CHEMICAL ENGINEERING TRANSACTIONS
VOL. 63, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Jeng Shiun Lim, Wai Shin Ho, Jiří J. Klemeš

ISBN 978-88-95608-61-7; **ISSN** 2283-9216

DOI: 10.3303/CET1863032

Review on the Suitability of Waste for Appropriate Waste-to-Energy Technology

Mazalan Maisarah[a], Cassendra P.C. Bong[a], Wai Shin Ho[a,*], Jeng Shiun Lim[a], Zarina Muis[a], Haslenda Hashim[a], Sherien Elagroudy[b], Gabriel H.T. Ling[c], Chin Siong Ho[c]

[a]Process Systems Engineering Center (PROSPECT), Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia (UTM), 81310, Johor, Malaysia.
[b]Public Works Dept., Faculty of Engineering, Ain Shams University, Cairo, Egypt.
[c]Faculty of Built Environment, Universiti Teknologi Malaysia (UTM), 81310, Johor, Malaysia.
hwshin@utm.my

The proper treatment of waste to utilise them as a feedstock for resource harvesting is gaining increasing popularity. The Waste to energy (WtE) technology is the process that can produce solids, liquid or gaseous fuels from waste, which can be utilised to generate electricity and thermal energy. The WtE technology can be divided into two treatments, which are the thermal treatment (incineration, gasification, pyrolysis, refuse derived fuels) and the biological treatment (anaerobic digestion, composting). The municipal solid waste (MSW) is an attractive feedstock for WtE technology for resource harvesting due to their high organic content. MSW is heterogenous in nature. MSW can be categorised into mixed MSW and segregated MSW, which includes segregated food waste, green waste, paper waste, plastic waste and more. Different categories of waste exhibits different characteristics, such as variation in the moisture content, caloric value, C/N ratio, particle size and pH. These characteristics can be viewed interchangeably as the parameters for the WtE technology. Different technologies require appropriate waste with certain characteristic to serve as the suitable feedstock for the optimal performance. This paper aims to review the characteristics of different categories of waste under the MSW and propose a suitability matching between these waste with the available WtE technology. As a result, mixed MSW is suitable for incineration process whereas segregated MSW like food waste which is rich in labile organic matter, is more suitable for biological treatment. Plastic waste is suitable for the gasification and pyrolysis process due to its high calorific value and combustibility. The paper waste is suitable for the pyrolysis process due to the presence of hemicellulose and cellulose.

1. Introduction

The growing of population will give a massive impact to the environment including the municipal solid waste (MSW) generation. The MSW generation will be increased accordingly with the population growth, urbanisation and increasing standard of living (Shahholy et al., 2008). Current global MSW generation level is approximate at 1.3 Mt/y and it is expected that the amount will be doubled in 2025. This is parallel with the increasing demand on energy. WtE is the process that can produce solids, liquid or gaseous fuel from waste that can be used for electricity generation or for thermal energy generation (Lombardi et al., 2015). WtE technology offers a win-win strategy to combat waste accumulation and energy security.

The common WtE technology includes incineration, gasification, pyrolysis, anaerobic digestion and composting. All the WTE technologies have specific requirements in terms of preferable waste exhibiting certain characteristic which satisfies the operational parameter for efficient process. The incineration can be fed directly with the raw MSW and the waste can be burned completely to generate heat. For other technologies such as pyrolysis, it will require pre-treatment to reduce the size of the MSW to a maximum of 300 mm (Lombardi et al., 2015). Similarly, for gasification, size reduction is needed for the MSW as inappropriate size can lead to operational difficulties, such as the blockage on the gasification vessel.

Please cite this article as: Mazalan Maisarah, Cassendra Phun Chien Bong, Wai Shin Ho, Jeng Shiun Lim, Zarina Ab Muis, Haslenda Hashim, Sherien Elagroudy, Gabriel Ling Hoh Teck, Chin Siong Ho, 2018, Review on the suitability of waste for appropriate waste-to-energy technology, Chemical Engineering Transactions, 63, 187-192 DOI:10.3303/CET1863032

One of the attractive feedstock to WtE treatment is the MSW. MSW is generally characterised as high organic content, easily biodegradable, high moisture content and lower pH, which are the important factors that affected the performance of WtE treatment. MSW can be categorised into mixed MSW and segregated MSW, which includes segregated food waste, green waste, paper waste, plastic waste and more. Different categories of waste exhibits different characteristics which then determine their respective suitability for certain type of WtE treatment. Due to the heterogenous nature of MSW with varied composition, it brings difficulty to determine the suitable waste types for various types of established WTE technologies. Hence, this paper aims to review the suitability of waste type, based on their characteristics, and to match the exhibited characteristics against the operational parameters of the appropriate WTE technologies.

2. Methodology

This review is based on a literature search using ScienceDirect with the focus on several keywords: energy from MSW, waste-to-energy, thermal treatment, biological treatment.

3. Waste-to-Energy (WtE) Technology

The WtE technology can be divided into two categories, namely the thermal treatment and the biological treatment. The thermal treatment includes combustion, gasification and pyrolysis. These treatments involve the feeding of waste at varying high temperature and oxygen concentrations. Different by-products and end-products are produced following different technology in additional to energy generation.

The biological treatment includes anaerobic digestion (AD) and composting. The decomposition of OM is carried under the absence of oxygen during AD whereas for composting, the biological decomposition is carried out with the presence of oxygen. The final product of AD is biogas, which can be used of energy generation, and a nutrient-rich digestate. The end-product of composting, is a humus-like substance that can be used as fertiliser or soil amendment. Heat is constantly released during the composting process due to active microbial action.

Incineration is the process that involves the combustion and conversion of waste materials that can produce heat and energy at a minimum temperature of 850 °C. This is the most popular technology that is used for the process of waste to energy. There are many large scales incinerators available, such as the municipal waste combustors (MWC), medical waste combustors (MWI), hazardous waste incinerators (HWI), boiler and industrial furnaces (BIF), cement kiln (CK) and biomass combustor (BC) (Arena, 2011).

Gasification is the conversion of solid waste into fuel or synthesis gases (syngas) in the presence of an oxidant amount lower than that required for the stoichiometric combustion (Heerman et al., 2001) in an operating temperature of 200 - 300 °C. In gasification, the fuel is used for combustion to provide the heat needed for the gasification process. The product of the gasification process is known as syngas, which contains large amount of incompletely oxidised products with calorific value (Heerman et al., 2001). Syngas is a valuable commercial product and can be used for synthesis natural gas, methane, methanol, dimethyl ether and other chemical.

Pyrolysis is the thermal process in the absence of oxygen that breakdowns the long chain of polymer molecules into smaller, less complex molecules at a temperature higher than 400 °C (Lombardi et al., 2015). The three major products are oil, gas and char, which are valuable for the production and refineries of the industries (Arena et al., 2010). The pyrolysis process exhibits high flexibility because the process parameter can be manipulated to optimise the product yield. The liquid oil produced can be used for multiple purposes, including for boiler, furnace, turbines and diesel engine without upgrading (Sharudin et al., 2015). The pyrolytic products are more refined and can be used with greater efficiency. There are three pyrolytic modes which are differentiated by temperature and the processing or residence time of the biomass.

Anaerobic digestion (AD) is the process of degradation of organic compounds to simple substances by microorganisms and releasing biogas without of oxygen. It is a complicated process that involves several stages of physicochemical and biochemical reactions in sequential and parallel pathways (Pontoni et al., 2015). AD has been used as a biological treatment for various organic waste such as municipal solid waste, food waste, industrial waste, sewage sludge, animal manure and agriculture waste into energy source (Bridgwater, 2012). The energy source that can be formed by the AD process is known as biogas, which is a mixture of 60 % of methane (CH_4) and 39 % of carbon dioxide (CO_2), with a small amount of water vapor, hydrogen, sulphide and ammonia (Yen and Brune, 2007). This biogas can be used to generate heat or electricity or enriched into 99% of methane, that can be formed into bio-methane (Chen et al., 2008).

Composting is the process that breaks down and decomposes the organic wastes such as manure, sludge, leaves, fruits, vegetables and food wastes into a stabilised organic product by microorganisms under aerobic condition. Carbon dioxide (CO_2) is the main gaseous emitted along the process with the production of a

humus-like and nutrient rich product. Compost can be used to replace mineral fertiliser and act as soil conditioner that can be used to conserve soil moisture, reduce erosion by improving infiltration and reducing runoff.
Due to the different mechanisms among the WtE technologies, there is variation on the suitability of a selected waste stream on the optimal performance for the different WtE technologies. Table 1 presented the operational parameters for different WtE technologies, which can be referred as the suitable criteria to be exhibited by the waste in order to achieve optimal efficiency of the WtE technology.

Table 1: Operational parameters for the optimal efficiency of WtE with respect to the characteristic of waste

WtE technology	Parameters			
	Moisture content	Calorific value	C/N ratio	pH level
Incineration	< 50 %	Higher calorific value	N/A	N/A
Gasification	~ 50 % to be gasified without any pre-drying	Higher calorific value	N/A	N/A
Pyrolysis	N/A	5 – 15 MJ/m^3	N/A	N/A
Anaerobic digestion (AD)	~ 60 %	N/A	15 - 30	6.0 - 8.0
Composting	50 – 60 %	N/A	~ 30	6.0 - 8.0

4. Type of MSW and its characteristic

The MSW is heterogenous in nature and its composition varied seasonally and geographically. It can be further categorised into several categories where each has its own characteristics that will influence the performance of the WtE technology. The waste can be classified as either the mixed MSW or the segregated MSW as shown in Table 2.

Table 2: Type of MSW and their examples

Types of waste	Example	Moisture content (%)	Calorific value (kJ/kg)	C/N ratio
1) Mixed waste	Non-segregated MSW	N/A	N/A	N/A
2) Segregated waste				
Food waste	Vegetables waste, fruit waste	50 - 80	N/A	21.1 (Zhang et al., 2013)
Garden waste (Kumar et al., 2010)	Leaves, grass, twig	7 - 15	N/A	52.4
Paper waste		4 - 10		
Mill brock	Paper-trimming, paper scrap			
Pre-consumer	Unused discarded paper			
Post-consumer	Old magazine, newspaper			
Plastic waste				
High density polyethylene (HDPE)	Shopping bag, waste bag	1 - 4	11,216 - 18,540	
Low density polyethylene (LDPE)	Plastic bag, food packaging			
Polypropylene (PP)	Food packaging			
Polystyrene (PS)	Food packaging, items packaging			

Table 2 showed the types of waste as mixed MSW and segregated MSW with their examples. The mixed MSW comes from the non-segregated waste from the households while the segregated MSW can be found as food waste, garden waste, paper and plastic. The mixed MSW is difficult to handle, segregate and feed in a controller manner to WtE facilities (Marin et al., 2010). The example of food waste are vegetables, fruits waste, rice and more. The leaves, grass and twig are the examples for the garden waste. As for the paper waste, it can be classified into three types, which are mill brock (paper trimming, paper scrap), pre-consumer (unused discarded paper), post-consumer (old magazines, newspaper). The plastic waste has four different common types found in the MSW, which are high density polyethylene (HDPE) (e.g. plastic shopping, waste bag), light density polyethylene (LDPE) (e.g. plastic bags, food packaging, polypropylene (PP) (e.g. food packaging) and lastly, the polystyrene (PS) (e.g. food packaging, items packaging).

A suitability matching based on the waste characteristics against the operational parameters of the WtE technology will lead to an effective and efficient performance, including heat recovery, resource recycling, cost effective and time saving. MSW is generally a complex mixture of several materials with different physical and chemical characteristics, and size. They generally have high moisture content and high calorific value. MSW comes as a mix waste stream, which is a mix composition of organic and inorganic materials. There is certain waste that undergo segregation at the source and at the recyclable centre, such as paper and plastics. The glass and metals are not included because they are unsuitable for the energy recovery (Izumi et al., 2010). Each types of waste have different physical and chemical characteristics that have direct effects to the WtE technologies, which is discussed interchangeably as the parameter of WtE.

Table 3 presented a suitability matching on the type of waste with the types of technology. Some technologies will require the waste to undergo certain pre-processing process, such as drying and size reduction, to achieve effective operation.

Table 3: The matching of type of waste with type of WtE technologies

Type of waste	Type of WtE technologies
1. Mixed waste	Incineration
	Gasification (pre-processing)
	Pyrolysis (pre-processing)
	Anaerobic digestion (pre-processing)
2. Segregated waste	
a) Food waste	Anaerobic digestion
	Composting
	Incineration
	Gasification/pyrolysis (not solely developed)
b) Garden waste	Composting
	Pyrolysis
	Incineration/ Gasification (pre-processing)
c) Plastic waste	Pyrolysis
	Gasification
	Incineration
d) Paper waste	Gasification
	Pyrolysis
	Incineration

As presented in Table 3, a certain type of waste can be fed into several technologies where some can be fed directly but some required additional pre-treatment. The pre-processing treatment takes place before the waste, that is used as feedstock, entering the thermal or biological treatment unit. Pre-processing involves the manual and mechanical separation or sorting, shredding, grinding and drying process. The purpose of pre-processing is to produce a feed material with consistent physical characteristics and chemical properties and uniform in size for consistent feeding.

Pre-processing operations are designed to produce a material that can be safely handled, transported and stored. The sorting part of the process is to remove very large objects composed of inorganic materials, like metals and glass, that is unsuitable for the WtE technology. Waste as a feedstock of WtE technology required a reduction of size by shredding or grinding. The drying process is required for the waste that have high moisture content because thermal treatment required waste that have low moisture content in order to perform efficiently. The examples of pre-processing treatment are mechanical biological reactor (MBT) and refuse derived fuels (RDF). MBT is a type of waste processing facility that combines a sorting facility with a form of biological treatment like composting and anaerobic digestion. MBT is designed to process household mixed waste.

In addition to the utilisation of the MSW as feedstock, the refuse derived fuels (RDF) produced from MSW through the pre-processing unit is popular. RDF is a production of fuel from MSW that has undergone processing, which includes separation of recyclables and non-recyclables materials, shredding, size reduction and pelletising. RDF is a value-added material with a higher calorific value and a homogeneous particle size. Mostly, the RDF fuels are used in fixed bed reactor (Autret et al., 2007).

Figure 1 presented a schematic diagram showing the matching of suitability of different type of wastes against different type of WtE technology, with reference to the need of pre-processing unit.

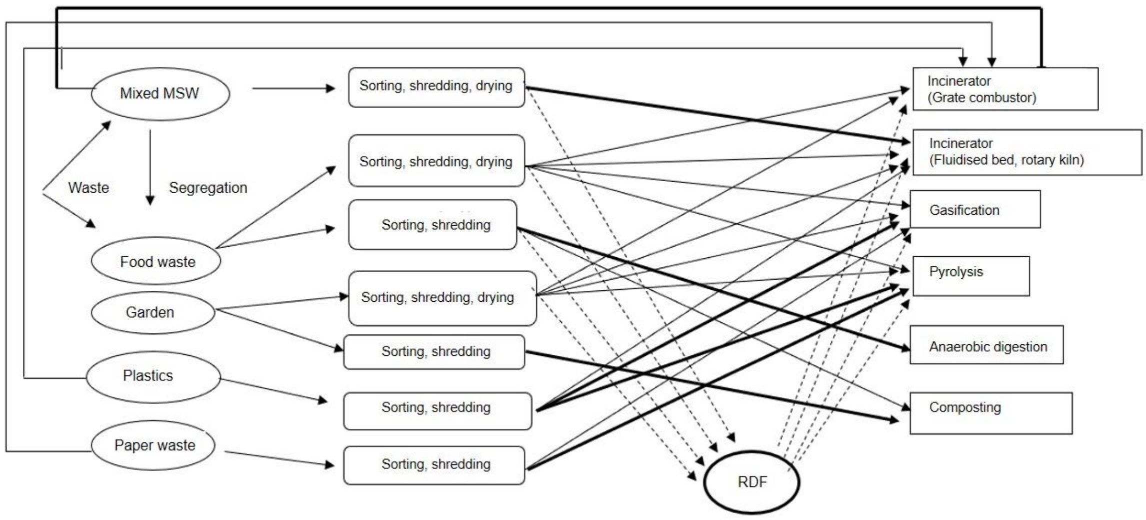

Figure 1: An illustrated mapping on the suitability of different types of waste with different WtE technology with reference to the need of pre-processing unit

From Figure 1, it can be summarised that the mixed MSW is suitable for the incineration using mixed combustor and the pre-processing of MSW is suitable for the fluidised bed incinerator and rotary kiln. The rotary kiln is mostly used for the hazardous waste and not for the mixed MSW. For segregated waste, taking food waste as the example, the most suitable technology for food waste treatment is anaerobic digestion due to the high moisture content and organic content, and non-combustible components. The food waste can be used for thermal treatment but with low efficiency due to the highly heterogenous nature and high moisture content of the food waste. The garden waste is another major component in MSW. The ideal technology is composting to achieve nutrient reclamation through the production of compost as biofertiliser or soil amendment. Fallen leaves or twig which is low in moisture content and high in carbon can be a good feedstock for thermal treatment, but the burning process can give nuisance to the publics. For the plastic waste, it can be fed into incineration, gasification and pyrolysis. By using incineration, it can cause pollution due to the high contents of polymer, so gasification and pyrolysis are the better choice for plastic waste treatment. Paper waste which represents a mainstream of combustible in MSW, can be fed for thermal treatment. Paper waste can be used in gasification and pyrolysis, but pyrolysis is more flexible than gasification in terms operation temperature.

The WtE technologies can give an excellent performance based on the composition of feedstock (waste). The performances of WtE technologies, their applications and their productions are dependent on the characteristic of the waste used. All types of waste can be suitable for certain WtE technologies if undergone proper pre-processing but this will require relatively high cost and seem unpractical for the technologies performances.

Although recycling does not fall under the WtE technology, recycling the recyclables such as paper and glass are significant in terms of environmental performance. Sevigné-Itoiz et al. (2015) stated a GHG reduction of 36 - 317 kg CO_2/ t waste paper collected, through material flow analysis (MFA) and life cycle assessment (LCA). The use of recovered paper as feedstock in a pulp and paper industry resulted in lowest energy use and a reduction of 1,100 kg CO_2/t in CO_2 emissions when biomass was excluded from the paper production (Laurijssen et al., 2010).

5. Conclusion

The types of waste (MSW) plays an important role on the efficiency of WtE technologies and the yields of production. The thermal treatment required waste that have low moisture content and high calorific value for good performances. For the biological treatment, it is mostly suitable for the organic waste that have high moisture content like food waste and garden waste. The types of waste are one of the important factors for the WtE performances and also for the implementation. The composition of waste and its characteristics may be different due to the different location. The composition of waste in that location should be determined in order to select the suitable WtE technology to be implemented in that location.

Acknowledgments

The authors would like to acknowledge the research grants from the Universiti Teknologi Malaysia (UTM) with the grant no. Q.J130000.2446.03G61 and Q.J130000.2546.12H89 and the Ainuddin Wahid Scholarship for supporting the postgraduate study.

Reference

Arena U., 2011, Process and technological aspects of municipal solid waste gasification- A review, Waste Management, 32, 625-639.

Arena U., Zaccariello L., Mastellano M.L., 2010, Fluidizes bed gasification of waste derived fuels, Waste Management, 30, 1212-1219.

Autret E., Berthier F., Luszerzanec A., Nicholas F., 2007, Incineration of municipal and assimilated wastes in France: assessment of latest energy and material recovery performances, Journal Hazardous Material,139, 569-639.

Bridgwater A.V., 2012, A review of fast pyrolysis of biomass and product upgrading, Biomass Bioenergy, 38, 68-94.

Chen Y., Cheng J.J., Creamer K.S., 2008, Inhibition of anaerobic digestion process: a review, Bioresource Technology, 99, 4044-4064.

Heerman C., Schwanger F.J., Whiting K.J., 2001, Pyrolysis and gasification of waste, A Worldwide Technology and Business Review (2nd Eds.), Juniper Consultancy Services Ltd, United Kingdom.

Izumi K., Okishio Y.K., Niwa C., Yamamoto S., Toda T., 2010, Effects of particle size on anaerobic digestion of food waste, International Biodeterioration & Biodegradation, 64, 601-608.

Kumar M., Ou Y.L., Lin J.G., 2010, Co-Composting of green waste and food waste at low C/N ratio, Waste Management, 30, 602-609.

Laurijssen J., Marsidi M., Westenbroek A., Worrell E., Faaji A., 2010, Paper and biomass for energy? The impact of paper recycling on energy and CO2 emissions, Resources, Conservation and Recycling, 54,1208-1218.

Lombardi L., Carmela E., Corti A., 2015, A review of technologies and performances of thermal treatment systems for energy recovery from waste, Waste Management, 37, 26-44.

Marin J., Kennedy K.J., Eskicioglu C., 2010, Effect of microwave irradiation on anaerobic degradability of model kitchen waste, Waste Management, 30, 1772-1779.

Pontoni L., Panico A., Salzano E., Frunzo L., Iodice P., Pirozzi F., 2015, Innovative parameters to control the efficiency of anaerobic digestion process, Chemical Engineering Transactions, 43, 2089-2094.

Sevigné-Itoiz E., Gasol C.M., Rieradevall J., Gabarrell X., 2015, Methodology of supporting decision-making of waste management with material flow analysis (MFA) and consequential life cycle assessment (CLCA): case study of waste paper recycling, Journal of Cleaner Production, 105, 253-262.

Shahholy M., Ahmad K., Mahmood G., Trivedi R.C., 2008, Municipal solid waste management in Indian cities- a review, Waste Management, 28, 459-467.

Sharudin S.D.A., Abnisa F., Daud W.M.A.W., Aroua M.K., 2015, A Review on pyrolysis of plastic waste, Energy Conversion and Management, 115, 308-326.

Yen H.W., Brune D., 2007, Anaerobic co-digestion of algae sludge and waste paper to produce methane, Bioresource Technology, 98, 130-134.

Zhang C., Xiao G., Peng L., Su H., Tan T., 2013, The anaerobic co-digestion of food waste and cattle manure, Bioresource Technology, 129, 170-176.