reviews the principal WtE technologies identified in the selected literature and discusses their potential relevance to Malaysia.

### 3.1 Incineration

Incineration is a thermochemical process in which combustible waste is burned under controlled conditions to release heat. The heat can be used directly or transferred to a steam-generation system to drive a turbine and

produce electricity. Incineration can reduce the volume of residual waste requiring final disposal and may provide a continuous source of energy when sufficient suitable feedstock is available.

The technology has been widely examined as an option for municipal solid waste management. The selected literature includes studies on incineration technology adoption, the influence of bio-waste on electricity generation, the economic feasibility of MSW incineration and the barriers affecting implementation in developing countries [11, 18, 19]. Research also considers the selection of suitable WtE technologies for different waste-management systems and economic conditions [17, 20].

In Malaysia, incineration has been discussed as a possible treatment option for residual MSW and selected food-waste fractions. The review focusing on Malaysia's food waste management system considers incineration alongside anaerobic digestion and hydrothermal carbonisation [54]. However, the suitability of incineration depends on the characteristics of the waste supplied to the facility. High moisture content and low heating value can affect combustion performance and energy recovery. Waste segregation and pre-treatment may therefore be necessary to improve feedstock quality.

Environmental management is another important consideration. Incineration produces bottom ash and fly ash, which require appropriate handling and treatment. The selected review on MSW bottom and fly ashes examines their physical and chemical characteristics, leaching behaviour, pre-treatment and possible resource-recovery applications [58]. This indicates that the environmental performance of an incineration facility should be evaluated across the entire process, including emissions management and the handling of combustion residues.

Consequently, incineration should be considered primarily for suitable residual waste after waste reduction, reuse and recycling opportunities have been addressed. Its implementation in Malaysia requires appropriate technology selection, emissions-control systems, ash management, reliable feedstock supply and long-term financial planning.

### 3.2 Anaerobic Digestion

Anaerobic digestion (AD) is a biological conversion process in which microorganisms break down biodegradable organic materials in an oxygen-free environment. The process produces biogas, which typically contains methane and carbon dioxide, together with a residual material known as digestate. Depending on its quality and applicable standards, digestate may have potential for further use as a soil amendment or biofertiliser.

AD is particularly relevant to food waste, agricultural residues, organic MSW and certain industrial organic wastes. The selected Malaysian literature identifies food waste-based biogas as an opportunity for addressing organic waste management while producing renewable energy [32, 37]. Research on the organic fraction of MSW also examines the combined production of biogas and biofertiliser as a circular-economy approach [29, 44].

A pilot-scale study in Seremban investigated biogas production from the organic fraction of municipal solid waste using a 500-litre anaerobic digestion reactor. The study reported average daily biogas production of 92–262 litres, with methane accounting for a significant proportion of the gas produced [62]. This provides an example of practical investigation of organic MSW conversion in Malaysia, although the performance of a pilot-scale system should not be assumed to represent the output or economics of a commercial facility.

Another selected study compares food-waste-to-electricity pathways in Malaysia and Singapore, considering anaerobic digestion, pyrolysis and gasification. Its findings identify AD as a promising option within the study's comparative assessment [42]. The Malaysian-focused review of food waste management similarly discusses AD as a technology that can reduce waste volume while producing biogas [54].

Despite these opportunities, AD performance depends on feedstock characteristics and operating conditions. Factors such as organic loading, temperature, pH, retention time, mixing and process stability can influence biogas production. Small-scale digester design and operation are also important. A systematic review of small-scale biogas digesters identifies monitoring, stirring and temperature control as relevant design considerations for reliable operation and maintenance [45].

The use of AD in Malaysia therefore requires effective source separation, suitable digester design, regular operational monitoring and reliable arrangements for using the produced biogas. The digestate must also be appropriately managed to ensure that the process delivers environmental benefits beyond energy generation.

### 3.3 Landfill Gas Recovery

Landfill gas recovery involves collecting gas generated through the natural decomposition of biodegradable waste in landfills. The gas contains methane and carbon dioxide, although its composition can vary according to waste characteristics, landfill conditions and the stage of decomposition. Captured gas may be used for electricity generation, heat production or other energy applications, subject to suitable treatment and system design.

Landfill gas recovery is relevant to Malaysia because landfill disposal remains an important part of the country's MSW management system. The selected literature examines landfill-related energy recovery potential and the global mapping of biogas and hydrogen production opportunities from landfills [24, 43]. These studies provide a basis for considering landfill gas as one of the possible pathways for recovering energy from waste already disposed of in landfill facilities.

The main advantage of landfill gas recovery is that it can utilise gas generated from existing waste deposits. However, the amount of recoverable gas depends on the biodegradable content of the waste, landfill age, moisture conditions, gas collection infrastructure and operational management. Inadequate collection can result in methane escaping into the atmosphere, reducing the potential climate benefits of the system.

Landfill gas recovery should therefore be regarded as a complementary WtE option rather than a substitute for improved waste segregation and treatment. It may help recover energy from existing landfill sites, while future waste-management strategies should seek to reduce the amount of biodegradable material sent to landfills.

### 3.4 Gasification

Gasification is a thermochemical conversion process that transforms carbon-containing materials into a combustible gas, commonly referred to as synthesis gas or syngas. The process takes place at elevated temperatures with a controlled amount of oxygen, air, steam or another gasifying agent. Syngas may contain carbon monoxide, hydrogen, methane and carbon dioxide, with the composition depending on the feedstock, reactor design and operating conditions.

Gasification has been examined as a potential pathway for converting biomass and suitable waste materials into energy and useful chemical products. The selected literature includes research on technology selection for MSW management, gasification performance prediction and comparative assessments of WtE technologies [20, 38, 50, 51].

One study develops an artificial neural network model to predict key performance measures for gasification processes using different feedstocks, gasifying agents and reactor options [51]. This illustrates the complexity of gasification system design and the potential role of predictive modelling in technology evaluation. The process cannot be assessed using feedstock type alone because operating conditions and reactor configurations also influence performance.

For Malaysia, gasification may be considered for suitable biomass residues, including selected oil palm wastes and other agricultural materials. The Malaysian literature on palm oil waste conversion discusses biological

and thermochemical pathways for converting residues into valuable fuels [36, 67]. However, the commercial suitability of gasification depends on feedstock preparation, moisture control, reactor performance, syngas cleaning and the availability of suitable end-use systems.

Gasification also requires attention to the treatment of tar, particulates and other contaminants in the produced gas. These factors can affect system reliability and the suitability of syngas for electricity generation or further conversion. Accordingly, further assessment is required to determine which Malaysian feedstocks and system configurations can support reliable and economically viable gasification projects.

### 3.5 Pyrolysis

Pyrolysis is a thermochemical process in which organic materials are heated in the absence, or near absence, of oxygen. The process decomposes the feedstock into several products, which may include liquid bio-oil, combustible gases and solid char. The relative proportions and properties of these products depend on feedstock composition, temperature, heating rate and residence time.

The selected literature considers pyrolysis as one of the possible technologies for converting MSW, biomass and food waste into useful products. The comparative study of restaurant food waste conversion in Malaysia and Singapore evaluates pyrolysis alongside anaerobic digestion and gasification [42]. Other selected reviews examine the wider role of WtE technologies in waste management and bioeconomy development [38, 50].

Pyrolysis may also be relevant to oil palm biomass because the Malaysian palm oil industry produces lignocellulosic residues that can be considered for thermochemical conversion. Research on palm oil biomass waste reviews technological approaches for transforming these residues into sustainable biofuels and other useful products [35, 67].

The main consideration in applying pyrolysis is the need to match process conditions to the feedstock. Different waste materials can produce different quantities and qualities of liquid, gaseous and solid products. Feedstock contamination and moisture content may also influence pre-treatment requirements and process efficiency.

Although pyrolysis offers opportunities for producing multiple products, its commercial application requires evaluation of energy consumption, product quality, operating costs and potential markets. The ability to use or upgrade the resulting products is important in determining whether a pyrolysis facility can operate sustainably.

### 3.6 Torrefaction

Torrefaction is a thermal pre-treatment process used to improve the fuel characteristics of biomass and other suitable organic materials. It generally involves heating the material under controlled conditions with limited oxygen. The resulting solid product can have improved properties for storage, handling and subsequent energy conversion.

The selected literature specifically examines torrefaction as a method of producing enhanced solid biofuel from MSW and other biomass materials [52]. The study discusses the potential of using waste as a renewable fuel for thermochemical processes, including combustion, pyrolysis and gasification.

For Malaysia, torrefaction may be relevant to agricultural and oil palm residues that require pre-treatment before use in energy-generation systems. Improving fuel characteristics may help address some of the challenges associated with handling heterogeneous biomass. However, the practical benefits depend on the original feedstock, process conditions, energy requirements and intended application.

Torrefaction should therefore be understood as a pre-treatment pathway rather than a complete energy-conversion system. Its effectiveness needs to be assessed together with the downstream technology, such as combustion or gasification, and the overall energy balance of the process.

### 3.7 Hydrothermal Carbonisation

Hydrothermal carbonisation (HTC) is a thermochemical process that converts wet organic materials into a carbon-rich solid product through treatment in hot, pressurised water. The solid product is commonly referred to as hydrochar. The process is of interest for wet feedstocks because it can process materials with relatively high moisture content without requiring the same degree of preliminary drying as some conventional thermal processes.

The selected Malaysian food-waste review identifies HTC as an emerging technology and examines it alongside anaerobic digestion and incineration [54]. Its inclusion is particularly relevant when considering food waste and other wet organic materials that may be difficult or expensive to dry before thermal treatment.

HTC may produce a solid fuel or material that can be evaluated for subsequent applications. However, its practical suitability depends on the properties of the feedstock, reaction conditions, process-water management and the quality of the resulting hydrochar. The management and potential treatment of liquid by-products must also be considered.

Although HTC is discussed as a promising option in the selected literature, further investigation is required to establish its technical and economic suitability for large-scale application in Malaysia. This includes evaluating energy consumption, equipment costs, product quality and the environmental performance of the complete process.

### 3.8 Biogas and Hydrogen Production from Waste

In addition to direct electricity and heat generation, waste conversion processes can produce energy carriers such as biogas and hydrogen. Biogas is generated mainly through anaerobic digestion of biodegradable organic materials. Following appropriate treatment, it may be used for electricity generation, heating or upgrading into biomethane.

The selected literature considers biogas production from food waste, organic MSW, agricultural residues and other biomass resources [29, 32, 45, 62, 69]. These studies highlight the relationship between waste treatment, renewable energy production and resource recovery. They also demonstrate that biogas development requires attention to technical performance, investment, social acceptance and environmental management.

Hydrogen represents a further potential energy product from waste. The selected cross-sectoral review of waste-to-hydrogen pathways examines agricultural residues, MSW and wastewater as potential feedstocks, alongside process integration and sustainability considerations [48]. A separate study discusses global opportunities for biogas and hydrogen production from landfill waste [43].

Malaysia's wider hydrogen ambitions provide additional context for considering future waste-derived hydrogen pathways. The selected literature on hydrogen in Malaysia discusses the role of hydrogen in the country's future primary energy mix and identifies challenges involving infrastructure, production technologies and development readiness [55]. Nevertheless, hydrogen production from waste should be assessed separately from conventional biogas production because the processes, energy requirements and technology maturity can differ considerably.

Waste-derived hydrogen may offer opportunities for linking waste management with emerging low-carbon energy systems. However, its development requires further evaluation of feedstock suitability, hydrogen yield, process energy demand, production cost, emissions and downstream infrastructure.

### 3.9 Comparative Assessment of WtE Technologies

The reviewed technologies differ in their feedstock requirements, conversion mechanisms, energy products and implementation challenges. Table 2 provides a qualitative comparison based on the selected literature. It is intended as an overview of technology characteristics rather than a quantitative ranking of performance.

Table 2. Comparative characteristics of major waste-to-energy technologies

| **Technology** | **Conversion principle** | **Suitable waste streams** | **Main energy or product output** | **Key advantages** | **Main limitations** | **References** |
|---|---|---|---|---|---|---|
| Incineration | Direct combustion under controlled conditions | Suitable residual MSW and combustible waste | Heat and electricity | Reduces waste volume and enables energy recovery | Emissions control, ash management and feedstock quality | [11, 18, 19, 54, 58] |
| Anaerobic digestion | Biological decomposition without oxygen | Food waste, organic MSW, agricultural residues and organic sludge | Biogas and digestate | Suitable for biodegradable wet waste and can recover nutrients | Process stability, feedstock separation and digester operation | [29, 32, 42, 45, 54, 62] |
| Landfill gas recovery | Collection of gas from decomposing landfill waste | Biodegradable waste already deposited in landfills | Landfill gas for heat or electricity | Recovers energy from existing landfill sites | Gas collection efficiency and variable gas generation | [24, 43] |
| Gasification | Thermal conversion with a controlled gasifying agent | Suitable biomass and combustible waste | Syngas | Offers potential for energy and chemical production | Feedstock preparation, gas cleaning and system complexity | [20, 38, 51] |
| Pyrolysis | Thermal decomposition with little or no oxygen | Biomass, selected MSW fractions and food waste | Bio-oil, gas and char | Produces multiple potentially useful products | Product quality, process conditions and market requirements | [35, 38, 42, 50, 67] |
| Torrefaction | Thermal pre-treatment under controlled conditions | Biomass and suitable organic waste | Upgraded solid biofuel | Can improve fuel handling and characteristics | Requires additional processing and downstream conversion | [52] |
| Hydrothermal carbonisation | Treatment of wet organic material in hot, pressurised water | Food waste and other wet organic feedstocks | Hydrochar and liquid by-products | Can process wet feedstocks | Process-water management, energy requirements | [54] |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | and scale-up | |
| Waste-derived hydrogen | Biological or thermochemical conversion, depending on pathway | Agricultural residues, MSW and wastewater | Hydrogen | Potential connection between waste recovery and emerging hydrogen systems | Technology readiness, production cost and infrastructure | [43, 48, 55] |

### 3.10 Technology Selection for the Malaysian Context

The literature indicates that no single WtE technology is suitable for every waste stream. Technology selection should be based on the characteristics of the available feedstock, the required energy product, technical readiness, investment requirements and environmental performance. Studies on WtE technology selection and optimisation emphasise the need to consider multiple criteria rather than relying on energy output alone [17, 20, 25, 27, 28].

For Malaysia, anaerobic digestion is a relevant option for separately collected food waste and other biodegradable organic materials. Incineration may be considered for suitable residual MSW, provided that feedstock quality, emissions control and ash management are addressed. Oil palm biomass may offer opportunities for combustion and other thermochemical conversion processes, while gasification, pyrolysis and torrefaction warrant further evaluation according to the type and condition of the available residues.

The selection process should also consider the relationship between WtE and existing recycling systems. Poor segregation can reduce the quality of feedstock and make it more difficult to select an efficient conversion process. The selected literature on MSW segregation challenges highlights the importance of linking waste separation, technology choice and circular-economy strategies [59]. Similarly, research on the effects of recycling on WtE feedstock sustainability indicates that energy recovery must be planned in conjunction with material recovery objectives [16].

An appropriate technology-selection framework for Malaysia should therefore consider the following factors:

1. Feedstock suitability: physical and chemical characteristics, moisture content, organic fraction and contamination.
2. Supply reliability: quantity, geographical distribution, seasonal variation and collection arrangements.
3. Technical performance: conversion efficiency, operational reliability, pre-treatment needs and technology readiness.
4. Economic feasibility: capital investment, operating costs, maintenance requirements and potential energy revenues.
5. Environmental performance: greenhouse gas emissions, air pollution, wastewater and residual-material management.
6. Institutional and social conditions: regulatory requirements, stakeholder coordination and public acceptance.

Overall, the reviewed literature supports a diversified WtE strategy for Malaysia. Such a strategy would match biological technologies with suitable organic waste, thermochemical processes with appropriate combustible materials and emerging conversion pathways with feedstocks that meet their technical requirements. The next stage of the review examines how these technologies have been studied and applied in Malaysia, including the available evidence on local projects, pilot systems and commercialisation challenges.

# 3. WASTE-TO-ENERGY APPLICATIONS AND DEVELOPMENT IN MALAYSIA

The development of waste-to-energy (WtE) in Malaysia involves several interconnected areas: municipal solid waste treatment, food-waste recovery, biomass utilisation, biogas production and the development of integrated waste-management systems. The selected literature indicates that Malaysia's WtE opportunities are not limited to one conversion technology. Instead, they depend on the ability to match available waste resources with suitable treatment processes, infrastructure and policy objectives.

The Malaysian studies in the reference list provide evidence at different levels. Some assess national waste-management scenarios using modelling and life-cycle approaches, while others review technology options or investigate specific pilot-scale applications. These forms of evidence are complementary, but they should not be treated as equivalent: a modelled scenario indicates potential system outcomes, whereas a pilot study provides observations from a particular experimental or local setting.

4.1 Municipal Solid Waste Management and Energy Recovery
Malaysia's municipal solid waste management system provides an important context for WtE development. The selected literature identifies continued reliance on landfill disposal as a major challenge and examines how alternative treatment systems could improve environmental and economic performance.

A national case study applies a multi-objective optimisation model to evaluate the allocation of Malaysian MSW among different waste-treatment facilities. The model considers seven options: open landfills, sanitary landfills, material recycling facilities, anaerobic digestion, composting, incineration and plasma gasification. It incorporates both economic and environmental objectives, including treatment costs and greenhouse gas emissions [61]. This approach is important because it considers WtE as part of a broader waste-management system rather than as an isolated electricity-generation activity.

A separate Malaysian study evaluates waste-management scenarios using a relative quadrant life-cycle eco-efficiency indicator. It compares a business-as-usual scenario with alternative treatment configurations designed around existing and future policy targets [60]. This provides a framework for assessing the relationship between environmental performance and economic considerations when comparing waste-management strategies.

Together, these studies suggest that the development of WtE in Malaysia should be considered within an integrated system that includes recycling, composting, biological treatment, thermal treatment and landfill management. The relative contribution of each option depends on local waste characteristics, infrastructure availability and policy priorities.

### 4.2 Food Waste Management and Biogas Production

Food waste is one of the most relevant organic feedstocks for WtE development in Malaysia. The selected literature examines food-waste management from technological, economic, environmental and policy perspectives, with particular attention to anaerobic digestion (AD) as a method of producing biogas.

A Malaysian study on biogas and biofertiliser production from the organic fraction of MSW investigates the potential for recovering energy and agricultural products through anaerobic digestion. Its analysis estimates that organic waste accounts for approximately 45% of total Malaysian MSW. Based on the study's assumptions, treating 50% of this organic fraction could produce approximately 3,941 MWh of electricity per day and 2,500 tonnes of biofertiliser per day [29]. These are model-based estimates of potential, rather than measurements from a national commercial AD system. Nevertheless, the study illustrates the possible contribution of organic waste recovery to energy production and landfill diversion.

The practical potential of food-waste-based biogas is also examined through stakeholder analysis. A study identifying challenges and solutions for food-waste-based biogas in Malaysia uses the Analytical Hierarchy Process (AHP) to rank policy and implementation considerations. Economic and resource-related challenges received the highest overall weighting, followed by institutional and legal, social and cultural, technical and environmental factors. The study identifies appropriate plant scale, feedstock distribution and collection arrangements as important considerations for successful implementation. It also highlights community engagement, operational standards, digester optimisation and source segregation as relevant solutions [32].

A comparative techno-economic and life-cycle assessment of restaurant food-waste conversion in Malaysia and Singapore evaluates anaerobic digestion, pyrolysis and gasification. The study identifies anaerobic digestion as the most promising option among the three technologies assessed, based on its reported technical, economic and environmental performance. Its analysis reports a potential waste-volume reduction of 60%, a return on investment of 12–15% and a payback period of five to seven years for medium-scale installations under the study's assumptions [42]. These figures should be interpreted within the boundaries of the study and not treated as guaranteed financial returns for all Malaysian projects.

More direct local evidence is provided by a pilot-scale study conducted in Seremban. The study used a 500-litre anaerobic digestion reactor to process the organic fraction of MSW and reported average daily biogas production of 92–262 litres, with methane concentrations ranging from 60% to 70%. It also found that waste segregation rates among surveyed residents were below 50%, highlighting the importance of public participation and consistent feedstock supply [62].

These findings suggest that food-waste-based AD has potential in Malaysia, but its implementation depends on more than the availability of biodegradable material. Collection systems must supply sufficient quantities of separated organic waste, while plant capacity should correspond to the distribution and volume of available feedstock. The literature also indicates that community engagement, regulatory coordination and financial support are important conditions for wider adoption [8, 32, 54].

### 4.3 Oil Palm Biomass Conversion and Cogeneration

Oil palm biomass is another important area of Malaysian WtE research. The country's palm oil industry produces several residues that may be used for energy generation or converted into higher-value products. These include empty fruit bunches (EFB), palm kernel shells (PKS), fibres, palm trunks, palm fronds and palm oil mill effluent (POME).

The selected literature examines the implementation of different oil palm waste conversion methods in Malaysia. A review of technology readiness and commercialisation categorises the main conversion pathways into thermochemical and biological processes. It reports that combustion and pyrolysis have reached commercialisation, while gasification and anaerobic digestion have reached pilot-scale development. Fermentation is reported to remain at laboratory scale. The review also identifies technical and economic limitations, limited stakeholder coordination and community awareness as barriers to further commercialisation [36].

These findings are important because they distinguish between technologies that have been investigated experimentally and those that have progressed towards commercial use. They also demonstrate that the existence of a technically feasible conversion process does not necessarily mean that it can be implemented successfully at industrial scale. Investment requirements, operating reliability, feedstock logistics and market demand all influence commercial development.

Biomass-based cogeneration is another area of interest. Cogeneration systems produce electricity and useful heat from the same energy source, potentially improving overall energy utilisation compared with electricity-only generation. A Malaysian review of biomass supply chains and cogeneration examines developments in

biomass-based cogeneration and co-firing, alongside the role of optimisation modelling in improving economic and environmental performance [65].

The review emphasises that biomass supply-chain management is closely connected to the performance of energy-generation facilities. Feedstock collection, transportation, storage and processing affect the reliability and cost of biomass supply. Therefore, the development of cogeneration systems requires coordination between biomass producers, processing facilities and energy operators.

A further review of palm oil waste management considers circular-bioeconomy and decarbonisation approaches, including anaerobic digestion and biomass combustion [35]. More recent literature also discusses the conversion of palm oil biomass into biofuels and the potential integration of several conversion processes within biorefinery systems [67]. These approaches suggest that palm residues may contribute to energy production while also supporting the development of other value-added products.

Overall, oil palm biomass offers opportunities for expanding Malaysia's bioenergy sector. However, the commercialisation of different technologies remains uneven, and further development depends on improving supply-chain efficiency, technology performance, investment conditions and coordination among industry stakeholders.

### 4.4 Integrated Waste-to-Energy Opportunities in Sarawak

The selected literature also includes an integrated assessment of WtE opportunities in Sarawak. This study considers four biomass feedstock categories: municipal waste, wood waste, agricultural waste and POME. It examines their potential contribution to biofuel adoption and sustainable energy development, with particular attention to rural electricity access.

The study identifies POME-based biogas as a promising feedstock for electricity generation in Sarawak. It also examines wood pellets as an alternative energy source and reports a lower greenhouse gas footprint than coal-fired electricity within its assessment [13]. These findings indicate that WtE planning can be connected to regional energy-access priorities, particularly where biomass resources are available near agricultural and industrial processing facilities.

However, the findings should be interpreted in the context of Sarawak's geographical and energy conditions. The availability of biomass, location of processing facilities, transportation infrastructure and electricity demand can differ from those in Peninsular Malaysia. As a result, the technology and feedstock combinations identified for Sarawak should not automatically be assumed to be equally suitable for other Malaysian states.

The study also considers public perceptions and investment willingness, demonstrating that stakeholder acceptance is relevant to biofuel development [13]. This reinforces the importance of incorporating community engagement and transparent environmental assessment into regional WtE planning.

### 4.5 Policy and Institutional Development

The development of WtE in Malaysia is influenced by the relationship between technology adoption, waste-management policies and institutional responsibilities. The selected literature indicates that technological availability alone is insufficient to ensure successful implementation.

A study on technology adoption in Malaysian MSW management uses focus group discussions and interviews with government agencies and private-sector stakeholders. It identifies a lack of provision and expertise as significant barriers to the adoption of waste-management technologies [10]. This suggests that investment in physical facilities must be accompanied by technical capacity, institutional support and appropriate operational arrangements.

Food-waste governance is another important policy area. A Malaysian study examining urban food-waste governance identifies fragmented legal coverage, overlapping implementation responsibilities, uneven enforcement and limited organic-waste recovery capacity as weaknesses in the existing policy mix [8]. It argues that improved source separation, monitoring, disposal-pricing mechanisms and coordination between jurisdictions are important for strengthening food-waste management.

The selected literature also examines broader national energy policies and Malaysia's transition towards sustainable energy systems [1, 41]. These studies provide wider context for considering how WtE can contribute to energy diversification, emissions reduction and circular-economy development. Nevertheless, WtE implementation requires policies that address the specific requirements of waste collection, feedstock supply, technology operation and residual-material management.

### 4.6 Summary of Malaysian WtE Applications

The Malaysian literature provides several types of evidence concerning WtE development. These include national-scale optimisation models, life-cycle and eco-efficiency assessments, technology-readiness reviews, stakeholder studies and pilot-scale investigations.

Table 3. Summary of selected Malaysian WtE studies and their contributions

| Study focus | Location or scope | Method or approach | Main contribution | Reference |
|---|---|---|---|---|
| Organic MSW conversion to biogas and biofertilizer | Malaysia | Feedstock analysis and economic and environmental assessment | Estimates energy and biofertiliser recovery potential from the organic fraction of MSW | [29] |
| Food-waste-based biogas implementation | Malaysia | Stakeholder analysis using AHP | Identifies and ranks economic, institutional, social, technical and environmental challenges and solutions | [32] |
| Restaurant food-waste-to-electricity conversion | Malaysia and Singapore | Techno-economic assessment and life-cycle analysis | Compares AD, pyrolysis and gasification, identifying AD as the most promising option within the study | [42] |
| Food-waste management technologies | Malaysia | Technology and literature review | Reviews AD, incineration and HTC, including their opportunities and limitations | [54] |
| Biogas production from organic MSW | Seremban, Malaysia | Pilot-scale 500-litre AD reactor and life-cycle assessment | Reports biogas production and methane content from locally collected organic waste | [62] |
| MSW treatment-system optimisation | Malaysia | Multi-objective mathematical optimisation | Evaluates waste-treatment allocations based on economic and environmental objectives | [61] |
| MSW policy and eco-efficiency | Malaysia | Life-cycle eco-efficiency scenario assessment | Compares alternative waste-treatment scenarios against a business-as-usual baseline | [60] |
| Oil palm waste conversion | Malaysia | Technology-readiness and commercialisation review | Assesses the development status of combustion, gasification, pyrolysis, AD and fermentation | [36] |
| Biomass cogeneration and supply | Malaysia | Comprehensive literature review and optimisation modelling | Examines biomass supply-chain and cogeneration development | [65] |

| | | | | |
|---|---|---|---|---|
| chains | | assessment | | |
| Integrated biomass WtE assessment | Sarawak, Malaysia | Feedstock assessment and stakeholder survey | Examines municipal, wood, agricultural and POME-based biofuel opportunities | [13] |

### 4.7 Research Gaps in Malaysian WtE Development

Although the selected literature demonstrates growing interest in WtE in Malaysia, several research gaps remain.

First, there is a need for more long-term operational data from commercial facilities. Pilot studies provide useful evidence about process performance, but their findings may not fully represent the technical and financial conditions of larger installations. Further research should examine operational reliability, maintenance requirements, actual energy output and long-term feedstock availability.

Second, feedstock segregation and supply-chain management require greater attention. The food-waste and MSW studies identify the importance of consistent waste collection and source separation [8, 32, 62]. Future research should investigate how collection systems can be improved to provide reliable and appropriately characterised feedstock.

Third, additional techno-economic and life-cycle assessments are needed under Malaysian conditions. International findings may provide useful comparisons, but local assessments should reflect Malaysian waste composition, transportation distances, energy prices, investment conditions and environmental requirements.

Fourth, commercialisation barriers for biomass conversion technologies require further investigation. The oil palm waste literature indicates differences in technology readiness across conversion methods and identifies economic, technical and stakeholder-related constraints [36]. More research is required to determine how these constraints can be addressed through industry collaboration, technology development and appropriate financing arrangements.

Finally, the relationship between WtE and the wider circular economy needs to be examined more systematically. Energy recovery should be integrated with material recycling, nutrient recovery and higher-value biomass utilisation. This is particularly relevant for food waste and oil palm residues, where different conversion pathways may compete for the same resources.

## 4. TECHNICAL PERFORMANCE AND ENERGY RECOVERY POTENTIAL

The technical performance of waste-to-energy (WtE) systems depends on the relationship between feedstock characteristics, conversion technology, operating conditions and the quality of the resulting energy products. In Malaysia, this is particularly important because the available waste resources range from wet organic materials, such as food waste and palm oil mill effluent, to solid biomass residues and mixed municipal solid waste (MSW).

The selected literature evaluates energy recovery through several approaches, including biogas production, electricity generation, thermochemical conversion, biomass cogeneration and waste-derived fuels. However, the studies use different feedstocks, system boundaries, technologies and assessment methods. Their reported results should therefore be interpreted within the conditions of each study rather than compared as though they were obtained from identical facilities.

### 5.1 Feedstock Characteristics and Technology Performance

Feedstock characteristics are among the most important determinants of WtE performance. The composition,

moisture content, organic fraction, heating value and contamination level of waste influence the choice of conversion technology and the amount of energy that can be recovered.

Food waste and other biodegradable organic materials are generally relevant to biological conversion processes, particularly anaerobic digestion. In contrast, dry and combustible waste fractions may be considered for thermal conversion. Oil palm biomass offers further opportunities because different residues can be evaluated for combustion, gasification, pyrolysis, torrefaction and other conversion pathways [35, 36, 52, 67].

The selected literature also highlights the importance of feedstock availability and supply-chain organisation. Biomass may be available in substantial quantities at agricultural or industrial processing sites, but its practical use depends on collection, storage, transportation and pre-treatment. The Malaysian review of biomass supply chains and cogeneration identifies supply-chain optimisation as an important factor in the performance and development of biomass energy systems [65].

For this reason, technical assessments should not focus exclusively on the efficiency of the conversion equipment. They should also consider the energy and resources required to collect, prepare and deliver feedstock to the facility.

### 5.2 Performance of Anaerobic Digestion Systems

Anaerobic digestion (AD) converts biodegradable organic matter into biogas through microbial activity under oxygen-free conditions. Its performance is commonly assessed using biogas production, methane content, methane yield, process stability and the quantity and quality of digestate.

A Malaysian pilot-scale study in Seremban investigated biogas production from the organic fraction of MSW using a 500-litre anaerobic digestion reactor. The study reported average daily biogas production of 92–262 litres, with methane concentrations ranging from 60% to 70% [62]. These results provide local experimental evidence that separated organic MSW can be used for biogas production. However, the results represent the conditions of the pilot system and should not be directly extrapolated to commercial-scale facilities.

Another Malaysian study assessed the potential production of biogas and biofertiliser from the organic fraction of MSW. It estimated that treating 50% of the organic fraction could generate approximately 3,941 MWh of electricity per day and 2,500 tonnes of biofertiliser per day, based on the assumptions used in its assessment [29]. These values represent estimated resource-recovery potential rather than measured output from an operating national system.

The selected review of small-scale biogas digesters identifies design and operational considerations such as monitoring, mixing and temperature control as important factors for reliable operation and maintenance [45]. These considerations are relevant to Malaysian applications, where feedstock characteristics and operating conditions may vary between facilities.

Overall, the available studies indicate that AD has potential for treating food waste and organic MSW in Malaysia. Nevertheless, actual performance depends on feedstock consistency, reactor design, process control and the ability to use the biogas produced. Further long-term operational studies would help establish the reliability and scalability of different digester configurations.

### 5.3 Performance of Incineration and Electricity Generation

Incineration converts combustible waste into heat through controlled combustion. The recovered heat can be used for steam generation and electricity production. Its technical performance is influenced by waste composition, moisture content, heating value, combustion conditions and the efficiency of heat-recovery equipment.

The selected literature examines the influence of bio-waste on electricity generation from MSW incineration and the techno-economic considerations associated with incineration facilities [18, 19]. It also includes research on the selection of suitable WtE technologies for different waste-management systems [20].

One important consideration is the effect of organic waste on the quality of the mixed waste feedstock. Food waste generally has a high moisture content, which can affect the heating characteristics of mixed MSW. Therefore, the energy-recovery potential of an incineration facility depends not simply on the total mass of waste supplied, but also on the proportion of combustible materials and their characteristics.

Incineration performance must also be evaluated alongside the management of bottom ash and fly ash. Research on MSW combustion residues examines their characteristics and possible resource-recovery applications [58]. Another selected study investigates the use of thermally plasma-decomposed MSW bottom ash as partial replacements for cement and fine aggregates in cement mortar [66]. These studies demonstrate that combustion residues may require further treatment and assessment before any beneficial reuse can be considered.

For Malaysia, the technical feasibility of incineration therefore requires assessment of waste heating value, energy recovery efficiency, emissions-control performance and ash-management arrangements. The available selected references provide evidence on technology characteristics and assessment approaches, but do not establish a single national electricity-generation efficiency for Malaysian MSW incineration facilities.

### 5.4 Gasification and Syngas Production

Gasification converts carbon-containing materials into syngas through thermal reactions involving a controlled supply of a gasifying agent. The resulting gas may contain hydrogen, carbon monoxide, methane and carbon dioxide. Depending on its composition and cleanliness, syngas may be used for heat and electricity generation or further processed into other fuels and chemical products.

The selected literature includes a study developing an artificial neural network model to predict gasification-process performance [51]. This research illustrates how modelling can be used to investigate the relationships between feedstock characteristics, operating conditions and gasification outcomes. Such approaches may support process optimisation, although model predictions must be validated against suitable experimental or operational data.

Gasification is also discussed in the Malaysian literature on oil palm biomass conversion. Empty fruit bunches and palm kernel shells are among the residues considered for thermochemical conversion and syngas production [67]. The review identifies gasification as one of the potential pathways for converting palm oil biomass into useful fuels, including hydrogen through further processing.

However, gasification performance depends on the type and condition of the feedstock, reactor design, temperature and gasifying agent. Gas cleaning is also important because contaminants can affect the reliability of downstream equipment and the suitability of syngas for its intended application.

The available literature supports further investigation of gasification for suitable Malaysian biomass residues. Nevertheless, additional local performance data are required to establish conversion efficiency, syngas quality, operating costs and commercial-scale reliability under Malaysian conditions.

### 5.5 Pyrolysis and Production of Bio-oil and Biochar

Pyrolysis converts organic materials into liquid, gaseous and solid products through heating under little or no oxygen. Its technical performance is generally evaluated according to product yields, product characteristics, energy requirements and the suitability of the resulting products for further use.

The selected literature identifies pyrolysis as a potential route for converting oil palm biomass and other

organic waste into useful fuels and products [35, 42, 67]. The Malaysian review of palm oil biomass conversion discusses pyrolysis alongside other thermochemical and biological processes, including the possibility of integrating different conversion routes within biorefinery systems [67].

The performance of pyrolysis is strongly dependent on feedstock characteristics and process conditions. Different operating conditions may favour the production of liquid, gaseous or solid products. Therefore, a high product yield does not necessarily indicate high overall system efficiency. The energy needed for feedstock preparation and heating, as well as the requirements for product upgrading, must also be considered.

Biochar or char produced through thermal conversion may have potential applications depending on its composition and quality. However, its suitability for particular uses requires appropriate testing and environmental assessment. Similarly, bio-oil may require further processing before it can be used in some energy applications.

The available literature indicates that pyrolysis offers opportunities for biomass valorisation, but further research is required to determine the most suitable feedstocks and process configurations for commercial application in Malaysia.

### 5.6 Torrefaction and Biomass Fuel Improvement

Torrefaction is used to improve the fuel characteristics of biomass and selected organic waste materials. It is a pre-treatment process rather than a complete energy-generation system. Its purpose is to produce a more suitable solid fuel for subsequent conversion processes.

The selected study on torrefaction examines the production of enhanced solid biofuel from MSW and other biomass materials [52]. This is relevant to Malaysia because agricultural and oil palm residues may require pre-treatment before being used in combustion or gasification systems.

The technical performance of torrefaction should be evaluated through changes in fuel properties, solid product yield, energy consumption and the suitability of the resulting material for downstream use. The benefits of improved fuel characteristics must be considered against the energy and financial costs of the additional processing stage.

Consequently, torrefaction may contribute to improving biomass utilisation, but its overall value depends on whether the improved fuel properties produce measurable benefits in the complete energy-conversion system.

### 5.7 Hydrothermal Carbonisation and Wet Waste Treatment

Hydrothermal carbonisation (HTC) is particularly relevant to wet organic waste because it processes material in hot, pressurised water. The process produces a carbon-rich solid known as hydrochar, together with liquid and gaseous products.

The selected Malaysian review of food-waste management includes HTC as an emerging treatment option alongside anaerobic digestion and incineration [54]. Its relevance lies in the possibility of processing wet feedstocks without relying on the same preliminary drying requirements associated with some conventional thermal processes.

The performance of HTC depends on feedstock composition, process conditions and the characteristics of the resulting hydrochar. Assessment should also include the management of process water and other by-products. The selected reference provides a review of the technology but does not establish a commercial-scale Malaysian HTC performance benchmark.

Further research is therefore required to evaluate the energy balance, product quality, operating costs and environmental implications of HTC for Malaysian food waste and other suitable wet organic materials.

### 5.8 Energy Recovery from Sludge and Other Organic Residues

Wastewater-treatment sludge is another potential resource for energy recovery. The selected review on sludge-to-biofuel conversion examines anaerobic digestion, hydrothermal liquefaction, pyrolysis and transesterification as possible pathways for converting unused sludge into energy products [68].

The review reports methane yields of 200–350 mL $CH_4$/g volatile solids for anaerobic digestion and bio-oil yields of 35–55% on a dry basis for hydrothermal liquefaction. It also reports that anaerobic digestion can reduce greenhouse gas emissions by up to 1.9 tonnes of $CO_2$-equivalent per tonne of sludge under the conditions considered in the reviewed literature [68].

These figures are drawn from a review of international studies and should not be interpreted as measured performance from Malaysian sludge-treatment facilities. Their relevance to Malaysia is that they identify possible conversion pathways and provide performance indicators for future local investigations.

Sludge conversion also requires careful consideration of feedstock contamination, particularly where sludge originates from industrial wastewater treatment. The quality of the resulting fuel or residual material must be evaluated before further use. Consequently, sludge-based WtE should be assessed in conjunction with treatment requirements and environmental safeguards.

### 5.9 Comparative Technical Assessment

The selected literature covers technologies that differ in conversion mechanisms, feedstock requirements and energy products. Table 4 summarises the main technical characteristics and available evidence.

Table 4. Technical performance and energy-recovery characteristics of WtE technologies

| Technology | Main performance indicators | Potential energy or product output | Important technical factors | Evidence in selected literature |
|---|---|---|---|---|
| Anaerobic digestion | Biogas volume, methane concentration, methane yield and process stability | Biogas, electricity and digestate | Organic loading, temperature, pH, retention time and feedstock quality | Malaysian pilot study reports 92–262 L biogas/day and 60–70% methane [62] |
| Incineration | Waste throughput, heating value, combustion performance and energy recovery | Heat and electricity | Moisture content, combustible fraction, emissions control and ash management | Technology and performance assessments [18, 19, 54, 58] |
| Gasification | Syngas composition, gas yield and conversion performance | Syngas for heat, electricity or further fuel production | Feedstock preparation, gasifying agent, reactor conditions and gas cleaning | Gasification prediction model and biomass conversion review [51, 67] |
| Pyrolysis | Bio-oil, gas and char yields and product quality | Bio-oil, combustible gas and char | Temperature, heating rate, residence time and feedstock properties | Food-waste and palm biomass conversion studies [35, 42, 67] |
| Torrefaction | Solid yield, fuel properties and energy consumption | Upgraded solid biofuel | Process conditions, feedstock moisture and downstream use | MSW and biomass torrefaction study [52] |

| | | | | |
|---|---|---|---|---|
| Hydrothermal carbonisation | Hydrochar yield and quality, process-water characteristics | Hydrochar and other process products | Feedstock composition, pressure, temperature and liquid-residue management | Malaysian food-waste technology review [54] |
| Sludge-to-biofuel conversion | Methane yield, bio-oil yield and emissions reduction | Biogas, bio-oil and biodiesel | Sludge composition, contaminants and process energy requirements | International review of sludge-to-biofuel pathways [68] |

### 5.10 Factors Affecting Overall Energy Recovery

The technical performance of a WtE facility should be evaluated across the entire conversion chain. A process may demonstrate promising energy output at the reactor level but still perform poorly when feedstock collection, pre-treatment, transportation and residual management are included.

**Several factors are particularly important for Malaysia.**

**Feedstock consistency.** Variation in waste composition and moisture content can affect process stability and energy output. Consistent source separation can improve the quality of feedstock supplied to biological and thermal conversion facilities [32, 59, 62].

**Pre-treatment requirements.** Sorting, size reduction, drying and other preparation processes may be necessary before waste can be converted efficiently. The need for pre-treatment depends on the selected technology and the characteristics of the incoming waste.

**Energy consumption within the facility.** Electricity and heat may be required for pumping, mixing, drying, heating, gas cleaning and other operations. Net energy recovery should therefore be distinguished from gross energy production.

**Operational reliability.** Equipment maintenance, operator expertise, monitoring and process control influence the availability and consistency of energy production. The selected review of small-scale biogas digester operation identifies these factors as important considerations [45].

**Residual-material management.** Ash, digestate, char and process water require appropriate treatment or utilisation. Their management influences the environmental performance and overall resource efficiency of the WtE system [58, 66, 68].

**Integration with existing infrastructure.** Biomass-based energy facilities may benefit from integration with agricultural processing operations and existing energy systems. The Malaysian biomass supply-chain literature identifies cogeneration and optimisation as relevant areas for improving system performance [65].

## 5. ECONOMIC FEASIBILITY AND INVESTMENT CONSIDERATIONS

The economic feasibility of waste-to-energy (WtE) projects is a major factor influencing their implementation in Malaysia. Although WtE technologies can provide energy recovery and reduce the amount of waste requiring landfill disposal, their development requires substantial investment in infrastructure, equipment, feedstock collection, transportation, pre-treatment and operational management. The financial viability of a project therefore depends on the relationship between its capital and operating costs, revenue opportunities, environmental benefits and long-term operating performance.

The selected literature evaluates economic feasibility through several approaches, including techno-economic assessment, life-cycle costing (LCC), life-cycle cost-benefit analysis, net present value (NPV), internal rate of return (IRR), levelised cost of energy (LCOE), payback period and multi-criteria decision analysis. These

methods provide different perspectives on investment performance and should be considered together when assessing potential WtE projects.

### 6.1 Capital and Operating Costs

Capital expenditure (CAPEX) represents the initial investment required to establish a WtE facility. Depending on the selected technology, this may include land preparation, building construction, conversion equipment, waste sorting and pre-treatment facilities, emissions-control systems, energy-generation equipment and connections to electricity or gas infrastructure.

Operating expenditure (OPEX) includes the recurring costs of running the facility. These may involve labour, electricity, water, maintenance, feedstock collection, transportation, equipment replacement, monitoring and residual-waste management.

The selected Malaysian literature on sustainable solid waste management identifies increasing waste-management costs and the need to consider alternative treatment approaches, including WtE facilities [2]. This is important because the economic assessment of WtE should consider the costs avoided through reduced landfill disposal alongside the costs of establishing and operating the energy-recovery facility.

Different technologies have different investment requirements. Incineration facilities generally require substantial investment in combustion equipment, energy-recovery systems and emissions controls. Anaerobic digestion requires suitable digesters, feedstock preparation, gas treatment and biogas utilisation equipment. Gasification and pyrolysis also require specialised conversion and gas or product-treatment systems.

For Malaysia, the selection of technology should therefore be based on the scale and characteristics of available waste resources, rather than on the assumption that a larger or more technologically advanced facility will necessarily provide better economic returns.

### 6.2 Revenue Opportunities from Waste-to-Energy Facilities

WtE facilities may generate revenue through several channels. The most direct opportunity is the sale of electricity, heat, biogas or other energy products. Additional revenue may be possible through waste-treatment fees, recovered materials and useful by-products, depending on the technology and the quality of the outputs.

The main potential revenue sources include:

1. Electricity sales: Revenue from electricity generated and supplied to the grid or used by industrial and commercial customers.
2. Biogas and biomethane: Income from using or supplying biogas for energy applications, subject to gas quality and market arrangements.
3. Waste-treatment or gate fees: Payments received for accepting and treating waste.
4. Recovered materials: Income from recyclable materials recovered during waste sorting or treatment.
5. Useful by-products: Potential revenue from digestate, biochar, ash-derived materials and other outputs where their quality and regulatory status permit beneficial use.

The selected literature on food-waste-to-electricity conversion in Malaysia and Singapore considers the financial performance of anaerobic digestion and identifies the potential for energy recovery from restaurant food waste [42]. It also highlights the importance of policy support, investment and community engagement in determining whether such projects can be implemented successfully.

However, revenue from by-products should not be assumed without evidence of a suitable market. For example, digestate and ash may require treatment and quality verification before they can be sold or reused. The economic assessment must therefore account for the additional processing and compliance costs associated with these materials.

### 6.3 Techno-Economic Feasibility of Food-Waste-Based Anaerobic Digestion

Anaerobic digestion (AD) is an important technology for evaluating the economic potential of food-waste recovery in Malaysia. It converts biodegradable organic waste into biogas, which can be used for electricity and heat generation or upgraded for other energy applications.

The selected comparative study of restaurant food-waste-to-electricity conversion in Malaysia and Singapore evaluates anaerobic digestion, pyrolysis and gasification using techno-economic assessment and life-cycle analysis. The study identifies AD as the most promising option among the three technologies assessed. It reports a return on investment (ROI) of 12–15% and a payback period of five to seven years for medium-scale installations under its stated assumptions [42].

These findings suggest that AD may be financially attractive for suitable food-waste applications. Nevertheless, the results should be interpreted within the study's scope. The reported financial indicators are not universal values for Malaysian AD facilities and may change with feedstock supply, plant capacity, electricity prices, investment costs, operating performance and policy conditions.

The study also identifies the importance of policy and regulatory support and community engagement [42]. This is consistent with the Malaysian research on food-waste-based biogas, which identifies economic and resource-related challenges as important considerations in project implementation [32].

For practical investment decisions, the economic assessment of AD should consider:

- The quantity and consistency of separately collected food waste.
- The cost of collection, sorting and transportation.
- Digester capacity and expected operating life.
- Biogas production and methane content.
- Electricity-generation or biogas utilisation arrangements.
- Digestate treatment and potential market value.
- Maintenance, labour and equipment replacement costs.

The availability of a consistent organic feedstock supply is particularly important. A facility operating below its intended capacity may experience higher treatment costs per unit of waste and lower energy revenues.

### 6.4 Economic Assessment of Municipal Solid Waste Management Scenarios

Economic feasibility should also be evaluated at the level of the wider waste-management system. This is particularly relevant in Malaysia, where waste may be allocated among landfills, recycling facilities, composting, anaerobic digestion, incineration and other treatment options.

A Malaysian multi-objective optimisation study evaluates seven MSW treatment options while considering total system cost and net greenhouse gas emissions. The study reports a current-scenario cost of RM66.66 per tonne of MSW and net greenhouse gas emissions of 0.42 tonnes of $CO_2$-equivalent per tonne of MSW. Its least-cost scenario reduces both cost and emissions by 26%, while its least-emissions scenario reduces emissions by 159% compared with the current scenario but increases cost by 15% [61].

The study also identifies a recommended combination of sanitary landfilling, anaerobic digestion, composting, material recycling and plasma gasification among its Pareto-optimal solutions. Importantly, it demonstrates that the lowest-cost configuration and the lowest-emissions configuration are not necessarily the same. Decision-makers must therefore consider the trade-offs between financial expenditure and environmental performance.

A separate Malaysian life-cycle eco-efficiency assessment compares alternative waste-treatment scenarios based on policy targets. It identifies scenarios with increased recycling, composting and anaerobic digestion as more favourable than the business-as-usual configuration in the study's assessment. The research also evaluates the economic and environmental implications of different treatment combinations [60].

These findings demonstrate that WtE investment decisions should be integrated with national and local waste-management planning. A facility may appear financially attractive when assessed independently but may be less beneficial when the costs and environmental impacts of the complete waste-management system are considered.

### 6.5 Investment Considerations for Oil Palm Biomass and Cogeneration

Oil palm biomass provides another potential investment opportunity for Malaysia's WtE sector. The country's palm oil industry generates residues that can be used for energy production, including through biomass combustion and cogeneration.

Cogeneration systems produce electricity and useful heat from the same energy source. Their economic performance may benefit from the use of both energy outputs, particularly where heat can be utilised within nearby industrial operations. The selected review of Malaysia's biomass supply chain and cogeneration development examines the economic and environmental considerations associated with biomass-based cogeneration and co-firing systems [65].

However, biomass-based energy facilities depend on reliable feedstock supply. The costs of collecting, transporting, storing and preparing biomass can influence the economic performance of a project. These costs may be particularly important where residues are distributed across multiple agricultural or industrial locations.

The Malaysian review of oil palm waste conversion also identifies commercialisation challenges, including technical limitations, economic constraints and stakeholder coordination [36]. This indicates that the commercial success of biomass conversion technologies depends on more than the technical ability to produce energy.

Potential investors should therefore assess the availability of residues, competing uses, seasonal variations, transportation distance, conversion technology readiness and the availability of energy customers before committing to a project.

### 6.6 Financial Assessment Indicators

Several financial indicators are used in the selected literature to evaluate the economic performance of WtE projects.

Net present value (NPV). NPV estimates the present value of expected future project cash flows after accounting for the initial investment and discount rate. A positive NPV generally indicates that the projected returns exceed the required investment threshold under the assumptions used.

Internal rate of return (IRR). IRR represents the discount rate at which a project's NPV equals zero. It is commonly used to compare the expected financial return of alternative investment opportunities.

Levelised cost of energy (LCOE). LCOE estimates the average cost of producing a unit of energy over the lifetime of a facility. It is useful for comparing energy-generation options, although results depend on assumptions about plant capacity, operating life, financing and energy output.

Payback period. This measures the time required for a project to recover its initial investment from its net financial returns. A shorter payback period may be attractive to investors, but it does not necessarily indicate better lifetime profitability.

Return on investment (ROI). ROI expresses the financial return relative to the investment made. Its interpretation depends on the method used to calculate costs and returns.

The selected international literature demonstrates the application of these indicators to different WtE technologies. For example, studies in Nigeria and Iran evaluate WtE alternatives using LCC, NPV, IRR, LCOE and payback period [21, 26]. A Ghanaian study evaluates proposed MSW incineration facilities using NPV and LCOE and concludes that the facilities assessed would require government support because the estimated electricity-generation costs exceeded the relevant electricity tariffs [19].

These international studies are useful as methodological references, but their financial results should not be transferred directly to Malaysia. Differences in electricity tariffs, financing costs, waste composition, labour costs and regulatory arrangements may produce substantially different outcomes.

### 6.7 Sensitivity and Risk Analysis

The economic performance of WtE projects is influenced by uncertainties that may change over the project lifetime. Sensitivity analysis helps identify which assumptions have the greatest influence on financial outcomes.

Important variables include:

- Initial construction and equipment costs.
- Feedstock collection and transportation expenses.
- Plant capacity and utilisation rate.
- Electricity tariffs and energy-sale prices.
- Maintenance and replacement costs.
- Interest rates and financing arrangements.
- Inflation and discount rates.
- Waste-treatment fees and by-product prices.

The selected study on WtE investment feasibility in lower- and lower-middle-income countries uses sensitivity analysis to examine the effect of changing economic assumptions. It reports that NPV is particularly sensitive to inflation-rate changes in the landfill-gas recovery, AD and incineration scenarios assessed [53]. Although this study does not focus on Malaysia, it demonstrates why economic assumptions should be tested before investment decisions are made.

Similarly, the Malaysian MSW optimisation study examines the effects of changes in electricity prices and waste-separation rates on system costs and emissions [61]. Its findings indicate that improved waste separation can influence both economic and environmental outcomes.

For Malaysia, sensitivity analysis should ideally include different feedstock-supply scenarios, energy-price assumptions, technology-performance levels and financing arrangements. This would help investors and policymakers understand the conditions under which a WtE project remains financially viable.

### 6.8 Government Incentives and Policy Support

Government policy can influence the economic feasibility of WtE projects through financial incentives, regulatory arrangements, waste-management targets and support for renewable energy development.

The selected Malaysian review on solid waste management identifies government incentives and the growing costs of waste management as relevant considerations when evaluating alternative treatment approaches [2]. The Malaysian food-waste literature also identifies economic and institutional support as important conditions for developing food-waste-based biogas systems [32].

Potential policy mechanisms relevant to WtE development include:

- Financial incentives for eligible renewable energy projects.
- Support for research, development and technology demonstration.
- Appropriate waste-treatment fees and financing arrangements.
- Improved coordination between local authorities and private operators.
- Clear standards for emissions, digestate, ash and other treatment residues.
- Support for waste segregation and reliable feedstock collection.

However, incentives should be designed carefully. Financial support for energy recovery should not encourage unnecessary waste generation or undermine recycling and material-recovery objectives. Instead, it should support projects that demonstrate measurable improvements in waste management, energy recovery and environmental performance.

### 6.9 Comparison of Economic Evidence from Selected Studies

Table 5 summarises selected economic assessments from the uploaded reference list. Malaysian findings are separated from international comparisons to avoid treating overseas project results as established Malaysian outcomes.

Table 5. Economic assessment of selected waste-to-energy studies

| Study location | Technology or system assessed | Economic assessment method | Main findings reported | Reference |
|---|---|---|---|---|
| Malaysia and Singapore | Restaurant food-waste conversion using AD, pyrolysis and gasification | Techno-economic assessment and life-cycle analysis | AD reported ROI of 12–15% and a payback period of 5–7 years for medium-scale installations under the study assumptions | [42] |
| Malaysia | National MSW treatment configurations | Multi-objective optimisation of cost and greenhouse gas emissions | Current-scenario cost reported as RM66.66 per tonne of MSW; alternative configurations showed different cost-emissions trade-offs | [61] |
| Malaysia | MSW treatment scenarios | Life-cycle costing and eco-efficiency assessment | Scenarios incorporating increased recycling, composting and AD were assessed as more favourable than the business-as-usual scenario | [60] |
| Malaysia | Biomass supply chains and cogeneration | Literature review and optimisation-modelling assessment | Identifies economic and environmental viability, feedstock logistics and optimisation as important development considerations | [65] |
| Nigeria | AD, incineration, gasification and landfill gas recovery | LCC, LCOE, NPV, IRR and payback analysis | Most assessed systems were economically feasible in Abuja and Lagos, with an exception for landfill gas recovery in Abuja | [21] |
| Iran | Landfill gas recovery, incineration and AD | NPV, IRR and LCOE | AD was identified as the most profitable scenario in the case study, despite incineration having the highest estimated annual energy production | [26] |

| | | | | |
|---|---|---|---|---|
| Ghana | MSW incineration | NPV and LCOE | Estimated electricity costs exceeded the relevant electricity tariffs, leading the study to identify a need for government support | [19] |
| Ghana | AD, gasification, plasma gasification and pyrolysis | Fuzzy TOPSIS multi-criteria assessment | Gasification ranked first overall, followed by AD, pyrolysis and plasma gasification | [28] |
| Selected lower- and lower-middle-income countries | Incineration, AD and landfill gas recovery | Techno-economic and environmental feasibility assessment | Economic preference varied by country and technology, demonstrating the influence of local conditions | [53] |

### 6.10 Economic Barriers to WtE Commercialisation in Malaysia

Despite the potential economic benefits of WtE, several barriers may limit investment and commercial development in Malaysia.

**High initial investment.** Some WtE technologies require specialised equipment, large facilities and supporting infrastructure. This may create difficulties for smaller operators and local authorities with limited financial resources.

**Uncertain feedstock supply.** Facilities require a reliable supply of waste with suitable characteristics. Inconsistent collection, inadequate source separation and contamination may reduce plant utilisation and increase operating costs.

**Uncertain revenue streams.** The financial performance of WtE facilities may depend on electricity prices, waste-treatment fees and markets for recovered products. Changes in these factors can affect project cash flows.

**Technology and operational risks.** Some technologies require specialised expertise, maintenance and process monitoring. Limited technical capacity may increase operational costs or reduce plant reliability.

**Long investment recovery periods.** Large infrastructure projects may require long periods to recover initial investment. This can discourage private investors, particularly when policy or revenue arrangements are uncertain.

**Coordination among stakeholders.** WtE projects involve waste generators, collection operators, local authorities, technology providers, energy companies and regulators. Poor coordination may affect project development and operation.

These barriers are consistent with the Malaysian literature on food-waste biogas and oil palm waste commercialisation, which identifies economic, institutional, technical and stakeholder-related constraints [32, 36].

## 6. ENVIRONMENTAL IMPACTS AND SUSTAINABILITY ASSESSMENT

The environmental performance of waste-to-energy (WtE) systems is an important factor in determining their suitability for Malaysia's waste management and renewable energy strategies. Although WtE technologies can reduce the volume of waste sent to landfills while recovering useful energy, their environmental benefits depend on feedstock composition, conversion efficiency, emissions-control systems, energy requirements and

the management of residual materials. Therefore, WtE should be evaluated through a life-cycle perspective rather than solely by the amount of electricity or heat produced.

In Malaysia, this assessment is particularly relevant because municipal solid waste (MSW) contains a substantial organic fraction, while agricultural and industrial activities generate biomass residues that may be suitable for energy recovery. The environmental performance of these systems must also be considered alongside waste prevention, recycling, resource recovery and the country's wider circular economy objectives.

### 7.1 Greenhouse Gas Emissions and Climate Change Mitigation

One of the principal environmental benefits associated with WtE is its potential to reduce greenhouse gas (GHG) emissions. This benefit can arise from diverting biodegradable waste from landfills, recovering energy that would otherwise be supplied by conventional energy sources and improving the management of organic residues.

Landfill disposal of food waste and other biodegradable materials can generate methane under anaerobic conditions. Methane has a substantially greater warming effect than carbon dioxide over a 100-year assessment period. Consequently, diverting suitable organic waste to anaerobic digestion (AD) or other controlled treatment processes may reduce emissions associated with uncontrolled landfill decomposition.

AD offers an opportunity to capture biogas from food waste, sewage sludge and palm oil mill effluent (POME). The biogas can subsequently be used for electricity and heat generation or upgraded for other energy applications. However, the climate benefits depend on effective gas collection and utilisation. Methane leakage from digesters, storage systems and gas-handling equipment can reduce the overall environmental advantage.

Thermal WtE technologies, including incineration, gasification and pyrolysis, may also contribute to emissions reduction when they recover useful energy and displace fossil-fuel-based electricity or heat. Nevertheless, their environmental performance is influenced by the composition of the waste. Materials containing fossil-derived carbon, particularly certain plastics, can generate fossil carbon dioxide during thermal treatment.

Malaysian waste-management scenario assessments demonstrate that changes in waste-treatment arrangements can influence both economic costs and GHG emissions. One optimisation study reported that a least-cost scenario could reduce costs and emissions by approximately 26% compared with its baseline scenario, while a least-emissions scenario achieved a larger emissions reduction but involved a higher cost [61]. These findings are based on modelled scenarios and should not be interpreted as measured reductions achieved across Malaysia.

### 7.2 Air Emissions from Thermal Conversion Technologies

Air emissions are an important consideration in the environmental assessment of incineration, gasification and pyrolysis. Thermal conversion processes may release pollutants if waste composition, combustion conditions and emissions-control systems are not properly managed.

Potential air pollutants include:

- Carbon dioxide ($CO_2$), arising from the oxidation of carbon-containing materials.
- Nitrogen oxides ($NO_x$), which may form during high-temperature combustion.
- Sulphur oxides ($SO_x$), depending on the sulphur content of the feedstock.
- Particulate matter, including fine particles and fly ash.
- Carbon monoxide (CO), which may indicate incomplete combustion.
- Acid gases and trace pollutants, depending on the waste composition and process conditions.

Modern incineration facilities generally require integrated emissions-control systems to manage particulate matter, acid gases and other pollutants. Gasification and pyrolysis also require appropriate gas cleaning before the product gas or syngas is used for energy generation.

For Malaysia, the environmental suitability of thermal WtE facilities should therefore be assessed through technology-specific emissions data, continuous monitoring arrangements and compliance with applicable environmental requirements. The selection of a thermal technology should not be based exclusively on its electricity-generation potential.

### 7.3 Wastewater, Leachate and Water Quality

Water pollution is another important consideration in WtE development. Waste treatment and energy convers-

ion may generate wastewater through feedstock preparation, equipment cleaning, process operations and the handling of organic residues.

For organic waste treatment, wastewater may contain high concentrations of organic matter, suspended solids, nutrients and other contaminants. POME is particularly relevant in Malaysia because of its generation by the palm oil industry. Anaerobic treatment of POME can support biogas recovery while reducing its organic pollution load, provided that the treatment system is appropriately designed and operated.

Landfill diversion can also reduce the long-term generation of leachate from biodegradable waste. However, this benefit depends on the remaining waste composition and the effectiveness of landfill management.

Important environmental controls include:

1. Proper collection and treatment of process wastewater.
2. Prevention of uncontrolled discharge into rivers and drainage systems.
3. Monitoring of wastewater quality before discharge or reuse.
4. Appropriate management of digestate and other liquid residues.
5. Protection of groundwater and surface-water resources.

The environmental assessment of Malaysian WtE projects should include water consumption, wastewater generation and treatment requirements, especially where facilities are located near agricultural areas, rivers or sensitive ecosystems.

### 7.4 Management of Ash and Other Solid Residues

WtE processes do not eliminate all waste. Instead, they convert part of the original material into energy while generating residual materials that require further management.

Incineration produces bottom ash and fly ash. Bottom ash generally consists of non-combustible materials and mineral residues, while fly ash may contain higher concentrations of certain contaminants and requires careful handling. Research examining ash characteristics and potential reuse applications is relevant to determining whether selected residues can be recovered as secondary materials [58].

One potential application is the incorporation of suitably treated ash into construction materials. A Malaysian study investigated the reuse of ash in cement mortar, demonstrating the relevance of evaluating waste-derived materials for potential construction applications [66]. However, reuse should only be considered where material properties and environmental safety requirements are satisfied.

AD produces digestate, which may contain nutrients and organic matter that could support agricultural applications. Its suitability depends on feedstock quality, contaminant levels and treatment requirements. Digestate derived from mixed or contaminated waste should not automatically be regarded as a safe fertiliser.

Other conversion processes also generate solid residues. Gasification may produce char, slag or ash, while pyrolysis produces char and other residual fractions. Their environmental implications depend on the feedstock and operating conditions.

Effective residue management should therefore follow a hierarchy:

- Prevent contamination of incoming waste.
- Recover reusable and recyclable materials where technically feasible.
- Assess suitable residues for safe material recovery.
- Treat or stabilise residues where necessary.
- Dispose of unsuitable materials through properly controlled facilities.

### 7.5 Life-Cycle Assessment of WtE Systems

Life-cycle assessment (LCA) provides a systematic approach for evaluating the environmental impacts of WtE systems across different stages of their operation. Instead of considering only emissions from the conversion facility, LCA examines the environmental burdens associated with the entire waste-to-energy chain.

A comprehensive assessment may include:

1. Waste generation and collection.
2. Transportation to treatment facilities.
3. Sorting, separation and feedstock preparation.
4. Energy and material inputs during conversion.
5. Electricity, heat or fuel production.
6. Treatment and disposal of residual materials.
7. Avoided impacts from alternative waste-management and energy-production systems.

The selection of a suitable functional unit is essential. Examples include impacts per tonne of waste treated, per megawatt-hour of electricity generated or per unit of useful energy delivered.

Malaysian research has examined environmental and economic performance through life-cycle and eco-efficiency approaches [42], [60]. These studies highlight the importance of considering both environmental impacts and the resources required to achieve energy recovery.

For example, a system that generates a high quantity of electricity may not necessarily have the lowest environmental impact if it requires substantial transport, energy-intensive processing or extensive pollution-control inputs. Similarly, a technology that treats wet organic waste may perform differently from one treating dry agricultural residues.

Comparisons between WtE technologies should therefore use consistent system boundaries, functional units and assumptions. This is particularly important when comparing Malaysian studies with international research because waste composition, electricity generation mixes, transport distances and regulatory conditions may differ.

### 7.6 Environmental Performance of Anaerobic Digestion

AD is particularly relevant to Malaysia because food waste, sewage sludge and POME contain biodegradable organic matter that can be converted into biogas.

Its potential environmental benefits include:

- Recovery of methane for useful energy production.
- Reduction of biodegradable waste requiring landfill disposal.
- Potential reduction in organic pollution from wastewater streams.
- Production of digestate that may be suitable for further nutrient recovery.
- Support for renewable electricity and heat generation.

However, AD also presents environmental challenges. Methane leakage can reduce climate benefits, while poorly managed digestate can contribute to odour, nutrient runoff and water pollution. Feedstock contamination may also affect digestate quality and limit its potential reuse.

The environmental performance of AD facilities therefore depends on reliable feedstock separation, appropriate reactor operation, effective biogas collection and suitable digestate management.

For Malaysian applications, integrating food-waste collection with AD facilities could provide environmental benefits, particularly in locations with a consistent supply of organic waste. Nevertheless, the feasibility of each project should be assessed according to local waste availability, transport requirements and the intended use of biogas and digestate.

### 7.7 Environmental Performance of Oil Palm Biomass Recovery

Oil palm processing generates several biomass residues, including empty fruit bunches, palm kernel shells, mesocarp fibres and POME. These materials provide opportunities for energy recovery and resource utilisation.

The use of agricultural residues for energy can reduce dependence on fossil fuels and improve the utilisation of materials generated by existing industrial activities. In particular, POME treatment through AD can support biogas recovery, while solid residues may be used in combustion, gasification or other conversion processes.

A Sarawak-based integrated biomass assessment identified POME biogas as a promising option for electricity generation and reported favourable GHG performance for wood pellets compared with coal within the study's assessment framework [13]. Such findings indicate the potential contribution of biomass-based energy recovery, although results should be interpreted within the geographical and methodological boundaries of the individual study.

Sustainable biomass utilisation requires attention to feedstock availability, competing uses, transportation, land-use implications and the management of processing residues. Energy recovery should prioritise genuine waste and by-product streams rather than encourage unsustainable extraction of biomass resources.

### 7.8 Circular Economy and Resource Recovery

The environmental sustainability of WtE should be considered within the broader principles of the circular economy. The circular economy seeks to retain the value of materials for as long as possible through waste prevention, reuse, recycling and resource recovery.

WtE can contribute to this approach by recovering energy from residual waste that cannot reasonably be reused or recycled. However, energy recovery should not replace opportunities for material recovery, particularly for recyclable materials such as metals, glass, paper and suitable plastics.

An integrated waste-management hierarchy can be represented as follows:

1. Waste prevention: Reduce unnecessary material consumption and waste generation.
2. Reuse: Extend the useful life of products and materials.
3. Recycling: Recover materials for use in new products.
4. Biological treatment: Convert suitable organic waste into biogas and recoverable nutrients.

5. Energy recovery: Convert appropriate residual waste into useful energy.
6. Final disposal: Dispose of remaining residues through controlled facilities.

This hierarchy is important for Malaysia because the organic fraction of MSW creates opportunities for biological treatment, while recyclable materials may be better managed through material recovery systems. A well-designed WtE strategy should therefore complement waste separation and recycling rather than compete with them.

### 7.9 Social and Environmental Sustainability Considerations

Environmental sustainability is closely connected to social acceptance and the quality of local waste-management services. WtE facilities may raise concerns among nearby communities regarding air pollution, odour, traffic, noise and potential effects on public health.

Public acceptance can be improved through transparent communication, accessible environmental monitoring information and meaningful community engagement. Project developers should also consider the location of facilities, transportation routes and the distribution of environmental benefits and burdens.

For Malaysia, institutional coordination is important because WtE projects may involve local authorities, waste-management operators, energy providers, industrial organisations and environmental regulators. Clear responsibilities and transparent monitoring arrangements can strengthen public confidence.

Social sustainability should also include the effects of waste-management changes on existing recycling activities and informal recovery workers. The transition towards more advanced treatment systems should support appropriate participation and avoid undermining established material-recovery activities.

### 7.10 Comparative Environmental Assessment of WtE Technologies

Table 6 summarises the main environmental opportunities and considerations associated with the principal WtE technologies discussed in this review.

Table 6. Environmental opportunities and considerations of major WtE technologies

| Technology | Potential environmental benefits | Main environmental considerations | References |
|---|---|---|---|
| Incineration | Reduces waste volume and recovers energy | Air emissions, ash generation and fossil-derived $CO_2$ | [11], [18], [19], [54] |
| Anaerobic digestion | Captures biogas and treats biodegradable waste | Methane leakage, digestate quality and wastewater management | [32], [40], [42], [54], [62] |
| Landfill gas recovery | Captures methane that may otherwise escape | Incomplete gas collection and continuing emissions from landfills | [43] |
| Gasification | Converts suitable feedstock into combustible gas | Syngas cleaning, air emissions and solid residues | [40], [51], [54] |
| Pyrolysis | Produces char, liquid products and gas | Process energy demand and management of by-products | [40], [42], [54] |
| Torrefaction | Improves biomass fuel characteristics and may support more efficient biomass utilisation | Energy consumption and emissions during processing | [52] |
| Hydrothermal carbonisation | Treats wet biomass and produces hydrochar | Process-water treatment and energy requirements | [40], [54] |

### 7.11 Key Environmental Sustainability Requirements for Malaysia

Several requirements should guide the development of environmentally sustainable WtE systems in Malaysia:

- Reliable waste characterisation: Determine moisture content, organic composition, calorific value and contamination levels before selecting a conversion technology.
- Source separation: Improve separation of organic, recyclable and residual waste to enhance treatment efficiency.
- Emissions management: Apply appropriate pollution-control systems and monitoring arrangements to thermal facilities.
- Methane control: Minimise leakage throughout biogas collection, storage and utilisation systems.
- Residual-material management: Establish safe treatment, recovery and disposal routes for ash, digestate and other by-products.
- Life-cycle evaluation: Assess environmental impacts across collection, processing, energy recovery and final disposal.
- Circular economy integration: Ensure that energy recovery complements waste prevention, reuse and recycling.
- Transparent monitoring: Provide clear environmental performance information to regulators and affected communities.

These requirements can help ensure that WtE development contributes to environmental improvement rather than transferring pollution from landfills to treatment facilities.

## 7. POLICIES, REGULATIONS AND INSTITUTIONAL FRAMEWORK

The successful implementation of waste-to-energy (WtE) technologies in Malaysia depends not only on technical and economic feasibility but also on an effective policy, regulatory and institutional framework. Waste management involves multiple stakeholders, including federal and state governments, local authorities, environmental regulators, energy-sector agencies, waste-management operators and private investors. Their coordination is important for ensuring that waste is collected, treated and converted into energy in a manner that is environmentally responsible and economically sustainable.

Malaysia's WtE development must also be considered within the broader objectives of sustainable waste management, renewable energy development and the circular economy. Policies that encourage waste reduction, recycling, organic waste treatment and renewable energy generation can create favourable conditions for WtE projects. However, clear regulatory responsibilities, consistent implementation and appropriate financial mechanisms are necessary to translate these objectives into operational projects.

### 8.1 National Solid Waste Management Policy and Strategic Direction

Malaysia's solid waste management framework provides the foundation for managing municipal waste and improving waste-treatment practices. The national policy direction emphasises more sustainable approaches to waste management, including waste minimisation, recycling, recovery and improved disposal practices.

For WtE development, this policy direction is relevant because the composition and quantity of waste determine the suitability of different conversion technologies. Organic waste may be directed towards anaerobic digestion (AD), while suitable residual waste may be considered for thermal treatment. Recyclable materials should, where practical, be recovered before the remaining waste is considered for energy recovery.

The reviewed Malaysian literature identifies policy implementation, waste-management practices and technology adoption as important factors influencing the development of WtE systems [8], [10], [54]. These

studies suggest that technology deployment should be integrated with improvements in waste collection, separation and institutional management rather than treated as an isolated energy-generation activity.

### 8.2 Solid Waste Management and Public Cleansing Management Act 2007 (Act 672)

The Solid Waste and Public Cleansing Management Act 2007 (Act 672) is an important part of Malaysia's legislative framework for solid waste management and public cleansing. It provides a legal basis for the regulation and administration of specified solid waste management activities in areas where the Act applies.

The relevance of Act 672 to WtE includes the organisation of waste collection, transportation, treatment and disposal activities. These functions influence the availability and quality of feedstock supplied to WtE facilities. Effective implementation can support more systematic waste-management arrangements, although the application of the Act must be considered alongside the different administrative arrangements among Malaysian states.

For WtE projects, regulatory clarity is important in determining responsibilities for waste supply, facility operation, treatment standards and residual disposal. Developers and local authorities must therefore establish the applicable legal and administrative requirements before project implementation.

### 8.3 Environmental Quality Act 1974 and Pollution Control

The Environmental Quality Act 1974 provides the principal legislative framework for controlling pollution and

protecting environmental quality in Malaysia. Its relevance to WtE facilities includes the management of air emissions, wastewater, scheduled wastes and other potential environmental impacts arising from waste-treatment and energy-conversion activities.

Different WtE technologies create different environmental risks. Incineration and other thermal processes require appropriate control of air pollutants and solid residues, while AD facilities require suitable management of wastewater, digestate and biogas. Facilities must therefore be assessed according to their specific processes and environmental risks.

Environmental assessment and pollution-control requirements are important for ensuring that waste treatment does not transfer environmental burdens from landfills to the surrounding air, water or land. For this reason, environmental compliance should be considered during project planning, facility design, construction and operation.

### 8.4 Renewable Energy Policy and Energy-Sector Support

Malaysia's renewable energy policy direction provides an important context for WtE because energy recovered from suitable waste streams can contribute to renewable energy supply. Biomass, biogas and selected waste-derived energy pathways may support electricity generation and reduce reliance on conventional energy sources.

The development of WtE projects is influenced by the mechanisms available for connecting renewable electricity generation to the grid, securing energy offtake and obtaining appropriate approvals. These arrangements are particularly important for projects requiring substantial initial investment.

The reviewed literature identifies economic incentives, investment conditions and technology adoption as factors influencing the commercial development of WtE in Malaysia [10], [20], [54]. However, the specific eligibility, tariff arrangements and approval requirements applicable to a proposed project must be checked against current regulatory provisions and programme guidelines.

### 8.5 Renewable Energy Incentives and Financial Mechanisms

Financial incentives are important for encouraging investment in WtE facilities because these projects may involve high capital expenditure, specialised equipment and long development periods. The availability of predictable revenue and appropriate financing arrangements can influence whether a proposed facility progresses from feasibility assessment to commercial operation.

Potential financial support mechanisms include:

- Renewable electricity support: Arrangements that allow eligible biogas or biomass electricity generators to sell electricity to the grid.
- Investment incentives: Tax-related incentives or investment support for qualifying renewable energy and waste-treatment projects.
- Public–private partnerships (PPPs): Cooperation between government bodies and private operators to share investment, operational responsibilities and project risks.
- Green financing: Financing arrangements that support projects with demonstrable environmental and sustainability benefits.
- Waste-treatment service payments: Payments for treating and managing waste, which may provide an additional revenue stream alongside energy sales.

For Malaysian WtE projects, financial support should reflect the differences between technologies. For example, AD facilities may generate revenue from biogas utilisation and waste-treatment services, whereas thermal facilities may depend more heavily on electricity sales and the scale of waste supplied.

The economic studies included in the reviewed literature indicate that project viability is sensitive to capital

costs, operating costs, feedstock availability and energy revenue assumptions [18], [19], [42], [53]. Consequently, incentives should be designed to support environmentally appropriate projects without creating unnecessary dependence on public subsidies.

### 8.6 Institutional Roles and Responsibilities

WtE development requires coordination among institutions responsible for waste management, environmental protection, energy regulation and investment. Each institution has a different role in ensuring that projects comply with relevant requirements and contribute to national development objectives.

The main institutional responsibilities can be summarised as follows.

Federal government: Provides national policy direction, legislative frameworks and strategic priorities for solid waste management, renewable energy and environmental protection.

State governments: Play an important role in land matters, local development decisions and waste-management arrangements, particularly where state-level administrative responsibilities apply.

Local authorities: Support waste collection, local waste-management planning, public cleansing and coordination with waste-management service providers.

Environmental regulators: Oversee environmental assessment and pollution-control requirements, including relevant emissions, wastewater and residual-waste management obligations.

Energy-sector institutions: Oversee relevant electricity-sector requirements, renewable energy arrangements and the technical or regulatory conditions for connecting eligible generation facilities to the electricity system.

Private-sector operators: Develop, finance, construct and operate WtE facilities, while ensuring compliance with applicable technical, environmental and contractual requirements.

The reviewed literature highlights institutional coordination and technology adoption as important considerations in improving Malaysian MSW management and WtE implementation [8], [10]. A coordinated approach is therefore necessary to reduce administrative uncertainty and improve the effectiveness of project delivery.

### 8.7 Waste Segregation and Feedstock Management Policies

Waste segregation is a fundamental requirement for improving the performance of WtE facilities. The quality and consistency of feedstock directly influence conversion efficiency, operating costs, environmental performance and the quality of recovered products.

In Malaysia, mixed municipal waste can contain food waste, garden waste, paper, plastics, metals, glass and other materials. These materials have different physical and chemical characteristics, meaning that a single conversion technology may not be appropriate for the entire waste stream.

Policy measures should therefore encourage separation of waste at source and improve the organisation of collection and treatment systems. Important measures include:

1. Strengthening household and commercial waste-separation practices.
2. Improving separate collection of food waste and other biodegradable materials.
3. Expanding material recovery and recycling before residual waste treatment.
4. Establishing appropriate quality requirements for feedstock supplied to WtE facilities.
5. Improving coordination between waste generators, collection operators and treatment facilities.

For AD projects, separating biodegradable waste from plastics, metals and other contaminants can improve feedstock quality and digestate management. For thermal facilities, waste characterisation and the removal of unsuitable materials can improve process consistency.

The Malaysian literature on food-waste management and biogas implementation identifies waste governance, collection arrangements and feedstock-related barriers as important considerations [8], [32], [54]. These findings reinforce the need to treat segregation and feedstock management as essential parts of WtE policy rather than secondary operational matters.

### 8.8 State-Level Differences and Regional Implementation

Malaysia's administrative structure creates differences in waste-management arrangements between states and regions. These differences influence the availability of waste, institutional responsibilities, infrastructure development and the suitability of WtE projects.

A uniform national technology strategy may therefore be less effective than an approach that considers regional waste characteristics and local institutional conditions.

For example, highly urbanised areas may generate relatively concentrated quantities of MSW and commercial food waste. These locations may provide opportunities for centralised treatment facilities, subject to suitable land availability, transportation arrangements and community acceptance.

In contrast, agricultural and industrial regions may have greater access to specific biomass residues. In oil palm-producing areas, POME and other processing residues may provide opportunities for biogas production, cogeneration and other biomass-conversion pathways.

The reviewed literature on Sarawak's biomass resources illustrates the potential for regionally integrated energy recovery, particularly through POME biogas and the utilisation of other biomass resources [13]. Malaysian oil palm biomass studies also identify differences in the maturity and implementation status of individual conversion technologies [36], [67].

Regional planning should therefore consider:

- Local waste generation and composition.
- Existing waste-treatment and energy infrastructure.
- Availability of suitable land and transport connections.
- Proximity to electricity users and potential energy offtakers.
- Regional industrial and agricultural activities.
- State-level administrative and regulatory arrangements.

This approach can help match WtE technologies to the waste resources and development conditions of individual regions.

### 8.9 Public Participation, Awareness and Social Governance

Public participation is important because WtE facilities are often located near residential, commercial or industrial areas. Communities may have concerns about air emissions, odour, traffic, noise, wastewater and the long-term environmental effects of treatment facilities.

Policy and institutional arrangements should therefore provide opportunities for meaningful public engagement throughout project development. Public participation should not be limited to communication after a facility has already been designed.

Important measures include:

- Providing accessible information about the proposed technology and its environmental performance.
- Explaining the purpose of emissions-control and wastewater-treatment systems.
- Communicating monitoring results in a transparent manner.
- Establishing channels for public feedback and complaints.
- Consulting affected communities during facility planning.
- Supporting public education on waste separation and responsible disposal.

The Malaysian literature on food-waste governance and technology adoption indicates that institutional and behavioural factors influence the implementation of improved waste-management systems [8], [10]. Public awareness and participation should therefore be treated as part of the overall WtE implementation framework.

### 8.10 Policy Challenges and Regulatory Gaps

Despite the potential of WtE technologies, several policy and institutional challenges may limit their wider adoption in Malaysia.

Fragmented institutional responsibilities: Waste management, environmental regulation and energy development involve different institutions. Coordination is required to ensure that project approvals, waste supply and energy arrangements are aligned.

Inconsistent feedstock supply: WtE facilities require a relatively stable supply of suitable waste. Weak source separation and changing waste composition may affect facility performance and operating costs.

Uncertainty in project financing: High capital costs and uncertain revenue streams can discourage investment, particularly for projects that depend on long-term waste supply and electricity offtake agreements.

Differences in regional implementation: State-level administrative arrangements and variations in infrastructure can create different conditions for WtE project development.

Environmental compliance requirements: Facilities must manage emissions, wastewater and residual materials appropriately. These requirements can increase investment and operating costs but are essential for environmental protection.

Public acceptance: Community concerns may delay projects or reduce support if environmental risks and monitoring arrangements are not communicated clearly.

The reviewed studies on technology adoption, economic feasibility and food-waste management indicate that technical suitability alone is insufficient to guarantee successful implementation [10], [18], [32], [42], [54]. Policy development must address the interaction between technology, finance, institutional capacity and public participation.

### 8.11 Proposed Policy and Institutional Measures

To strengthen WtE implementation in Malaysia, several policy and institutional measures can be considered.

1. Improve institutional coordination: Establish clearer coordination between waste-management authorities, environmental regulators, energy-sector institutions and local authorities.
2. Strengthen waste segregation: Improve source separation and collection systems to provide cleaner and more consistent feedstock for biological and thermal treatment.
3. Develop region-specific WtE plans: Match technologies to local waste resources, infrastructure, energy demand and administrative conditions.
4. Improve project bankability: Encourage appropriate financing mechanisms, transparent waste-supply arrangements and reliable energy-offtake structures.
5. Strengthen environmental monitoring: Ensure that facilities have appropriate monitoring, reporting and residual-management systems throughout their operational life.
6. Support technology development: Encourage research, pilot-scale demonstration and commercial validation of technologies suited to Malaysian feedstocks.
7. Increase public participation: Improve awareness, consultation and access to environmental information to strengthen community confidence.
8. Integrate WtE with circular economy objectives: Ensure that energy recovery complements waste prevention, reuse, recycling and biological resource recovery.

These measures are consistent with the challenges identified in the reviewed Malaysian literature concerning waste governance, technology adoption, economic feasibility and resource utilisation [8], [10], [32], [36], [54].

### 8.12 Summary of Policy and Institutional Requirements

Table 7 summarises the main policy areas relevant to WtE development in Malaysia and their implications for implementation.

Table 7. Policy and institutional framework for WtE development in Malaysia

| Policy or institutional area | Main purpose | Relevance to WtE development | References |
|---|---|---|---|
| National solid waste management policy | Establish strategic direction for waste management | Supports waste reduction, recycling, treatment and | [8], [10], [54] |

| | | | |
|---|---|---|---|
| | | recovery | |
| Solid Waste and Public Cleansing Management Act 2007 (Act 672) | Provide a legal framework for specified solid waste management and public cleansing activities | Influences waste collection, transportation, treatment and disposal arrangements | [8], [10] |
| Environmental Quality Act 1974 | Control pollution and protect environmental quality | Provides the environmental regulatory context for emissions, wastewater and residual management | [13], [60], [66] |
| Renewable energy policy and support mechanisms | Encourage renewable energy development | Provides a policy context for electricity generation from eligible biomass and biogas resources | [13], [36], [54] |
| Investment and financial incentives | Improve project investment conditions | May support capital-intensive WtE facilities and commercialisation | [18], [19], [42], [53] |
| Waste segregation and feedstock management | Improve the quality of collected waste | Supports more reliable AD and thermal conversion performance | [8], [32], [54] |
| State and local authority coordination | Align regional waste-management responsibilities | Supports suitable facility planning and consistent waste supply | [8], [10], [13] |
| Public participation and awareness | Improve public understanding and acceptance | Supports waste separation and community confidence in WtE projects | [8], [10] |
| Research and technology development | Improve technical performance and local suitability | Supports pilot projects, technology validation and commercialisation | [20], [36], [51], [54] |

# 8. CHALLENGES AND BARRIERS TO WASTE-TO-ENERGY IMPLEMENTATION IN MALAYSIA

## 9.1 Introduction

Although Malaysia has considerable potential to develop waste-to-energy (WtE) systems, the implementation of these technologies remains constrained by technical, economic, environmental, institutional and social challenges. The availability of waste materials does not automatically translate into a reliable energy resource. Successful WtE development requires consistent feedstock supply, appropriate conversion technologies, adequate infrastructure, sustainable financing, effective regulation and public acceptance.

Malaysia's waste management system continues to rely substantially on landfilling, while the adoption of alternative treatment and energy recovery technologies varies across regions and waste sectors. Studies on Malaysian municipal solid waste (MSW), food waste and oil palm biomass identify several barriers that affect the transition towards more integrated waste management and energy recovery systems [8], [10], [32], [36], [54], [67].

This section discusses the principal barriers to WtE implementation in Malaysia and identifies measures that could support wider adoption.

### 9.2 Inconsistent Waste Feedstock Quality and Availability

One of the main challenges facing WtE development is the inconsistent quantity and quality of available waste feedstock. Although Malaysia generates substantial amounts of municipal and organic waste, the composition, moisture content and energy characteristics vary according to location, season, consumption patterns and waste collection practices.

Mixed municipal waste may contain food residues, plastics, paper, textiles, metals, glass and other materials. When these materials are collected together, their heterogeneous composition makes treatment more difficult and may reduce conversion efficiency. High moisture content in organic waste can also affect the suitability of certain thermal conversion technologies.

Food waste presents additional challenges because its composition varies according to its source. Household food waste, restaurant waste, market residues and food-processing waste may have different organic compositions and contamination levels. These variations influence anaerobic digestion (AD) performance and the quality of the resulting biogas [32], [42], [54].

Oil palm biomass is another important potential feedstock. However, its availability depends on plantation activities, processing locations, transportation arrangements and competing uses. Although palm biomass offers opportunities for combustion, gasification, pyrolysis and other conversion processes, the management of feedstock supply remains important for consistent plant operation [36], [65], [67].

### 9.3 Inadequate Waste Segregation and Collection Systems

Effective waste segregation is essential for improving the quality of materials entering WtE facilities. However, inadequate separation at source can result in contamination between organic and non-organic materials.

For example, food waste mixed with plastics, metals and other materials may require additional sorting and preprocessing before it can be used in anaerobic digestion. Similarly, recyclable materials mixed with residual waste may be unnecessarily directed towards thermal treatment instead of material recovery.

Collection and transportation arrangements also influence feedstock availability. Waste generated across different residential, commercial and industrial locations may require coordinated collection systems to ensure a consistent supply to treatment facilities.

Research on Malaysian waste management highlights the importance of improving public participation, source separation and waste management practices to support more effective technology adoption [8], [10], [54].

### 9.4 High Capital and Operating Costs

The financial requirements of WtE facilities represent another significant barrier. Technologies such as incineration, gasification and advanced thermal treatment generally require substantial investment in equipme-

nt, construction, pollution-control systems and supporting infrastructure.

In addition to initial capital expenditure, operating costs may include:

- Waste collection and transportation.
- Feedstock sorting and preprocessing.
- Energy consumption during plant operation.
- Equipment maintenance and replacement.
- Skilled personnel and technical supervision.
- Emission monitoring and environmental compliance.

- Residue treatment and disposal.

Smaller facilities may experience difficulties achieving economies of scale, while larger facilities require sufficient waste supply and long-term financial commitments.

Economic studies of WtE systems indicate that financial performance depends on factors such as plant capacity, feedstock characteristics, technology selection, energy prices and operating costs [18], [19], [42], [53]. Therefore, the economic feasibility of a project should be assessed under realistic local operating conditions rather than relying solely on theoretical energy-generation potential.

### 9.5 Technological and Operational Limitations

Different WtE technologies have different technical requirements, operating conditions and levels of commercial maturity. Selecting an unsuitable technology may result in inefficient operation, higher maintenance costs and reduced energy recovery.

For instance, incineration requires appropriate waste characteristics and effective emission-control systems. Gasification and pyrolysis require controlled operating conditions and suitable feedstock preparation. Anaerobic digestion depends on biological process stability, feedstock composition and appropriate operating conditions.

Malaysia's oil palm biomass research also indicates differences in the maturity of available conversion technologies. Combustion and pyrolysis have been reported as more commercially established in the reviewed context, while gasification and anaerobic digestion have been associated with pilot-scale development in the relevant studies [36].

Operational limitations may include:

1. Insufficient technical expertise.
2. Equipment reliability and maintenance difficulties.
3. Variations in feedstock quality.
4. Process instability.
5. Limited local experience with advanced conversion systems.
6. Difficulty maintaining consistent energy output.

These limitations demonstrate the importance of technical assessment, demonstration projects and local capacity development before large-scale implementation.

### 9.6 Environmental Compliance and Pollution Control

WtE technologies must be implemented with appropriate environmental safeguards. Although energy recovery can reduce dependence on landfill disposal, poorly designed or operated facilities may create environmental problems.

Thermal treatment technologies require suitable air-pollution control systems and continuous attention to em-

ission performance. Residues such as bottom ash and fly ash must also be managed appropriately. Wastewater, leachate and other process-related discharges require suitable treatment.

Anaerobic digestion can reduce the amount of biodegradable waste requiring disposal, but it also requires appropriate management of digestate, wastewater and potential gas leakage.

Life-cycle assessment (LCA) is therefore important when comparing WtE technologies. Environmental performance should be evaluated across the entire system, including waste collection, transportation, pretreatment, conversion, energy generation and residue management. Malaysian environmental assessment

studies provide a basis for considering the wider environmental implications of waste management and resource recovery options [54], [60].

### 9.7 Public Acceptance and Community Concerns

Public acceptance is an important factor influencing the development of WtE facilities. Communities may express concerns regarding air emissions, odour, noise, traffic, environmental safety and possible effects on surrounding areas.

These concerns can become more significant when project planning and consultation processes are insufficient. Limited access to reliable information may also create uncertainty about the environmental performance and operational safety of proposed facilities.

Public participation should therefore be included throughout the project development process. Authorities and project developers should provide clear information about:

- The type and quantity of waste to be treated.
- The technology selected and its operating requirements.
- Pollution-control and monitoring arrangements.
- Residue handling and disposal procedures.
- Environmental assessment findings.
- Community consultation and complaint mechanisms.

Public awareness and stakeholder engagement are particularly important for improving waste segregation and encouraging participation in sustainable waste management programmes [8], [54].

### 9.8 Policy, Regulatory and Institutional Challenges

WtE development involves several areas of governance, including solid waste management, environmental protection, renewable energy and local planning. Coordination between relevant authorities is necessary to ensure that projects comply with applicable requirements and receive appropriate institutional support.

Differences in state-level waste management arrangements may also influence project implementation. Regulatory responsibilities, waste collection systems, land availability and local infrastructure can vary between regions.

Policy uncertainty may affect investment decisions, particularly when developers are unable to determine the long-term arrangements for feedstock supply, electricity sales, project approvals and environmental compliance.

Research on Malaysian waste management and technology adoption highlights the importance of institutional coordination and supportive policy arrangements in encouraging wider implementation of alternative waste treatment technologies [10], [54].

### 9.9 Competition for Waste Resources and Circular Economy Priorities

Waste materials may have alternative uses that compete with energy recovery. For example, paper, plastics,

metals and other recyclable materials may be more appropriately directed towards material recycling. Organic waste may also be used for composting, animal feed where suitable and permitted, or other forms of resource recovery.

Similarly, oil palm residues may already be used in existing industrial processes, including energy generation and agricultural applications. Expanding WtE facilities without considering these competing uses could create feedstock supply difficulties or undermine higher-value resource recovery options [36], [65], [67].

WtE development should therefore follow the waste hierarchy and circular economy principles. Energy recovery should generally focus on suitable residual materials that cannot reasonably be prevented, reused or recycled.

### 9.10 Limited Commercialisation and Investment Confidence

The commercialisation of WtE technologies requires more than successful laboratory experiments or pilot-scale demonstrations. Projects must demonstrate reliable operation, stable feedstock supply, acceptable environmental performance and sustainable financial returns.

Investors may be reluctant to support projects where the availability of waste feedstock, electricity revenue, operating costs or regulatory arrangements remain uncertain.

Comparative techno-economic studies provide useful information on the potential performance of different conversion technologies. However, results from international projects cannot be transferred directly to Malaysia because local waste characteristics, infrastructure, labour costs, energy prices and institutional conditions may differ [42], [53].

A stronger evidence base from Malaysian demonstration and commercial facilities would help reduce uncertainty and improve investment confidence.

### 9.11 Regional Infrastructure and Technical Capacity Gaps

The suitability of WtE technologies can differ between urban, rural and industrial areas. Urban locations may generate larger quantities of municipal waste, while agricultural and industrial regions may provide more concentrated biomass resources.

However, not all areas have the infrastructure required to support advanced WtE facilities. Limitations may include insufficient transportation networks, restricted access to suitable sites, inadequate waste collection coverage and limited availability of technical personnel.

In regions with dispersed waste sources, transportation costs may reduce the economic attractiveness of centralised treatment facilities. Smaller decentralised systems may be more appropriate in certain circumstances, particularly for organic waste generated by agricultural or food-processing activities.

The selection between centralised and decentralised systems should therefore consider regional feedstock availability, infrastructure, energy demand and operational capacity.

### 9.12 Summary of Major Challenges and Potential Solutions

Table 8. Major challenges affecting WtE implementation in Malaysia and potential improvement measures

| Challenge | Main implications | Potential improvement measures | Relevant references |
|---|---|---|---|
| Inconsistent feedstock quality | Unstable conversion performance and energy output | Improve waste characterisation, segregation and feedstock preparation | [32], [36], [54], [67] |
| Inadequate waste segregation | Contamination and higher preprocessing requirements | Strengthen source separation and collection systems | [8], [10], [54] |
| High capital and | Financial uncertainty and | Conduct realistic techno-economic | [18], [19], |

| | | | |
|---|---|---|---|
| operating costs | investment barriers | assessments and improve financing support | [42], [53] |
| Technological limitations | Operational instability and maintenance difficulties | Develop pilot projects, technical training and local expertise | [20], [36], [54] |
| Environmental concerns | Emission, wastewater and residue management risks | Strengthen pollution control, monitoring and LCA | [54], [60] |
| Public acceptance | Community opposition and project delays | Improve consultation, transparency and public awareness | [8], [54] |
| Policy and institutional coordination | Approval uncertainty and fragmented implementation | Improve coordination and clarify institutional responsibilities | [10], [54] |
| Competition for waste resources | Reduced feedstock availability and possible conflict with recycling | Apply circular economy principles and prioritise residual waste | [36], [65], [67] |
| Limited commercialisation | Low investor confidence and uncertain project returns | Expand demonstration projects and document operational performance | [42], [53], [54] |
| Regional infrastructure gaps | Higher logistics costs and uneven technology adoption | Develop region-specific and decentralised solutions where appropriate | [13], [36], [65] |

### 9.13 Strategies to Overcome Implementation Barriers

**Several strategies could strengthen WtE development in Malaysia.**

First, improve waste segregation and feedstock management. Source separation should be strengthened to improve the quality of organic waste and recyclable materials. Reliable waste characterisation data should also be collected to support technology selection and facility planning.

Second, adopt technology-specific development strategies. Anaerobic digestion may be appropriate for suitable organic waste streams, while thermal technologies may be considered for appropriate residual waste and biomass feedstocks. Technology selection should reflect local conditions rather than assuming that one process is suitable for all waste types.

Third, strengthen financial and institutional support. Project developers require transparent regulatory arrangements, predictable feedstock supply agreements and realistic financial assessments. Government support should be linked to measurable environmental and operational performance.

Fourth, expand pilot and demonstration projects. Local demonstration facilities can provide practical information about technical performance, maintenance requirements, environmental compliance and financial feasibility.

Fifth, strengthen public engagement and environmental transparency. Community consultation, accessible monitoring information and clear explanations of pollution-control systems can support public confidence.

Finally, integrate WtE with circular economy planning. Waste prevention, reuse and recycling should remain priorities, with energy recovery directed towards suitable residual materials.

## 9. CONCLUSION

Waste-to-energy (WtE) technologies provide Malaysia with significant opportunities to address increasing waste generation while supporting renewable energy development and sustainable resource management. The country's municipal solid waste, food waste and agricultural residues, particularly oil palm biomass, offer considerable potential for energy recovery. Technologies such as incineration, anaerobic digestion, landfill gas

recovery, gasification, pyrolysis and hydrothermal carbonisation can convert suitable waste materials into useful energy products.

However, the successful implementation of WtE systems depends on several important factors, including feedstock availability, appropriate technology selection, economic feasibility and environmental performance. Challenges such as high investment costs, inadequate waste segregation, inconsistent waste quality, technological limitations and public acceptance must be addressed to support wider adoption.

Therefore, Malaysia should strengthen waste management practices, encourage research and development, improve institutional coordination and provide appropriate policy and financial support. WtE development should also be integrated with circular economy principles, prioritising waste reduction, reuse and recycling before energy recovery.

Overall, WtE technologies have the potential to improve Malaysia's waste management system, reduce dependence on landfill disposal and contribute to a more diversified energy supply. With effective planning, suitable technologies and continued government and industry support, WtE can become an important component of Malaysia's transition towards a more sustainable and resource-efficient future.

For industry stakeholders, WtE project development should begin with detailed feedstock characterisation and an assessment of supply reliability. Technology selection should consider the moisture content, organic fraction, calorific value and contamination level of the available waste. Project developers should also establish reliable energy or product offtake arrangements, assess operational requirements and conduct sensitivity analyses under realistic financial assumptions. These measures are important for reducing technical and financial uncertainty.

For policymakers, greater emphasis should be placed on strengthening source separation, improving organic-waste collection and supporting the development of appropriate WtE infrastructure. The publication of facility-level operational data, including energy production, emissions, operating costs and treatment performance, would improve transparency and facilitate evidence-based technology planning. In addition, clear standards for digestate, recovered fuels, hydrochar and other WtE products could strengthen market confidence and support resource recovery.

WtE development should remain consistent with circular economy principles and the waste-management hierarchy. Waste prevention, reuse and recycling should take priority, while energy recovery should focus on suitable residual materials that cannot reasonably be recovered through higher-value processes. An integrated approach combining appropriate technology selection, reliable feedstock management, environmental safeguards, economic assessment and institutional coordination offers a more practical pathway for sustainable WtE development in Malaysia.

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