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Waste-to-energy nexus: An overview of technologies and implementation for sustainable development

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ABSTRACT

Prominent among problems of developing nations are access to affordable and reliable energy as well as clean and livable environment. The abovementioned points coincide with the sustainable development goals 7 (SDG 7) and 11 (SDG 11) of the United Nations (UN), respectively. Adopting waste-to-energy system could leverage on the possibility of reducing the adverse environmental impact occasioned by waste generation and ensuring production of renewable and sustainable energy while achieving circular economy. A review of most commonly used technologies for solid waste management worldwide, such as incineration, pyrolysis, gasification, anaerobic digestion, and landfilling with gas recovery in order to achieve waste-to-energy nexus is presented. A brief discussion on the economic, environmental and social impact as well as the implementation levels, some challenges and possible solutions to the implementation of the mentioned technologies for both developed and developing countries are included. This paper also addresses waste-to-energy (WtE) as a contributor to achieving sustainable development. It is evident from this paper that the waste stream of developing countries contained 50–56% food and garden wastes making anaerobic digestion technology more appropriate for treatment. Incineration is widely adopted in developed countries with more than 1,700 incineration plants operational worldwide. This paper offers to add to the pool of literature while helping researchers and decision-makers to make an informed decision on the feasibility of WtE as a pathway for sustainable waste management and renewable energy generation.

1. Introduction

Energy is significant to societal development and is the main driver of global technology. It plays a pivotal role in virtually every aspect of human endeavour. Energy is a factor of production and is therefore a nexus for sustainable development (Mapako and Stafford, 2020). The current means of meeting energy demands has been dominated by burning fossil fuels which is found to be unsustainable and environmentally unfriendly Alao et al., 2022. Over the years, fossil fuels such as coal, natural gas and oil have been exploited to meet several energy services such as electricity, transportation, heating and cooking purposes. Gaseous emissions from exploration and exploitation of fossil fuels have caused unprecedented environmental havoc. Unfortunately, the reserves of these fossil resources are limited; and with its current spate of exploitation, they may be completely used up in no distant time.

There is a steady growth rate in global population with an accompanied increase in waste generation due to increased consumption of goods and services. This has culminated into increase in energy demand. So, an increase in population and municipal solid waste (MSW) generation as well as unprecedented growth rate in energy demands are critical and challenging issues in the world; but seriously affected are the developing countries. There have been national and international outcries for sustainable energy generation and waste management systems to meet an ever-increasing energy demand. The conventional methods of MSW treatment (i.e., open dumping and burning) and power supply (i.e., from fossil fuels) pose a serious threat to the environment due to the emission of dangerous gases and fluids that are capable of contaminating the land, air and water.

MSW is non-hazardous mixed (heterogeneous) garbage (trash) produced from domestic, commercial and industrial activities. MSW consists of biodegradable, recyclables and inert materials. Table 1 shows the composition of a typical MSW. Waste generation has a positive correlation with the rate of urbanization, economic development, and population growth of a nation. It was reported that the world population increased from 3 billion in 1960 to 7 billion in 2015 and it is projected to rise to 8.1 billion people by 2025 (FAO, 2013).

According to a report published by the World Bank in 2018 (Kaza et al., 2018), the global MSW generation was approximated to

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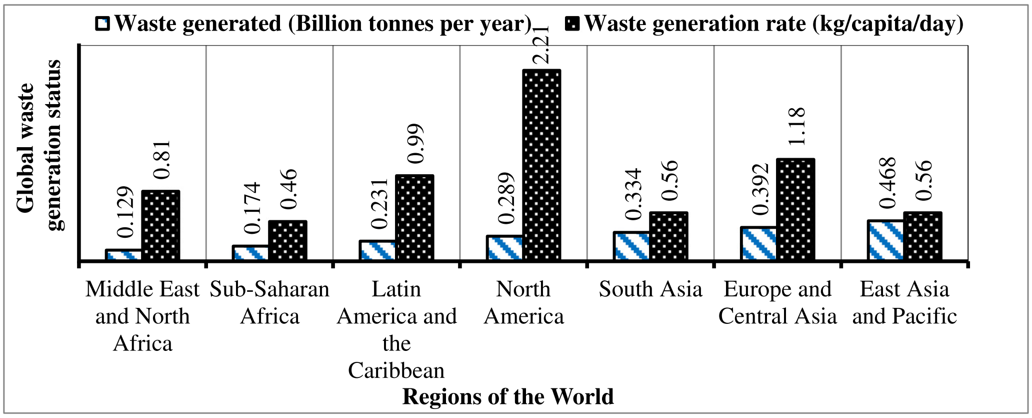

Fig. 1. Average global MSW generation status by regions adapted from (Kaza et al., 2018).

Table 1
Municipal solid waste classification and composition (Tsui and Wong, 2019).

Municipal solid waste classification	Municipal solid waste composition
Biodegradable waste	Food and kitchen waste, green waste, paper
Recyclable waste	Paper, cardboard, glass, bottles, jars, tin cans, aluminum cans, aluminum foil, metals, certain plastics, fabrics, clothes, tires, batteries, etc.,
Inert waste	Construction and demolition waste dirt, rocks, debris

be 2.01 billion tonnes at an average rate ranging from 0.46 to 2.21 kg/person/day differing within different areas and regions due to the local rate of urbanization and economic prosperity indicated by income levels. With the current rate of waste generation, it is anticipated that the global MSW will increase by 70% from the 2016 level to 2.59 billion in 2030 and 3.4 billion tonnes by 2050 (Kaza et al., 2018) .

Presently, the bulk amount of MSW is generated in developed countries. However, the fastest rate is predicted for emerging economies such as Africa, Asia and Latin America (Fazeli et al., 2016). Detail of the global waste generation per region is presented in Fig 1

From Fig. 1, it could be inferred that countries in the South Asia, East Asia and Pacific, North America, Europe and Central Asia regions generated the highest amount to the tune of about 74% of the world's total waste. This is expected because countries in these regions are well urbanized and of high-income status. The Middle East, North Africa and Sub-Saharan Africa regions produce the least amount of waste amounting to 15% of the world's waste. East Asia and Pacific generated an estimated amount of 0.468 billion tonnes in 2016, and the Middle East and North African region generated the least amount averaged at 0.129 billion tonnes. At a regional level, North America generated waste at a rate of 2.21 kg per capita per day, while Sub-Saharan Africa with countries mostly of low-income status generated wastes at 0.46 kg per capita per day. Fig. 1 indicates that substantial amount of wastes is generated in well urbanized and high-income countries. Waste composition reflects the consumption pattern of people which is influenced by the economic prosperity and income level of an individual/nation. The composition of municipal solid waste varies from place to place.

As the purchasing power of an individual increases, he/she tends to consume more of packaged foods and other goods thereby generating more of recyclables such as papers, plastics, tins, bottles and glass and less of organic wastes. According to a recent report presented by the World Bank as shown in Table 2, MSW in high-income countries such as North America and Europe is composed mainly of recyclables such as papers, cardboard, plastics, metal and glass with less organic fraction. In low income countries such as Africa and Asia their waste stream is characterized by wet organic content mostly food and green wastes. The high moisture content in the waste is responsible for the low calorific value (i.e., LHV). It is estimated that more than 50% of waste in low and middle-income countries have organic contents in the form food and green waste with less than 15% of recyclables.

It is also observed from Table 2 that as the countries' income level rises, the composition of waste changes with the share of recyclables increasing and the wet organic fraction declining. To ensure sustainable waste management and to increase the diversity of energy generation mix, one of the best solutions is to integrate a waste-to-energy (WtE) technologies into the energy/waste management system. The possibility of producing value-added products and energy carriers such as biogas, syngas, hydrogen gas, bio-oil from MSW has made it a potential renewable energy resource (Evangelisti et al., 2017). Availability, characteristic and composition of the waste stream of a location are essential for sustained profitability in the operation of a WtE system. Another crucial parameter for determining the suitability of a WtE system is the heating value (energy content) of the waste component. The heating (calorific) value is characterized into two: the lower heating value (LHV) and higher heating value (HHV). Some literatures also report the heating value in terms of calorific value as net calorific value (NCV) and gross calorific value (GCV) (Aderoju et al., 2019). Different units are also used to express the heating values such as MJ/kg (Hossain et al., 2014), kcal/kg (Chand Malav et al., 2020) which require conversion to maintain consistency. LHV or LCV is the net energy content contained in a fuel (waste stream) which is available from its complete combustion without considering the latent heat of vaporization of water present in waste stream. On the other hand, HHV or GCV is the gross (maximum) energy content of a fuel (waste stream) while considering the latent heat of vaporization of the moisture contained in the waste stream. The HHV is determined by measurement using a bomb calorimeter or theoretically determined using equations based on ultimate analysis of the feedstock. In the practical application, LHV is utilized in determining the electricity generation potential from a MSW incinerator (Komilis et al., 2014) and is estimated from HHV after removing the moisture content. A typical model for determining the LHV is as follows:

$$LHV = HHV - (9 \times \%H \times \Delta H_V)$$

ΔH_V is the heat of vaporization of water, approximately 2.420 MJ/kg and % H is the mass percentage of hydrogen in the organic compound (Arafat and Jijakli, 2013). The heating values of MSW of some locations/countries are presented in Table 3.

1.1. Review of some previous studies

Significant progress has been made on the application of WtE technologies as waste management options and methods for producing cleaner energy in developed and developing countries. As a result of

Table 2
The average percentage global MSW composition by the income levels adapted from (UNEP, 2019)

Income Level	Food and Green	Paper	Plastics	Metal	Glass	Rubber	Wood	Others
Low-income	56.0	7.0	6.4	2.0	1.0	-	0.4	27.0
Lower-middle	53.0	12.5	11.0	2.0	3.0	0.5	1.0	17.0
Upper-middle	54.0	12.0	11.0	2.0	4.0	1.0	1.0	15.0
High-income	32.0	25.0	13.0	6.0	5.0	4.0	4.0	11.0

Table 3
Heating Value of municipal solid waste in selected locations of the world.

Countries Status	Country name	Heating value of MSW	Ref.
Developing	Sierra Leone	6.4 MJ/kg	Ngegba and Bertin (2020)
	Bangladesh	3 MJ/kg	Hossain et al. (2014)
	Malaysia	7.53 MJ/kg	Tan et al. (2014)
	China	3–6.7 MJ/kg	Zhang et al. (2015)
	India	3.5–4.2 MJ/kg	Chand Malav et al. (2020)
	Brazil	7.03 MJ/kg	Drudi et al. (2019)
	Colombia	4. 73–8.73 MJ/kg	Arias et al. (2018)
Developed	USA	11–12 MJ/kg	Mukherjee et al. (2020)
	Japan	8.37–9.21 MJ/kg	Hla and Roberts (2015)
	UK	9.21–12.55 MJ/kg	Hla and Roberts (2015)

this, a vast number of studies (research articles and review papers) have been published on the applicability of WtE technologies for waste management as well as renewable and sustainable energy generation methods. For instance, (Mukherjee et al., 2020) presented a review on WtE technologies adoption in USA including their unique challenges. It was concluded that only 13% of MSW is used for energy recovery via mass-burn and refuse-derived fuel technologies from 86 facilities; and 53% is landfilled. In the work of (Chand Malav et al., 2020), a review on the challenges and health related issues for waste management in India including possibilities of energy recovery from the wastes. In Bangladesh, (Alam and Qiao, 2020) tried to review the current status of MSW management, treatment and disposal but little emphasis was paid to energy recovery from the MSW. It was pointed out that about 23,688 tons/day of MSW was generated in Bangladesh which contains about 70% organic solid waste with average moisture content and collection efficiency of 50% and 56%, respectively. A study by (Dlamini et al., 2019) focused on a review on WtE technologies and their implications on sustainable waste management with particular attention to the City of Johannesburg, South Africa. In the work of (Nanda and Berruti, 2021), a review of thermochemical and biological methods of WtE is conducted with a view to analyzing the potential for energy and material recovery. A review on the limiting factors for sustainable municipal solid waste management (MSWM) in the BRIC (Brazil, Russia, India and China) countries vis-a-vis the historical transition to a sustainable level in some high-income countries was conducted by (Iyamu et al., 2020). In the work of (Fodor and Klemes, 2012), a review on design of WtE technologies as an alternative for the production energy carriers was presented. It is important to note that waste-to-energy technologies is a sub-set of waste management. Most of the papers reviewed treated waste management issues including waste-to-energy technologies (WtE), their status and implementation in various countries around the world. Due to the significant attention being paid towards the MSW management through WtE technologies, this review paper is poised to add to the pool of literatures in this subject while addressing some of the identified gaps in previous studies such as implementation level of these technologies in some developing and developed countries, their economic, environmental and social impacts, the technologies selection criteria and sustainability drive of WtE technologies. Some challenges and possible solutions to the implementation of WtE technologies especially for developing countries are discussed in their study. With this in mind, this review paper therefore presents a discussion on the most mature WtE technologies as a promising solution to problems of MSW management as well as an effective and eco-friendly method of renewable energy generation for developing and developed countries. A brief discussion on the environmental and social impact as well as the implementation level of the discussed WtE technologies is included. This paper also addresses WtE as a contributor to achieving sustainable development while realizing circular economy. In order to accomplish the objectives of this study, peer reviewed articles published mostly in the last decade have been reviewed.

The rest of the paper is organized as follows: Section 2 considers the necessity for implementing waste-to-energy systems. Section 3 discusses the technological options including their pros and cons and suitability for developing and developed countries. The global waste-to-energy implementation is mentioned in Section 4 while Section 5 discusses the selection criteria for various waste-to-energy technologies. Section 6 is dedicated to discussing the concept of WtE as a means of achieving sustainable development goal (SDG). Discussions based on potential contribution of each WtE system in terms energy, environmental, economic and social as well as policy and incentive drives are discussed in Section 7. Section 8 is the conclusion section where concluding remarks as well as future outlook presented

1.2. Necessity for waste-to-energy implementation

There has been an unprecedented rise in the waste generation rate around the world with the largest coming from the developed nations due to their level of affluence. Also, in developing countries factors such as urbanization, population growth, and technological development are contributing to increasing MSW generation (Beyene et al., 2018). With the soaring population growth rate, improved living condition and urbanization, the world waste generation is projected to increase to 2.2 billion in 2025 reaching up to 9.5 billion tonnes by 2050 (Awasthi et al., 2019). Apart from waste generation, energy supply-demand gap is another problem due to rising global population especially developing nations. Conventional energy production is centralized from fossil-based resources such as natural gas, coal and oil. To meet the energy demand, more than 84% of the global primary supply is from fossil fuel (Ouda et al., 2016). The use of fossil fuel for power generation is not sustainable due to depletion in their reserves, volatility in their prices in the international market as well as environmental issues caused by the emission of greenhouse gases during their exploration, exploitation and utilization. The current waste management system is not only environmentally unfriendly but also inadequate with the current reality in waste generation rate. It is disheartening that about 30–90% of the

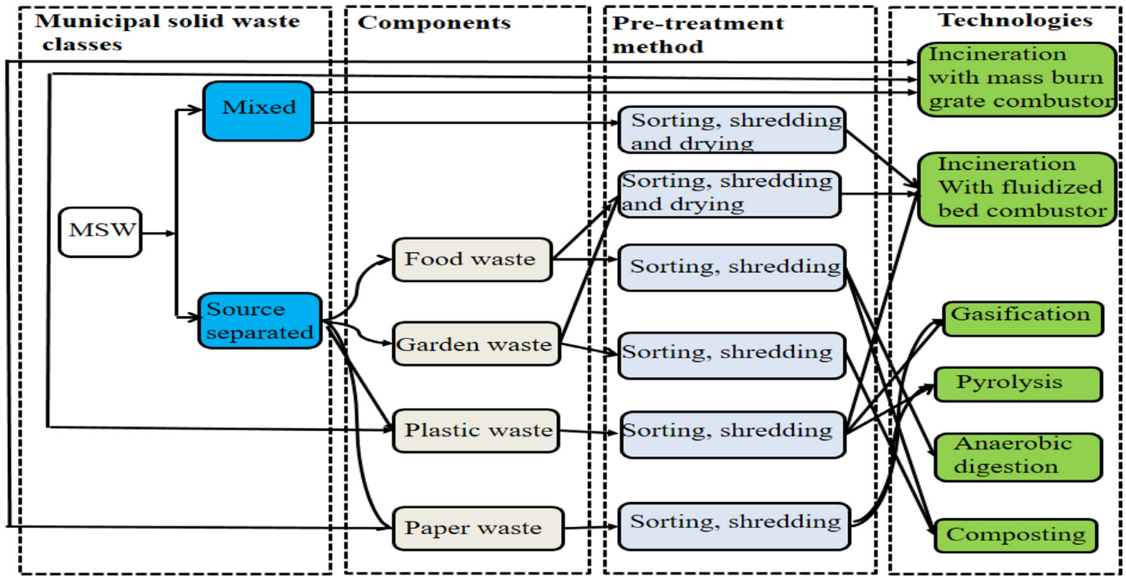

Fig. 2. Mapping of feedstocks with suitable waste-to-energy technologies (Maisarah et al., 2018).

waste generated is disposed of in landfill or dumpsite (UNEP, 2019) with Africa and Latin America and the Caribbean taking the lead. With the current scenario in waste generation rate, nations around the world are devising measures in tackling this trend. Poor collection and disposal rates have made MSW a big treat to the environment in terms of huge greenhouse gas emission from unwholesome waste handling and disposal. The rate of urbanization and industrialization is also putting pressure on the available land for waste landfilling. Due to land constraint issue, climate change, energy poverty and need for livable environment, waste volarisation technology has been identified to offer a win-win strategy to simultaneously address these challenging issues by ensuring waste management and power supply within a municipality. It could also minimize emissions arising from waste diversion from landfills and reduce health-related hazards from air, soil and water contamination.

2. Overview of waste-to-energy conversion technologies

Energy contained in the MSW can be extracted through what is called waste-to-energy (WtE) technologies where useable energy in the form of electricity, heat and fuels can be obtained. WtE technologies can simultaneously provide alternative to waste generation problem and be a potential renewable energy resource (Tan et al., 2015). There are two main recovery or conversion processes of WtE technologies (i.e., biochemical and thermochemical) depending on the waste composition and moisture content. Different technologies require appropriate waste components with certain characteristics to serve as suitable feedstock for their optimal performance (Maisarah et al., 2018). For effective performance and maximum output, the waste stream may be subjected to preprocessing/treatment prior to sending it into a waste-to-energy plant. Fig. 2 shows the waste suitability for each WtE technique.

Fig. 2 presents the technology-feedstock match including pretreatment processes. It could be deduced from this Figure that mass-burn incineration using grate combustor is best suited for mixed MSW. Due to the heterogeneity of mixed waste, there could be a need for additional energy or fuel required for combustion which may raise the operation costs and lower the system efficiency. The pre-treated MSW are more suitable with fluidised bed combustor and are more efficient.

Some technologies such as anaerobic digestion (AD), pyrolysis and gasification are better suited for homogeneous waste types after removing non-combustibles, recyclables and inert materials from the waste stream. It could be inferred from Fig. 2 that food wastes are better treated with AD technology for biogas extraction through which energy could be produced. The energy embedded in waste plastic and paper could be better extracted by feeding them in gasifiers or pyrolysis reactors after proper pre-treatment processes such sorting, shredded and grinding. The essence of these pre-treatment activities is to reduce the particle size, reduce the surface area and homogenize the feedstock which will cause increased rate of reactions and better product yields

The most mature and commercially available waste–to-energy conversion routes/technologies and their products are shown in Fig. 3.

2.1. *Thermochemical conversion process*

Thermochemical process involves decomposition of carbonaceous organic matter under high temperature to produce heat energy, fuel oil or gas and other value-added product such as charcoal. The main technological options under this category include incineration, pyrolysis and gasification. Thermochemical process is useful for less dense wastes and low moisture content (Rajaeifar et al., 2017). The three most commonly available thermal technologies are discussed.

2.1.1. *Incineration*

Incineration is a conventional thermal treatment method whereby the feedstock (MSW) is directly burnt in an excess supply of oxygen in a furnace with temperature in the range of 800°C–1000 °C and minimum residence time of 2 s leading to the production of heat and ash (bottom and fly ash) (DEFRA, 2013). It is the most mature and widely used technology for waste management worldwide. The main advantage of incineration is its capability to reduce the volume of waste by 80–90% and mass by 70–80% (Lombardi et al., 2015) leading to a significant reduction in the land space needed for landfilling and eventual elongation of the lifespan of the existing landfill sites. For instance, incinerating 1 million tonnes of MSW per year requires land area of less than 100,000 m^2 for an average of 30 years whereas landfilling 30 million tonnes of MSW requires a land of 300,000 m^2 (Arena, 2012) in a year. With this process, the working lifespan of landfill can be elongated for an average of 30 years. For a typical incineration plant with 300 tonnes per day (tpd), an approximately 0.8 hectares of land is required (Yap and Nixon, 2015). Apart from waste mass and volume minimization, the high temperature involved in the incineration process also helps in hazardous material destruction (Tsui and Wong, 2019). Incineration technology can also treat any type of waste and requires a low level of technology and human resource skills.

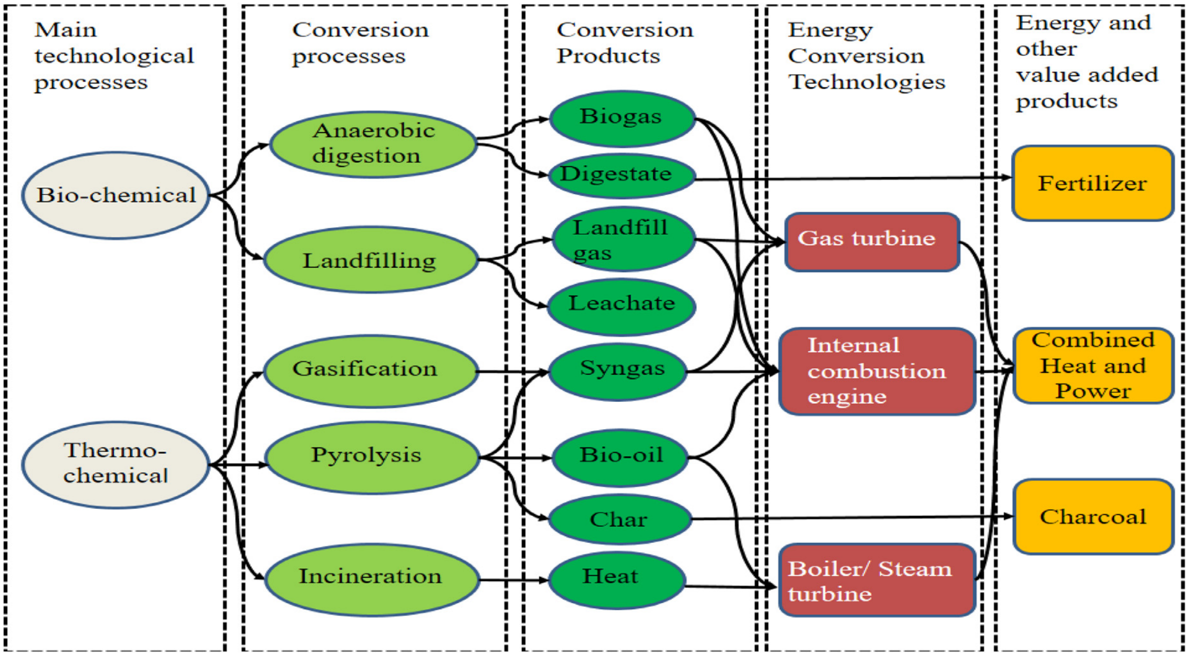

Fig. 3. waste-to-energy conversion routes/technologies (Ogunjuyigbe et al., 2017).

The hot flue gas produced in an incineration plant can be harvested as a useful product by cooling it in a high-pressure feed-water boiler to raise steam. The produced steam in supersaturated form can be made to turn a condensing steam turbine for power only application or a back-pressure steam turbine or an extraction-condensing steam turbine for combined heat and power (CHP) production through the conventional steam Rankine cycle. The steam produced can also be recovered for thermal energy application in district heating system or for industrial processes. Up to 80–90% of the energy contained in the waste can be recovered as heat in the boiler (DEFRA, 2013). The net electrical efficiency of 17–30% can be achieved from the steam turbine (Panepinto and Genon, 2011). In many countries such as Denmark and Sweden, incineration system is coupled with the power generation system for energy recovery. For instance in 2005, incineration plant provided nearly 5% of energy usage in Denmark which corresponded to about 14% of the entire household heat consumption (Bosmans et al., 2013).

Because of the high LHV of the waste composition of developed countries thermal treatment methods such as incineration and gasification have been the preferred option for treating MSW. This has resulted in increased waste incineration plants across Europe, United States and Japan. The low calorific value of MSW collected in developing countries leads to its overall poor quality for waste incineration and other thermal processes. In recent years, thermal WtE plants are also emerging in developing countries of Asia Pacific, including China and the United Arab Emirates, Thailand, the Philippines, Indonesia and Myanmar (UNEP, 2019) due to increased level of technological innovation in constructing incineration plants suitable for high moisture content organic wastes. Application of thermal based WtE technologies for the highly dense waste material with high level of moisture will require additional energy for drying thereby reducing the overall efficiency and increasing the operating total costs.

The major drawback to the implementation of incineration is the generation of high levels of air and waterborne pollutants with attendant environmental and health risks.

The direct combustion of MSW leads to the formation and reformation of dangerous carcinogenic compound such as dioxins and furans especially from plastic-containing wastes (Soni and Naik, 2016). This has generated a lot of public hatred and opposition to the deployment of incineration technology in many countries and has resulted into stoppage or delay in the implementation of incineration projects. A typical example of such is that of the La Chaumière incinerator project in Mauritius (Neehaul et al., 2020) where social unrest led to the delay and eventual suspension of the incineration project.

The flue gases are composed of a mixture of gases and compounds including other heavy metals. Other prominent products of incineration are bottom and fly ashes. About 75–90% of the total ashes formed the bottom ash and 10–25% represents the fly ash (Qazi et al., 2018b). Therefore, adequate clean-up of the flue gas is required before exiting the furnace. The emission control systems comprise of an electrofilter for dust removal, a dry scrubber injected with sodium bicarbonate and activated carbon for removal of acidic gas (such as SO_2 and HCl), a baghouse filter for removal of residual and generated dust, selective catalytic system for oxide of nitrogen (NO_X) reduction (Panepinto and Zanetti, 2018). The emission control measures and gaseous effluent treatments are responsible for increased installation and operation and maintenance costs of incineration system. Bottom ash otherwise called slag forms a substantial amount of incineration product and should be well treated or reused. Bottom ash can be used as an aggregate for backfilling in road construction application (Qazi et al., 2018b) and concrete making (Joseph et al., 2018) subject to compliance with environmental control strategy already put in place. For an incineration system to be economical, a minimum waste throughput of 50,000 million tonnes per year and waste heating value greater than 7 MJ/kg are required (Lombardi et al., 2015) otherwise when the heating value is less than 6 MJ/kg an auxiliary fuel may be needed to make the process self-sustaining (DEFRA, 2013).

Most of the waste combustors (i.e., equipment used to burn the waste) that are in use today are mainly of three types: moving or fixed grate, rotary kiln and fluidized bed combustors (Lombardi et al., 2015). The choice of incinerator could be attributed to waste characteristics and composition. Waste with higher moisture content is better incinerated in fluidized bed while less moist waste is incinerated with grate incinerator. Fluidized bed combustors are less used in developed countries such as Europe but are widely utilized in developing countries in Asia especially China (Dong et al., 2018) owing to the appealing characteristics to treat high-moisture content MSW.

2.1.2. Gasification

Gasification is an advanced thermal treatment process which involves decomposition of carbon enriched fuels such as coal or MSW at high temperature in the range of 550–1600°C in an insufficient and controlled supply of oxidant lower in amount than that required for the stoichiometric combustion (Arena, 2012). Depending on the source of heat for combustion of feedstock, gasification can be classified as auto-thermal and allo-thermal. An auto-thermal gasification is that in which the heat required to gasify the feedstock is provided by a part of the input feedstock (i.e., fuel). Example of an auto-thermal gasification is air gasification. In the case of an allo-thermal gasification, an external source of heat energy such as plasma torch is provided to gasify the feedstock. A typical example of this is the case of plasma arc gasification (Arena, 2012). In both cases, the product of gasification is a combustible gas called syngas or producer gas. The syngas is a combination of a variety of gases such as hydrogen, carbon monoxide and little amount of methane as well as some impurities. The chemical composition, heating value, quality and yield of the syngas depend mainly on the operating temperature and gasifying agents such as air, oxygen-enriched air and steam (Qazi et al., 2018b). With air as the gasifying agent, the syngas produced has a higher concentration of non-combustible atmospheric nitrogen gas. The presence of this non-combustible gas in the syngas is responsible for the smaller lower heating value (LHV) ranging between 4 and 7 MJ/Nm^3. For pure oxygen as the gasifying agent, a syngas free of atmospheric nitrogen gas is generated with a higher LHV ranging between 10 and 15 MJ/Nm^3 and lastly for the steam gasification the syngas generated is nitrogen-free with a high concentration of hydrogen and lower heating value of 15–20 MJ/Nm^3 (Arena, 2012).

It can also be turned into higher value products such as transportation fuels, chemicals, fertilizers, and even as a substitute for natural gas (Soni and Naik, 2016). The raw syngas contains a variety of impurities such as particulate, tar, alkali metals, chloride and sulfide (Lombardi et al., 2015) which makes it unsuitable for any downstream applications such as electrical power or heat energy generation (Luz et al., 2015). It is therefore essential to purify the syngas before utilization in any downstream application to prevent damage to equipment and emission limitation. Depending on the conversion technology, the syngas could be directly used in a boiler to produce heat energy at an efficiency ranging from 20–40% or for electricity generation, in a conventional Rankine Cycle steam turbine of efficiency 17–28%, in a gas turbine at efficiency 24–33%, in an internal combustion engine (ICE) with efficiency 25–37% or in a solid oxide fuel cell (SOFC) 41– 60% (Luz et al., 2015). Syngas clean-up could be achieved by dry or wet process. In dry gas cleaning system there is no usage of water and consists of equipment such as cyclone, fabric filters, sand bed filters, thermal cracking of tars. Whereas, in wet gas cleaning system the utilization of water is required and the equipment involved are wet electrostatic precipitators, wet scrubbers and wet cyclones. For a typical gasification plant a combination of both wet and dry cleaning processes could be adopted where a cyclone or baghouse filter can be attached to the gasifier for dust particle removal; wet scrubbing for heavy tar removal, catalytic adsorption for NOx removal and activated carbon for absorbing CO_2 (Kumar and Samadder, 2017).

Gasification technology is well suited for homogenous carbon-based organic material with a high degree of heating value (Nobre et al., 2020). The heterogeneous nature of MSW will require pretreatment such as densification (Sarkar et al., 2014) to obtain a much more homogenous feedstock by reducing the moisture content, particle size with the view to increase the calorific (heating) value of the feedstock (Sharma et al., 2020) prior to feeding into the gasifier. The main essence of feedstock pretreatment is to enhance the energy efficiency of the process (Arena, 2012) and to obtain quality and maximum product yield. The gasifiers (reactors) available for solid waste gasification are fixed-bed, fluidized-bed (circulating and bubbling), entrained-flow, moving grate, rotary kiln and plasma gasifiers (Kumar and Shukla, 2016). The fixed bed gasifier can be classified as downdraft or updraft depending on the direction of flow of the feedstock, the gasifying agent and the produced syngas (Jurado and Cano, 2006). In a downdraft gasifier, the feedstock is fed from the top of the gasifier and the gasifying agent is introduced from the top or sides and the produced gases flow downwards (Jurado and Cano, 2006). For the updraft gasifier, the feedstock is fed in at the top and the gasifying agent is fed at the bottom, so that the feedstock moves oppositely to the syngas (Arena, 2012). Downdraft gasifier can generate syngas with low tar content (less than 0.5 g/Nm^3) compared to fluidized bed (up to 40 g/Nm^3), circulating fluidized bed (up to 12 g/Nm^3) and fixed-bed updraft gasifier (up to 150 g/Nm^3) (Indrawan et al., 2018).

Gasification is a well-established technology in petrochemical and power industries for homogenous solid fuels such coal and woody biomass. However, large scale commercial MSW gasification plants is very limited (Rajaeifar et al., 2017), as around a hundred plants are reported to process MSW worldwide (Dong et al., 2019) most of them are located in developed countries such as Europe and in Japan (Dong et al., 2018) where lack of land space is forcing them to find alternatives to landfilling. The application of gasification in developing countries is still very minimal which may be due to heterogeneity of MSW composition, variation in the particle size of MSW and high moisture content, poor efficiency of gasifier and gas cleaning systems (Rajaeifar et al., 2017). One of the advantages of gasification over the conventional combustion is its low emission tendencies. The required oxygen for gasification is very limited and this oxygen-deficient atmosphere does not provide the environment needed for dioxins and furans to form or reform. Rapid cooling by water quench prevents de-novo synthesis of dioxins and furans and clean-up system in gasification process removes any fine metal particulates responsible for dioxins and furans formation (Vaish et al., 2019)

2.1.3. Pyrolysis

Pyrolysis involves decomposition of solid waste in an environment totally deficient in air (oxygen) at high temperatures in the range of 300–900 °C (Chen et al., 2014) to produce different forms of energy carriers including char, pyrolysis oil and combustible gases (syngas). Pyrolysis is the only thermal process that produces fuels in all three states of matter (i.e., solid, liquid and gaseous fuels). Pyrolysis is an old technology as it has been used to produce charcoal from wood for thousands of years (Chen et al., 2014). The quantity and quality of pyrolysis products depend largely on the heating rate, process temperature, residence time, feedstock composition and characteristics, type of reactor (Hasan et al., 2021) as well as addition of catalysts (Sharuddin et al., 2016).

Raw MSW is usually not appropriate for pyrolysis and typically would require some pre-treatment by removing the glass, metals and inert materials (such as rubble) prior to processing the remaining waste. Wastes with high moisture content such as food wastes are not suitable for pyrolysis and if it were to be used, additional energy is required for drying which may increase the operating costs and perhaps reduce the overall system efficiency. For good quality pyrolysis products, specific and homogenous waste types such as plastic, tire, paper, wood waste, etc. are more appropriate. Plastic wastes produce oil as the main product while wood and woody biomass give syngas and char as their main product (Chen et al., 2014). Plastic waste contains different types of polymers such as Polystyrene (PS), Polypropylene (PP), Polyethylene (PE) (including low-density and high-density polyethylene (LDPE and HDPE)), Polyvinyl chloride (PVC) and Polyethylene terephthalate (PET). It has been reported that PP and PE form the largest portion of the waste plastics stream in MSW in China (Wang et al., 2013), Nigeria (Ayodele et al., 2018a), South Africa (Ayeleru et al., 2016) and also worldwide (Chen et al., 2014). Among the plastic types, PVC is not suitable for pyrolysis due to production of toxic chlorinated compounds such as dioxins and furans (Sharuddin et al., 2016). Pyrolysis can be classified into slow, fast and flash pyrolysis depending on the heating rate of feedstock, temperature and residence time (Vaish et al., 2019). Slow pyrolysis (conventional pyrolysis) involves low heating rates rang-

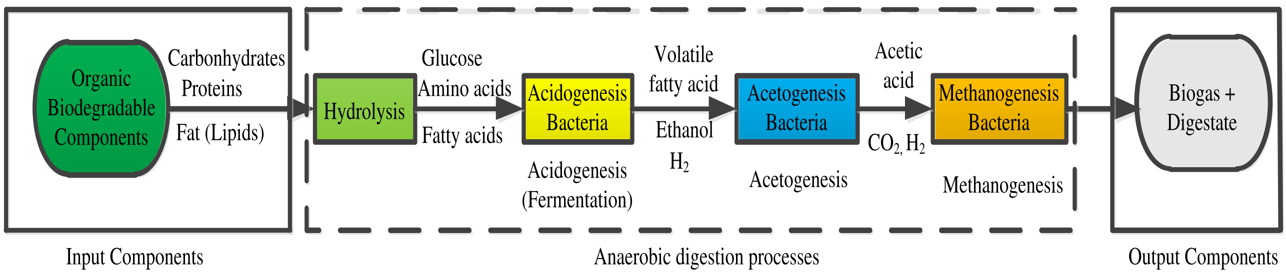

Fig. 4. Stages of anaerobic digestion of organic substrates (Ogunjuyigbe et al., 2017).

ing from 0.1–2 °C/s, residence time from 450–550 s and low temperature 277–677°C with the main products formed being char and tar. The fast pyrolysis operates at moderate temperature 577–977 °C, heating rates above 2°C/s and residence time from 0.5–10 s, with the key products formed being tar and bio-oil. Flash pyrolysis involves temperatures from 777–1027 °C, high heating rates of 200–10^5 °C/s and very short solid residence time less than 5 s, with gases rich in ethylene being the main product formed (Qazi et al., 2018b). The pyrolytic oil/gas produced can be used for electricity generation through appropriate energy conversion devices such as gas engine, internal combustion engine and diesel engine.

Type of pyrolysis reactors are fixed-bed reactors, rotary kilns and fluidized bed reactors (Chen et al., 2014). Fluidized- bed reactors are widely used for the pyrolysis of plastic waste due to low thermal conductivity and high viscosity of polymers. Fixed-bed reactor is seldom used in commercial scale due to its inefficiency while rotary kilns and tubular reactors are applied to the scale-up facilities (Chen et al., 2014). The rotary kiln is the only type of reactor that has successfully achieved industrial-scale implementation (Dong et al., 2019). Pyrolysis is more environmentally friendly than conventional incineration due to its lower toxic pollutant emission tendencies because oxygen-deficient atmosphere in a pyrolysis reactor does not provide the environment needed for dioxins and furans to form or reform. Pyrolysis plant also produces less noise pollution than a typical incineration plant.

2.2. Biochemical conversion process

The biochemical conversion process involves decomposition of biodegradable organic components of the waste under the influence of bacterial. The microbial action can take place either in the presence or absence of oxidant (oxygen) leading to the production of different products (compost or biogas). The biochemical conversion processes are preferred for wastes that have high percentage of bio-degradable organic matter and high level of moisture/water content, which aids microbial activity. The main technological pathways for biochemical process are anaerobic digestion, composting and landfilling.

2.2.1. Anaerobic digestion

Anaerobic digestion (AD) is the process in which the microorganisms cause the decomposition of the organic component of the waste in the absence of oxygen to produce methane-rich gas called biogas and digestate. There are four complex consecutive stages in anaerobic digestion process such as hydrolysis, acidogenesis, acetogenesis and methanogenesis as shown in Fig. 4 (Ogunjuyigbe et al., 2017). Hydrolysis is the first stage of digestion which involves the breaking down of complex organic material such as carbohydrates (starch), protein and fats into soluble organic matter such as glucose (sugar), amino acid and fatty acids. The formation of volatile fatty acid (VFA) during hydrolysis limits the rate of reaction. However, the rate-limiting tendency in hydrolysis can be reduced by subjecting the organic fraction of the MSW into pre-treatment before feeding into the digester (Kumar and Samadder, 2020). Acidogenesis also called fermentative stage further breaks down the products of hydrolysis process to produce ethanol, fatty acids, carbon-dioxide (CO_2) and hydrogen gas (H_2). Acetogenesis is the third stage where the organic acids produced from acidogenesis stage are converted into acetic acids, carbon-dioxide (CO_2) and hydrogen gas (H_2). The final stage is methanogenesis where biogas (a combination of methane (CH_4) and CO_2) is produced along with other gases such as H_2S, water vapour etc.

Biogas is composed of two main greenhouse gases (GHG) i.e., methane (CH_4) and carbon dioxide (CO_2). CH_4 is about 55–75% by volume and CO_2 consists about 25–45% by volume (Ogunjuyigbe et al., 2017). Other components of biogas are trace concentration of non-methane organic compounds (NMOCs) such as hydrogen sulphide (H_2S). Although, CH_4 is a GHG, its high energy content (LHV) (i.e. 37.2 MJ/kg) can be of great advantage if properly collected. However, the biogas needs to be purified by removing CO_2 and other trace gases through physical absorption or adsorption approach using caustic soda, activated carbon and silica gel. The upgraded biogas can be fed into an internal combustion engine (ICE) or gas turbine for electricity or combined heat and power generation or as a fuel for automobile and stationary engines (Rajaeifar et al., 2017). Another useful product of AD is a slurry-like material called digestate which can be used as a soil conditioner and/or as an organic amendment in agricultural field (Kumar and Samadder, 2017). The yield of the generated biogas, methane content and the overall stability of digestion process depend on the process parameters such as operating temperature, pH value, carbon-nitrogen (C/N) ratio and the substrate composition (Sharma et al., 2020). The operating temperature is usually in the range of 10–65°C while the anaerobic medium should be kept at around neutral pH (i.e., pH of 7) value. At pH less than 6.5 and more than 8.5, the growth of methane forming bacteria is hampered and the methanogenesis process is inhibited (Jain et al., 2015) thereby reducing the methane yield. It is reported that a pH value between 7 and 7.2 is considered optimum for proper functioning of an anaerobic digester (Coelho and Chavez, 2020). It has been reported that for appropriate functioning of an anaerobic digester, the C/N ratio should be between 15 and 30 (Kumar and Samadder, 2020). The different biodegradable materials are suitable feedstocks for biogas production in an anaerobic digestion process. In rural areas, manure and plant biomasses are used in biogas plants, while from municipalities, food waste and sewage sludge are the mostly used as feedstock for biogas processes (Kelebe and Olorunnisola, 2016).

Co-digestion of different substrates has been proved to improve biogas/methane yield and also ensure stable biogas process. According to (Zhang et al., 2013), anaerobic co-digestion of food waste (FW) with cattle manure (CM) could enhance the biodegradation process resulting in a higher methane yield. It was reported by (Li et al., 2009) that a 44% improvement on the methane yield could be obtained by co-digesting FW with CM. Pre-processing/pre-treatment involves the manual and mechanical separation or sorting, shredding, grinding and drying of feedstock prior to feeding into the digestion plant. Pre-treatment of OFMSW prior to feeding into bio-digester can enhance the rate of degradation of organic components thereby resulting in improved methane yield and more stable end products (Kumar and Samadder, 2020).

Table 4
Factors that determine choice of anaerobic digesters (Igoni et al., 2008, Coelho and Chavez, 2020).

Classification basis	Digester types
Substrate feeding	Batch and continuous digesters
Operating temperature	Mesophilic (20–45°C), Thermophilic (45–60°C) and Psychrophilic (10–15°C) digesters
Substrate Solid contents	Dry and wet digesters
Substrate type	High solids (> 20%TS) and low solids (< 20% TS) digesters
AD process complexity	Single stage and multistage digesters
Scale of digester	Farm-based, food processing and centralized digesters

The AD process can occur naturally or made to occur in specially made structures called bio-digester. Bio-digester, sanitary landfill and bioreactor landfill are prominent technologies for biogas generation through AD process. Anaerobic bio-digester is an air-tight biologically-engineered structure or container constructed with materials such as concrete, steel, plastic or brick where biodegradable organic materials are placed (Nizami, 2012). The choice of digester type depends on a number of factors such as the moisture content of feedstock (wet or dry), the solid content in the feedstock (high or low solid), the feeding rate (batch or continuous), operating temperature (mesophilic, thermophilic and psychrophilic), and the system complexity (single stage or multi stage) (Ayodele et al., 2018b). Table 4 shows some of the operating parameters of bio digesters. Depending on the total solid content of the waste, the digester can be operated in batch or continuous-flow form.

The batch digester can handle a significant amount of the waste with little quantity of water, whereas in a continuous-flow digester the waste needs to be grounded to small and fine particles, and diluted with so much water to meet the desired total solids (Igoni et al., 2008). Generally, the batch system is usually associated with dry and high solids wastes of low volume such as municipal solid waste, while the continuous stirred tank reactor (CSTR) considers wet and low solids wastes of high volume such as municipal wastewater (MWW) (Igoni et al., 2007).

Some of the commercially available digester designs, their characteristics and the countries of origin are shown in Table 5

2.2.2. Landfilling and landfill gas recovery systems

Landfilling is the deposition of waste materials in landfill or dumpsites where the waste materials are buried. It is the final disposal of wastes. Landfilling is the most predominantly practiced method for waste disposal in the world especially in developing countries. It has been reported that on average about 90% of the waste collected in Africa and Latin America and the Caribbean is disposed of in landfills and open dumps (UNEP, 2019). For example, about 74% of the waste generated in Nigeria is landfilled (Ayodele et al., 2020), 90% of waste landfilled in South Africa (Dlamini et al., 2019) and about 80–90% of the MSW generated is landfilled in Malaysia (Johari et al., 2012). Although landfilling is inexpensive, its practice is environmentally detrimental due to the emission of obnoxious gases such as greenhouse gases (CH_4 and CO_2), NH_3, H_2S etc., into the environment. It requires large area of land and can take up to 36 hectares. There could also be a high risk of methane explosions in landfills. Landfilling can lead to loss of valuable resources such as land that are useful for agricultural or industrial purposes. Its environmental implication is premised on the huge CH_4 gas emitted from landfills. Around 30–70 million tonnes of CH_4 is released from landfills into the atmosphere (Beyene et al., 2018). CH_4 is about 28–36 more potent than CO_2 in terms of the climate change-inducing effect over a 100-year period (LMOP, 2016).

In the near future, this method will not be able to handle the increasing generation rate of MSW since the current landfills are reaching their maximum capacity limit. It is estimated that in South Africa, the City of Johannesburg's landfills' airspace will be completely depleted by year 2023 (Baker and Letsoela, 2016). Scarcity of land is the major constraint for the location of new dumpsites in developed countries especially in Japan and other developed economies. Landfill gas recovery technology (LFGR) can be implemented by collecting the gases (landfill gas) emitted and used for electricity or heat generation through an internal combustion engine. The generated landfill gas is collected through a system of pipes and wells involving an active or a passive system using vertical wells and horizontal trenches by means of natural pump or pressure gradient (Amini, 2011). Energy recovery from landfill does not only ensure environmental sustainability but also allows revenues generation through carbon markets and from the sale of electricity.

It is possible that some of the degradable matter within the landfill may not be subjected to biodegradation for lack of moisture that is required to sustain bacterial growth. This may reduce the amount of landfill gas (methane) generated per tonne of MSW. In order to accelerate the rate of waste degradation in the landfill and thus increase the generation of landfill gas, a bioreactor landfill is implemented (Themelis and Ulloa, 2007). In a bioreactor landfill, the aqueous effluent (leachate) produced is recirculated and distributed throughout the landfill to enhance waste biodegradation (Ayodele et al., 2018b). Another novel and advanced method of optimizing biogas recovery from landfill is biocell technology. Biocell technology is an extension of the bioreactor landfill whereby biological decomposition occurs in three stages such as anaerobic, aerobic and mining stages. In the anaerobic stage, landfill gas is produced using leachate recirculation similar to bioreactor. In the second stage, the biocell operates as aerobic bioreactor whereby air is injected into the solid waste matrix for compost formation. In third stage, the biocell is mined to extract recyclable materials and space recovery for reuse (Davis, 2014). From these processes, it is evident that biocell considers waste as a resource for sustainable development (Meegoda et al., 2013).

3. Global status of waste-to-energy generation

This section gives a brief overview of the status of the level of implementation of WtE plants around the world.

3.1. Global implementation of incineration system

Incineration with energy recovery has been largely adopted in high-income and land-constrained countries. In 2011, nearly 800 thermal WtE projects were functioning in almost 40 countries globally and that 11% of the MSW treated generated up to 429 TWh of power (Dlamini et al., 2019). Due to increased level of technology and better

Table 5
Large scale anaerobic digesters and their design parameters (Kumar and Samadder, 2020).

Process name	Countries of Origin	Capacity tons/yr	Retention time (days)	Number of stages	Biogas yield (m^3/ton)	Total Solid (TS) content (%)	Operating Temperature Condition
BTA	Germany	1,000–150,000	2	Single	80–120	< 20 (Wet)	Mesophilic
Valorga	France	10,000 –270,000	21	Single	80–160	20–35 (Dry)	Mesophilic/Thermophilic
Linde	Germany	15,000 –150,000	–	Single/Two	100	20–45 (Dry)	Mesophilic/Thermophilic
Dranco	Belgium	3,000 –120,000	15–30	single	100–200	20–40 (Dry)	Thermophilic
Kompogas	Switzerland	1,000–110,000	15–20	Single	130	23–28 (Dry)	Thermophilic
WASSA	Finland	3,000–230,000	-	Single	100–150	10–15 (Wet)	Mesophilic/Thermophilic

Table 6
Incineration plants across the world and amount of waste incinerated (UNEP, 2019)

Countries	Number of incineration plants	Amount of waste incinerated (million tons)
Switzerland	30	4
Sweden	34	6
South Korea	35	5
Italy	41	6
United Kingdom	46	10
Austria	65	4
United States	77	30
Germany	121	26
France	126	14
China	286	5
Japan	754	30
Ethiopia	1	0.35
Total	**1616**	**140.35**

consciousness to environmental concern, more than 1,700 incineration plants with energy recovery are currently in operation worldwide with more than 80 per cent located in developed countries, led by Japan, France, Germany and the United States and more than 200 incineration plants are currently under construction and will be operational between 2020 and 2023 (UNEP, 2019). In Malaysia, only one incineration plant is in operation which can produce 1 MW of electricity from 100 tonnes/day of MSW (Tan et al., 2015). The premier waste incineration plant constructed in Ethiopia with a capacity of 55 MW which is the first of its kind in Sub-Saharan African will process 1,400 tonnes of waste per day (Stafford, 2020). Singapore has a total of five incineration plants (Qazi et al., 2018b). Despite huge amount of MSW generated in Nigeria, there is no functional incineration plant to treat the waste except for hospital waste where small scale incinerators are used to treat the hazardous waste. The three incinerators built in Lagos, Nigeria in 1979 were later dismantled and converted to civic centre in 1989 (Ogwueleka, 2009). Table 6 shows number of some incineration plants and their locations across the world.

3.2. Global implementation of anaerobic digestion systems

Implementation of AD around the world varies significantly from small-scale household digesters in developing countries such as China, India, Malaysia and Africa to large farm-scale or centralized digesters in developed countries especially in Europe and United States (Vasco-Correa et al., 2018). In developed countries most of the produced biogas is used for combined heat and power (CHP) applications and sometimes upgraded to use as transportation fuel (Nielsen and Angelidaki, 2008). The centralized digesters have capacity up to 8000 m^3 (Nielsen and Angelidaki, 2008) while farm-scale are in the range of 200–1,200 m^3 (Weiland, 2010).

In Denmark there are about 150 biogas plants with 20 centralized plants and plans are in place to increase the capacity in the nearest future. In Germany, farm-scale digesters are majorly used, with about 9,000 already operational and there is a plan to have about 10,000–12,000 digesters by 2020 (Wilkinson, 2011). In the United States and Canada, about 250 and 100 farm-scale digesters respectively are in operation (Vasco-Correa et al., 2018). Small-scale digesters are mostly household units of capacity in the range of 2–10 m^3 and are located in rural areas in Asia and other developing countries (Surendra et al., 2014). There are mainly three types of small-scale digesters: the Chinese fixed dome digester, Indian floating drum digester, and the tube digester (Surendra et al., 2014).

Due to the peculiarity of rural dwellers, the biogas produced from anaerobic digester is used mostly for cooking (in cooking stoves) and for lighting thereby reducing demand for wood to meet cooking and heating needs and deforestation reduction in the long run. China is the largest user of small-scale digesters. It is reported that more than 43 million digesters, serving about 100 million people in rural areas have been installed and operational in China followed by India with about 4.7 million digesters, Bangladesh 90,000 while Nepal has installed more than 300,000 digesters (REN21, 2020). In Africa and Latin America, the utilization of anaerobic digestion technology is slow, but there is a renewed effort towards adoption and implementation usually at small-scale level for treating different types of waste, such as animal manure, organic fraction of MSW, and industrial waste. By 2015, about 60,000 digesters were in operation in Kenya, Burkina Faso, Ethiopia, Tanzania, and Uganda (REN21, 2020). In 2015, South Africa implemented an anaerobic digestion project that processed cattle waste and produced about 4.4 MW of electricity. There are on-going projects on biogas-to-energy generation in Zimbabwe. For example, an 800 m^3 digester plant (2 by 400 m^3) to be co-fed with sewage and organic agricultural waste from the Mbare market place is on-going. The biogas will run a 100–200 kVA generator and the electricity generated will be used in Mbare area. The global energy production from biogas in year 2000 was estimated to be around 0.28 million Tera Joules and it reached almost 1.3 million Tera Joules by 2014, with an annual average increase of 13.2% (IEA, 2016). With the current trend in anaerobic digestion implementation worldwide, there is a great potential in biogas contribution to the global renewable energy production with the view to achieving sustainable energy generation.

3.3. Implementation of landfill gas recovery around the world

There are a number of landfill gas plants that collect landfill gas for energy generation around the world. As of 2005, there were about 955 landfill gas (LFG) plants worldwide with the largest number located in the United States (Themelis and Ulloa, 2007). The number has marginally moved to 1,000 LFG plants where most of these plants are situated in Europe and United States (LMOP, 2016). The technology is gaining more attention in Africa with South Africa taking the lead with 4 LFG plants in operation (Njoku et al., 2018). In Johannesburg South Africa, in 2016 the Robinson Deep landfill gas recovery began generating 3 MW of renewable electricity which is enough to supply power to more than 5,500 homes (Dlamini et al., 2019). In Goudkoppies and Marie Louise landfill sites, the gas collected is being flared and installation of gas collection system and a generator are underway, each site is expected to generate 3 MW of electricity while Ennerdale and Linbro Park landfill sites are both expected to generate 1 MW of electricity that will be fed to the City Power electricity grid (Baker and Letsoela, 2016). In Malaysia, only 10% of the total operational landfill sites are sanitary with 5 of them equipped with methane recovery for electricity generation (Tan et al., 2015). There is no functional sanitary landfills for energy recovery in Nigeria (Ogunjuyigbe et al., 2017).

4. Factors for selecting waste-to-energy technologies

Identifying the proper WtE technology for a certain area depends on a number of factors ranging from technical, economic, environmental, policy to social. Such factors as maturity level of the technology, waste composition and characteristics, land area requirement, capital and maintenance costs, technological complexity coupled with labor skill requirements, geographical locations of the plants and technology's efficiency are some of the criteria to be considered. Table 7 shows the comparisons among various WtE technologies in terms of technical, economic, environmental and social factors.

It could be observed from Table 6 that each waste-to-energy option performs differently based on the identified criteria. Although it is possible to have a change in the performance of each WtE technology with respect the criteria due to technological advancement, it is difficult to make a clear-cut decision in selecting the most appropriate technologies considering the technical, economic, environmental and social factors concurrently because no technology has a total advantage over others.

Table 7
Comparison of various WtE technologies (Ouda and Raza, 2014, Yap and Nlxon, 2015, Qazi et al., 2018b)

Parameters	Technologies				
	AD	LFGR	INC	GAS	PYR
Technical					
Waste type	Organic Fraction	Mixed waste	Mixed waste	Homogeneous waste	Homogeneous waste
Technology maturity	Very High	Very High	Extremely High	Emerging	Emerging
Waste Volume Reduction	45–50%	Low	75–90%	75–90%	50–90%
Technology complexity	Low	Low	Low	High	High
System efficiency	50–70%	10%	50–60%	70–80%	70%
Residence time	15–30 days	Years	2 s	10–20 s	Second –Weeks
Labour skill requirement	Low	Low	Low	High	High
Land requirement	Large	Very Large	Small	Small	Small
Pre-treatment	Required	Not required	Not required	Required	Required
Future Potential	High	High	Moderate	High	High
Economic					
Capital cost	Medium-High	Low	Medium-High	High	High
Operation and maintenance costs	Medium-High	Low	Medium-High	High	High
Pre-treatment cost	Medium	None	None	High	High
Social and Environmental					
GHG Emissions	Least	High	Extremely High	Low	Low
Dioxin and Furan Emissions	Extremely Low	Extremely Low	Very High	Very Low	Very Low
Social Opposition	Very Less	Less	Extremely High	High	High

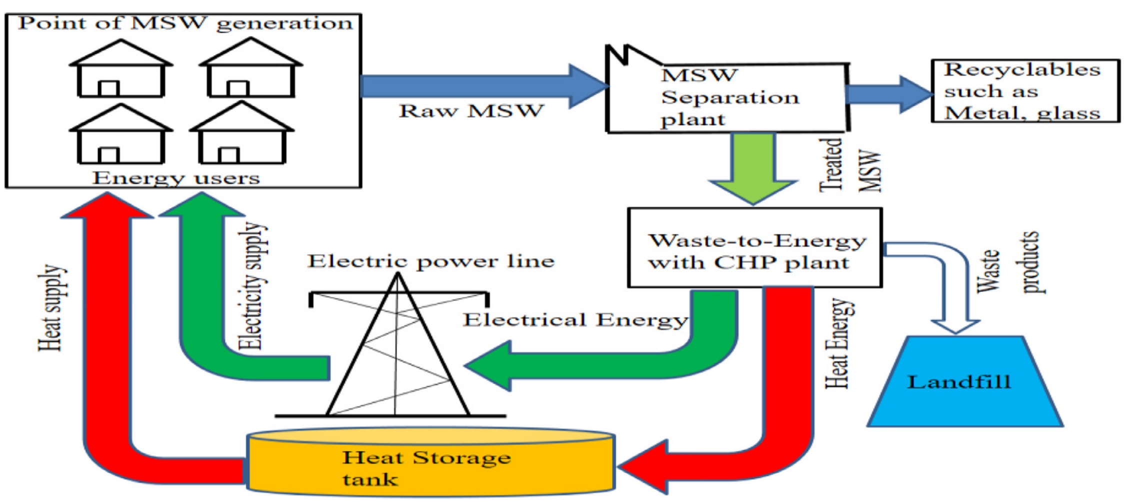

Fig. 5. WtE as a contributor to sustainable development.

5. Waste-to-energy as a cleaner technology and panacea for sustainable development

Sustainable development is defined as the capability of the present generation to satisfy their needs without jeopardizing the capability of the future generation from achieving the same goal (meeting their needs). Prominent among societal needs are access to affordable and reliable energy as well as clean and livable environment. The abovementioned points coincide with the sustainable development goals 7 (SDG 7) and 11 (SDG 11) of the United Nations (UN). In the same vein, a circular economy is one of the conditions for achieving sustainable development, due to a number of benefits it offers, including among others less environmental pollution by reducing greenhouse gas emissions, improved security of supply of raw materials, bolstering economic growth and jobs creation (Khan and Kabir, 2020). The use of cleaner energy technologies and systems is critical to achieve sustainable development driven by circular economy. This is because cleaner energy technologies ensure livable environment and improve peoples' quality of life by reducing air and water pollution. They also reduce energy dependence by creating renewable resources in local communities. WtE technologies have been recognized as clean energy technologies which have the capability of ensuring clean society and foster energy security by leveraging on the possibility of reducing the adverse environmental impact occasioned by waste generation and ensuring production of renewable and sustainable energy while achieving circular economy.

Fig. 5 shows the basic of WtE as a pathway for sustainable development. It is observed from this Figure that WtE could allow creation of new jobs during construction and operation of WtE plant. Also, jobs are created from the collection and transportation of MSW to pretreatment/separation plants prior to WtE plant. Production of energy from the WtE plant will stimulate the economic growth and additional jobs could be created while ensuring adequate treatment of the effluent (solid, liquid or gaseous) for cleaner environment.

6. Discussion

This section presents the possible energy potential, the economic viability as well as the environmental and social impacts of waste to energy technologies.

6.1. Energetic potential arising from waste-to-energy technologies

Heat, fly and bottom ashes are the products of incineration process. The heat energy produced can be used for power only, thermal only and combined heat and power (CHP) or co-generation application via a conventional Rankine cycle steam turbine. The co-generation application of incinerator is most efficient as the total system efficiency can reach up to 80–90% (DEFRA, 2013). It is reported that when combusting 1 metric tonne of MSW in a contemporary incineration plant, about 80% of energy embedded can be recovered as heat to raise steam in steam-turbine (DEFRA, 2013) for generating 500–600 kWh of electricity (Awasthi et al., 2019, Kaza and Bhada-Tata, 2018) and 1000 kWh of thermal energy (Kaza and Bhada-Tata, 2018). Based on this hypothesis and using data in Table 6, the total amount of electricity that could be produced from waste incineration plants is 70.18–84.21 TWh and heat is 140.35 TWhth. The waste heat could be used in providing process heat for industrial application for district heating systems. For effective operation of incineration with CHP application, identifying potential heat users will enhance maximum utilization of the available heat energy. Therefore, it will be cost effective and highly efficient to locate an incinerator close to the proximity of the heat customers or installed as a part of an industrial facility or built in conjunction with a district heating system.

The bottom ashes are used as an aggregate for backfilling in road construction application (Qazi et al., 2018a), concrete making (Joseph et al., 2018), cement and building materials (Shah et al., 2021)

For an anaerobic digestion system, it was also reported by (Murphy and McKeogh, 2004) 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). Based on these research outcomes, 1 tonne of biodegradable waste can produce 426.36 kWh. (Note: 1 tonne of OFMSW can produce 209 m^3 of methane at 0.717 kg/m^3 density). According to (Nixon et al., 2013), around 100–350 m^3 of biogas can be produced from 1 tonne of OFMSW. It can be deduced from Fig. 1 and Table 2 that the total biodegradable (food and green waste) components of global MSW amount to 941.55 million tonnes per year. If the whole of these wastes (food and green waste) are digested anaerobically and the biogas produced is utilized for electricity generation, the total recoverable electricity will amount to 401.44 TWh. This huge amount of energy indicates the potential of AD technology as a means of providing renewable energy for sustainable development.

The potential of electricity production through LFGR from Florida counties in the United States was estimated to be approximately 0.4–1.0 TWh per year in 2010 and projected to be between 0.8–2.6 T Wh per year in 2035 (Amini, 2011). This is equivalent to removing some 70 million vehicles from highways or replacing over 800 million barrels of oil consumption during the 2010–2035 timeframe (Amini, 2011). It was also reported that Brazil has the potential of generating approximately 660 MWh of electricity per day from MSW landfills alone (Kumar and Samadder, 2017) and Malaysia is expected to generate 2.63 TWh of electricity from landfill gas (LFG) alone by the year 2020 (Noor et al., 2013). As of 2016, 652 LFGR facilities were already operating in 48 states in the United States with an estimated capacity of 17 TWh for electricity generation and 98 billion cubic feet of LFG for direct end user (LMOP, 2016).

6.2. Economic and cost analysis of waste-to-energy technologies

Economic as well as cost consideration is crucial for effective implementation of waste-to-energy system. The cost analysis of the various WtE technologies for typical developed and developing countries is depicted in Tables 8a and 8b. The capital costs and operation and maintenance costs are major cost considerations for the development, implementation and in choosing a suitable alternative waste-to-energy.

With reference to Tables 8a and 8b, the initial capital cost is generally very high irrespective of the regions (developing or developed), but also varies according to the chosen technology. The initial capital cost of a WtE plant can also be influenced by its production capacity (Neehaul et al., 2020) but can take advantage of economies of scale. The capital cost of plants in developed countries is higher due to higher labour costs, land scarcity and more stringent and emission control standards (UNEP, 2019) compared to developing countries where there is cheap labour and availability of large and inexpensive expanse of land such as in Nigeria, India and China. These factors are actually responsible for diverse costs values for WtE implementation between developed and developing countries. The operation and maintenance costs are strongly technology-dependent. The lifespan of the plant, availability of cheap raw materials and skilled labour, incentives from government etc., (Kumar and Samadder, 2017) influence the operation and maintenance costs. The lifespan of a WtE facility is considered to be in the range of 20–40 years (IRENA, 2012). In developing countries, lack of skilled and experienced contractors that can design and build WtE plants may jerk up the initial capital cost as those skilled resources have to be imported from developed countries or elsewhere. From Tables 8a and 8b, it is obvious that thermal-based WtE technologies (Incineration, Pyrolysis and Gasification) have huge costs compared to anaerobic digestion and landfilling. Landfilling with gas recovery presented the least costs which affirm its cheapness but when influences such as health impact, environmental impact, land degradation, and ground water contamination are considered, landfilling becomes the worst option (Awasthi et al., 2019).

Table 8a
Cost analysis of WtE technologies for a typical developing country (such as India) (Yap and Nixon, 2015).

Technologies	Capital cost (US$/ton)	Operation cost (US$/ton/annum)
Incineration	155–250	85
Pyrolysis	170–300	65–112
Gasification	170–300	65–112
Anaerobic digestion	50	5–30
Landfilling with Gas recovery	10	0.2–0.3

Table 8b
Cost analysis of WtE technologies for a typical developed country (such as UK) (Yap and Nixon, 2015).

Technologies	Capital cost (US$/ton)	Operation cost (US$/ton /annum)
Incineration	620–700	62–70
Pyrolysis	620–850	75–102
Gasification	620–850	74–102
Anaerobic digestion	310–400	19–28
Landfilling with Gas recovery	155–200	11–14

6.3. Environmental impact of waste-to-energy technologies

Waste-to-energy implementation has been proved to have positive impact on global warming due to reduction in greenhouse gases (such as CO_2) compared to the baseline case (i.e., waste dumping, open burning and landfill with gas collection). In terms of climate change mitigation, for example, each tonne of MSW incinerated in a thermal WtE plant, an equivalent of 1,010 kg of CO_2 can be avoided by diverting waste from landfills without methane gas utilization when excluding biogenic carbon emissions (UNEP, 2019). Similarly, CO_2 emissions by an incinerator are 0.22 kg CO_2/kWh while the emissions in a gasification plant are lower than an incinerator at around 0.114 kg CO_2/kWh. Estimations for the CO_2 emissions from electricity generated from AD plants are 0.2 kgCO_2/kWh whereas 1–1.2 kg CO_2/kWh are for landfill gas recovery system (Murphy and McKeogh, 2004). Anaerobic digestion has been proved to be most environmentally friendly among the reviewed WtE technologies as confirmed by (Alao et al., 2020). Specifically, (Khan and Kabir, 2020) reported that gasification, pyrolysis, and AD were 33%, 65%, and 111% more sustainable waste-to-energy generation technologies than direct combustion.

6.4. Social impact of waste-to-energy implementation

Implementation of waste-to-energy projects has the potential to create new jobs for the local community people. During construction and while in operation, waste-to-energy plant can create direct, indirect, temporary and permanent jobs for the local communities. According to (Kabir and Khan, 2020), a waste-to-energy generation plant with moderate capacity can employ around 100 employees in developing countries.

7. Challenges, policy and incentive drive for waste-to-energy implementation

While most developed countries have successfully adopted and implemented WtE technologies, there are challenges hindering their implementation in developing countries. These challenges have been identified to cover logistic, technical, financial, socio-environmental and policy-based. Logistically, inadequate waste collection facilities and lack of waste segregation at the source are major concerns for waste-to-energy implementation in developing countries. There is limited availability of technical data on waste quality and quantity in developing countries. The quality of waste in terms of the physical (proximate) and chemical (ultimate) analysis is very critical in determining the calorific value of the waste. Limited or lack of knowledge about the composition and characterisation of waste may result in inappropriate equipment and technology choices (Oelofse et al., 2016) with eventual waste of resources and time. From the economic viewpoint, WtE technologies are capital intensive which require costly equipment. Many developing nations lack the financial power for investment in waste to energy. The construction and start-up operation and maintenance costs of incineration facilities may be too high and unaffordable for developing countries (Ogwueleka, 2009). For instance, in Malaysia, incinerators operation were suspended due to the high operational costs as a result of fuel costs and maintenance costs (Johari et al., 2012).

For cost effectiveness in the implementation of WtE technologies, the government of different countries should put in place financial incentives (such as Feed-in-Tariff, Credits for Carbon Reductions, Tax exemptions, Credits for Renewable Energy etc.,) (GMI, 2014) that will encourage investments in the waste-to-energy sector. Regulatory framework and policies should be initiated through legislative action that can stimulate public private partnership (PPP) in the waste-to-energy market. Feedstock availability is crucial for successful implementation of waste-to-energy system; therefore, authorities in different countries at local and national levels should impose strict sanctions and penalties on waste landfilling by having a standard gate or tipping fee similar to what is available in most developed countries to maximize waste diversion from landfills and ensure availability of waste feedstock for waste-to-energy implementation. Segregation of waste will improve its calorific value and require fewer operating costs compared to mixed waste type. To ensure more homogeneous waste components, source separation is required where waste fractions are segregated at the generation point. This could be achieved by putting in place laws and regulations and ensure strict compliance by enforcing the laws because enforcement of available laws will not only improve the waste situation at community level especially in African municipalities (Stafford, 2020) but also ensure cost effectiveness in waste-to-energy implementation.

8. Conclusion

This paper presents a review of different WtE technologies as a potential source of renewable energy and waste management strategy for developing as well as developed countries. In this study, five waste-to-energy techniques divided into biochemical and thermochemical processes were reviewed. It was observed that biochemical based technologies such as anaerobic digestion appears to be the most suitable in developing countries due to the high moisture content and dominant biodegradable composition such as food waste in the range of 50–56% in their waste stream whereas the high component of recyclable and organic hydrocarbon-based components (e.g., plastics) in the waste stream of developed countries makes thermochemical processes especially incineration the most preferred technology. Either for developing or developed countries, adequate pretreatment of waste could enhance the suitability for a conversion technology although at the expense of the operating costs. Enactment of laws, relevant regulations and policies with firm enforcement invigorated with clear and workable roadmap can enhance the adoption of WtE system in developing countries especially Africa. Provision of incentives by the government to woo the would-be investors and political-will in terms of good budgetary allocation for integrated waste management could stimulate investment and encourage public-private partnership in the waste to energy market for developing countries. In order to unlock the great potential in the humongous municipal solid waste generated on daily basis in developing nations, collaboration in terms of technology transfer and knowledge sharing among university scholars, equipment manufacturers and all concerned stakeholders in waste-to-energy industries in developed and developing nations could go a long way in helping developing countries actualize their waste-to-energy implementation dream and ambition.

Based on the literature reviewed, implementation of waste-to-energy systems either in developing or developed nations has the potential to contribute to the energy generation mix, mitigate environmental impact, reduce health risks and create jobs for the local populace.

9. Future research perspective

For effective and optimized waste-to-energy project, it could be more promising to combine two or more technological options. A combination of two or more waste-to-energy systems ensures maximum utilization of feedstock with eventual optimization of energetic yield as well as environmental benefits compared to separate application. Integration of anaerobic digestion which produces biogas from easily degradable organic waste such as food waste and gasification that produces syngas from slowly degradable organic wastes such as wood, agricultural residues as well as recyclables such as paper and plastics will ensure optimum utilization of the waste components in MSW stream. There is a limited research effort on techno-economic, environmental and social implications of a hybrid implementation of waste-to-energy system. One of the few researches on hybrid application is the financial analysis of a hybrid of anaerobic digestion and gasification presented by (Mabalane et al., 2021) and found that integration of gasification and anaerobic digestion performed financially better than separate system. In the work of (Alao et al., 2020), it was also reported that a hybrid application of anaerobic digestion, landfill gas recovery and pyrolysis for the city of Lagos, Nigeria can ensure greenhouse reduction of 91.16%. More research effort is expected in the area of integrated application of waste-to-energy technologies. It is expected that a hybrid application of waste-to-energy technologies stands to be more sustainable and more efficient for cities than standalone applications. There are other emerging techniques for simultaneous waste management and energy generation such as torrefaction, plasma arc gasification, fermentation (bio-ethanol production), bio-hydrogen production, use of microbial fuel cell and esterification. The future research efforts should be directed towards extensive study of these emerging technologies. Overall, each of the WtE technologies performs differently in technical, economic, environmental and social parlances based on qualitative and quantitative criteria. Multi-criteria-based approaches which have the capability to simultaneously take into consideration qualitative and quantitative criteria is a subject of future work

Declaration of Competing Interest

The authors hereby declare that there is no conflict of interest regarding this manuscript

Data availability

Data will be made available on request.

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