Waste Management 69 (2017) 407–422

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

A review on technological options of waste to energy for effective management of municipal solid waste

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ARTICLE INFO

Article history:
Received 21 April 2017
Revised 25 August 2017
Accepted 26 August 2017
Available online 5 September 2017

Keywords:
Municipal solid waste management
Waste to energy
Waste to energy technologies
Developing countries
Developed countries
Review

ABSTRACT

Approximately one-fourth population across the world rely on traditional fuels (kerosene, natural gas, biomass residue, firewood, coal, animal dung, etc.) for domestic use despite significant socioeconomic and technological development. Fossil fuel reserves are being exploited at a very fast rate to meet the increasing energy demands, so there is a need to find alternative sources of energy before all the fossil fuel reserves are depleted. Waste to energy (WTE) can be considered as a potential alternative source of energy, which is economically viable and environmentally sustainable. The present study reviewed the current global scenario of WTE technological options (incineration, pyrolysis, gasification, anaerobic digestion, and landfilling with gas recovery) for effective energy recovery and the challenges faced by developed and developing countries. This review will provide a framework for evaluating WTE technological options based on case studies of developed and developing countries. Unsanitary landfilling is the most commonly practiced waste disposal option in the developing countries. However, developed countries have realised the potential of WTE technologies for effective municipal solid waste management (MSWM). This review will help the policy makers and the implementing authorities involved in MSWM to understand the current status, challenges and barriers for effective management of municipal solid waste. This review concluded WTE as a potential renewable source of energy, which will partly meet the energy demand and ensure effective MSWM.

Contents

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http://dx.doi.org/10.1016/j.wasman.2017.08.046
0956-053X/

1. Introduction

Currently fossil fuels are the most reliable sources of energy, meeting almost 84% of the global energy demand (Shafiee and Topal, 2009). It is the time to realise the potential of waste to energy (WTE) as an option for sustainable solid waste management and as one of the most significant future renewable energy sources, which is economically viable and environmentally sustainable (Bajić et al., 2015; Kalyani and Pandey, 2014; Stehlik, 2009). Ali et al. (2012) concluded that WTE is not only sustainable waste management solution, but also an economically feasible, especially for developed countries. Baran et al. (2016) reported that energy recovery from waste incineration (one of the WTE technologies) is an integral part of environmentally sustainable waste management strategy. However, Yay (2015) did not find incineration as always economically sustainable due to its high operational and maintenance cost. WTE is a way to recover the energy from waste materials in the form of useable heat, electricity (by passing gas or steam through turbine), or fuel (Zhao et al., 2016). WTE technologies are now considered as the most suitable options for solving the waste related problems.

This paper aims to investigate municipal solid waste (MSW) as a potential renewable energy source. The present paper reviewed the available literatures on current global scenario of WTE technologies, necessary requirements for effective energy recovery and environmental impacts of different waste disposal techniques. The WTE technologies adopted in developed countries have been assessed to identify the challenges and barriers for effective implementation of WTE technologies in developing countries. In this review, 155 articles published in reputed journals, technical reports, and books related to WTE technologies (from year 1995 to 2017) were selected. More than 70% of the selected references were from year 2010 to 2017. For performing the review, a systematic approach was followed in which different aspects of WTE were identified. The identified aspects are: (i) the present status of WTE at global level, (ii) need of WTE, (iii) generation, characteristics and compositional requirements for effective energy recovery, (iv) WTE technological options and challenges associated with them in developed and developing countries, and (v) environmental and health impacts of WTE facilities. The previously published literatures and reports were selected and categorised based on these identified aspects. This study will provide a source of scientific information and analysed gap in the field of WTE to the scientific audience and waste management planners.

Global urban population is increasing at a fast rate (1.5%) than that of the total population (Ouda et al., 2016). At present, more than half of the world population live in urban areas, so the global escalation of MSW generation is mainly due to the population growth, urbanisation and economic development (Kumar and Samadder (2017)). Presently, the per capita MSW generation rate in developed countries is more than that of the developing countries, because generation rate depends on economic and social prosperity of a country. It was estimated that in coming decades the developing countries of Asia and other parts of the world will match the MSW generation rate of developed countries (Fazeli et al., 2016). Slowly, the people of developing countries are adapting lifestyle of developed nations due to globalisation, resulting in generation of large quantities of wastes. Thus, the escalation in MSW generation rate is mainly due to changing food habits, consumption pattern and living standards of the urban population (Khan et al., 2016).

Many researchers have reported that recycling is more preferred option than energy recovery (Tan et al., 2014; Ouda et al., 2016). It was observed from previous findings that the countries, which exercised high rate of energy recovery from wastes had appreciable rates of recycling, whereas, for the developing countries where landfilling is the most prevalent waste management option, recycling rates were low (Achillas et al., 2011). Arafat et al. (2015) reported the average recoverable energy contents (in terms of electrical energy efficiency) for different components of MSW using different WTE technologies (Fig. 1). From Fig. 1, it is evident that, anaerobic digestion is the best suited WTE option for food and yard wastes, whereas, gasification is the best WTE option for treating plastic wastes. Incineration remains an attractive option amongst all the waste streams (as specified by Arafat et al., 2015), as it can be used for energy recovery from all the

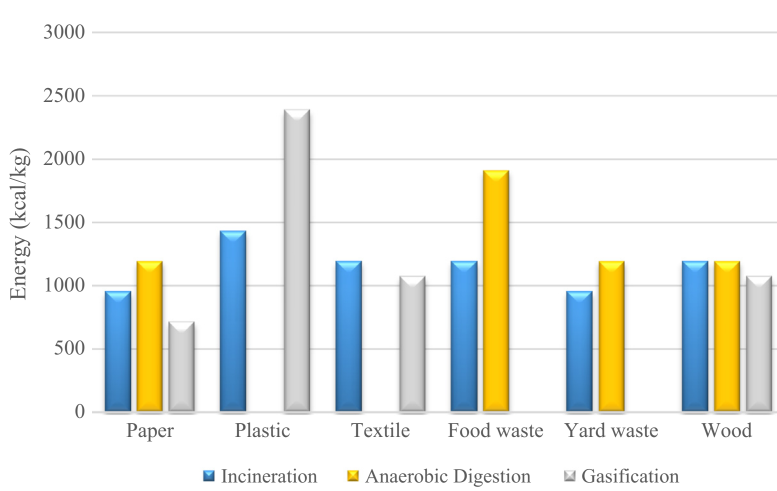

Fig. 1. Energy recovery potential of different WTE technologies for different MSW stream.

reported waste streams. However, other types of wastes such as inert, metals, glass, etc., were not considered in that study.

A major challenge, however, remains in identifying better WTE technologies. There are some social oppositions for development of the WTE facilities due to potentially toxic emissions (Zhao et al., 2016). On the other hand, some characteristics of WTE facilities are also not favourable, such as high costs and difficulties in arranging fund (Zhang et al., 2010). However, one of the major problems of WTE facilities is the protests from local communities, especially in developing countries with high population density (Ren et al., 2016; Kalyani and Pandey, 2014). Thus, for successful implementation of any WTE facility, its acceptance by the local community is important (Kikuchi and Gerardo, 2009). Developed countries have realised the potential of WTE options and have started implementing it for effective waste management successfully.

1.1. Present scenario of waste to energy at global level

The world population was 3 billion in 1960, which has increased to 7 billion in 2011 and it is expected to reach 8.1 billion by 2025 (FAO, 2013). The dramatic increase in global population coupled with economic development had led to rapid urbanisation and industrialisation, which changed the consumption pattern of the population that ultimately lead to the proliferation of MSW at an alarming rate. Many countries started adopting the WTE technologies for effective management of huge quantity of waste to produce energy. An estimate by the International Renewable Energy Agency, showed that the world has a potential of generating approximately 13 Giga Watt of energy from WTE sector alone (IRENA, 2016). The WTE technologies have been greatly modernised and prioritised especially in the developed nations. In 2012, USA alone generated 14.5 million MWh of electricity from 84 WTE facilities (ERC, 2014). Incineration is the most widely used WTE option in populous countries like China (Liu et al., 2006), which had around 160 incineration plants in operation till 2010 (Lianghu et al., 2014). There were about 1900 waste incineration plants in Japan, out of which, only 190 incineration plants were equipped with power generation facilities (Montejo et al., 2011), but Bajić et al. (2015) reported that only 102 waste incineration plants were in operation for electricity generation in Japan. Japan is followed by the European Union (mainly France), and then the United States in terms of quantity of waste incinerated (Montejo et al., 2011). Out of the total quantity of MSW generated, 74% in Japan, 54% in Denmark, 50% in both Switzerland and Sweden are incinerated (The World Bank, 2012; Psomopoulos et al., 2009). Italy installed many anaerobic co-digestion plants with capacity ranging from 50 kW to 1 MW (Pantaleo et al., 2013). The International Solid Waste Association (ISWA) reported that, globally more than 130 million tonnes of MSW per year (10% of the total generated waste globally) is treated to generate electricity (ISWA, 2012). A study carried out by Earth Engineering Center of Columbia University in 2013 regarding the percentage of waste recycled/composted, landfilled or diverted towards WTE facility across different countries found that most of the developed countries prefer to use environmentally sustainable techniques such as recycling/composting and WTE for the management of their generated wastes (ERC, 2014). The European countries such as Netherlands, Belgium, Denmark, Germany, Austria, Sweden and Switzerland divert most of their wastes from landfill for recycling and composting facilities (Defra, 2013). In Asian countries, Singapore recycles 44% of their generated wastes, while in other countries (mostly developing), typically 8–11% wastes are recycled (Ngoc and Schnitzer, 2009). It has been reported that, some cities such as Hanoi, achieved recycling rate of 20–30% (Velis et al., 2012). Many developing countries such as India, Vietnam, and Malaysia have started recovering energy from organic wastes, but at smaller scale. Nguyen et al. (2014) estimated that, food waste alone could meet up to 4.1% of Vietnam's electricity demand if converted into biogas using anaerobic digestion process. The potential of WTE technologies has not yet been recognised by many of the developing countries.

1.2. Need of waste to energy

At the end of this century, the global energy demand is expected to be about six times more than that of the current demand (Kothari et al., 2010). The current available energy supply is much lower than the actual energy required for consumption in many of the developing countries. At present, one of the primary sources of energy throughout the world is fossil fuels that meet the demand of approximately 84% of the total electricity generation (Ouda et al., 2016). Due to rapid depletion of fossil fuel reserves, the world needs alternative sources of energy such as WTE for mitigating the future energy crisis (Charters, 2001). The problem of disposal of huge quantity of generated MSW and the requirement of reliable source of renewable energy are common in many developing countries. MSW causes serious environmental pollution, thus its use as a potential renewable energy source would serve the purpose of meeting increased energy demand as well as waste disposal.

Technological advancement, improved pollution control systems, governmental incentives and stringent regulations have made WTE technology a potential alternative, especially for the developed countries. It not only provides a source of energy, but also reduces the potential harmful impacts of waste on the environment. If 1 tonne of MSW is incinerated for electricity generation instead of landfilling (without gas recovery), then 1.3 tonnes of CO_2 equivalent emissions can be avoided if equivalent CO_2 emissions from fossil fuel based power plants are also considered to generate the same amount of electricity (ASME, 2008). The waste incineration plants with energy recovery facility run with pre-treated MSW as a primary fuel have slightly low net carbon emission factor (0.04–0.14 kg/MJ) compared to fossil fuel based power plants (Patumsawad and Cliffe, 2002). The restrictions on landfill sites for MSW disposal and increase in public awareness on environmental impacts of MSW have forced the governments to find more effective ways of MSW disposal (Zhao et al., 2016). The land requirement for WTE facilities is much less than that of landfill facilities for handling same quantity of waste (Jamasb and Nepal, 2010). WTE plant processing 1 million tonnes of wastes per year has an average working life of more than 30 years and requires less than 100,000 m^2 of land, whereas a landfill for 30 million tonnes of MSW requires a land of 300,000 m^2.

2. Waste generation, characteristics and composition

Before selection and implementation of WTE technologies, it is necessary to know the amount of waste generated its characteristics and compositions. According to the World Bank report 2012, the global MSW generation rate was 1.3 billion tonnes per year with average generation rate of 1.2 kg/c/d. The generation rate of MSW is expected to reach 2.2 billion tonnes per year by 2025 and 4.2 billion tonnes per year by 2050 (Hoornweg and Bhada-Tata, 2012). The solid waste generation rate is directly proportional to the Gross Domestic Product (GDP) of developing countries. Fig. 2 depicts the relationships between GDP of some countries and their per capita MSW generation rates. Countries were categorised by International Monetary Fund into developed and developing countries based on GDP per capita (Troschinetz and Mihelcic, 2009). The countries with GDP per capita greater than US$ 10,000 per annum were termed as developed nations. Accordingly, the countries with

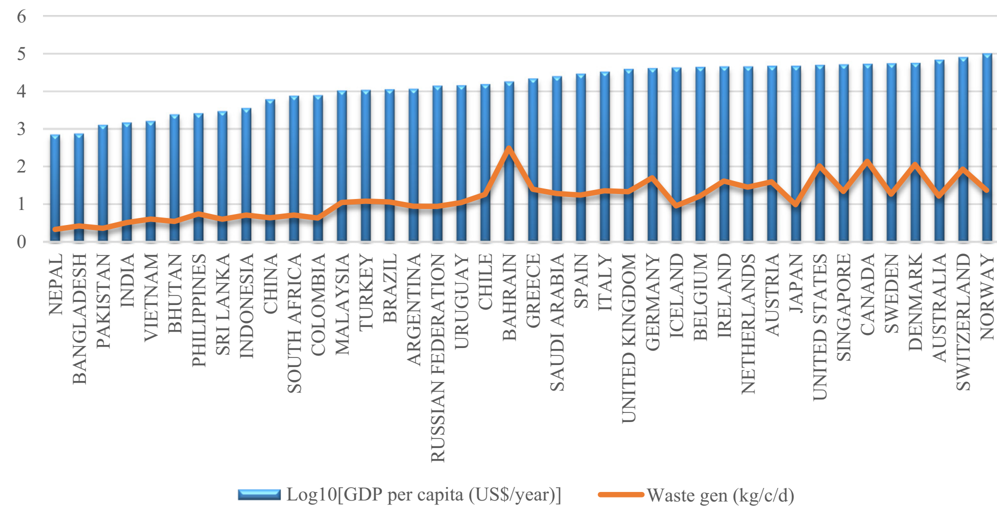

Fig. 2. Distribution of Waste generation rate and GDP of the different countries (Waste Atlas, 2016).

a numerical value of more than 4 [i.e. $\log_{10}$ {GDP per capita (US$/year)}] were considered as developed and the rest of the countries were considered as the developing countries in the present study. The MSW generation rate is directly linked with overall development of a country. Most of the countries (as presented in Fig. 2) showed linear relationships between GDP per capita and MSW generation rate per capita. This result is consistent with the previously reported studies (Hoornweg and Bhada-Tata, 2012; Shekdar, 2009). However, Medina (1997) reported a weak correlation between the wealth of a country and MSW generation rate. Another important observation from the Fig. 2 is that, a few of the developed countries such as Iceland, Japan, Singapore, Sweden, Australia, and Norway had less MSW generation rate as compared to the other developed countries; this may be attributed to the different definitions of MSW adopted by different countries (Aleluia and Ferrão, 2016) as well as the adopted waste reduction policies in countries such as Japan (Tanaka, 2014). The typical waste generation rate of developed countries ranges from 1.00 to 2.50 kg/c/d and 0.50 to 1.00 kg/c/d for developing countries (Thitame et al., 2010).

For an effective management of MSW of a city using suitable WTE facilities, it is absolutely essential to know the characteristics and compositions of the generated waste (Yadav and Samadder, 2017). Actual energy production from MSW is significantly dependent on these two parameters. The characteristics such as particle size, moisture content, calorific value and density (Aleluia and Ferrão, 2016) are important factors for selecting and developing an appropriate WTE facility. The waste characteristics and composition vary significantly across developed and developing countries, even the cities of the same country have different waste characteristics because of the heterogeneous nature of MSW. The waste composition in various income group countries is shown in Table 1 (Hoornweg and Bhada-Tata, 2012). The physical composition and characteristics of MSW depend upon various factors, such as socioeconomic profile, climatic conditions of an area, extent of recycling, collection frequency, demography, etc. Using the previously reported studies on physical classification of MSW, the waste stream has been divided into six different components namely; kitchen/yard waste, paper/cardboard, plastic, metals and glass, inert and miscellaneous (Table 2). The MSW of

Table 1
Average waste composition in various income group countries.

Type of countries	Organic (%)	Paper (%)	Plastic (%)	Metals and glass (%)	Others (%)
Low income group	64	6	9	6	15
Middle income group	56	12	13	7	12
High income group	28	30	11	13	18

Table 2
Physical classification of MSW.

Component	Material	References
Kitchen/yard waste	Food waste (e.g., food and vegetable refuse, fruit skins, corncob), yard waste (e.g., leaves, grass, tree trimmings), etc.	Bajić et al. (2015), Qu et al. (2009) and Eddine and Salah (2012)
Paper/cardboard	Paper bags, cardboard, corrugated board, box board, newsprint, magazines, tissue, office paper, and mixed paper, etc.	
Plastic	High-valued plastics [LDPE bottles (shampoo bottles, detergent bottles, etc.), polypropylene bottles (mess tins made from rigid plastics, etc.), PET bottles (beverage bottles, etc.)], Low-valued plastics (Polythene plastic bags, polystyrene plastic packages such as mess tins made from flexible plastics and plastic cup for yoghurt, ice-cream, etc.) and others.	
Metals & glass	Ferrous (e.g., food cans, etc.), non-ferrous (e.g., aluminium cans, foil, ware, and bimetal, etc.), wire, fence, knives, bottle covers, etc., and bottles, glassware, light bulbs, ceramics, etc.	
Inert	Stones and silt, soil, ash, dust, other inorganic material, etc.	
Miscellaneous	Discarded clothes, rags, leather, rubber, used batteries, medical waste, nappies/sanitary products, etc.	

Table 3
Calorific value of MSW of developed and developing countries.

Countries	Calorific value (kcal/kg)	References
Developing	Bangladesh (717)	Hossain et al. (2014)
	China (1200–1600)	Zhou et al. (2014)
	India (800–1100)	Unnikrishnan and Singh (2010)
	Malaysia (1500–2600)	Kathirvale et al. (2004)
	Sri Lanka (950–1250)	Reddy (2011)
	Thailand (500–1500)	Reddy (2011)
Developed	Japan (2000–2200)	Hla and Roberts (2015)
	S. Korea (2600–3000)	Yi et al. (2011)
	UK (2200–3000)	Hla and Roberts (2015)

developed countries has less moisture content, for e.g., in USA and European countries it varies from 20 to 30% as compared to 50 to 70% in developing countries such as in China and India (Cheng et al., 2007; Mohee and Mudhoo, 2012). However, the waste stream of developed countries has high calorific values (2000–4000 kcal/kg) as compared to the developing countries (700–1600 kcal/kg) due to the presence of high percentage of paper and other dry organic wastes (Patumsawad and Cliffe, 2002). The calorific values of MSW stream of some of the countries are shown in Table 3. In high income group countries, the decomposable organic fraction in their MSW stream is less and the fraction of plastics, paper, textiles and other recyclable wastes is more. The organic content in MSW is below 30% (by weight) in developed countries such as Japan, USA, Singapore and South Korea, but the same in developing countries such as China, Sri Lanka, Pakistan, and India is more than 50% (Aleluia and Ferrão, 2016).

3. Heating values of municipal solid waste

One of the important parameters for determination of energy content of MSW is the heating value or the calorific value. Therefore, it is necessary to have reliable and accurate heating value data of MSW components for efficient design and successful operation and maintenance of a WTE facility (Shi et al., 2016). A major problem is the inconsistencies in reporting the energy content of MSW. Generally, the reported studies described the energy content in terms of higher heating value (HHV), lower heating value (LHV), calorific value, net heating value, gross heating value (Kathiravale et al., 2003; González et al., 2001). Although these values are inter-related, but this inconsistency causes confusion to the readers in comparing the results. The calorific value is normally classified into HHV and LHV. LHV is the energy content available from complete combustion and does not consider the latent heat of vaporisation of moisture present in waste stream. Whereas, HHV is the theoretical maximum energy content in which latent heat of vaporisation of wastes is taken into consideration and is generally measured with the help of a bomb calorimeter and sometimes with the help of equations, which is a function of ultimate analysis of the substrate (Komilis et al., 2012). However, the measurements of heating value using bomb calorimeter is tedious, requires skilled operator and all MSW management (MSWM) facilities are not always equipped with bomb calorimeter (Kathiravale et al., 2003). The most commonly used equation in theoretical estimation of heating value is Dulong equation (Kathiravale et al., 2003), which was originally developed for estimation of heating value of coal and may not be applicable for the estimation of heating value of MSW (Shi et al., 2016). LHV calculation is based on the HHV and moisture content of feedstock (Abu-Qudais and Abu-Qdais, 2000; Komilis et al., 2012). LHV has more practical applications than HHV and it is largely used in energy estimation, as this is the energy that is actually used in electricity generation from a MSW incinerator (Komilis et al., 2014).

4. Waste to energy options

The aims of any waste management system are material and energy recovery, followed by disposal of the residues. But, an optimal choice for a waste processing technology is not only subject to economic requirements, energy recovery or waste destruction ability, but also to look for environmental regulatory compliance requirements of the concerned area. Therefore, it is necessary to select the best available technology for waste processing, which fulfils all the required criteria for a successful operation (Ali et al., 2010). A variety of waste conversion processes are available, in which the three most widely used technologies are (Kalyani and Pandey, 2014): (i) thermal conversion [(incineration, pyrolysis, gasification, production of energy from refuse derived fuel (RDF)], (ii) biological conversion (anaerobic digestion/biomethanation and composting), and (iii) landfilling with gas recovery. The MSW treatment techniques along with the typical reaction products are shown in Fig. 3.

4.1. Thermal conversion technologies

Thermal conversion involves thermal treatment of organic matter present in MSW to produce either heat energy, fuel oil or gas. Thermal conversion technology is generally useful for dry waste (low moisture content) with high percentage of non-biodegradable organic matter. Sometimes, thermal conversion technology is applied to RDF, which is a combustible material with high calorific value. For production of RDF, the recyclable and non-combustible materials are removed from MSW followed by shredding and/or pelletisation of the remaining waste. Incineration, which is a controlled combustion of wastes at high temperature is the most widely used method in thermal conversion technology (Shi et al., 2016). The other thermal conversion technologies (pyrolysis and gasification) are still in research phase and they are not feasible for commercial purpose at large scale, may be due to lack of proper MSW characterisation data, poor feedstock quality and inappropriate design of the facility (Appels et al., 2011; Shi et al., 2016). There are very few commercially operating pyrolysis/gasification plants across the world for treating MSW. These plants operate for treating MSW along with some other type of wastes such as industrial waste, biomedical waste, biomass, etc. (Ionescu et al., 2013). The typical reaction conditions and products from thermal treatment processes are shown in Table 4. The main differences among these three thermal treatment processes are the atmospheric condition (i.e., presence of oxygen) and the operating temperature. The quality of the final products and the useful intermediate products depends mainly on these two parameters. Operating temperature of thermal processes largely depends on the process design and feedstock materials. For incineration process, pre-treatment of MSW is generally not practiced in developing countries; raw MSW is directly used as a feedstock materials.

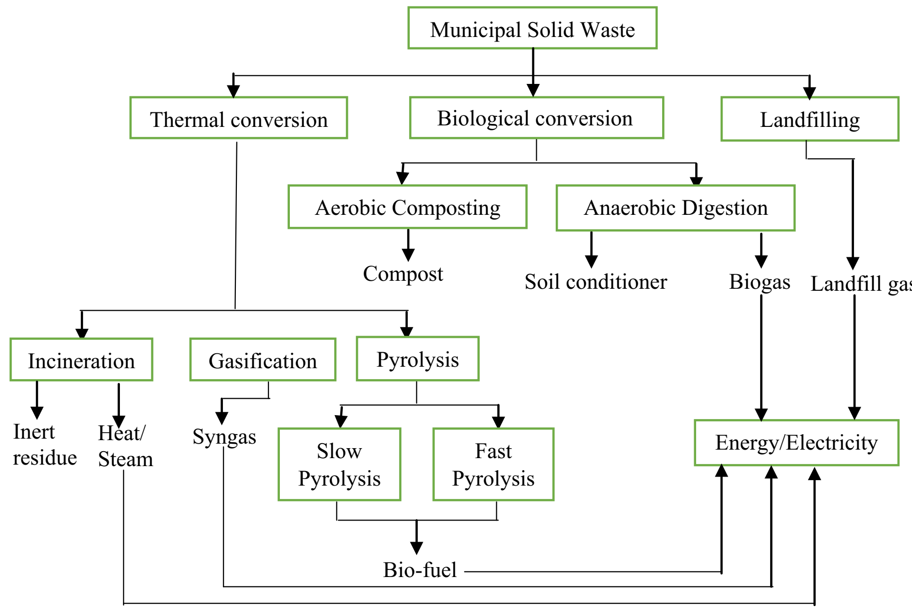

Fig. 3. Municipal solid waste treatment techniques and their products.

Table 4
Typical reaction conditions and products from thermal treatment processes.

Parameters		Incineration	Pyrolysis	Gasification
Principle		Full oxidative combustion	Thermal degradation of organic material in the absence of oxygen	Partial oxidation
Operating temperature (°C)		850–1200	400–800	800–1600
Atmosphere		Presence of sufficient oxygen	Absence of oxygen	Controlled supply of oxygen
Reaction products	Solid	Bottom ash, fly ash, slag, other non-combustible substances like metals and glass	Ash, char (combination of non-combustible and carbon)	Ash, slag
	Liquid		Condensate of pyrolysis gas (pyrolysis oil, wax, tar)	
	Gas	CO_2, H_2O, O_2, N_2	Pyrolysis gas (H_2, CO, hydrocarbons, H_2O, N_2)	Syngas (H_2, CO, CO_2, CH_4, H_2O, N_2)
Pre-treatment		Not necessary	Required	Required
Raw MSW		Usually preferred	Usually not preferred	Usually not preferred

4.1.1. Incineration

Initially the incinerators were used for volume reduction and protecting the men and environment from the hazardous wastes, but not for energy recovery (Brunner and Rechberger, 2015). After advances in air pollution control technologies, incineration is now considered as an attractive waste treatment option, especially in the developed countries (Psomopoulos et al., 2009; Ouda et al., 2016). Scarlat et al. (2015) reported that incineration is one of the most common waste disposal techniques in the developed countries (EU, US and Japan) due to the stringent waste-related regulations on waste disposal using landfilling. The emissions from waste incinerators have been reduced to such an extent that in 2003, the United States Environmental Protection Agency (US EPA) declared incineration of MSW as a cleaner source of energy (Leme et al., 2014). Incineration is the most common waste treatment techniques in which, the waste mass and volume can be reduced by 70% and 90% respectively (Cheng and Hu, 2010; Nixon et al., 2013a,b; Gohlke and Martin, 2007; Lombardi et al., 2015); at the same time, heat and/or electricity can also be produced (Singh et al., 2011). From incinerators, heat is supplied if there is a requirement for district heating (in cold countries), sometimes it is supplied to the industries like paper mill, and electricity is produced in all the other cases (Brunner and Rechberger, 2015). But in a few recent studies (Meylan and Spoerri, 2014; Allegrini et al., 2014), the scientists highlighted some other advantages of incineration apart from volume reduction and electricity generation such as, utilisation of bottom and fly ash of incineration plants in road construction & cement production and recovery of ferrous and non-ferrous substances. Thus, further technological development in metal recovery from dry bottom ash of incineration plants will enhance the acceptance of WTE facilities (Morf et al., 2013). But in the developing countries, the incineration is considered as the most reliable and economical when it is used for mass burning without pre-treatment of MSW for electricity generation. Incineration generally takes place at different stages depending upon the operating conditions and type of wastes incinerated (Table 5). One of the main advantages of MSW incineration is the complete destruction of any living organisms and mineralisation of organic substances into harmless end products (Brunner and Rechberger, 2015).

MSW composition and characteristics are highly heterogeneous, thus they must be evaluated before designing any WTE

Table 5
Stages of incineration process.

S. No.	Steps	References
1	• Drying and degassing • Pyrolysis and gasification • Oxidation	Tabasová et al. (2012)
2	• Incineration • Energy recovery • Air pollution control	Lee et al. (2007) and Zheng et al. (2014)
3	• Waste delivery and storage section (bunker) • Waste combustion section (furnace) • Energy recovery and conversion section • Flue gas cleaning section	Branchini (2015)

facility (Turconi et al., 2011). Tan et al. (2014) suggested that, incineration is suitable for combustible non-biodegradable MSW with low moisture content. Sometimes auxiliary fuels are used along with MSW during incineration, but it is worth to note that the use of auxiliary fuels along with MSW is not required when the LHV of waste is between 1000 kcal/kg and 1700 kcal/kg or above (Chen and Christensen, 2010; Komilis et al., 2014). According to the World Bank report, the average calorific value of MSW should be at least 1700 kcal/kg (World Bank, 1999) for an effective incineration operation with energy recovery, whereas, according to International Energy Agency, the values must be greater than 1900 kcal/kg for the incineration operation to be feasible (Melikoglu, 2013). It is apparent that the presence of inert waste and moisture content reduces the calorific value and affects the combustibility of MSW, which directly affects the performance of an incinerator. As the moisture content increases in the waste stream, its calorific value starts decreasing due to latent heat of vaporisation. Therefore, sometimes pre-treatment (thermal, mechanical, chemical and biological) of wastes are done to remove the excess moisture content, inert waste and toxic elements such as chlorine and mercury (Lombardi et al., 2015). A typical incinerator generates 544 kWh of energy and 180 kg of solid residue per tonne of MSW incinerated (Zaman, 2010).

4.1.1.1. Incineration in developed and developing countries. Modern MSW incineration plants operate quite well for recovering energy in the form of steam for electricity generation in cities of industrialised nations (Psomopoulos et al., 2009). Less annual capital cost, operational cost, better skill of the operators, higher daily throughput (Psomopoulos et al., 2009), and high calorific value of the MSW altogether made incineration a more attractive than other WTE technologies for the cities of developed countries. In Asian countries, Japan is particularly famous for waste incineration technology due to stringent regulation and limited land area for waste dumping. Incineration of MSW is done widely in different Western European countries ranging from 35% to as much as 80% of the total waste generated (Reddy, 2011). Other European countries also rely significantly on incineration for handling municipal waste. The North-eastern US recovers energy from more than 40% of its total solid waste generated using incineration only. Incineration is not feasible for many developing countries except those with fast growing economies (such as China, Malaysia, etc.), due to (a) the high capital, operating and maintenance costs, (b) unfavourable characteristics and composition of wastes, (c) lack of technical expertise in the field, and (d) availability of comparatively low cost land for waste disposal. But, China had gone for huge expansion in MSW incineration in the past decade and is expected to reach up to 500,000 tonnes/d by 2020 (Lu et al., 2017). Li et al. (2015) reported that, till 2013 China had 166 operational incineration plants for generation of electricity using MSW at the rate of 166,000 tonnes/d. Cheng and Hu (2010) claimed that the waste incineration had more contribution to the overall renewable energy generation in China. But Lombardi et al. (2015) reported that China is facing several problems in MSW incineration due to poor waste feedstock quality, incomplete combustion, and increased air pollution. High moisture content, variable composition and low energy content are some other major difficulties faced in incinerating wastes in developing countries (Reddy, 2011).

4.1.2. Pyrolysis

Pyrolysis is an advanced thermal treatment method. It takes place in the temperature range of 400–800 °C in absence of oxygen. It produces pyrolysis gas, oil and char, whose yield and quality mainly depend upon the heating rate, process temperature, residence time (Lombardi et al., 2015), composition of wastes, and particle size of the waste (Kalyani and Pandey, 2014). At lower temperature (500–550 °C), pyrolysis oil, wax and tar are the major products, and at higher temperature (>700 °C), pyrolysis gases are the major products. For good quality pyrolysis products, the feedstock should be of specific type of wastes (plastic, tyre, electronic equipment, electric waste, wood waste, etc.). Pyrolysis of specific type of wastes was reported in various previous studies, which focussed on the process itself rather than the possible commercial use of pyrolysis products. In particular, pyrolysis has received special attention recently for recycling of scrap tyres for recovery of oil, wire, carbon black and gas (Lombardi et al., 2015). As, it is evident that pyrolysis performs well in treating specific waste stream, but very limited studies have been reported about energy recovery from MSW using pyrolysis at commercial scale. A plant of 110 tonnes/d capacity in Burgau, Germany has been successfully generating electricity through MSW pyrolysis since 1987 (Lombardi et al., 2015). Panepinto et al. (2014) reported about some other successfully operating MSW pyrolysis plants such as in Hamm, Germany (275 tonnes/d), Toyohashi, Japan (295 tonnes/d), UK (22 tonnes/d), and France (191 tonnes/d). Baggio et al. (2008) reported that pyrolysis of MSW for production of gas can be used for energy recovery using Gas Turbines with a net conversion efficiency of 28–30%.

4.1.3. Gasification

Gasification is another thermal conversion technology, in which organic compound gets converted into syngas in controlled atmosphere of oxygen at high temperature. Syngas is the main product of gasification process, which can be used to produce energy through combustion. It can also be used to produce feedstock for chemicals and liquid fuel (Yap and Nixon, 2015). Most of the reported gasification studies are focussed on homogeneous flow of solid fuel (coal, wood, etc.) and specific type of MSW. Gasification has been widely used in coal industry, but recently it has been considered as a potential energy recovery option from MSW (Arafat and Jijakli, 2013). Panepinto et al. (2014) investigated 100 plants around the world that use gasification technique to process

MSW. MSW gasification technology is widely used in Japan, where 85 plants were operating till 2007. In other countries (such as in USA, UK, Italy, Germany, Norway and Iceland), gasification has been used to process MSW at smaller scale (Panepinto et al., 2014). It has been reported that gasification process generates less CO_2 than the incinerator of similar capacity (Murphy and McKeogh, 2004). Defra (2013) reported that, modern gasification units come with enclosures, which effectively reduce the chance of water and soil contamination. Asia has seen a huge leap in the gasification technology in last few years and can be considered as one of the most favourable markets for gasification technology followed by Europe, Africa and USA (Ouda et al., 2016).

Zaman (2010) reported that pyrolysis and gasification technologies are more favourable than the incineration technology for MSW from environmental impact and energy recovery prospective. Pyrolysis and gasification technologies can reduce the waste volume by 95% and require less intensive flue gas cleaning as compared to incineration (Yap and Nixon, 2015). Pyrolysis and gasification techniques are better than other WTE options in view of environmental emissions and energy recovery efficiency. However, they are yet to be established at large scale across the world (predominantly in developing countries) for energy recovery from MSW (Luz et al., 2015) due to poor efficiency of gasifiers and gas cleaning systems, heterogeneity in MSW composition & particle size, and high moisture content.

4.2. Biological conversion technology

Biological conversion technology is based on microbial decomposition of the organic content of MSW. Many researchers reported this technology as environmentally suitable for energy recovery from wastes (Pant et al., 2010). It is generally preferred for the wastes with high percentage of organic biodegradable matter (putrescible) and high moisture content. The main technological option for energy recovery under this category is anaerobic digestion or biomethanation.

4.2.1. Anaerobic digestion

Anaerobic digestion (or biomethanation) is a process of microbial degradation of organic biodegradable matter in absence of oxygen that produces biogas and stabilises the sludge. The quality of the generated biogas depends on the process parameters and substrate composition; the biogas is typically composed of 50–75% CH_4, 25–50% CO_2 and 1–15% of other gases (such as, water vapour, NH_3, H_2S, etc.) (Surendra et al., 2014). The produced slurry/sludge can be used as a soil conditioner and/or as an organic amendment in agricultural field (Pivato et al., 2016; Tambone et al., 2009). Anaerobic digestion is used to recover both nutrient and energy from biodegradable waste. Ali et al. (2016) reported that, the quality (as a fertiliser) of solid products of anaerobic digestion depends mainly on the quality of feedstock (proteins, minerals and vitamins content of waste). Browne et al. (2014) reported that European legislation prohibited the use of solid products of anaerobic digestion as a fertiliser, due to the presence of undesirable materials in feedstock. In anaerobic digestion, the organic fraction of the biodegradable MSW gets degraded and converted into methane through a series of stages. The initial stage is called hydrolysis, in which the complex organic compounds of MSW like carbohydrates, proteins and fats get converted into soluble organic materials such as sugars, amino and fatty acids. Fermentation is the next stage of anaerobic digestion process in which the organic molecules break into acetic acid, H_2 and CO_2. The final stage is methanogenesis, in which methane formation takes place. The detailed process flow for conversion of organic matter into methane is shown in Fig. 4. The anaerobic digestion processes are mainly of two types, "wet" (10–15% of dry matter content), and "dry" (24–40% of dry matter content) processes (Luning et al., 2003). Wet process produces more liquid waste and less solid product. The required volume of reactor for wet process is less than that of the dry process. The type of reactors (single stage or multi stage), processes (wet or dry) and methane yield depend on the region, quality of feedstock and the product requirements.

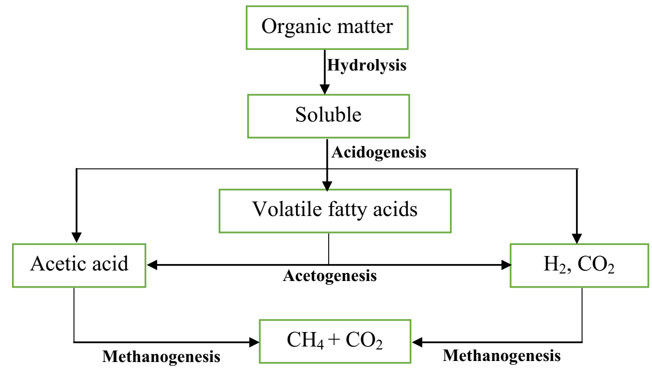

Fig. 4. Stages in anaerobic digestion process.

It has been estimated that anaerobic digestion can produce 2–4 times more methane per tonne of MSW in 3 weeks than that of a landfill in 6–7 years (Ahsan, 1999; Saxena et al., 2009). Murphy et al. (2004) reported that 1 m^3 of biogas produced from anaerobic digestion process can generate 2.04 kWh of electricity taking conversion efficiency of 35%. About 150 kg of methane can be generated from anaerobic digestion of 1 tonne of MSW considering 60% organic matter and 40% moisture (Scarlat et al., 2015). However, the major problem associated with this process is the long duration (typically 20–40 days) of microbial reaction (Pham et al., 2015). Sometimes, presence of nitrogen rich components and cations (such as sodium, potassium, and calcium) in the waste stream increases ammonia and salt concentrations (Fountoulakis et al., 2008; Chen et al., 2008) that makes the process toxic for methanogenic activities. Several studies (Gomez et al., 2006; Cristancho and Arellano, 2006) suggested co-digestion of MSW with low nitrogen content waste, sewage sludge, and food waste to reduce the high ammonia concentrations and to increase the biogas yield of the process. The methane yield of organic fraction of MSW under different operating conditions reported by various researchers is summarised in Table 6. Most of the researchers used food wastes along with the suitable inoculum for maximum gas recovery. The quality of the biogas generated using anaerobic digestion technology can be improved by removing CO_2 and other trace gases for use as a transportation fuel called biomethane. This can substitute natural gas in variety of domestic and industrial applications (Kasturirangan, 2014; Appels et al., 2008). Earlier, anaerobic digestion was used for treatment of domestic sewage, agricultural waste, organic waste and animal manure, but now it is extensively used for energy recovery from MSW especially in the developing countries, where wastes have high moisture content (Yap and Nixon, 2015). Abbas et al. (2017) and Ali et al. (2013a,b) evaluated the feasibility of biogas recovery and found that the biogas recovered from anaerobic digestion technology is economically and environmentally sustainable.

4.3. Landfilling

Sanitary landfilling is defined as the controlled disposal of wastes on land to reduce the negative impact on the environment through biogas recovery and leachate management (Fig. 5). However, unsanitary landfilling offers a simpler and affordable solution

Table 6
Methane yield during anaerobic digestion of MSW.

References	Feedstock material	Sampling area	Type of reactor	Operating conditions	Inoculum	Methane yield	Observations/remarks
Zhang et al. (2007)	Food waste from restaurants, hotels and grocery store	San Francisco, California	Batch (1 L)	Avg. moisture content and Volatile Solids/Total Solids (VS/TS) was 70% and 83% respectively, temperature was thermophilic (50 ± 2 °C). The reactor was monitored for 28 days	Sludge from wastewater treatment plant	435 mL CH_4/g of VS	Samples of weekends were not taken for the analysis. Samples were taken from the waste management company (responsible for waste collection). Thus, direct sampling from the source of generation could have reduced the contamination of food waste from other types of wastes and the methane yield might have increased.
Macias-Corral et al. (2008)	Organic fraction of MSW (OFMSW)	New Mexico, USA	Batch	Avg. VS was 82%, temperature was thermophilic (55 °C)	Supernatant from anaerobic wastewater treatment plant	37 mL CH_4/g of dry waste	Samples were taken from kerbside collection truck and then segregated into organic fraction which might have reduced the quality of the samples. The OFMSW contains mainly paper waste (70%).
Yong et al. (2015)	Food waste and straw	Beijing, China	Batch (1 L)	Organic loading was 5 g VS/L, performed at mesophilic temperature (35 °C)	Anaerobic granular sludge from starch processing waste water	0.392 m^3 CH_4/kg of VS	The methane yield has been increased by 39.5% and 149.7% compared with individual digestion results of food waste and straw respectively. The carbon to nitrogen (C/N) ratio for optimum digestion should be in range of 25–30. But the C/N ratio of food waste and straw was 28.4 and 43.4 respectively and thus the C/N ratio of mixed waste was on slightly higher side of optimum values.
Scano et al. (2014)	Fruit and vegetable wastes	Sardinia, Italy	Continuous (1.13 m^3)	The reactor was monitored for 174 days and maintained at mesophilic conditions (35 ± 0.5 °C)	Digestate of pig manure	0.43 Nm^3 CH_4/kg of VS	Fruit wastes have high sugar content which increases the CO_2 concentration in the biogas and reduces the CH_4 yield. Thus, optimum loading rate of substrates is very much essential.
Komemoto et al. (2009)	Food waste	Saitama, Japan	Batch (2 L)	TS and VS of the sampled waste was 16% and 94% respectively. The experiment was performed at six different temp. 15 °C, 25 °C, 35 °C, 45 °C, 55 °C and 65 °C	No inoculum	64.7 mL CH_4/g of VS	Biogas production was found more at mesophilic conditions (35 °C and 45 °C) than the thermophilic, which is contrary to the findings of several previous researches. But at thermophilic condition the HRT is less which will effectively reduce the reactor size.
Haider et al. (2015)	Food waste and rice husk	Islamabad and Faisalabad, Pakistan	Batch (1 L)	TS of food waste and rice husk was 24% and 90% resp., whereas VS was 92% and 81% resp. The reactor was monitored for 45 days at mesophilic conditions (37 ± 1 °C)	Acclimatised cow dung	584 mL biogas/g of VS	Food waste and rice husk were mixed in different ratios to get the desired level of C/N ratio. Cow dung as inoculum reduces the accumulation of VFA, thus protects digester from failure. Purity of the biogas was not mentioned.
Ma et al. (2011)	Kitchen waste	Belgium	Batch (1.2 L)	TS and VS of waste was 166 g/kg and 155 g/kg resp. The reactor operated at thermophilic conditions (55 ± 2 °C)	Sludge from potato waste treatment plant	520 mL biogas/g of COD	Different pre-treatment techniques (acid, thermal, thermo-acid, pressure-depressure, freeze-thaw) were applied to the kitchen waste and were found that the biogas yield improved with the pre-treated kitchen waste as compared to the raw kitchen waste. However, the process is not feasible in the developing countries due to less conversion efficiency of biogas to energy, making the process costly.

for disposal of the increasing waste quantity and is the most common practice in developing countries, that poses a serious threat to the environment (Wang and Geng, 2015). Previous studies showed that landfilling causes the highest environmental impact compared to other waste management options (Cherubini et al., 2009; Emery et al., 2007; Marchettini et al., 2007; ISWA, 2012). It has been reported that most of the cities of developing countries, the waste is disposed on low lying areas located at the outskirts of the city (Talyan et al., 2008; Kumar and Chakrabarti, 2010). When the factors such as environmental impact, health impact, land degradation, and groundwater contamination are considered, landfilling becomes the worst option. However, developed countries have started to discourage landfilling of wastes through stringent regulations, waste reduction and recycling. The landfill leachate (a dark effluent of unusually variable composition with recalcitrant compounds) is a major polluting substance released from landfills or

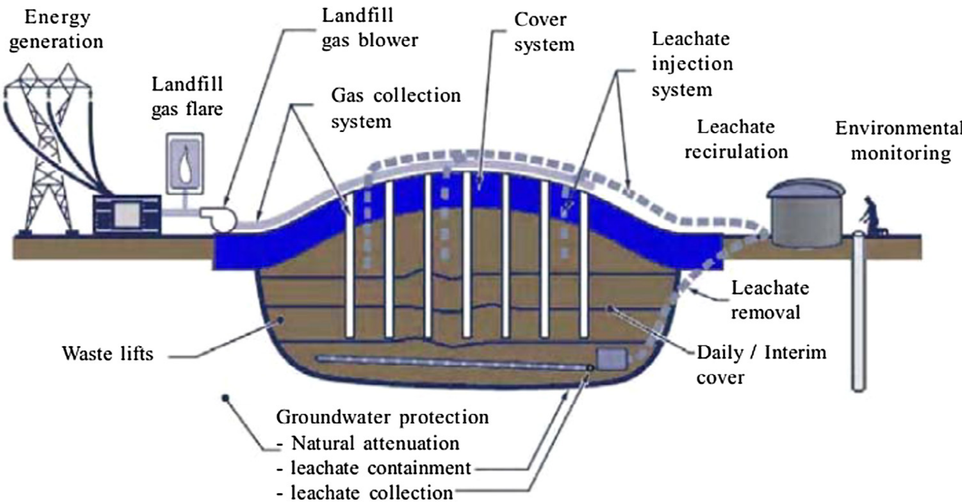

Fig. 5. A typical engineered landfill with biogas recovery system. Source: Zaman, 2010.

dumpsites (Müller et al., 2015) that pollutes the nearby surface water courses and groundwater aquifers. According to experts, only 10–15% of the total waste generated should go for landfilling and it should be the last option for cities where land is limited.

4.3.1. Modelling landfill gas generation

The organic matter present in the deposited wastes in landfills undergoes complex biological and chemical decomposition that results in the production of landfill gas (LFG). The degradation of organic matter into LFG occurs in five different phases (Noor et al., 2013). The first phase is hydrolysis/aerobic degradation, in which the aerobic bacteria breaks complex organic matter into CO_2 and H_2O. The second phase is hydrolysis and fermentation, in which the soluble organic components are decomposed into CO_2, H_2, NH_3 and organic acids in presence of facultative bacteria. The third phase is acidogenesis/acetogenesis, in which the organic acids produced during second phase get converted into acetic acid, formic acid, alcohols, H_2 and CO_2 by anaerobic bacteria. In the fourth phase (methanogenesis), the methanogenic bacteria consumes the product of the third phase and produces primarily CH_4, CO_2, as well as other trace gases in smaller amount. The final phase is oxidation, in which CH_4 gets converted into CO_2 and H_2O under aerobic condition. The LFG production rate inside a landfill depends on various factors, such as, type of landfill, waste composition, climatic condition (temperature and precipitation), moisture content, and waste age (Scarlat et al., 2015). LFG contains 50–60% methane (Unnikrishnan and Singh, 2010) and is considered as one of the major source of anthropogenic methane emissions. As per an estimate, 30–70 million tonnes of methane gas is emitted per year from waste landfills (Johari et al., 2012). Therefore, recovery of methane from a landfill for electricity generation or other use is necessary to reduce the emission. Sometimes, recovery of LFG is technically not feasible, in that case on-site flaring of LFG is done. But, for this it is necessary to get the estimates of trapped LFG inside a landfill. The recommended approach involves modelling of LFG generation. There are various models available to predict the methane emissions from landfills. Some of the most widely used models (seven models) are described in Table 7. However, different emission models give different results for a single landfill and the models give accurate results for the region it has been developed, as the waste composition differs across the countries. Out of the seven models, six models are based on the European scenario and one on the USA scenario. These models have greatly reduced the tedious measurement techniques generally applied for methane estimation from landfills. Although, TNO-model was developed for the waste characteristics of Netherland, but this can be used for the estimation of LFG for other countries also as it has less relative error (22%) between observed and calculated values. In a study, it was estimated that 1 tonne of MSW generates 80 m^3 of LFG and China alone may contribute 10 billion m^3 LFG to the global LFG emissions in 2020 (Qu et al., 2009).

5. Energy recovery potential and economics of WTE technologies

At present, China generates about 300 million tonnes of waste annually (World Energy Resources, 2016) and the waste contains high proportion of food waste of low calorific value and high moisture content similar to that of other developing countries. Therefore, the conventional incineration plants used in developed countries are expected to perform poorly in such conditions. Thus, China has developed new circulating fluidised bed based incineration plants to counter this problem and currently 28 such plants are successfully generating electricity by processing 800 tonnes/d of MSW (World Energy Resources, 2016; Zhao et al., 2016). Cheng et al. (2007) reported that the grate based circulating fluidised bed incinerator is well suited for MSW with high moisture and low energy content. A waste incineration plant in Ethiopia with capacity of 50 MW (the first WTE facility in Sub-Saharan Africa) is expected to be commissioned in 2017, which will process 350,000 tonnes of waste per year. However, the plant may struggle for its operational cost due to many issues such as low calorific value of incoming MSW stream, lack of local technical expertise, and low energy prices (World Energy Resources, 2016). Perkoulidis et al. (2010) reported that a WTE facility in Central Greece was expected to recover 0.55 MW electricity per tonne of MSW, with net conversion efficiency of 22.5%. As per the estimate, Malaysia is expected to generate 2.63×10^9 kWh of electricity from LFG alone by the year 2020, which will generate revenues worth of US$ 262 million for Malaysia (Noor et al., 2013). The energy recovery potential of five anaerobic digestion plants of Greece Municipality was found to be 695 kWh/tonne with an average operating cost of 84 US$/tonne (Karagiannidis and Perkoulidis, 2009). Brazil has a potential of generating approximately 660 MW electricity per day from MSW landfills alone. The present study reviewed more than 100 published articles from 2010 to 2017 on WTE technologies, out of which the critical observation on some of the recent literature on WTE technological options across

Table 7
Description of methane generation potential models.

Models	Formula	Model description	Remarks
IPCC-model (IPCC, 2006)	$Q = \left[\sum_{x=S}^{T-1}\{MSWT_x \times MSWF_x \times L_{0,x}(e^{-k(T-x-1)} - e^{-k(T-x)})\} - R\right] \times (1 - OX)$ where, L_0 = methane generation potential (Gg of CH_4/Gg of waste) = 1.33 × $F \times DOC \times DOC_F$ F = fraction by volume of CH_4 in landfill gas DOC = amount of degradable organic carbon (Gg C/Gg MSW) DOC_F = fraction of DOC decomposes Q = methane emissions (Gg/year) $MSWT$ = total MSW generated (Gg/year) $MSWF$ = fraction of MSW landfilled k = reaction constant ($year^{-1}$) T = inventory year for which emissions are calculated x = year in which waste was landfilled S = start year of inventory calculation R = recovered methane (in Gg/year) OX = oxidation factor (fraction)	First order decay model (the IPCC-2006 revised equation). It takes into account the rates of waste degradation and methane generation over time. Based on waste landfilled and degradable organic fraction.	Emissions estimations produced by the model will allow countries to assess the impacts of different waste management and emission mitigation practices. It was basically developed for the European countries.
LandGEM (US-EPA, 2001)	$Q_{CH_4} = \sum_{i=1}^{n}\sum_{j=0.1}^{1} kL_0(M_i/10)(e^{-kt_{ij}})$ where, Q_{CH4} = estimated methane generation flow rate (m^3/year) L_0 = methane generation potential (m^3/tonne) M_i = mass of solid waste disposed in the i^{th} year (tonne) t_{ij} = age of the jth section of waste mass disposed in the ith year (decimal years) i = one year time increment n = (year of the calculation) − (initial year of waste acceptance) j = 0.1 year increment k = methane generation rate ($year^{-1}$)	Microsoft Excel-based software application developed by EPA that uses a first-order decay rate equation to calculate estimates for methane and LFG generation. It assumes that methane generation is at its peak shortly after initial waste placement and rate of methane generation then decreases exponentially as organic material is consumed by bacteria.	Based on US waste composition. Inaccurate assumptions about variables such as organic content, future disposal rates, site closure dates and collection efficiencies can result in large errors.
TNO-model (Oonk and Boom, 1995)	$\alpha_t = \varsigma 1.87AC_0k_1e^{-k_1t}$ where, α_t = landfill gas production at a given time (m^3/year) ς = dissimilation factor 0.58 1.87 = conversion factor A = amount of waste (in tonne) C_0 = amount of organic carbon in waste (kg of C/tonne of waste) k_1 = degradation rate constant 0.094 ($year^{-1}$) t = time elapsed since depositing (year)	First order model whose parameters were based on real data of landfill gas generation. Direct estimation of methane or landfill gas.	Information on organic component of waste components are not available. The model is validated by emission measurement at 20 landfills across Netherlands and was found that the mean relative error between observed and calculated landfill gas was 22%. It is one of the few model, where the models data were validated with the actual site landfill gas measurement.
GasSim (Gregory et al., 2003)	Not available	GasSim is a first order multiphase model, which quantifies all landfill gas related problems of a landfill, ranging from methane emissions, effects of utilisation of landfill gas on local air quality to landfill gas migration via the subsoil to adjacent buildings.	GasSim is based on UK waste statistics. Calculation modules in the program are protected.
Afvalzorg (Scharff and Jacobs, 2006)	$\alpha_t = \varsigma\sum_{i=1}^{3} cAC_{0,i}k_{1,i}e^{-k_{1,i}t}$ where, α_t = landfill gas production at a given time (m^3/year) ς = dissimilation factor i = waste fraction with degradation rate $k_{1,i}$ c = conversion factor (m^3 of LFG/kg of org. matter degraded) A = amount of waste (tonne) C_0 = amount of organic matter (kg of org. matter/tonne of waste) $k_{1,i}$ = degradation rate constant of fraction i ($year^{-1}$) t = time elapsed since depositing (year)	In this multiphase model, eight waste categories and three fractions are distinguished. For each fraction LFG production is calculated separately.	Based on Netherlands waste characteristics. Organic matter or carbon content data were not available for all waste categories.
EPER France (Scharff and Jacobs, 2006)	$FE_{CH_4} = \sum_x FE_0 \times (\sum_{1,2,3} A_i \times p_i \times k_i \times e^{-k_it})$ where, FE_{CH4} = annual methane production (m^3/year) FE_0 = methane generation potential (m^3/tonne of waste) A_i = normalisation factor p_i = waste fraction with degradation rate k_i k_i = degradation rate of fraction i ($year^{-1}$) t = age of waste (year)	It gives two approaches, either of which can be used for the estimation of methane generation from landfill. The second approach has been explained in this paper based on ADEME model.	The left and right hand side of the equation is not dimensionally matched. However, a normalisation factor is included in the model equation, but it seems it is missing from the spreadsheets. The model mentions three waste category and different k values for each category.

(continued on next page)

Table 7 (*continued*)

Models	Formula	Model description	Remarks
EPER Germany (Scharff and Jacobs, 2006)	$Me = M \times BDC \times BDC_f \times F \times D \times C$ where, Me = amount of diffuse methane emission (tonne/year) M = annual amount of landfilled waste (tonne/year) BDC = prop. of biodegradable C (tonne of C/tonne of waste), 0.15 BDC_f = proportion of biodegradable C converted, 0.5 F = calculation factor of carbon converted into CH_4, 1.33 D = collection efficiency (for, active degassing, D = 0.4, for no recovery, D = 0.9, and for active LFG recovery and cover, D = 0.1) C = methane concentration, 50%	It is a zero order model that takes unconditioned residential and commercial waste.	For the emission estimate purpose, coarse household waste, household waste and commercial waste were considered. The model is useful for the estimation of large fluctuation of methane emissions. It is basically used in Germany.

Table 8
Observations on the case studies of available WTE options.

References	Study area	Description of the study	Critical observation
Abila (2014)	Nigeria	Review of options for deriving energy and improving material recovery from MSW	Due to the high percentage of biodegradable content in Nigeria, biogas production from MSW is the best option.
Paleologos et al. (2016)	UAE	Role of recycling and incineration for effective management of waste of high income countries by energy and material recovery.	Recycling and incineration appeared to be most feasible waste management solution, because the Abu Dhabi and Dubai, the two most urbanised and populated cities were located in the coastal areas of UAE, where landfilling is not advisable due to lack of appropriate hydrogeological condition.
Korai et al. (2016)	Hyderabad, Pakistan	Different treatment options have been evaluated using power generation potential for possible waste to energy recovery.	Maximum power generating potential was shown by biochemical and thermochemical methods respectively, but again the single strategy is not sufficient to provide the solution.
Jeswani and Azapagic (2016)	UK	Identification of environmentally sustainable WTE option amongst incineration and landfill gas recovery using Life Cycle Assessment.	From energy recovery perspective, incineration has lesser impact than landfilling with gas recovery. In current scenario, diverting all the MSW intended for landfilling to incineration with energy recovery, it could meet 2.3% of UK's electricity demand and would save 2–2.6 million tonnes of GHG emissions per year.
Fruergaard and Astrup (2011)	Denmark	Evaluation of energy recovery and emission potential of incineration and AD for source separated organic waste and mixed high calorific waste using LCA.	Waste incineration with energy recovery proved to be an environmentally sustainable solution for overall waste management, whereas AD is a least preferable based on Danish condition.
Psomopoulos et al. (2009)	USA	Current status of WTE facilities in USA with regard to GHG, dioxin and mercury emissions, energy production and land conservation.	The emission of toxic and dangerous substances from WTE facilities have been significantly reduced in the last decade with the advancement of technologies. Also, the WTE facilities in USA have quite lesser emission as compared to other power production facilities from conventional fuel.
Cheng and Hu (2010)	China	Environmental and economic impact of waste incineration technology in China.	WTE incineration is expected to have a greater contribution in future renewable energy resources along with the solutions to waste related problems of developing countries.
Noor et al. (2013)	Malaysia	Estimation of energy potential of landfill gas for possible methane recovery.	Methane recovery from landfill gas will not only reduce the burden of GHG from the environment, but also provides a cleaner fuel, which will act as an alternative to fossil fuels.
Curry and Pillay (2012)	Montreal, Canada	Feasibility analysis of AD process by estimation of biogas production potential of urban food wastes using ultimate analysis, molecular formula analysis, computer simulation techniques and a literature review.	The decentralised or small-scale AD unit is an ideal solution for the generated organic waste of an urban centres, which will save the waste transportation cost along with reduction in the amount of waste sent for landfilling.

Table 9
Cost comparison of WTE technologies.

WTE technologies	Capital cost (US$/tonne of MSW/year)	Operational cost (US$/tonne of MSW/year)
Incineration	400–700	40–70
Pyrolysis	400–700	50–80
Gasification	250–850	45–85
Anaerobic digestion	50–350	5–35
Landfilling with Gas recovery	10–30	1–3

different countries has been summarised in Table 8. In most of the studies listed in Table 8, WTE option was recommended as a potential technology with minimum environmental impacts.

The cost analysis of different WTE technologies was taken from the previously published literatures (Ouda et al., 2016; Yap and Nixon, 2015; Tolis et al., 2010) and are presented in Table 9. The capital cost is the initial investment cost such as, land acquisition, equipment procurement, raw material requirement; and the indirect costs include the cost of planning, contractual support, and technical & financial services throughout the development stage. The operation cost is the daily running cost such as labour and maintenance cost. The capital cost for a WTE plant depends on the quality of waste to be processed, the technology employed and its location. The average lifetime of a WTE facility has been considered as 30 years. The range of cost as given in Table 9 is valid for both developed and developing countries. The lower value of a range of cost represents the cost in developing countries (such as India) and the higher value represents the cost in developed countries (such as UK) (Yap and Nixon, 2015). The costs as shown in the Table 9 are the estimated costs, as the actual cost depends on various other factors such as, governmental incentives, raw material and the availability of skilled labour (Ouda et al., 2016).

6. Environmental and health impacts

MSW incineration may result in air pollution (due to the emissions of SOx, NOx, COx, dioxin and furans), soil and water pollution (due to the presence of heavy metals in the fly ash and bottom

Table 10
Global warming potential of different waste treatment options.

Waste treatment options	Global warming potential (kg CO_2 equivalent per unit MWh electricity generation)	References
Incineration	424	Zaman (2010)
Pyrolysis and Gasification	412	Zaman (2010)
Anaerobic digestion	222	Whiting and Azapagic (2014)
Landfilling (without gas recovery)	746	Zaman (2010)

ash). But there has been a significant development in the pollution control technologies and energy recovery systems for incineration, which made it an attractive MSWM option (Damgaard et al., 2010). The use of air pollution control equipment in incineration plants is mainly to capture particulate matters, nitrogen oxides, dioxin and furans for minimisation of the environmental impacts than the conventional coal based thermal power plants (Liamsanguan and Gheewala, 2007).

Numerous studies reported the perceived health risk of waste incineration plants. Even the developed countries (such as UK) are facing public opposition due to perceived health risk due to emissions from incineration plants (Nixon et al., 2013a,b). Though incinerators potentially emit large number of pollutants, but the main concern has been the emissions of the group of organic compounds known as "dioxins" such as polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans and polychlorinated biphenyls (Giusti, 2009) produced due to incomplete combustion. International Agency for Research on Cancer concluded dioxins as highly carcinogenic based on the laboratory experiments on animals and a cohort study of the groups living in industrial areas (Giusti, 2009). However, many studies reported inconclusive and unconvincing results of public health impact of incinerators (World Energy Resources, 2016). A well developed and controlled system is essential for a waste incineration project successful and effective.

7. Impact on climate change

The studies on the impact of WTE plants and other MSWM options on climate change are largely based on developed countries (UNEP, 2010). Climate change is a global problem that requires a collective efforts from all the nations for its mitigation. It is vital to implement technologies that can reduce greenhouse gas (GHG) emissions and mitigate the climate change created by the production and consumption of energy generated from conventional means (IPCC, 2007). MSW has been considered as the third largest source of anthropogenic methane gas in the environment, which is almost 3–4% of the global anthropogenic GHG emissions (Annepu, 2012; IPCC, 2006) and the total waste sectors are responsible for approximately 18% of global methane emissions (Aleluia and Ferrão, 2016). At present, there is no fully established method for direct measurement of methane emission from landfills, as a result theoretical models based on number of assumptions are used for this purpose (UNEP, 2010). Methane has high energy content and need a mechanism to capture it judiciously to use it as a source of energy and to protect the environment from highly potential (21 times more potent than that of CO_2) GHG. Waste minimisation and recycling can effectively reduce the global GHG emissions (Ali et al., 2013a,b). Aracil et al. (2017) reported that, biofuels produced from MSW (non-recyclable) will bring positive impact on the climate change. The global warming potential of WTE technologies is presented in Table 10. Wilson et al. (2010) estimated that integrated solid waste management using 3Rs (Reduce, Reuse, and Recycle) principle can reduce global GHG emissions by 15–20%.

8. Conclusions

This paper presents a comprehensive review of different WTE technologies used for energy recovery. An attempt was made to summarise the current scenario of WTE sectors across the world. The MSW can be considered as one of the most potential renewable energy sources if WTE technologies are adopted that will not only reduce the dependency on conventional energy sources to meet the ever-increasing energy demand, but also reduce the problem of MSWM. After reviewing all the available WTE technologies, it can be inferred that the most feasible MSWM solutions in developing countries are anaerobic digestion for organic wastes, incineration for mixed MSW (other than biodegradable waste), pyrolysis and gasification for specific type of wastes (plastic, tyre, electronic equipment, electric waste, wood waste, etc.) and landfilling for inert wastes. However, the characteristics and composition of MSW play a vital role in selecting a suitable WTE technique.

GHG emissions can be reduced significantly by promoting WTE technologies for MSWM. WTE technologies have been extensively used in the developed countries for effective management of MSW. However, WTE facilities in most of the developing countries lack proper infrastructure, pollution control system, and maintenance. The study found that the WTE sectors are well established and prioritised in many of the developed countries, where the technology is matured. The developed countries are emphasising more on improvement on the process efficiency, recycling/recovery and pollution control strategy. In developing countries, it is essential to develop the WTE facilities following the requirements and the regulations of that country. WTE plants have been installed in some of the developing countries, but at smaller scale.

Government policies and regulations, financial support, improved technologies will strengthen the scenario of WTE facilities of developing countries. This paper will help the readers and the strategic decision makers in identifying the best WTE technology for both developed and developing countries.

Acknowledgements

The authors acknowledge the support provided by the Department of Environmental Science & Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad for carrying out the research work.

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