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REVIEWING THE SUITABILITY OF THERMAL TECHNOLOGIES FOR MALAYSIA'S SOLID WASTE MANAGEMENT

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Abstract: About 90% of Malaysia's solid waste ends up in landfills. This puts a burden on the capacity of these landfills to support increasing solid waste disposal, which, when left unabated, leads to unsustainable waste management. In this review, we discussed and evaluated the use of thermal treatment to offset landfilling, which consist of technologies such as incineration, pyrolysis, and gasification. To support our arguments, we used secondary literature consisting of case studies, government policies and research studies as references. The technologies are also evaluated in terms of their capacity, efficiency, emissions, and costs associated with the construction and operation of each technology. Based on the discussions, we found that incineration provides the best thermal technology for solid waste management due to its ability to thermally decompose the country's highly heterogeneous solid waste composition and is financially feasible in compared with pyrolysis and gasification.

Keywords: Thermal treatment, incinerator, pyrolysis, gasification, sustainability.

Introduction

Studies to improve solid waste management have been extensively conducted, but these improvements are seldom put into effect (Gahana Gopal *et al.*, 2018) due to various reasons, such as inadequate financial budgets, vague policies, low technology transfer and lack of human capital (Taweesan *et al.*, 2017). Choon *et al.* (2017) and Moh and Abd Manaf (2017) argued that ineffective governance, lack of involvement of authorities and low public awareness of solid waste management further add to the problems. As a result, many continue to divert their solid wastes to landfills despite the knowledge that large portions of these wastes can be treated using a myriad of technologies (Aparcana, 2017; Taweesan *et al.*, 2017). The lackadaisical attitude inevitably increases the problems associated with solid waste management and hinders the success of a sustainable waste management agenda.

In Malaysia, it is argued that the generation of solid wastes is increasing to an estimated 40,000 tonnes per day (Kamaruddin *et al.*, 2017; Bashir *et al.*, 2019; Hamzah *et al.*, 2019). About 90% of these wastes usually end up in landfills or, worst, open dumpsites (Agamuthu, 2017; Kamaruddin *et al.*, 2017; Bashir *et al.*, 2019; Agamuthu & Bhatti, 2020). An individual Malaysian contributes an average of 1.17 kg solid waste per person per day with the average differing slightly based on localities (i.e. urban and rural areas) (Hamzah *et al.*, 2019). Generally, solid wastes in Malaysia are highly heterogeneous, consisting of high moisture and organic contents, with a bulk density of more than 200 kg/m^3 (Abd Manaf *et al.*, 2009; Kamaruddin *et al.*, 2017). These organic materials accounted for about 44–70% of solid wastes, whereby the majority of which is food waste (Ramdzan *et al.*, 2018; Hamzah *et al.*, 2019). Other solid waste components include paper, plastics, metals, and other solid materials (Table 1). Due to the heterogeneity, Agamuthu and Bhatti (2020) argued that many waste collectors prefer landfilling rather than sorting or handling wastes individually.

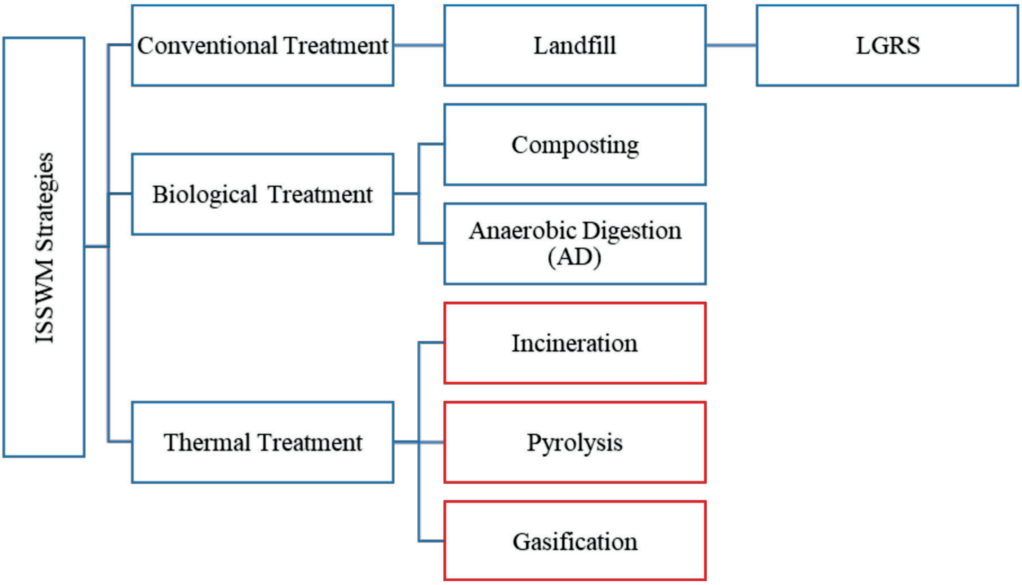
Table 1: Solid waste components and composition in Malaysia

Component	Food	Yard	Paper	Plastics	Metal	Glass	Textile	Wood
Composition (%)	41.06	2.45	20.93	22.23	1.96	3.63	7.74	0.05

Sources: (Agamuthu, 2017; Malakahmad *et al.*, 2017)

In an effort to push for sustainable solid waste management, Malaysia has introduced a range of solid waste strategies, such as 3R initiatives (reduce, reuse, recycle) and waste recovery, as well as relying more on sustainable waste treatment technologies that include biological and thermal treatments (Malakahmad *et al*. 2017; Alias *et al*., 2018). Heralded as an integrated sustainable solid waste management (ISSWM) strategies, the ISSWM's key agenda is to support waste minimisation and reduce landfill dependency (Ali, 2017). The ISSWM hierarchy of solid waste treatments, including their specific treatment methods, is illustrated in Figure 1. It was argued that by implementing the ISSWM, Malaysia could ensure continued environmental protection and an equitable society, instead of supporting economic growth (Gahana Gopal *et al.,* 2018).

Figure 1 illustrates three major treatments of solid waste: conventional, biological and thermal treatments. This paper, however, will focus only on the thermal treatment approach for ISSWM, as the accompanying technologies are widely supported for the mass reduction of solid waste in landfills (Abd Manaf *et al.*, 2009; Abd Kadir *et al.*, 2013; Chua *et al.*, 2019). The thermal treatment is preferred partly because it is more efficient than the biological treatment (Tan *et al.*, 2015); Wong *et al.* (2016) argued that thermal treatment provides the best choice for the ISSWM strategies due to its high success factors. Thermal treatment can reduce the volume of solid wastes by almost 80%, lower greenhouse gas (GHG) emissions compared with conventional treatment, minimise waste contamination into the environment, particularly from leachate runoff, and can be used as fuel



Source: (Chua *et al.*, 2019)

Figure 1: The hierarchy of Malaysia's ISSWM strategies
Note: LRGS in the figure stands for Leachate Gas Recovery System

sources in terms of heat energy conversion to help fulfil the increasing global energy demand (Tan *et al.*, 2015; Wong *et al.*, 2016; Yi *et al.*, 2018; Choong *et al.*, 2019; Chua *et al.*, 2019).

In contrast with other review papers, this paper will assess the strengths and weaknesses of three thermal treatment technologies, including their operating conditions and general processes, rather than reviewing them individually. Subsequently, these assessments will help answer the main objectives of this paper: (a) to evaluate which of these technologies provides more benefits for ISSWM practice in Malaysia and (b) whether Malaysians should reconsider thermal treatment to manage their increasing generation of solid waste. To assist the assessment, secondary literature consisting of case studies, policies and research studies conducted in Malaysia and around the world were used to support arguments.

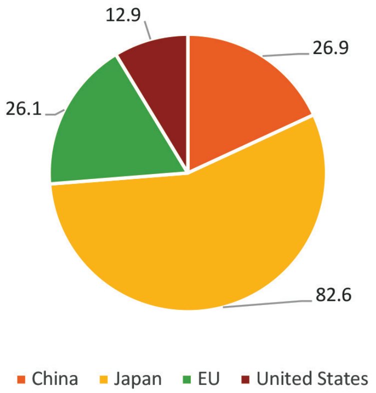
Discussion

Thermal Treatment: Incineration

Incineration is involved in the process of total combustion and degradation of solid waste under controlled aerobic conditions (Chaliki *et al.*, 2016; Wong *et al.*, 2016; Dong *et al.*, 2018). The decomposition of solid waste inside the incinerator is carried out at high temperatures, typically between 850°C and 1200°C, to ensure that the waste disintegrate completely (Wong *et al.*, 2016; Dong *et al.,* 2018). Furthermore, high temperatures in incinerators are essential to remove all traces of toxic chemicals or pathogenic microorganisms from the environment (Lu *et al.,* 2017). Besides, incineration can reduce the volume of combustible solid wastes by almost 90%, which is comparatively higher than other thermal technologies due to its higher decomposing capacity (Chaliki *et al.*, 2016). In newer incineration technologies, thermal decomposition allows for energy recovery that can be utilised as a fuel source for the generation of renewable energy mix (Chaliki *et al.*, 2016; Wong *et al.*, 2016; Lu *et al.*, 2017), whereby the incineration process could potentially generate up to 2000 kWh of energy per tonne per day (Tan *et al,* 2015).

Lu *et al.* (2017) argued that there is a positive correlation between incineration with economic growth and environmental protection, to which He and Lin (2019) applied a cost-effective study (Massarutto, 2015) and verified long-term reductions in GHG emissions, dioxin emissions, and toxic pollution compared with landfills. However, incineration is limited by the composition and component of the solid waste, as those with high moisture contents can significantly reduce combustion efficiency (Wong *et al.*, 2016). Currently, there are three types of solid waste incinerators: (a) mechanical grate furnace, (b) fluidised bed incinerators and (c) rotary kiln incinerator (Wong *et al.*, 2016).

Incineration has become a foundation for developing countries in managing their solid waste generation. It is argued that incineration is a relatively mature technology and thus remains one of the best ways of eliminating solid waste from landfilling (Lu *et al.*, 2017; He & Lin, 2019). Based on several case studies of solid waste incineration around the world, it is found that about 90% of solid wastes from countries with incinerators are actively diverted from landfills and from there, approximately 20% is processed by incineration (Figure 2) (Chaliki *et al.*, 2016; Lu *et al.*, 2017). Comparatively, Japan incinerates more than 80% of its solid waste (Lu *et al.*, 2017). Generally, most countries that have a high rate of solid waste diversion into incinerators enforce effective policies that discourage and penalise landfilling (Bourtsalas *et al.*, 2019). In the case of Japan, the incineration of solid waste is vital to prevent land wastage in a very populated country (Lu *et al.*, 2017). As such, the total volume of landfills in these countries is far below their capacity, as the landfilled solid wastes constitute those that are non-recyclable, non-compostable and with no recovery values (Chaliki *et al.*, 2016; Bourtsalas *et al.*, 2019).



Source: (Lu *et al.*, 2017)

Figure 2: Solid waste incineration percentage in China, Japan, the EU and the US

In Malaysia, solid waste incineration is less preferred and mainly operated on a small scale due to lack of financial and policy support for the technology as a means of minimising solid waste (Salwa Khamis *et al.*, 2019). Coupled with strong public opposition to technology, media bias and uncertainties in the operational impacts, incineration remains less favourable for the majority of Malaysians (Abd Kadir *et al.*, 2013; Shafie & Rizal, 2019). Referring to Table 1, we see that a significant portion of Malaysia's solid waste is composed of food waste, which has a very high moisture content (Ramdzan *et al.*, 2018; Hamzah *et al.*, 2019). Ideal SSWM practice promotes the composting of food waste. This practice is also advised under the Solid Waste and Public Cleansing Management (SWPCM) Act 2007 as a method of diverting the composition of food waste from landfills. However, (Abd Manaf *et al.*, 2009 and Kamaruddin *et al.* (2017) have suggested that the majority of food waste are mixed with other solid waste, rendering it unsuitable for composting. When incinerated, this type of solid waste requires the addition of heat energy to make it combustible. In order to resolve this problem, heterogeneous waste often requires the use of waste torrefaction to reduce the moisture content (Chua *et al.*, 2019) or diesel fuel, which, according to Abd Kadir *et al.* (2013), adds significant financial burden on operational costs and GHG emissions.

Over the years, Malaysia has planned to construct a centralised large-scale incineration facility with increased combustion capacity that can sustain increasing solid waste generation (Abd Kadir *et al.*, 2013). However, the feasibility of this incineration facility in Malaysia was questioned when five of the country's first incineration facilities in Pulau Tioman, Langkawi, Labuan, Pulau Pangkor and Cameron Highlands (Abd Manaf *et al.*, 2009) were found to be under-performing and unable to cope with Malaysia's highly heterogeneous solid waste (Abd Kadir *et al.*, 2013). To address this, the Department of National Solid Waste Management (DNSWM) designed a strategic plan in 2012 to study options for solid waste treatments based on the solid waste management hierarchy for the treatment of other non-recyclable and non-reusable wastes. Several incineration technologies were considered, including mass-burn incineration (stoker type), mass-burn incineration (circular fluidised bed type) and mass-burn incinerator (rotary kiln type) (PEMANDU, 2015). Table 2 shows no difference between the volume reduction potential and CO_2 reduction potential, which is estimated to be around 90% and 0.12 CO_2/MW, respectively (PEMANDU, 2015). However, differences are observed in the energy potential, energy efficiency, capital costs and operational costs, whereby (a) the stoker-type incineration is capable of generating more energy of about 20 megawatt energy (MWe) and is expensive to construct, which costs around RM550 million; (b) circular fluidised bed-type incinerator have a higher energy efficiency of 25%; and, (c) rotary kiln-type incinerators are the most expensive to operate at RM249 per tonne per year (PEMANDU, 2015). Tan *et al.* (2015) argued that sufficient technical and financial considerations are required to choose the right incineration technology to ensure that Malaysia can unlock the potential for waste minimisation, GHG reduction and energy harvesting. Abd Kadir *et al.* (2013) added that the government needed to manage public sentiment on incinerations and work on their public branding. Currently, only the Kajang waste-to-energy

Table 2: Comparison of incineration options for Malaysia's solid waste management

	Incinerator Type		
	Stoker	**Circular Fluidised Bed**	**Rotary Kiln**
Capacity (ton day^{-1})	1000	1000	100
Volume Reduction Potential (%)	90	90	90
Energy Potential (per 1000 tonne per day) (MWe)	20	16	1
Energy Efficiency (%)	21	25	20
CO_2 Reduction (CO_2/MW)	0.12	0.12	0.12
Estimated Capital Cost (RM' million)	550	360	68
Estimated Operation Cost per tonne per tear (RM)	102	110	249

Source: (PEMANDU, 2015)

(WtE) facility provides the much-needed good example of the capabilities of incineration in Malaysia, whereby the facility generates 8 MWe and processes approximately 1100 tonnes of solid waste per day (Yong *et al.*, 2019).

Thermal Treatment: Pyrolysis

Pyrolysis is a process of chemical decomposition of solid waste (depending on the composition) into solid (char), liquid (tar/oil) and gaseous (syngas) components under anaerobic conditions (Figure 3) (Wong *et al.*, 2016; Dong *et al.*, 2018; Chua *et al.*, 2019). Generally, pyrolysis consists of three main types: (a) fast pyrolysis, which is utilised to produce liquid tar/oil; (b) intermediate pyrolysis, which is utilised to produce syngas; and, (c) slow pyrolysis, which is utilised to produce char (Czajczyńska *et al.*, 2017; Chua *et al.*, 2019). Depending on the pyrolysis types and the intended outputs, each process is highly dependent on the reaction temperature, residence time, type of solid waste and heating rate (Dong *et al.,* 2018). There are several advantages of pyrolysis, including (a) reducing particulate emissions, such as alkali salts and heavy metals, by retaining them as process residues; (b) preventing dioxin formation, in particular, polychlorinated dibenzo(p)dioxin and furan (PCDD/F) compound; and, (c) reducing NO_x and SO_x emissions into the atmosphere (Wong *et al.*, 2016). As for pyrolysis reactors, they can be divided into several types depending on the feeding and discharge processes, such as batch, semi-batch and continuous units (Chua *et al.*, 2019). Besides, depending on the heat transfer methods, as well as the flow and reaction patterns, these reactors can be further categorised into (a) fixed bed, (b) fluidised bed and (c) screw kiln (Wong *et al.*, 2016).

The utilisation of pyrolysis to manage solid waste is still low and currently operated by small numbers of solid waste operators in the European Union (Dong *et al.*, 2018). Pyrolysis is less preferred mostly due to the issue of solid waste heterogeneity, whereby pyrolysis can only offer to "incinerate" homogeneous solid waste rather than heterogeneous solid waste (Dong *et al.*, 2018). Nevertheless, unlike incineration, choosing pyrolysis as a tool to manage solid waste can be advantageous as the technology is capable of processing high-moisture solid waste components, in particular food waste, and completely disintegrate them without the addition of torrefaction process to support thermal combustion (Chua *et al.*, 2019). Besides, pyrolysis is highly efficient in the conversion of solid waste as compared with other thermal treatments with by-products, which can be utilised as other raw materials, for example as energy fuel, and has lower CO_2 emission that can help tackle environmental issues, such as climate change (Dong *et al.*, 2018; Chua *et*

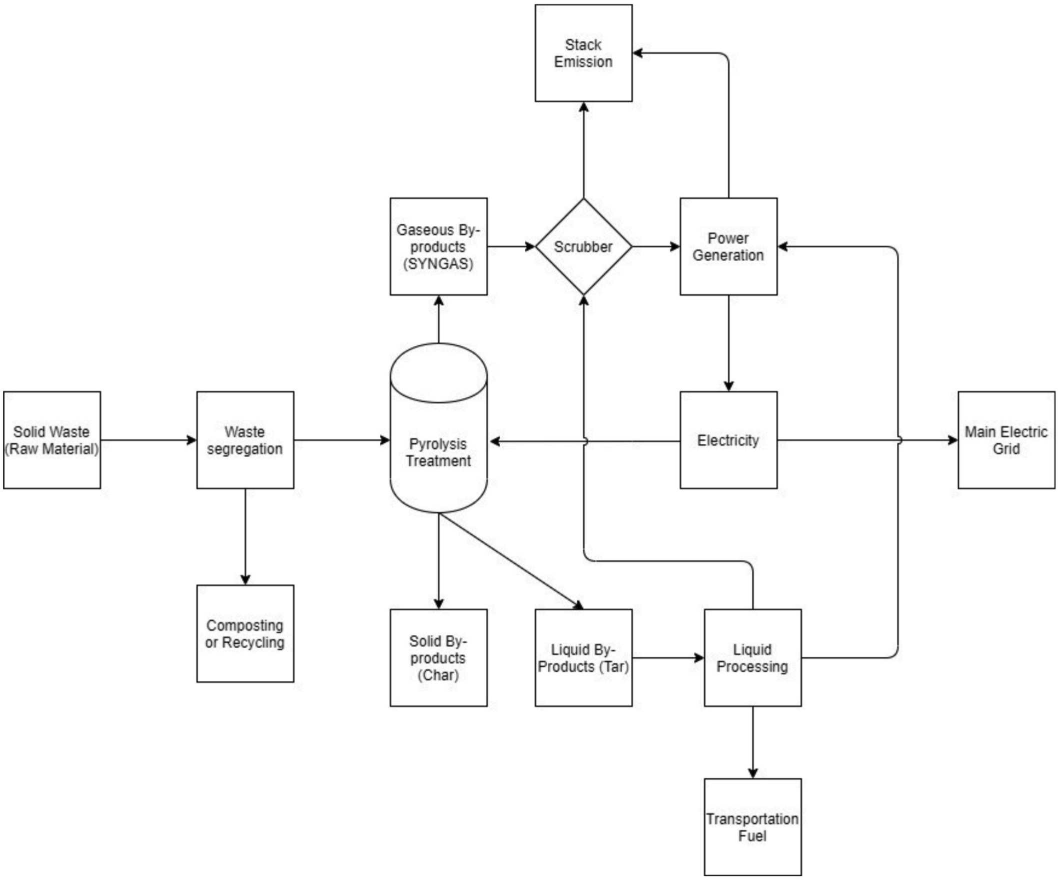


Figure 3: General pyrolysis treatment process based on the schematic process for pyrolysis by Young (2010)

al., 2019; Snyder, 2019)stimulated by a more sustainable waste-to-energy (WtE. Furthermore, the ability of pyrolysis to remove excess CO_2 from the atmosphere can be traded as a carbon credit, thus generating extra income for the government to fund this technology for SSWM (Snyder, 2019) a potentially long-lived carbon sink, and renewable fuels. While a number of studies of the costs of pyrolysis exist, many fail to value the carbon storage benefit associated with biochar. Here, we evaluate the costs of three types of small-scale pyrolysis systems (slow and fast, compared with gasification. Other environmental advantages of pyrolysis include reducing the impacts of terrestrial eutrophication, lowering human airborne toxicity, minimising the formation of photochemical ozone and preventing solid ecotoxicity (Dong *et al.*, 2018).

In Malaysia, pyrolysis has not yet been given any priority as there is no available facility or even a plan to install this technology to reduce the amount of solid waste in the country. As such, most of the literature reviewed with an interest in evaluating the integration of pyrolysis into Malaysia's solid waste strategies is mostly theoretical. Obviously, in DNSWM's strategic planning for solid waste management, pyrolysis technology is not even considered as an option for thermal treatments technologies, which focus primarily on incineration and plasma arc gasification (PEMANDU, 2015). The lack of support for this technology in the country may be due to the fact that costs associated with the construction of pyrolysis facilities are considered to be high, which, according to Snyder (2019), may cost between US$400 million and US$1.2

billion depending on the pyrolysis type. Tangri and Wilson (2017) further argued that several pyrolysis facilities in the EU are now closed and the closures were caused by a) failure to support their operations financially, b) failure to meet pollution control standards, c) frequent equipment damage due to corrosion, d) inability to maintain effective reaction temperature, and e) low energy efficiency. Given the considerable amount of investment and uncertainties, the utilisation of pyrolysis, including its suitability in Malaysia, could lead to even greater public dissatisfaction as waste facilities are funded using taxpayers' money (referring to Abd Manaf *et al.* (2009), five under-performed incinerators, for example).

Thermal Treatment: Gasification

Similar to pyrolysis, the gasification process uses the chemical decomposition process of converting solid waste into syngas by thermal combustion with limited input of air or oxygen (Figure 4) (Young, 2010; Vaish *et al.*, 2019). Interestingly, pyrolysis itself, when operated under certain circumstances, can mimic the conventional gasification process, whereby, instead of producing char, tar and syngas, decomposition produces mainly char and syngas (Young, 2010). These circumstances can only exist in a fast pyrolysis reaction, of which many pieces of literature will often combine these processes as pyrolysis/gasification treatment (Wong *et al.*, 2016; Dong *et al.*, 2018). Nevertheless, there are several distinct features between pyrolysis and gasification process treatment. Gasification treatment uses temperatures between 550°C and 1000°C to break carbonaceous bonds in solid waste under oxidising conditions into two by-products of either fuel or synthesis gaseous components consisting of CO, CO_2, CH_4, H_2O and H_2 gases (Vaish *et al.*, 2019). Also, unlike pyrolysis, thermal combustion in gasification still uses less air intake under controlled conditions to help the decomposition process (Wong *et al.*, 2016).

Despite air inputs, the flue gas emission from gasification is less compared to the flue gas emission from an incinerator, thus considering for solid waste thermal treatment (Wong *et al.*, 2016). In terms of energy, gasification offers an attractive solution to manage solid waste volumes and energy demand, as the treatment itself produces economical gases, mainly CH_4 and H_2, which can be channelled for power generation (Young, 2010; Vaish *et al.*, 2019). There are three main types of gasification reactors: a) fixed bed gasifiers, b) fluidised bed gasifiers, and c) rotary kiln bed gasifiers (Wong *et al.*, 2016). On top of these three reactors, Moya *et al.* (2017) found that there are other types of gasification technologies, including plasma reactors, vertical shafts and moving grate gasifiers.

The majority of case studies on actual gasification treatment are focused on the practices of developed countries, where the technology itself is considered mature and readily available (Wong *et al.*, 2016). For example, in Japan, solid waste gasification treatment facilities are observed to be capable of diverting approximately 100 – 400 tonnes of municipal solid waste a day and can be utilised to generate 2 – 9 MWe of power (Arena, 2012). Also, depending on the type of gasification technology, the amount of solid waste diverted and the amount of power generated may differ, such as a) in the case of the Battelle gasification processes, whereby the solid waste treated from this facility is estimated around 900 tonnes a day and b) in the case of the Termiska gasification process, whereby the solid wastes treated from this facility is estimated to be around 1800 tonnes a day (Vaish *et al.*, 2019). As far as power generation is concerned, both facilities are capable of producing 703 kWh per tonne and 781 kWh per tonne in energy, respectively (Vaish *et al.*, 2019).

According to Arena (2012), the environmental benefits of gasification technology are comparatively better than those of incineration or pyrolysis technologies, where the treatment process produces low dioxin and furan emissions, including GHGs, due to its reaction process and therefore requires low

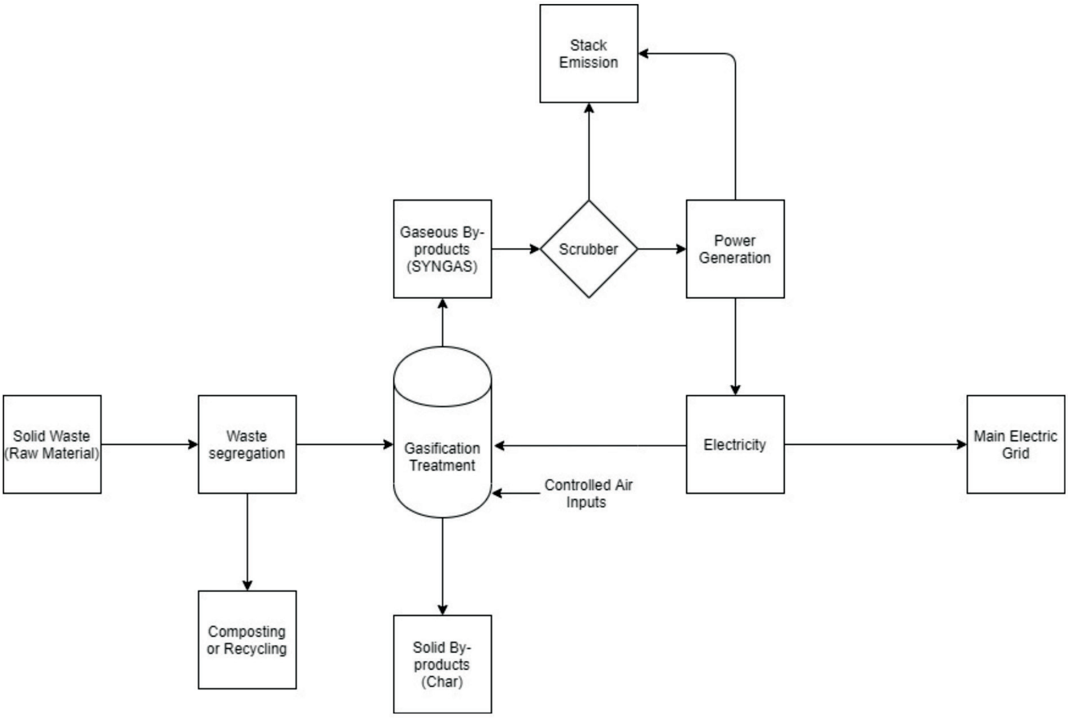


Figure 4: General gasification treatment process based on the schematic process for gasification by Young (2010)

Table 3: Plasma gasification treatment option for Malaysia

Capacity (ton day^{-1})	**Volume Reduction Potential (%)**	**Energy Potential (per 1000 tonne per day) (MW)**	**Energy Efficiency (%)**	**CO_2 Reduction (CO_2/MW)**	**Estimated Capital Cost (RM' million)**	**Estimated Operation Cost per ton per year (RM)**
1000	90	40	43	-	650	120

Source: (PEMANDU, 2015)

operational costs, especially concerning its air pollution control. This would add to the appeal of this technology as it has low environmental footprints and contributes to the SSWM agenda. Vaish *et al.* (2019) added that the impacts of gasification on human health are also low due to low chemical emissions into the atmosphere.

Numerous calls have been made to the Malaysian government to explore the possibility of installing a gasification treatment facility to support the country's ISSWM strategies (Fazeli *et al.*, 2016; Saharuddin *et al.*, 2019) and unsanitary sites. This paper summarizes the status of the waste management techniques currently being used in Malaysia followed by an overview of sustainability analysis of the potential energy-recovered waste treatment techniques. It is concluded that retrofitting current landfill sites to capture methane is of great interest as it requires less time and investment in comparison with standard energy-recovered waste incinerator. The use of sophisticated waste incineration plants will be inevitable and other approaches such as gasification, and pyrolysis should be considered as well. Gasification, and pyrolysis are easily adaptable to bulky or powder-like wastes and drying of wet waste is performed through osmosis at no energy expenses. Due to the high level of moisture in Malaysian MSW, they therefore appear to be suitable options. In addition, an upgraded Feed-in-Tariff (FiT. Currently, the majority of the Malaysian gasification literature are based on experimentations and pilot test data rather than on a large-scale setting (Saharuddin *et al.*, 2019; Munir *et al.*, 2019). Nevertheless, the results of these studies tend to verify the advantages of gasification by making it more eco-friendly and able to process solid waste materials more effectively compared with either incineration or pyrolysis (Fazeli *et al.*, 2016; Zainu, 2018) and unsanitary sites. This paper summarizes the status of the waste management techniques currently being used in Malaysia followed by an overview of sustainability analysis of the potential energy-recovered waste treatment techniques. It is concluded that retrofitting current landfill sites to capture methane is of great interest as it requires less time and investment in comparison with standard energy-recovered waste incinerator. The use of sophisticated waste incineration plants will be inevitable and other approaches such as gasification, and pyrolysis should be considered as well. Gasification, and pyrolysis are easily adaptable to bulky or powder-like wastes and drying of wet waste is performed through osmosis at no energy expenses. Due to the high level of moisture in Malaysian MSW, they therefore appear to be suitable options. In addition, an upgraded Feed-in-Tariff (FiT. In terms of feedstock, gasification is more flexible compared with pyrolysis as it can process heterogeneous solid waste that is better suited to Malaysia's solid waste compositions (Zainu, 2018; Munir *et al.*, 2019). As such, it may be co-utilised with the incineration process to effectively remove all solid waste from landfills. Like incineration technology, DNSWM is also interested in building a plasma gasification facility. In comparison with conventional gasification, plasma gasification uses high intensity ionised gas sourced from electrical discharge to support and sustain the combustion process, thus enabling high-efficiency waste conversion (Sanlisoy & Carpinlioglu, 2017). Furthermore, instead of producing char and syngas, high-intensity combustion of plasma gasification would primarily produce syngas in the form of CO, CO_2 and H_2, which can be used as energy fuels and as a source of revenue to offset the cost of building a gasification facility (Munir *et al.*, 2019). From Tables 2 and 3, there are several distinct differences between gasification and incineration, particularly in terms of their energy potential, energy efficiency and capital costs. Gasification technology is expected to generate more energy potential (about 20 MWe more than a stoker-type incinerator) and has a higher energy efficiency (about 18% more than a circular fluidised bed incinerator), but is more expensive to build (about RM400 million more compared with the most expensive rotary kiln incinerator).

Thermal Treatment: Final Discussion

In general, thermal treatment has become very popular in solid waste management due to its higher efficiency rate compared with conventional and biological treatments (Abd Manaf *et al.*, 2009; Abd Kadir *et al.*, 2013; Chua *et al.*, 2019). In this paper, we reviewed three thermal technologies consisting of incineration, pyrolysis, and gasification. As Malaysia is projected to see a rise in the generation of solid waste due to an increase in population growth, the integration of efficient thermal technologies to reduce the burden on landfills are deemed vital and necessary. Their ability to divert almost 90% of solid waste from landfills with a low retention time also adds to the appeal of using it to complement other existing solid waste treatments. Other advantages, such as small land areas, are required for the construction of these thermal facilities. Low GHG emissions, and low dioxin/furan emissions, a reduction of leachate leakage risks, and low transmission of pathogenic and hazardous chemical exposures add to the need for thermal treatment to manage solid waste sustainably.

Table 4: Comparison between incineration, pyrolysis and gasification

	Incineration	**Pyrolysis**	**Gasification**
Process Goal	To maximise waste conversion to high-temperature flue gases, mainly CO_2 and H_2O.	To maximise thermal decomposition of solid waste to gases and condensed phases.	To maximise waste conversion to high heating value fuel gases, mainly CO, H_2 and CH_4
Operating Condition	Oxidising (oxidant amount larger than stoichiometric combustion)	No oxidant	Reducing (oxidant amount lower than stoichiometric combustion)
Reactant Gas	Air	None	Air, pure oxygen, oxygen-enriched air, steam
Temperature	850 1200	50000	(in air gasification)
Pressure	Atmospheric	Slight over-pressure	Atmospheric
Output	CO_2, H_2O	CO, H_2, CH_4 and other hydrocarbons	CO, H_2, CO_2, H_2O, CH_4
Pollutants	SO_2, NO_x, HCl, PCDD/F, particulate	H_2S, HCl, NH_3, HCN, tar, particulate	H_2S, HCl, COS, NH_3, HCN, tar, alkali, particulate
Gas cleaning	Usually treated using air pollution control units to meet the emission limits and then sent to the stack.	Require syngas cleaning unit to meet the standards of chemicals production processes or those of high-efficiency energy conversion devices.	Require syngas cleaning unit to meet the standards of chemicals production processes or those of high-efficiency energy conversion devices.

Reproduced from Arena (2012)

Table 4 presents the overall comparison between incineration, pyrolysis and gasification in terms of process objectives, process conditions, limitations, outputs, pollutants, and gas cleaning criteria. Although all treatments involve similar thermal decomposition of solid wastes, each thermal technology is ultimately differentiated by the process conditions under which it affects the type of product, as well as the equipment needed to either clean, purify or treat these outputs (Wong *et al.*, 2016). Furthermore, the type of process conditions will also influence the efficiency of each technology in treating different solid waste compositions, whereby we have reviewed that incineration is better capable of treating heterogeneous solid waste compositions followed by gasification and pyrolysis.

In addition to the treatment of solid wastes, there have been various suggestions for integrating energy harvesting into the thermal treatment of renewable energy sources (Chua *et al.*, 2019; Yong *et al.*, 2019). Termed as WtE, the majority of the literature reviewed positively argued for the potential of energy generation during the thermal decomposition process. Among the three thermal technologies, in theory, gasification has a higher energy potential and conversion efficiency of 40 MWe and 43%, respectively, compared with incineration or pyrolysis (PEMANDU, 2015). The improved energy potential and efficiency add to the appeal of using gasification technology as it does not only help in the handling of solid waste generation, but also generate much-needed energy to meet increasing energy demands (Newell *et al.*, 2019). Table 5 adds, as a supplement, the feasibility arguments for thermal treatments to which each thermal technology is evaluated by its energy generation potential (in kilowatt-hours) per tonne of thermally treated solid waste in one day. From this table, it can be seen that

Table 5: Energy generation comparison between incineration, pyrolysis and gasification

Type of Thermal Treatment Technologies	**Energy Generation Potential (kWh/tonne/day)**
Incineration	164.7[c] – 1910[b]
Pyrolysis	4.2[b] – 184.5[c]
Gasification	40[a] – 400[b]

Sources: [a](PEMANDU, 2015), [b](Tan *et al.*, 2015), [c](Chua *et al.*, 2019)

incineration still has the most energy production capacity followed by gasification and pyrolysis.

Conclusion

As a country that disposes almost 90% of its solid waste into landfills, the consideration of thermal treatment for the proper management of solid waste disposal is necessary to support Malaysia's ISSWM strategy. DNSWM outlined various strategic approaches to the integration of thermal treatment, including an illustration of the strengths of each technology as an SSWM tool. However, the success rate was low due to issues such as inadequate funding, low human capital, low public awareness, and improper tracking of outlined initiatives. Nevertheless, among the three technologies discussed, incineration remains the best option for Malaysia, as the technology is capable of catering to the country's highly heterogeneous waste and is more economically viable, compared with either a pyrolysis or gasification facility.

Here, incineration might not be the perfect holistic tool for solid waste management, but incineration is technologically advanced and has greater operational reliability than other thermal technologies. Hence, to ensure the success of incineration technology in the country, proper funding, strict waste disposal enforcement in compliance with the SWPCM Act 2007 and adequate human capital are required, so that incineration can be successful. Furthermore, the government should also consider building a better image branding for incineration, such as integrating the best available technologies or equipment to reduce the risks of environmental pollutions and endangering the quality of social health to pacify societal concerns. Although the feasibility of incineration in Malaysia is continually debated and criticised as to whether it remains suitable as a tool for managing the increasing amount of solid waste in the country, it nevertheless provides a better solution than landfilling.

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