A technical review of bioenergy and resource recovery from municipal solid waste

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A B S T R A C T

Population growth, rapid urbanization, industrialization and economic development have led to the magnified municipal solid waste generation at an alarming rate on a global scale. Municipal solid waste seems to be an economically viable and attractive resource to produce green fuels through different waste-to-energy conversion routes. This paper reviews the different waste-to-energy technologies as well as thermochemical and biological conversion technologies for the valorization of municipal solid waste and diversion for recycling. The key waste-to-energy technologies discussed in this review include conventional thermal incineration and the modern hydrothermal incineration. The thermochemical treatments (e.g. pyrolysis, liquefaction and gasification) and biological treatments (e.g. anaerobic digestion and composting) are also elaborated for the transformation of solid wastes to biofuel products. The current status of municipal solid waste management for effective disposal and diversion along with the opportunities and challenges has been comprehensively reviewed. The merits and technical challenges of the waste-to-energy technologies are systematically discussed to promote the diversion of solid wastes from landfill disposal to biorefineries.

1. Introduction

Rapid industrialization and energy consumption go hand-in-hand with globalization and urbanization. The prosperity of a nation for economic development and urbanization often leads to compromising the natural environment. It is projected that the world population will increase from the current 7.7 billion to 8 billion by 2030 (United States Census Bureau USCB, 2020). With the rise in the global population, the basic needs of survival are also indispensable, which includes food, water, air, shelter, clothing, energy source and lifestyle requirements such as fuel and electricity. There is an upsurge in the per capita energy consumption with a human birth eight seconds (Nanda et al., 2015). Fossil fuels (e.g. crude oil, gasoline, diesel, coal and natural gas) have dominated the global energy market since the industrial revolution. Fossil fuels have augmented the worldwide industrialization, but have also compromised environmental quality. The exploiting use of fossil fuels has led to an increase in greenhouse gas (GHG) emissions, air pollution, acid rain, smog, global warming and climate change.

Fawzy et al. (2020) have systematically reviewed some key approaches to abate climate change, which include conventional mitigation, negative emissions and radiative forcing geoengineering. Conventional mitigation technologies aim to mitigate CO_2 emissions from fossil fuels by making a paradigm shift and adapting to nuclear power and carbon-neutral renewable energy sources (e.g. solar, tidal, wind and biofuels). On the other hand, negative emissions technologies intend to capture and sequester CO_2 through the application of biochar, afforestation, reforestation, ocean fertilization, terrestrial weathering, ocean alkalinity enhancement, wetland restoration as well as direct air carbon capture and storage strategies. On the contrary, radiative forcing geoengineering strategies to curb climate change by regulating the earth's radiative energy budget and stabilizing global temperatures. This approach includes some notable techniques such as stratospheric aerosol injection, marine sky brightening, space-based mirroring, surface-based brightening and Cirrus cloud thinning, to name a few. A detailed description of these aforementioned topics can be found in the review by Fawzy et al. (2020).

Every year, the energy consumption and urban population augment by 1.1% and 1.5%, respectively (International Energy Agency IEA, 2007; Kumar and Samadder, 2017). Population growth, rapid urbanization and economic development have significantly increased the generation of municipal solid waste (MSW). Municipal solid waste is also known as garbage, thrash and refuse refers to the solid wastes discarded by the public daily. Currently, about 1.9 billion tonnes of MSW are produced

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Nomenclature

NH_4-N	Ammonia nitrogen		MSW	Municipal solid waste
$N-NH_3$	Ammoniacal nitrogen		MWL	Municipal waste leachate
NH_4^+	Ammonium ions		NASA	National Aeronautics and Space Administration
C/N	Carbon/nitrogen ratio		NO_3^-	Nitrates
COD	Chemical oxygen demand		NPK	Nitrogen, phosphorus and potassium
CNG	Compressed natural gas		OFMSW	Organic fraction of municipal solid waste
P_C	Critical pressure		O/C	Oxygen/carbon ratio
T_C	Critical temperature		PM	Particulate matter
DMF	Dimethylformamide		PCB	Polychlorinated biphenyls
GHG	Greenhouse gas		PCDD	Polychlorinated dibenzodioxins
HHV	Higher heating value		PCDF	Polychlorinated dibenzofurans
HCl	Hydrochloric acid		PAH	Polycyclic aromatic hydrocarbons
HF	Hydrofluoric acid		PNA	Polynuclear aromatic hydrocarbons
H_2O_2	Hydrogen peroxide		pH	Potential of hydrogen
LPG	Liquefied petroleum gas		SWOT	Strengths, weaknesses, opportunities and threats
LHV	Lower heating value		TOC	Total organic carbon
MDF	Medium density fiberboard		SDGs	United Nations Sustainable Development Goals
			VOC	Volatile organic carbon
			WtE	Waste-to-energy

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every year on a global scale, out of which nearly 30% remain uncollected by municipalities' waste management systems (Waste Atlas, 2018). However, the generation of MSW is expected to escalate to 3.4 billion tonnes by 2050 (The World Bank, 2020). According to The World Bank (2020), an average individual generates nearly 0.74 kg of solid waste footprint every day. After the collection of MSW, approximately 70% ends up in landfills, 19% is recycled and 11% is used for energy recovery. The effective management of MSW is categorized under two of the United Nations Sustainable Development Goals (SDGs), namely Goal 12 (Responsible Consumption and Production) and Goal 11 (Sustainable Cities and Communities) (United Nations, 2020). However, an additional goal (i.e. Goal 7: Affordable and Clean Energy) can also be achieved if the MSW is diverted for waste-to-energy conversion.

The composition of MSW varies greatly among different municipalities worldwide, but it typically comprises of both biodegradable and non-biodegradable materials from organic and inorganic sources. MSW is collected from households, offices, institutions and commercial enterprises, which typically include organic wastes (e.g. kitchen waste and yard waste), paper, plastics, glass, metal and miscellaneous garbage (e.g. electronic waste, inert materials, pharmaceuticals as well as construction, demolition and renovation wastes) as summarized in Table 1. The management of MSW varies within municipalities, cities, states and countries. The basic platforms in MSW management are: (i) generation of wastes at the source; (ii) collection and transfer of waste; and (iii) disposal, processing and treatment of wastes (Fig. 1).

MSW is one of such waste resources that require immediate attention to effective management techniques. Moreover, MSW is a valuable, renewable and economical waste resource that can recover usable solid, liquid and gaseous fuels to supplement the amplifying energy demands. The composition and management of MSW vary largely from municipalities to countries. Fig. 2 illustrates the composition of MSW on a global scale. Waste-to-energy is an economically viable and environmentally sustainable solution to recover energy from waste resources in the form of fuel, heat and electricity. It is indispensable for realizing the true potential of WtE conversion pathways to address the concerns of solid waste management and alternative energy generation. Typically, the WtE technologies are selected based on MSW composition, seasonality, communal socio-economic levels, local municipality policies, economic assessment and environmental impacts (Moya et al., 2017).

The available WtE technologies for MSW can be chiefly classified into thermochemical and biological processes (Fig. 3). Depending on the thermochemical conversion technologies, the major fuel products can be bio-oil, producer gas, synthesis gas and char. On the contrary, biological conversion processes include anaerobic digestion and composting that produce biogas (i.e. biomethane) and compost (i.e. decomposed organic matter). Some next-generation biological conversion processes that could be applied to the solid organic fraction and leachate of MSW to produce biohydrogen are dark and photo-fermentation, direct and indirect bio-photolysis, microbial electrolysis cells as well as microbial electro-hydrogenesis cells (Zhen et al., 2016; Allegue et al., 2020; Kamaraj et al., 2020; Osman et al., 2020; Sarangi and Nanda, 2020). The chief WtE technologies applied for MSW are conventional incineration and hydrothermal incineration and oxidation. Opposed to landfill disposal, these technologies have the candidacy to significantly reduce GHG emissions and transform MSW to usable fuels to energy products.

There is a lack of standard methods to assess the effective energy recovery and environmental impacts of different waste-to-energy (WtE) conversion technologies. Certain properties of MSW can aid in determining its candidacy for either thermochemical or biological WtE conversion technology. For example, a higher proportion of moisture-containing organic fraction in MSW (i.e. kitchen waste, food waste and yard waste) is found to be suitable for biological conversion technologies (e.g. anaerobic digestion and composting) as well as hydrothermal technologies (i.e. subcritical/supercritical water-assisted liquefaction, gasification and incineration). The biological conversion pathways involve the use of microorganisms and their enzymes to decompose the organic fraction of MSW for conversion to biomethane, biohydrogen, compost and digestate. The feedstock of biological conversion must be prepared considering the organic content, dry solids, volatile solids, carbon/nitrogen (C/N) ratio, moisture, micro-nutrients and macro-nutrients for microorganisms without any contaminants (e.g. pesticides, insecticides, disinfectants, antibiotics, pharmaceuticals, inert materials such as glasses, plastics and metals). Based on the metabolism of the responsible microorganisms (i.e. aerobic, anaerobic, photosynthetic or dark), the appropriate biological conversion pathways such as composting, anaerobic digestion, bio-photolysis, dark fermentation and photo-fermentation are determined.

On the contrary, MSW containing recalcitrant organic components (e.g. paper waste, packaging boxes and cardboards) and non-biodegradable organics (e.g. plastics, rubber, polymers and tires) are more suitable for thermochemical conversion technologies (e.g. pyrolysis, liquefaction and gasification). Some physicochemical properties of broadly heterogeneous MSW, which can help access their WtE valorization are proximate composition (i.e. moisture, volatile matter, fixed carbon and ash), ultimate composition (i.e. carbon, hydrogen, nitrogen, sulfur and oxygen), thermal stability (i.e. devolatilization pattern),

Table 1
Type and typical composition of municipal solid waste.

Category	Common sources
Organic waste	• Kitchen waste (e.g. food waste including fruit and vegetable residues) • Agro-food residues (e.g. solid food processing wastes) • Yard waste (e.g. leaves, grass, tree trimmings and barbeque wood)
Paper	• Scrap paper • Newspaper • Magazines • Books • Paper bags • Wet wipes • Tissue paper and napkins • Parchment paper • Wrapping paper • Cardboard • Packaging boxes
Plastic	• Bottles • Containers, container lids and caps • Boxes • Clear wraps • Ziplock bags • Polyethylene bags • Polystyrene • Cable wire • Pipes • CDs, DVDs and vinyl records
Glass	• Bottles • Broken glassware • Utensils • Mirror • Light bulbs • Decorative items • Window panels
Metal	• Cans and tins • Aluminum foils • Utensils • Cookware • Container lids • Appliances • Railings • Bicycles
Miscellaneous	• Electronic waste (e.g. thrashed computers, monitors, tablets, phones, watches, batteries and other electronic goods) • Broken appliances • Textiles • Leather • Rubber • Pet litter • Personal hygiene products • Health care products • Pharmaceuticals • Cosmetics • Discarded furniture • Inert materials (e.g. construction, demolition and renovation wastes, drywalls and ash)

Note: The classification of municipal solid waste presented in this table is subject to variation depending on the municipality and country and its local jurisdiction and waste management regulations.

elemental composition (micro- and macro-elements), particle size, porosity, bulk density and biopolymeric composition (i.e. cellulose, hemicellulose, lignin, fatty acids, proteins, lipids, amino acids and salts), to name a few.

The WtE technologies applied to MSW management can contribute to the circular economy for offsetting the environmental risks and impacts and GHG emissions, while at the same time, increasing waste recycling as well as resource and energy recovery rates. Farrell et al. (2020) reported a critical analysis of closed-loop recycling and open-loop cascading options of the circular economy, which are primarily used to evaluate the environmental impacts in waste management. Through the closed-loop recycling of MSW, the main products and by-products can enter its supply chain with wide-ranging applications

and marketability. In contrast, open-loop recycling of MSW can be performed when the main products do not meet the quality requirement for direct commercial applications but can find utility in alternative industries. The cascade option in open-loop recycling refers to the post-processing of the product before it can enter into other industrial processes as a precursor to undergo re-designing and engineering for opportunistic recovery.

There is a growing interest in effectively and safely managing municipal solid waste in nexus with its efficient valorization. According to the Scopus database, in the last ten years (2010–2020), more than 13,000 technical documents (e.g. articles and reviews) were published in indexed journals on "municipal solid waste" mentioned in the article title, abstract and keywords (Scopus, 2020). However, only 240 articles were indicated during the same decade with "municipal solid waste to energy" as the search option. Although tremendous amounts of MSW are generated in both developing and developed countries, there is a lack of technology transfer between the nations. Based on this notion, the current paper intends to comprehensively review MSW as a potential resource for alternative energy generation across the world. This paper attempts to systematically review the incineration as a popular WtE technology as well as different thermochemical and biological conversion technologies. These MSW treatment technologies have been technically evaluated to identify the opportunities, challenges and barriers to effective implementation and sustainable waste management.

2. Thermochemical conversion technologies

2.1. Conventional incineration

Incineration is the most common waste treatment technology dealing with the combustion or burning of organic waste materials. Incineration is referred to as a traditional and widely used WtE technology that recovers high-temperature heat from the combustion of waste materials for combined heat and power plants. The heat released through the incineration of wastes can also be used to generate electricity. Incineration of MSW has been a preferred alternative to landfills that are malodorous, space-consuming and compete with residential or agricultural land areas. Incineration typically reduces the weight of the original MSW by 80–85% and volume by 95–96% (RenoSam and Rambøll, 2018). It is worth mentioning that the garbage collection trucks in most municipalities reduce the volume of collected wastes using a built-in autonomous hydraulic compressor before unloading it at the incinerator site. In simple words, incineration dramatically reduces the volume of MSW for disposal. However, waste compaction is also a common practice in many metropolises at the landfills.

The amount of heat generation from the incineration is influenced by the macroscopic and microscopic analytical properties of MSW. The macroscopic properties include heterogeneity, proximate and ultimate analysis, moisture content, calorific value, elemental composition, feedstock particle size, bulk density and ash fusion temperature. The microscopic properties include thermal analysis, chemical kinetic studies and mineral matter. The thermal properties of MSW, especially specific heat, specific gravity, thermal conductivity, volatiles emissions vary greatly with moisture content, incineration temperature and magnitude of thermal degradation. The volatile matter emissions from incineration can include moisture, light hydrocarbons, CO_2, CO, H_2, CH_4, volatile organic carbons (VOC), polycyclic aromatic hydrocarbons (PAH), dioxins, furans and tars. The temperature, heating rate, mineral matter, inert materials and inorganic components in MSW control the yields of gases, ash, slag and heat from the incineration. In addition to the composition, other features of MSW such as heterogenic nature, source and origin influence the heat recovery and product distribution from incineration. A combustion environment is another important factor for consideration in incineration. In combustion, the carbon in MSW is oxidized to produce CO_2, whereas the H_2 is oxidized to water. The typical operating conditions for different thermochemical and

Generation of MSW at the Source

• MSW is generated in households, offices, institutions and commercial enterprises.
• MSW in developed countries contains higher fraction of plastic and paper waste with low moisture content and high heating value.
• MSW in developing countries contain higher fraction of organic matter with high moisture content and low heating value.

Collection and Transfer of MSW

• Waste segregation/sorting at the source is done in developed countries but usually not practised in developing countries.
• In developed countries, the garbage collection truck by local municipality collects the MSW from households and designated areas.
• The waste transfer stations are found in metropolitan cities that handle and distribute the wastes to sorting and processing facilities.

Disposal, Processing and Treatment

• Landfilling is a preferred MSW disposal method in developed countries.
• In most developing and developed countries, incineration is practiced for MSW volume reduction and heat and power generation.
• Implementation of waste-to-energy processes such as pyrolysis, liquefaction, gasification and anaerobic digestion can produce specific fuels such as bio-oil, producer gas, synthesis gas, methane and hydrogen.
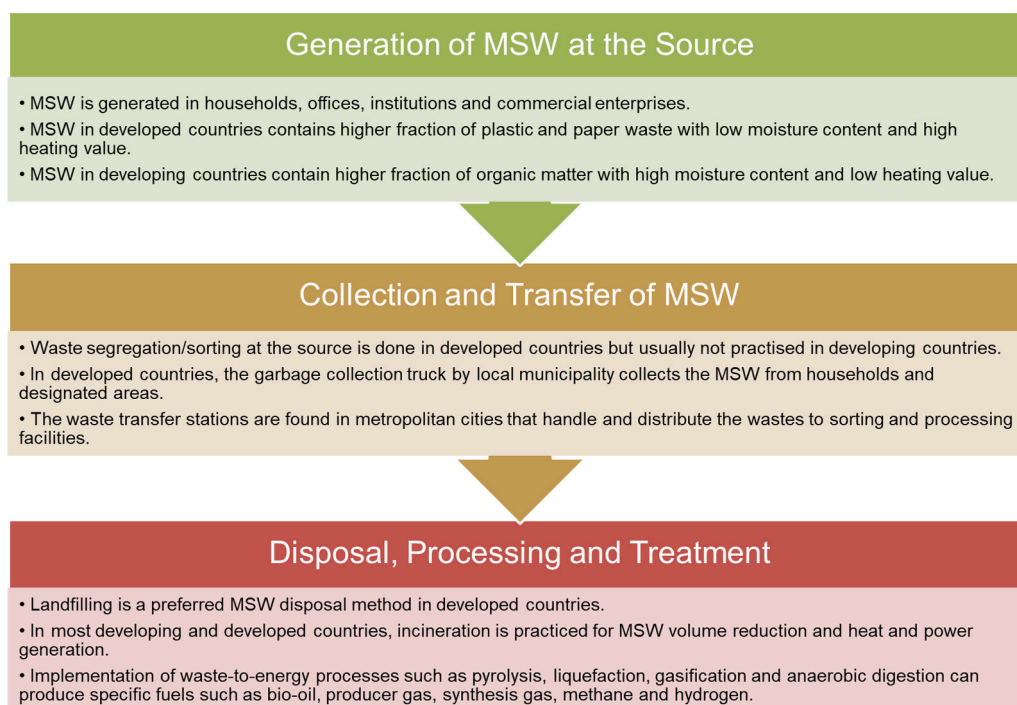
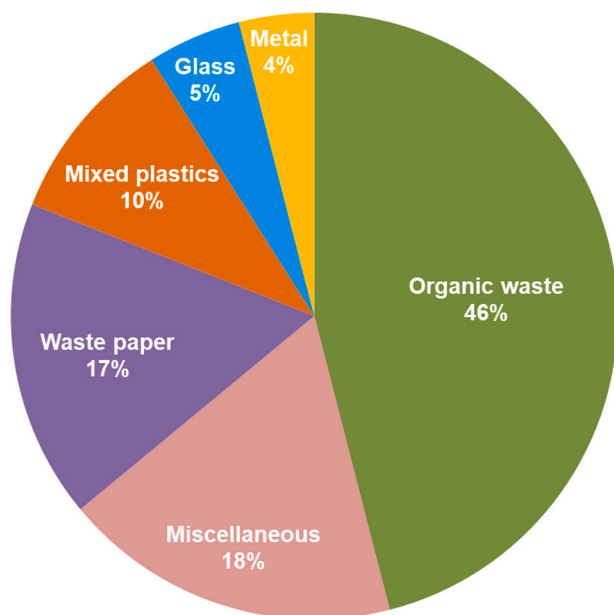**Fig. 1.** Sequential platforms in a typical municipal solid waste (MSW) management system.

Fig. 2. Typical composition of municipal solid waste by a component fraction at a global scale.
(Data Source: The World Bank, 2020).

biological WtE processes are summarized in Table 2.

Upon incineration, the waste materials are converted into bottom ash, fly ash, flue gas, slag and heat. The ash is generated by the inorganic components in the waste and appears in the form of fly ash and bottom ash. Bottom ash refers to the non-combustible and slag-like residues remaining after incineration at the bottom of the furnace or incinerator. It can appear as clinkers sticking to the inner walls of the incinerator. On the other hand, fly ash is the lighter fraction of the ash that escapes through the furnace vent in the flue gas. The composition of bottom ash and fly ash can vary considerably depending upon the source and

physicochemical properties of the waste biomass being incinerated. Regardless, most fly ashes contain significant amounts of metals (e.g. Ar, Be, B, Ca, Cr, Co, Pb, Mg, Hg, Se, Sr, Tl and V), minerals (e.g. SiO_2, Al_2O_3, CaO and asbestos), dioxins, furans and polycyclic aromatic hydrocarbons (e.g. anthracene, naphthalene and phenanthrene).

Fly ash generated as a solid residue of MSW incineration poses serious health issues to humans and animals. Therefore, it is a mandate in certain countries to separate and/or stabilize the fly ash before disposal. The best practice is to scrub the flue gas by particle filtration techniques such as electrostatic precipitation and adsorption to trap the particulate pollutants and fly ash before they disperse into the atmosphere via the furnace vent. The stabilization of fly ash can be achieved through solidification with cement and concrete (Morandeau et al., 2015), vitrification (Alhadj-Mallah et al., 2015), chemical stabilization and heavy metal leaching with acids (Wang et al., 2018). Besides, fly ash can also be used in construction materials (e.g. cement, ceramics, glass and composites), geotechnical (e.g. road pavement and embankment), agriculture (e.g. soil amendment), CO_2 capture and special domain applications (e.g. sorbent and sludge conditioning) (Belviso, 2018; Xu and Shi, 2018; Dindi et al., 2019).

Jung et al. (2005) studied the behavior of metals in ash melting during the gasification of MSW. The study involved a gasification-melting system, which was classified into the fluidized bed, shaft and kiln. The concentration of incineration fly ash was found to strongly influence the generation of melting furnace fly ash. Melting of ash is catalyzed by inorganic species that lead to hard deposits on the cooler regions of furnace walls and heat exchangers, which gradually corrode over time. The presence of potassium in the feedstock tends to decrease the ash melting point, whereas calcium and magnesium increase it (Obernberger et al., 2006). The behavior of ash melting is important to access ash sintering, agglomeration intensity and chances of reactor corrosion. Therefore, ash fusion temperature becomes significant to add flux to the reaction. High concentrations of calcium, sodium and iron can decease the ash fusion temperature (Yao et al., 2020).

Traditionally, incineration was used to reduce the volume of the accumulated wastes and prevent the development of rodents, pests, flies and foul odors from microbial decomposition. Due to a lack of awareness
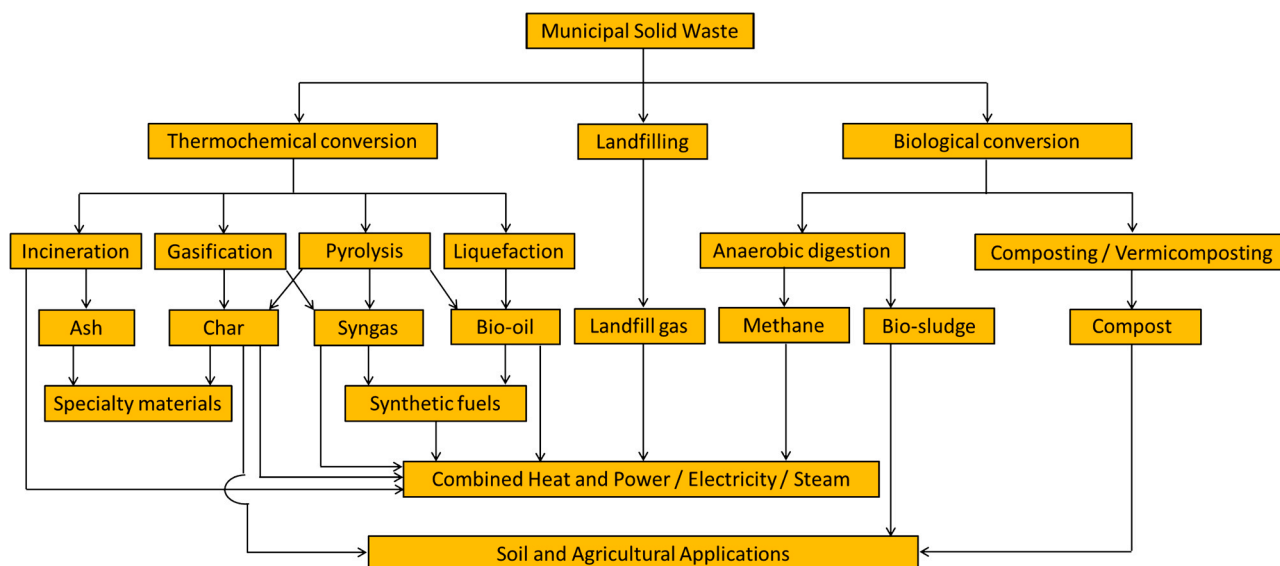
Fig. 3. Different waste-to-energy technologies including thermochemical and biological conversions for municipal solid waste management.

Table 2
Typical operating conditions for thermochemical and biological waste-to-energy conversion technologies.

Technology	Temperature (°C)	Heating rate (°C/s)	Residence time	Typical product distribution
Incineration	800–1200	Variable	Variable	Bottom ash > Fly ash > Slag > Gas
Fast pyrolysis	400–500	10–200	30–1500 ms	Bio-oil > Gas > Biochar
Slow pyrolysis	300–700	0.1–1	10–100 min	Biochar > Bio-oil > Gas
Intermediate pyrolysis	500–600	2–10	10–20 s	Bio-oil ≥ Biochar > Gas
Flash pyrolysis	800–1000	1000	0.5 s	Bio-oil > Gas > Biochar
Liquefaction	250–450	0.05–5	1–40 min	Bio-oil > Tar
Gasification	700–1000	Variable	30–90 min	Syngas > Biochar
Anaerobic digestion	35–37	None	Days	Methane > Other gases > Biosludge
Composting	25–55	-	1–2 months	Humus > Nutrients > Minerals

of environmental impacts, many rural communities globally still practice the open burning of agricultural biomass, garbage and municipal solid waste to reduce the waste accumulation volume. For example, India's capital, New Delhi has been under the spotlight for its horrific smog and air pollution, which are directly attributed to the intentional burning of garbage in its rural population (NDTV New Delhi Television Limited, 2020). In terms of the alarming air pollution levels, India's capital Delhi in many ways is competing with China's capital Beijing, which is well known for its chronic pollution (BBC News, 2020). Along with vehicular emissions and construction dust, opening burning of biomass and MSW is a potential non-point source of particulates and GHG emissions in developing countries like India and China (Ji et al., 2016; Chen et al., 2017; Kumari et al., 2019). In China, the capacity of MSW incineration has significantly expanded over the years in the following order: 2006 (40,000 tonnes/day) < 2013 (158,500 tonnes/day) < 2015 (231,600 tonnes/day) (Ji et al., 2016; Lu et al., 2017). It is also estimated that China's MSW incineration sector could expand up to using 500,000 tonnes/day of wastes by 2020. MSW incineration has been contributing significantly to renewable energy

generation in China attributable to electricity and steam production. However, several reports claim MSW incineration to deteriorate the air quality of China due to poor MSW quality, incomplete combustion and exploiting waste management (Ji et al., 2016; Chen et al., 2017; Hong et al., 2017).

Currently, in India, the policies of banning MSW burning are being made more stringent. Recent reports reveal that the concentration of particulate matter ($PM_{2.5}$) in many Indian metropolitan cities has soared over 15 times higher than the allowable limit by Indian government's norms and to over 90 times greater, the level determined safe by the World Health Organization (NDTV New Delhi Television Limited, 2020). $PM_{2.5}$ is the group of ultrafine particulate matter with a diameter of 2.5 μm or less that are mostly emitted through waste incineration. Routine exposure to $PM_{2.5}$ can turn fatal and carcinogenic as the ultrafine particles can deeply penetrate the lungs, cause irritation, corrode the lungs' alveolar walls and impair lung function (Xing et al., 2016). Furthermore, the localized burning of MSW also results in the release of several pollutants into the atmosphere that includes CO, CO_2, SO_x, NO_x, particulate matter, dioxins, furans, benzene, ethylbenzene, 1-hexene, toluene and other hazardous emissions. The acidic gases emitted from MSW incineration are SO_x, NOx, SO_2, hydrofluoric acid (HF) and hydrochloric acid (HCl). Not only do these pollutants and GHGs cause global warming, but they also lead to other environmental deterioration such as acidification and acid rain threatening vegetation and corroding historic monuments.

Significant advancements have been made in emission and pollution control technologies to make incineration as an attractive waste treatment option because it is less time consuming, less space-consuming as well as produces heat and electricity to the power plants. This makes incineration far more advantageous than landfilling and anaerobic digestion processes. The top ten nations that widely use incineration to treat MSW are: China (231,600 tonnes/day), European Union (207,104 tonnes/day), Germany (52,554 tonnes/day), France (45,334 tonnes/day), The Netherlands (18,600 tonnes/day), Italy (17,825 tonnes/day), Sweden (14,477 tonnes/day), Denmark (10,900 tonnes/day), the U.S. (88,765 tonnes/day) and Japan (92,203 tonnes/day) (Lu et al., 2017). Due to stern waste disposal regulation and policies relating to landfilling and lack of space for new landfills in metropolitan areas, most developed countries prefer incineration as the favored waste management technology. For the developing countries, incineration is considered the most reliable, economical and faster process with the potential for heat and electricity generation to power domestic and industrial sectors. Incineration of MSW is widely

implemented in many Western European countries, with about 35–80% of the total solid wastes being incinerated every year. Other European countries also rely significantly on incineration for handling municipal waste.

Incineration has fewer capital expenses, less operational costs, less human labor requirement and high daily throughput, which adds on to its benefits. Another advantage of MSW incineration is the complete thermal degradation of biohazards or debris from dead organisms as well as mineralization of organic matter into the least innocuous end products. The organic matter load and high moisture content in MSW can dramatically hamper its combustibility, decrease the energy recovery and lower the performance of the incinerator. The moisture content of MSW has a direct influence on its thermochemical conversion technologies including incineration, pyrolysis, liquefaction and gasification. With increasing moisture content in MSW, the calorific value decreases due to the latent heat of vaporization. In addition to sorting and separation of heterogeneous components (metals, minerals, glasses and inert materials), MSW could also require drying to remove moisture, which might add costs to the overall WtE process.

Auxiliary fuels are used for MSW incineration, especially when its heating value is low. However, MSW with the lower heating value (LHV) in the range of 1000–1700 kcal/kg does not necessitate auxiliary fuels to complete incineration (Kumar and Samadder, 2017). Most reports suggest that the average heating value of MSW should be between 1700 and 1900 kcal/kg for an efficient incineration operation with high-energy recovery. Incineration of combustible, low moisture content and non-biodegradable MSW components such as plastics, rubber and polymers is found profitability with high-energy recovery.

Since the industrial revolution, coal has been the favorite and reasonable source of electricity and fuel gas via gasification and combustion. However, the GHG emissions, as well as air and water pollution from these coal-driven processes, cannot be denied. In the context of emissions, co-firing MSW with coal when compared to individually incinerating coal or MSW can help mitigate the total GHG and particulates emissions per unit energy recovered (Zhang et al., 2018). Co-firing or co-combustion is a technology that is related to incineration. Co-firing involves the combustion of biomass and organic wastes together with coal for power production. Through co-firing of solid wastes with coal, both NO_x and SO_x emissions can be reduced with benefits of CO_2 capture (Więckol-Ryk et al., 2018).

Co-firing of MSW with coal also resolves many underlying issues such as enhancement of boiler performance and reduction in ash volume, smoke, CO and particulates emission. Coal can also supplement the calorific value of MSW that is relatively lower due to moisture and organic matter. Besides, the coal boilers could potentially be retrofitted to deploy MSW as a co-fuel, which can boost the process economy. Moreover, coal-firing plants can also earn carbon credits for using biomass (or MSW) as an alternative fuel to reduce carbon emissions that would otherwise be higher by using coal alone as the fuel (McIlveen-Wright et al., 2011; Basu et al., 2011; Nanda et al., 2016f). Co-firing of MSW with coal can be a cost-effective strategy to syndicate environmentally friendly energy generation and waste reduction.

Demirbas (2008) co-fired coal with the organic fraction of MSW in a bubbling fluidized bed combustor at 850 °C. The results indicated a reduction in SO_x and NO_x emissions due to negligible sulfur and nitrogen in MSW. Moreover, MSW was proposed to be a re-burning fuel and re-generable biofuel during co-firing because 10–20% of the total heat input led to a nearly 70% reduction in NO_x emissions.

In another study, Dong et al. (2002) performed the co-firing of MSW with bituminous coal in a fluidized bed. The high volatile matter in MSW dominated the combustion process, which resulted in faster carbon conversion from coal-MSW blended fuel. As the carbon conversion increased, the combustion efficiency also elevated up to about 99% leading to near-complete conversion. This also led to the lowering of the char or ash yields. MSW blends notably lowered the emissions of SO_2, NO and N_2O. However, the release of acidic emissions such as HCl from the blended fuel was only pronounced at low-temperature combustion.

Muthuraman et al. (2010) made a comparative evaluation of co-combustion characteristics of Indian coal with hydrothermally treated MSW and cedarwood. The devolatilization properties and coal reactivity considerably improved with wood and MSW blending. Moreover, high blends of MSW revealed synergistic interactions with coal causing a significant lowering of coal ignition temperature. The decrease in the ignition temperature of coal can significantly reduce the overall energy requirement, lessen the process expenditure, resulting in the complete combustion of the fuel and cut the emissions of CO, CO_2, NO_x, SO_x and VOCs. The results suggest that the blending of MSW with low-grade coal could complement the combustion performances and calorific values of individual fuel due to the enhancement of ignition characteristics.

2.2. Hydrothermal incineration and oxidation

As mentioned earlier, conventional incineration of MSW generates many harmful pollutants such as particulates, dioxins, furans, hydrocarbons, NO_x, SO_x, VOCs, PAHs and benzene-like compounds. These pollutants pose a serious threat to the natural ecosystem and living organisms. Furthermore, the stable components of MSW incineration such as acetic acid, ammonia, anthracene, naphthalene, phenanthrene, pyrene, benzene and phenolics require complex energy-intensive processes for their breakdown into simpler molecules. Recently, hydrothermal flame incineration has emerged as a new approach to innocuously remediate these recalcitrant compounds. Hydrothermal incineration of these stable organic compounds can significantly prevent the generation of intermediate toxic byproducts and lead to their complete degradation to release permanent gases e.g. CO_2, N_2, water vapor and lighter hydrocarbons (Cabeza et al., 2011).

There are many advantages of hydrothermal flame incineration or oxidation over conventional incineration. Some of the notable advantages are: (i) near-complete (> 99.9%) conversion of stable recalcitrant compounds, (ii) high reaction rates, (iii) low mass transfer limitations, (iv) less reaction time in the order of milliseconds, (v) less intermediate byproduct formation, (vi) no or negligible toxic residues, (vii) sustainability of controlled auto-thermal conditions, and (viii) high energy recovery (Reddy et al., 2015). Several challenges relating to hydrothermal flames are material corrosion, the stability of analytical probes and equipment at high-temperature and high-pressure, and safety concerns in highly reactive environments. Due to lack of literature and quantitative data, there is little understanding of the interactions between process parameters during hydrothermal incineration such as effects of temperature, pressure, flow rates of reactant and oxidant, as well as the concentration of reactant and oxidant. Hence, the research on hydrothermal flames is relatively nascent and in its budding stages.

Hydrothermal flames are generated in aqueous environments beyond the thermodynamic critical properties of water (Gordon et al., 2016). Supercritical water acts as the medium of hydrothermal incineration owing to its flexibility in tuning the water's thermo-physical properties such as critical temperature ($T_C \geq 375$ °C), critical pressure ($P_C \geq 22.1$ MPa), density (0.32 g/mL), viscosity (0.03 mPa s), dielectric constant ($\varepsilon \sim 5.9$), heat conductivity (160 mW/m/°C) and heat capacity (13 kJ/kg/°C) (Muangrat, 2016). Supercritical water features improved solvent properties due to its high diffusivities, which makes it an ideal medium for hydrothermal reactions such as oxidation, liquefaction, pyrolysis, gasification and incineration. Besides, the chemical reactions in supercritical water occur in a homogeneous phase, thus eliminating any mass transfer limitations (Reddy et al., 2014).

The ignition of flames in a hydrothermal environment requires an organic compound and oxidant (Qian et al., 2014). While the oxidant is usually oxygen or air, the selection of organic components mostly depends on its miscibility at an auto-ignition temperature close to water's critical temperature (i.e. 374.1 °C). Alcohols, especially C_1 to C_3, are preferred organic solvents in the hydrothermal ignition because of their complete miscibility at auto-ignition temperatures (i.e. typically

between 360 °C and 470 °C) (Sarathy et al., 2014). However, it should also be noted that the auto-ignition temperature of the alcohol-water mixture decreases beyond the critical pressure of water (22.1 MPa). The flammable alcohols act as co-fuel in the hydrothermal incineration of organic compounds. The organic solvents that have been investigated for hydrothermal flame ignition are methanol, ethanol, isopropanol, methane, ethane, heptane and toluene (Reddy et al., 2015).

Hydrothermal incineration of organic wastes involves a sequence of events (Reddy et al., 2015, 2017, 2019). In the preheating stage, the reactant or fuel (organic compound), solvent or co-fuel (alcohol) and reaction medium (water) are heated to the reach supercritical conditions. The oxidant (air or oxygen) is pre-heated in a separate stream. It should be noted that the term "fuel" primarily refers to the reactant or the organic matter used in hydrothermal incineration or oxidation, whereas the "co-fuel" usually refers to the organic solvents and alcohols, which aids in the flame ignition and improving the steady-state conditions during hydrothermal incineration and oxidation processes (Reddy et al., 2015; Abelleira et al., 2013; Zhang et al., 2019). As the supercritical conditions and auto-ignition temperature of the co-fuel are attained, supercritical water dissolves the organic compound creating a conducive environment for the ignition only after the oxidant is introduced into the system. With the aid of oxidant, hydrothermal flames are ignited to oxidize the combustible materials i.e. organic compounds and alcohols in the supercritical water medium. The flame is developed at the interface between the oxidant and co-fuel + fuel mixture in supercritical water and moves axially or radially with flame front velocity (Bermejo et al., 2009). There is an immediate increase in the reactor temperature from supercritical temperature (i.e. 374.1 °C) to the flame temperature (> 1000 °C). Hence, hydrothermal flames are beneficial in not only degrading the waste compounds but also generating heat energy. Supercritical water and co-fuel mixture overcome the mass transfer limitations to completely dissolve and oxidize the organic matter (fuel) to permanent gases (Zhang et al., 2019). High flame temperatures together with supercritical water pressure generate free radicals to degrade highly complex molecules into simple gases and water in milliseconds (Zhang and Ma, 2016).

The current waste disposal methods such as landfilling, offshore disposal, incineration, chemical oxidation and bioremediation have generated dubious concerns towards the sustainability of these waste management practices (Kikuchi et al., 2011). Conversely, the potential of hydrothermal oxidation and incineration can be applied to degrade nuclear wastes, municipal solid waste, landfill leachate, sewage sludge, biomedical and pharmaceutical wastes, as well as biogenic wastes generated in space missions (Moussiere et al., 2007; Hicks et al., 2012; Qian et al., 2014; Reddy et al., 2015; Scandelai et al., 2018). Hydrothermal flames have been used in underwater spallation of rocks and deep-well drilling for the extraction of crude oil and natural gas from deep ocean beds (Hu et al., 2018).

National Aeronautics and Space Administration (NASA) has investigated hydrothermal flame ignition using a portable supercritical water oxidation drop-rig set-up (Moussiere et al., 2007; Hicks et al., 2012; Reddy et al., 2017, 2019). The effects of buoyancy forces on flame ignition and thermal distribution in gravitational and zero-gravity environments were studied (Hicks et al., 2006). The primary objective for NASA is to use hydrothermal oxidation to degrade solid wastes generated in space shuttles during short-term and long-term extraterrestrial human missions. The solid wastes generated in human space missions include food waste, plastics and human metabolic wastes (e.g., feces and urine). However, the chemical properties of space solid wastes, gravitational forces and buoyant forces determine the flame type, ignition delay, flame stability, mass transfer and heat transfer mechanisms in zero gravity environments.

Miller et al. (2015) performed supercritical water oxidation of model fecal sludge without a co-fuel. The model fecal matter was a simulated feces containing 81.7% moisture, 18.6% total solids, 88.5% volatile solids, 3% ammoniacal nitrogen (N–NH$_3$), 2.1% nitrogen, 44.9%

carbon, 7.1% hydrogen and 0.2% sulfur with a chemical oxygen demand (COD) of 1.33, pH of 5.3, electrical conductivity of 5.7 mS/cm and C/N ratio of 17.3. The chemical composition of the stimulated feces was 800 g/kg water, 60 g/kg yeast, 20 g/kg cellulose, 35 g/kg psyllium, 35 g/kg miso, 40 g/kg oleic acid, 4 g/kg NaCl, 4 g/kg KCl and 2 g/kg CaCl$_2$. The stimulated feces were mixed at 100 °C before mixing with the reaction fluid at 375–450 °C and 24.1–28.9 MPa. It was reported that hydrothermal flames fully oxidized the model fecal compounds. Feed concentration showed a considerable impact on fluid temperature. However, a high amount of oxidant showed the maximum conversion of model fecal matter during hydrothermal oxidation. For example, approximately 48% of excess oxygen resulted in the highest temperature with the complete conversion.

Mizuno et al. (2000) studied the supercritical water oxidation of model MSW (i.e. dog food) using hydrogen peroxide (H$_2$O$_2$) as the oxidant at 400–550 °C. At low stoichiometric levels of oxidant, total organic carbon decreased with increasing temperature. The liquid effluents from hydrothermal oxidation contained high amounts of acetic acid, followed by propionic acid and isovaleric acid. Acetic acid and ammonium ions were the main refractory intermediate compounds with a high amount of oxidant. Owing to the highly reactive environment, HCl produced during the oxidation reactions leached out chromium from the stainless steel reactor by corrosion, which also led to the complete decomposition of ammonium ion. During hydrothermal oxidation, the activation energy of total organic carbon removal was relatively lower (97.2 kJ/mol) as opposed to the reduction of ammonium ion (130.8 kJ/mol). Moreover, high oxidant levels also removed color and odor from the model MSW.

Zou et al. (2014) performed supercritical water oxidation of MSW leachate to study the effect of operation parameters on its decomposition and removal of heavy metals. The studies were performed at variable temperatures (i.e. 400–500 °C), pressures (i.e. 26–30 MPa), reaction times (i.e. 30–150 s) and oxidant concentrations (i.e. 1.5–3.5%). It was reported that the removal of COD from the MSW leachate was influenced by process parameters in the order: oxidant > temperature > reaction time > pressure. However, for the removal of ammonia nitrogen (NH$_4$–N), parameters varied as temperature > oxidant > reaction time > pressure. Although pressure had minimal impacts, optimal levels of temperature and oxidant led to the decomposition efficiencies of COD and NH$_4$–N to a maximum of 98.5% and 76.2%, respectively. Besides, solid residues are comprised of calcium carbonate and a significant fraction of heavy metals from the original MSW leachate.

Al-Duri et al. (2015) studied the degradation of dimethylformamide (DMF) in a continuous (plug flow) supercritical water oxidation reactor. DMF is a highly robust nitrogen-containing hydrocarbon used the production of acrylic fibers, plastics, pesticides, adhesives, synthetic leather, surface coatings and films, and peptide coupling in pharmaceuticals. It is a hazardous component found in industrial effluents and MSW. The study showed that hydrothermal oxidation of DMF improved by the addition of isopropanol as a co-fuel premixed with the feedstock and a split-oxidant system. Isopropanol lowered the activation energy of supercritical water oxidation to achieve a higher organic denaturation. The co-oxidation of isopropanol resulted in the generation of extra free radicals along with that of supercritical water, which led to the near-complete destruction of DMF evident by greater total organic carbon and nitrogen removal rates. It also enhanced the utilization of the oxidant (i.e·H$_2$O$_2$). Nevertheless, hydrothermal oxidation of DMF helped to shift nitrogen-speciation towards gaseous nitrogen (i.e. N$_2$ and N$_2$O) as opposed to liquid nitrogen.

2.3. Pyrolysis

Pyrolysis is one of the chief thermochemical technologies used to convert waste biomass and other organic residues to energy-dense bio-oil. It is a biomass-to-liquid thermochemical conversion technology operating in the absence of oxygen to produce liquid hydrocarbon fuels.

The main fuel products from pyrolysis include bio-oil, char or gases. However, the product distribution is largely influenced by the limiting factors such as temperature, heating rate, vapor residence time, inert gas flow rate, reactor geometry and feedstock properties (e.g. moisture, particle size and elemental composition) (Nanda et al., 2013).

Pyrolysis can be categorized into slow, fast, intermediate and flash pyrolysis depending on the heating rate and vapor residence time. The reaction conditions in each of these pyrolysis processes are summarized in Table 2. Fast and flash pyrolysis processes are characterized by high temperatures, high heating rates and short residence times, which result in greater yields of bio-oil (Parakh et al., 2020). In contrast, slow pyrolysis is differentiated with its moderate temperatures, low heating rates and longer residence times, which improves the yields of char. Lignocellulosic biomass and biochar inherently contain a certain amount of alkali and alkaline earth metals, which could either catalyze or retard the pyrolysis reaction. Owing to its heterogeneous nature, MSW contains a variety of inorganic metals including alkalis. These metals together with sulfur are relevant in ash melting, fly ash generation, aerosol emission and reactor corrosion when used as a feedstock (Nanda et al., 2016a; Magdziarz et al., 2016).

High pyrolysis temperatures lead to the dehydration and depolymerization of biomass and other organics to produce volatile components. When condensed, the volatile components quench to produce bio-oil. The quenching process and residence time of the volatile vapors determine the quantity and quality of bio-oils. Bio-oils are oxygenated liquid products resulting from the thermal degradation of cellulose, hemicellulose, lignin, lipids, fats, sugars and organic residues present in biomass or MSW. Pyrolysis of cellulose and hemicellulose results in the occurrence of acids, alcohols, aldehydes, esters, ethers, furans, ketones, sugars and mixed oxygenates (Joshi and Lawal, 2012). On the contrary, bio-oil from pyrolysis of lignin produces catechols, guaiacols, phenols and syringols.

The bio-crude obtained from pyrolysis contains organic (e.g. oil and tar) and aqueous (e.g. water-soluble components) phases. The aqueous phase comprises acids (e.g. acetic and carboxylic), alcohols (e.g. phenol, methanol and ethanol), aldehydes, ketones, ethers and esters (Joshi and Lawal, 2012), whereas the organic phase is made of heavy oil, tar, carbonyls and phenolics. The oxygenated nature of bio-oil results in its less energy density, low heating value and reduced thermal stability. Several upgrading techniques used to selectively remove oxygen and moisture content from bio-oil and enhance its fuel properties include zeolite cracking, emulsification with diesel and catalytic hydrodeoxygenation. Several sub-reactions such as decarboxylation, decarbonylation, dealkoxylation, dealkylation, hydrocracking, hydrogenation, hydrogenolysis and methyl transfer are involved within the hydrodeoxygenation of bio-oil (Ruddy et al., 2014).

Biochar is a solid product of pyrolysis, which comprises stable aromatic forms of carbon resulting from dehydration, deamination, decarboxylation and dehydrogenation of biomass during pyrolysis and gasification (Mohanty et al., 2013; Nanda et al., 2017a; Azargohar et al., 2014, 2019). The physicochemical and structural properties of biochar that determine its applications are carbon content, elemental composition, specific surface area, pore size, pore volume, pH, electrical conductivity and ion-exchange capacity. These features are highly variable depending on the feedstock properties as well as pyrolysis or gasification conditions (i.e. temperature, heating rate, residence time and inert gas flow rate). Nanda et al. (2016a) reviewed the wide-ranging applications of biochar can be found in energy (e.g. co-pyrolysis, co-gasification, co-combustion and co-firing); specialty materials (e.g. activated carbon, adsorbents and electrode); reaction engineering (e.g. catalyst, catalyst support and fluidizing agent); agronomy (e.g. water retention, soil fertility and plant nutrition); environment (e.g. pollutant adsorption and carbon sequestration); and pharmaceutical (e.g. toxin adsorption, cleansing agent and cosmetics).

A slow pyrolysis study of organic fraction of municipal solid waste (OFMSW) by Yang et al. (2018) demonstrated that feedstock moisture content had insignificant effects when compared with process temperature. The raw material for slow pyrolysis (i.e. 450–850 °C) mostly consisted of the organic fraction of MSW, especially wood, grass, plastics, food waste and paper. High pyrolysis temperature reduced the liquid product yield but promoted gas yields. Besides, the aqueous fraction of liquid products from the pyrolysis of high moisture containing OFMSW at low temperatures resulted in acidic chemicals, whereas basic chemicals were noticed from low moisture containing OFMSW at high temperatures.

Islam et al. (2005) pyrolyzed MSW paper in a fixed bed reactor at 300–500 °C. Maximum liquid and gaseous product yields were found at 450 °C and 500 °C, respectively. A residence time of 40 min was found to be optimal for maximum liquid product yield at 450 °C. The bio-oil generated from MSW paper was oxygenated, acidic (i.e. 1.5) with a calorific value of 13.1 MJ/kg, a flashpoint of 200 °C, a pour point of −8 °C, a density of 1205 kg/m^3 and a viscosity of 2 cSt (at 35 °C).

Luo et al. (2010) studied the effect of particle size of individual components of MSW (i.e. kitchen garbage, wood and plastic) on pyrolysis product yield and composition. The particle sizes studied were 0–5, 5–10 and 10–20 mm at 800 °C in a fixed bed reactor. Smaller particle size biomass led to greater gas yields (i.e. H_2 and CO) with less tar and char formation. The char generated with smaller particle-sized MSW resulted in high ash and carbon content, especially from kitchen garbage and wood, whereas the char derived from plastics demonstrated higher volatile matter.

Fang et al. (2017) evaluated the thermal characteristics and kinetic behavior for different blends of MSW and paper mill sludge during a non-isothermal co-pyrolysis at 900 °C. The MSW used consisted of 46.4 wt% food waste, 4.7 wt% wood, 18.2 wt% paper and 30 wt% polyvinyl chloride. It was reported that a 10% blend ratio of paper mill sludge and MSW was suitable for co-pyrolysis.

Velghe et al. (2011) compared the product distribution and composition from slow and fast pyrolysis of MSW (e.g. disposed carpet, plastic, trace metal, cartons, paper and synthetic materials) in a semi-continuous laboratory-scale reactor. Slow pyrolysis was performed at 550 °C at a feeding rate of 12 g/min, whereas fast pyrolysis was operated at 450–550 °C at a feeding rate of 24 g/min. Fast pyrolysis of MSW at 510 °C with a 24 g/min feeding rate produced a viscous brown oil rich in poly(ethylene-co-propylene) wax and aliphatic hydrocarbons. Nevertheless, the pyrolysis oils exhibited higher heating values (i.e. 35–44 MJ/kg), low moisture content (i.e. 6 wt%) and a low oxygen/carbon (O/C) ratio (i.e. 0.2–0.3).

Chen et al. (2020) have reported a study to upcycle food waste digestate, which is a major component of MSW to produce solid fuels and biochar for the adsorption of heavy metals. The anaerobic digestate derived from food waste was co-granulated along with medium density fiberboard (MDF) dust and sodium silicate as the binder. The granules were carbonized through pyrolysis at 700 °C at a heating rate of 20 °C/min under N_2 atmosphere. The resulting biochar demonstrated superior fuel properties and performance for the adsorption of Pb and Cd. The concentration of binder (i.e. sodium silicate) in the granules revealed positive effects on the removal capacity of heavy metals by the biochar. For example, biochar generated from food waste digestate and MDF dust having 3 wt% sodium silicate as the binder exhibited the maximum lead removal capacity of 355.3 mg/g, which was six times greater than an analogously investigated commercial activated carbon.

Recently, Osman (2020) reported integrated combustion and pyrolysis of lignocellulosic biomass, which was found to be promising in reducing NO$_x$ emissions while producing biofuel products. The NO$_x$ emissions, particularly N_2O released from the combustion process was abated and converted to H_2O and N_2 by coupling a DeNO$_x$ catalyst (i.e. Pt/TiO$_2$/ZSM-5) with urea to construct an in situ ammonia-selective catalytic reduction system. Since the organic fraction of MSW, especially food waste contains several nitrogenous compounds (e.g. proteins, fatty acids, amino acids, lipids and fats), there conversion using such a DeNO$_x$ catalyzed integrated combustion and pyrolysis could be

promising in reducing NO_x emissions.

2.4. Liquefaction

Liquefaction is another biomass-to-liquid thermochemical technology that generates high quality and energy-dense bio-oil at high pressures and usually in the presence of catalysts. Liquefaction also leads to the production of value-added materials such as adhesives, epoxy resins, bio-polyols and polyurethane foams along with bio-oil (Li et al., 2017; Jiang et al., 2018). Liquefaction involves a sequence of chemical reactions such as: (i) reduction and thermal cracking of cellulose, hemicellulose, lignin, lipids, fats, proteins and other organics, (ii) hydrolysis of polysaccharides to glucose and other simple monomeric sugars, (iii) hydrogenolysis, (iv) reduction of amino acids, (v) dehydration, decarboxylation and other reformation reactions, (vi) C–O and C–C bond cleavage, and (vii) hydrogenation of functional groups (Nanda et al., 2014).

Thermochemical liquefaction usually operates at 200–370 °C and 4–20 MPa pressure (Isa et al., 2018). However, the involvement of catalysts in liquefaction can lower the reaction temperature, enhance the reaction kinetics and improve bio-oil yields. Alkali catalysts such as NaOH, Na_2CO_3, KOH and K_2CO_3 can suppress char formation and consequently enhance bio-oil yields (Nanda et al., 2014). In contrast, acid catalysts such as H_2SO_4, H_3PO_4 and p-toluenesulfonic acid can decrease the process temperature and reaction time (Parakh et al., 2020).

Liquefaction under hydrothermal condition has been reported for better biomass conversion and yield of relatively pure bio-oil. Hydrothermal liquefaction involves water as the liquefaction medium and is performed at 280–370 °C under 10–25 MPa pressure (Toor et al., 2011). Water in its subcritical or supercritical state is one of the promising solvents for hydrothermal liquefaction due to its better solvation properties, low cost and abundance. Hydrothermal liquefaction has several advantages over other biomass-to-liquid conversion technologies. One such advantage is the use of high moisture containing feedstocks such as algae, aquatic biomass, sewage sludge, MSW and cattle manure. The feedstocks do not necessitate drying for use in hydrothermal liquefaction because the medium of liquefaction is water, which significantly saves the operating costs.

There is limited literature on the liquefaction of the original MSW as the feedstock. However, significant research has been performed on liquefaction, hydrothermal liquefaction and co-liquefaction of several individual components of MSW. Wang et al. (2014) studied the feedstock interactions and product distribution during hydrothermal liquefaction of plastic waste, wheat straw and lignite in subcritical water. A synergistic effect was reported at an optimal blending ratio of 1:4:5 for plastic waste, wheat straw and lignite, which led to maximum oil and gas yields. High temperatures enhanced the liquefaction to form pre-asphaltene and asphaltene, which further decomposed to form oil. Furthermore, the addition of tourmaline during hydrothermal liquefaction resulted in enhanced liquefaction rates and greater oil yield.

Barnés et al. (2017) liquefied pinewood and various model components (e.g. cellulose, amylopectin and organosolv lignin) at 300–310 °C with 1-methylnaphthalene to study the reaction chemistry. The study suggested that char was formed through dehydration and precipitation of heavy carbohydrate and cellulose derivatives. Instead of contributing to char formation during liquefaction, lignin led to light and heavy bio-crude. The bio-crude from lignin indicated phenolic features similar to those generated from the carbohydrates. Distillate-range products were obtained from the liquefaction of carbohydrates, whereas both distillate-range products and vacuum residues originated from lignin. On the other hand, the gases were produced chiefly from the carbohydrates and to a lesser extent from the decomposition of their distillates.

Mosteiro-Romero et al. (2014) studied the dissolution of wood in subcritical water during hydrothermal liquefaction and gasification at 250–350 °C under 15–30 MPa pressure with various holding times. It was reported that as the temperature increased, the liquid and gas yields increased along with the carbon content in the char. Water-soluble products (i.e. aqueous phase) were predominant in the liquid products obtained from low-temperature hydrolysis, whereas methanol-soluble products (i.e. organic phase) were mostly found as a result of high-temperature hydrolysis. However, hexane-soluble components were not identified in the liquid products in any case. The gaseous phase consisted mainly of CO_2.

2.5. Gasification

Gasification is a biomass-to-gas thermochemical technology that can transform carbon-based organic materials to produce syngas. Syngas or synthesis gas is a mixture of H_2, CO, CO_2, CH_4 and trace amounts of C_2H_2, C_2H_4 and C_2H_6. Gasification is considered an attractive biomass-to-gas technology because it generates H_2 as a clean energy carrier with a superior heating value (141.7 MJ/kg) and lowest exergy rate among most hydrocarbon fuels (Nanda et al., 2017b; Salam et al., 2018; Okolie et al., 2020a). The medium of gasification can be air, steam or water. In hydrothermal gasification, subcritical or supercritical water is the reaction medium as well as the reactant. Water beyond its critical temperature ($T_C \geq 374.1$ °C) and critical pressure ($P_C \geq 22.1$ MPa) is known as supercritical water. On the other hand, subcritical water is the fluid phase of water that exists below the critical temperature ($T_C < 374.1$ °C) and pressure ($P_C < 22.1$ MPa). The thermo-physical properties of supercritical water provide optimal conditions for oxidation of organic wastes (Reddy et al., 2014). Supercritical water demonstrates gas-like viscosity and liquid-like density and demonstrates ionic (H^+ and OH^-) and free radical (•H and •OH) mechanisms during hydrothermal gasification, all of which contribute to better mass transfer and solvation properties of organic biomass.

The gasification of organic wastes consists of several stages. In the initial stage, as the biomass is heated up to 500 °C, it releases water vapor and volatile components from the polysaccharides (e.g. cellulose, hemicellulose and starch), lignin, lipids, fats, proteins and pectin. The degradation temperatures of hemicellulose, cellulose and lignin are reported to be 200–300 °C, 250–350 °C and 200–500 °C, respectively (Carrier et al., 2011). In the second stage (i.e. 500–600 °C), the decomposed components react to produce phenolics, aromatics, aliphatics, aldehydes and olefins. In the third stage (i.e. 600–900 °C), the intermediate degradation products are further cracked to produce permanent gases (e.g. H_2, CO, CO_2, CH_4 and C_{2+}) and tertiary products (e.g. benzene, naphthalene, anthracene, pyrene and phenanthrene) (Yahaya et al., 2020).

Compared to thermochemical gasification, hydrothermal gasification offers faster hydrolysis, enhanced feedstock solubility, rapid degradation, higher carbon conversion efficiency even at lower temperatures, increased H_2-rich syngas yields, low char and tar generation, and reduced chances of polymerization of intermediate components (Okolie et al., 2019, 2020b,c). Moreover, high moisture-containing biomasses such as MSW, sewage sludge and cattle manure can be gasified in supercritical water considering the aqueous reaction medium. Therefore, the expenses relating to biomass drying are abridged. High yields of H_2-rich syngas are obtained at optimally high temperatures and pressures, longer residence times and low feed concentrations. Moreover, several homogeneous and heterogeneous catalysts can accelerate hydrogenation, methanation and water-gas shift reaction to increase the individual gas yields depending on their selectivity. A wide variety of catalysts such as alkali (Nanda et al., 2016b,c,d), Lewis acids (Gong et al., 2017a,b) and transition metals (Nanda et al., 2016e, 2018; Rana et al., 2017, 2019) have been employed for hydrothermal gasification of organic wastes.

He et al. (2009) studied the effects of temperature and catalyst (i.e. calcined dolomite) on the steam gasification of MSW to produce H_2-rich syngas. The MSW used in the study was a composite mixture of kitchen garbage (i.e. 69 wt%), paper (i.e. 10 wt%), textile (i.e. 2.2 wt%), wood

(i.e. 7.4 wt%) and plastic (i.e. 11.5 wt%). The temperature for gasification was varied from 700 °C to 950 °C and the saturated steam was injected into the system at 110 °C and 141 kPa. The steam-to-MSW ratio was 0.77 for weight hourly space velocity of 1.29/h. At high temperatures (i.e. 850–950 °C), calcined dolomite catalyst increased H_2 and CO yields and enhanced the gasification efficiency by thermally decomposing the tar. At 950 °C, the H_2 concentration (i.e. 53.3 mol%), H_2 yield (i.e. 38.6 mol/kg) and H_2 yield potential (i.e. 70.1 mol/kg) reached their maximum. About 36.4–70.2 mol% of syngas was produced through catalytic steam gasification of MSW. The char generated from steam gasification of MSW at 950 °C had the highest ash content of 84%, negligible H_2 levels (i.e. 0.4 wt%) and lowest carbon content (i.e. 4.1 wt%) due to dehydrogenation and carbon gasification.

Zhao et al. (2010) generated and characterized the combustible gases through the gasification of MSW with hot blast furnace slag at 600–900 °C. The MSW used in the study contained 20.4 wt% plastic, 1.2 wt% rubber, 42.2 wt% kitchen waste, 23 wt% paper, 9.2 wt% wood and 4 wt% textile components. The concentration of the combustible gases, particularly H_2 and CO amplified with increasing gasification temperature, whereas that of CO_2 decreased. The CH_4 concentration did not show much variation though the temperatures. As the concentration of H_2 and CO increased with rising temperatures, the calorific value of the gases also increased. At different gasification media, the volume fraction of CO, H_2 and CH_4 increased in the order of $N_2 <$ air $<$ steam. Blast furnace slag performed as a heat carrier and catalyst, thus promoting the gasification efficiency of MSW.

Zhang et al. (2012) developed a plasma gasification melting process for MSW conversion in an updraft moving-bed gasifier. The plasma torches installed close to the air nozzles heated the air to 6000 °C, which melted and trapped the undesirable inorganic compounds in MSW in the form of a vitrified slag. The initial plasma power was 2.88–3.12 MJ/kg of MSW. The residual heat in the plasma-heated air provided additional heat energy to the gasification system. The syngas produced had LHV in the range of 6–7 MJ/Nm^3. With an increasing equivalence ratio (i.e. 0.08–0.12) in the case of air gasification of MSW, the gas yield and energy efficiency increased while the LHV of syngas decreased. In the case of high-temperature steam gasification of MSW, both the gas yields and LHV of syngas increased with equivalence ratio, which was due to the steam reforming of tar. The maximum energy efficiency with plasma gasification reached 60%, although tar formation attributed to the main energy loss. The inorganics and heavy metals present in MSW were sequestered inside the slag, which mostly comprised of SiO_2 and CaO. The slag demonstrated a high density of 2300 kg/m^3 and the volume ratio of slag-to-MSW was 1:50. The slag showed promising properties to be used as a building material for construction.

Nanda et al. (2016d) investigated the potential of several kitchen-derived food wastes, which is a major component of MSW for supercritical water gasification. The household solid wastes used in the study included Aloe vera rind, banana peel, coconut shell, lemon peel, orange peel, pineapple peel and sugarcane bagasse. These food wastes were gasified in a tubular batch reactor under supercritical conditions to study the impacts of temperature (i.e. 400–600 °C), reaction time (i.e. 15–45 min) and the biomass-to-water ratio (i.e. 1:5 and 1:10) at pressures of 23–25 MPa. High total gas yield (i.e. 5.5 mmol/g) and H_2 yield (i.e. 0.91 mmol/g) were obtained from the orange peel as a test feedstock at an optimally high temperature (i.e. 600 °C), lower feed concentration (i.e. 1:10 biomass-to-water ratio) and longer reaction time (i.e. 45 min). Nevertheless, coconut shell, due to its high lignin content, and in the presence of 2 wt%, K_2CO_3 as the catalyst produced maximum total gas yield (i.e. 15 mmol/g), H_2 yield (i.e. 4.8 mmol/g), H_2 selectivity (i.e. 45.8%) and better LHV of syngas (i.e. 1595 kJ/Nm^3). The results indicated that household food waste could be promising feedstocks for hydrothermal gasification to produce H_2-rich syngas.

Wei et al. (2017) studied the reactivity and synergy during the co-gasification of bituminous coal and hydrochar derived from MSW. The results indicated that higher gasification reactivity occurred at a greater fraction of MSW-derived hydrochar at elevated temperatures. High synergistic effects at relatively lower gasification temperature (i.e. 800–850 °C) resulted from the inhibition of active alkaline and alkaline earth metal (i.e. active calcium) transformation. Weak synergistic effects were found at high temperatures since the more catalytic activity of potassium was retained.

Yildirir et al. (2017) performed supercritical water gasification of refuse-derived fuel generated from the MSW treatment plant at 500 °C and 29 MPa with NaOH and RuO_2/γ-Al_2O_3 as the catalysts. RuO_2/γ-Al_2O_3 at a loading of 5 wt% after 30 min of reaction time resulted in the highest calorific value of syngas to be 22.5 MJ/Nm^3. However, the maximum gross calorific value of syngas using NaOH was found to be 32.4 MJ/Nm^3 in 60 min due to CO_2 fixation. Both NaOH and RuO_2/γ-Al_2O_3 enhanced the H_2 and CH_4 yields but a carbon conversion efficiency of 93% was achieved using 20 wt% of RuO_2/γ-Al_2O_3.

Molino et al. (2017) investigated the hydrothermal conversion of municipal waste leachate (MWL) to synthetic natural gas through supercritical water gasification and subsequent catalytic upgrading of syngas. The MWL used in the study was composed of 86 wt% water, 9.5 wt% total solids, 8.8 wt% lactic acid, 0.9 wt% acetic acid and 0.2 wt% ethanol. The carboxylic acids present in the MWL acted as the intermediate degradation product in supercritical water gasification and exhibited catalytic effects in syngas yield and H_2 enrichment. The MWL had a high heating value of 20 MJ/kg, whereas the heating value of the syngas was in the range of 15–17 MJ/kg. The H_2 and CH_4 concentrations in the syngas were 25–47 v/v% and 11–18 v/v%, respectively. Nickel-based catalysts were used in syngas upgrading, which increased CH_4 fraction in synthetic natural gas up to 50 v/v%. The integrated MSW gasification and syngas upgrading have tremendous potential in process efficiency, effective MSW remediation, energy recovery, resource recovery and process economics.

Arafat and Jijakli (2013) performed modeling studies and comparative assessment of gasification as an alternate process to incineration for energy production and treatment of MSW. The evaluation indicated that the heating value and energy recovery potential of MSW is highly dependent on its composition and source. For example, waste plastics and textiles have the highest heating values and conversion rates due to their long-chain carbon polymers, whereas yard waste has the lowest heating value. In developed countries where the global average income level is relatively higher, MSW tends to have greater energy content because of large proportions of waste plastics and textiles and smaller fractions of food and yard wastes. Conversely, in developing countries where the population of low and middle-income levels is more, the MSW has more organic (food and yard) waste, which reduces the heating value due to high moisture content. However, in such a scenario, supercritical water gasification of food wastes seems to be promising (Nanda et al., 2016d; Okolie et al., 2020a).

Both incineration and gasification can be implemented without the goal of energy and materials recovery. It was suggested that the incineration of MSW produces more energy than gasification. However, gasification has the benefit of producing syngas, which is considered as a multipurpose product. The syngas can be combusted in the gasifier or power plants for combined heat and power, recycled for electricity generation or used as a feedstock in the Fischer-Tropsch process to produce green diesel, high alcohols, long-chain hydrocarbons and gasoline-like products (Comazzi et al., 2016). Considering such versatility of syngas, the potential efficiency of MSW gasification could be much higher than that of incineration.

An assessment by Arafat and Jijakli (2013) also confirmed that temperature is an influencing factor of combustible gas yields from MSW gasification. Gas yields with satisfactory levels of H_2, CO and CH_4 are perceptible at optimal temperatures. The lower temperatures lead to incomplete gasification while extremely high temperatures may cause combustion and oxidation, in which case O_2, CO_2 and H_2O are obtained with a significant reduction of the energy content of syngas (Reddy et al., 2015, 2016). The quality and quantity of syngas from gasification of

MSW are usually determined by the inter-linked equilibrium between three chemical reactions, namely methanation, water-gas shift reaction and Boudouard reaction (Arafat and Jijakli, 2013).

3. Biological conversion technologies

3.1. Anaerobic digestion or biomethanation

Biogas or biomethane is produced by the natural or induced decomposition of organic matter under anaerobic conditions. The anaerobic digestion or biomethanation of biodegradable materials takes place in the absence of oxygen with the aid of anaerobic microorganisms (Prajapati et al., 2018). The process produces combustible biogas and stabilized biosludge. Wide varieties of biodegradable feedstocks that can be used for anaerobic digestion are MSW, cattle manure, sewage sludge and agricultural crop residues. Biomethanation is mostly widespread in rural areas in the developing countries because of the readily available feedstock materials, less human labor, low-cost process, less maintenance, less land area and infrastructure requirement, as well as the possibility for reuse of biosludge in agronomy for enhancing soil fertility.

Anaerobic digestion has been traditionally popular in rural communities because the biogas produced through anaerobic digestion requires less cleaning as it is usually rich in methane and can be easily transported to the households for cooking, heating and electricity. However, the process of anaerobic digestion is time-consuming (i.e. 20–40 days) and produces a nauseating foul odor near the digesters. Nevertheless, the possibility of intermittent addition of feedstock (e.g. cattle manure, poultry litter, MSW and plant debris) into the digester is an easy way of waste management and volume reduction. Moreover, high-moisture containing feedstocks can be used for anaerobic digestion, which reduces the capital cost involved in biomass pretreatment. The cost of anaerobic digestion of MSW and organic wastes is significantly reduced due to the readily available feedstock and the simple design of the digester.

Methane generated through anaerobic digestion is 2–4 times more per tonne of MSW in 3 weeks than that produced from landfills in 6–7 years (Kumar and Samadder, 2017). About one tonne of wet MSW (containing 60% organic matter and 40% moisture) can theoretically produce 200 Nm^3 or 150 kg of methane through anaerobic digestion (Scarlat et al., 2015). Approximately 1 m^3 of biogas generated from anaerobic digestion contains 6 kW h of heat energy and can produce 2 kW h of electricity (AQPER Association Québécoise De La Production D'énergie Renouvelable, 2020). The use of organic waste for biogas production is assumed to contribute to about 25% of the overall budget for renewable energy sources (Holm-Nielsen et al., 2009).

The route of biogas production through rural waste includes biodegradable feedstocks, digester and naturally occurring bacterial inoculum (i.e. a mixture of hydrolytic, acidogenic, acetogenic and methanogenic bacteria). The priming agents in anaerobic digestion are microorganisms that are involved in different stages of the process such as hydrolysis, acidogenesis, acetogenesis and methanogenesis. The first stage of anaerobic digestion is bacterial hydrolysis. The hydrolytic enzymes (e.g. amylases, cellulose, hemicellulases, lipases and proteases) produced by microorganisms depolymerize carbohydrates, polysaccharides, proteins, lipids and fats into sugar monomers and soluble derivatives. A few bacterial genera known to produce cellulose enzymes for biomass hydrolysis are *Acetivibrio*, *Bacillus*, *Cellulomonas*, *Clostridium*, *Erwinia*, *Microbispora*, *Ruminococcus*, *Streptomyces* and *Thermomonospora* (Jain et al., 2015). The acidogenic bacteria further breakdown the sugars, monosaccharides and amino acids into simpler molecules and volatile fatty acids. In the next step, acetogenic bacteria ferment volatile fatty acids into organic acids (acetic acid and propionic acid), CO_2, H_2 and NH_3. The microorganisms responsible for acidogenesis and acetogenesis are *Acetobacterium*, *Clostridium*, *Eubacterium*, *Ruminococcus* and *Sporomusa* (Jain et al., 2015). Finally, methanogenic bacteria consume H_2 as

their energy source and convert acetates and other intermediates to CH_4 and CO_2. A few methanogenic bacteria belong to the genus *Methanobacterium*, *Methanobrevibacter*, *Methanococcus*, *Methanocorpusculum*, *Methanoculleus*, *Methanofollis*, *Methanogenium*, *Methanomicrobium*, *Methanopyrus*, *Methanoregula*, *Methanosaeta* and *Methanosarcina*. *Methanosarcina* sp. has great potential in producing biomethane as they are comparatively robust in adjusting to various impairments when compared to other known methanogens (Vrieze et al., 2012).

Methanogenesis of acetic acid is the rate-limiting step as its degradation produces about 70% of CH_4, whereas the redox reaction of H_2 and CO_2 produces about 30% of CH_4 (Jain et al., 2015). The terminal electron acceptor in microbial methanogenesis is carbon, thus minor levels of oxygen can inhibit the fermentation process. The biogas generated through anaerobic digestion of organic wastes is typically composed of CH_4 (i.e. 50–75%), CO_2 (i.e. 25–50%) and other gases (i.e. 1–15%) such as NH_3, H_2S, H_2 and water vapor (Kumar and Samadder, 2017). According to Jain et al. (2015), biogas primarily comprises CH_4 (i.e. 60–65%), CO_2 (i.e. 35–40%), H_2S (i.e. 0.5–1%) and water vapor.

The substrate composition, microbial load and process parameters (e.g. temperature, pH, oxygen levels, carbon and hydrogen sources, nutrients, organic load and moisture) determine the quality of the generated biogas. The presence of nitrogenous compounds and cations (e.g. Na, Ca and K) in the waste substrate generates NH_3 and salts thus inhibiting the growth of methanogenic bacteria. Moreover, the dynamics of dissolved heavy metals in the MSW leachate can considerably affect acidogenesis, acetogenesis and methanogenesis by altering the pH (Xie et al., 2015). Nevertheless, anaerobic digestion is a known process that benefits the high organic loading, low cell yield, low nutrient demand and low operational expenses for the reactor and its maintenance.

The biogas produced through anaerobic digestion is very handy to store and finds primary application as cooking fuel. However, industrial-scale anaerobic digestion aims to produce high-purity methane for automotive fuel blending with hydrogen and liquefied petroleum gas (LPG) such as propane or butane to enhance the calorific value (Park et al., 2011). Upon upgrading and compression of biomethane, compressed natural gas (CNG) can be produced to replace LPG, gasoline and diesel. CNG is safer to handle because of its volatility and quicker dispersion, and its combustion produces relatively less GHGs and particulates. Biogas is reported to be 20% lighter than air with an ignition temperature between 650 °C and 750 °C (Aderinlewo and Layode, 2018). The volumetric energy density of CNG is nearly 42% and 25% compared to LPG and diesel, respectively (Envocare, 2020).

Somayaji and Khanna (1994) studied biomethanation using wheat and rice straw mixed with cattle manure in an anaerobic digester. The high cellulose content of plant residues can have energy value as high as 50 kJ/g when converted to biomethane. Rice straw was reported to be excellent biomass for biomethane production. Dhar et al. (2016) studied the effects of COD and volatile solid matter on biomethanation of OFMSW. It was reported that the COD influences the CH_4 production rate at variable pH levels. The hydrolysis and fermentation of OFMSW produce a high concentration of volatile fatty acids as intermediate degradation products, which lowers the pH of the medium and subsequently inhibits the metabolism of methanogenic bacteria.

Ariunbaatar et al. (2014) reviewed the potentials of different mechanical, thermal, chemical and biological pretreatment methods on efficiency, energy balance, process economics and environmental sustainability of anaerobic digestion. It was suggested that low-temperature (< 110 °C) thermal pretreatments coupled with two-stage anaerobic digestion offer many advantages than other pretreatments methods, which includes: (i) enhanced microbial hydrolysis and fermentation, (ii) higher biogas yields; (iii) inhibition of pathogenic microorganisms, (iv) less digestate generation; (v) reduction of overall reaction time, (vii) better energy balance and decisive economic feasibility. However, the efficiency of pretreatment processes is influenced by feedstock characteristics.

Anaerobic digestion leaves behind the digested slurry or biosludge

that can be used as a mineral-rich organic fertilizer for the soil amendment for conditioning (Pivato et al., 2016). Monlau et al. (2015) integrated anaerobic digestion with the pyrolysis of the digestate (biosludge) to increase the energy recovery and sustainability of the process. The MSW for anaerobic digestion composed of chicken manure (i.e. 5 wt%), groats (i.e. 9 wt%), olive oil cake (i.e. 29 wt%) and triticale (i.e. 57 wt%). The residual sludge after anaerobic digestion was pyrolyzed at 500 °C resulting in bio-oil (i.e. 58 wt%), char (i.e. 33 wt%) and syngas (i.e. 9 wt%). The higher heating value (HHV) and lower heating value (LHV) of bio-oil and syngas were 23.5 MJ/kg and 15.7 MJ/Nm^3, respectively. The anaerobic digestion–pyrolysis hybrid system could suggestively increase the production of electricity from 9896 to 14, 066 kW h/day, which is nearly 42% increase as opposed to anaerobic digestion alone.

3.2. Aerobic composting

Composting is the process of natural decomposition of solid organic wastes in the presence of air and moisture with the help of living microorganisms, worms and insects and their secreted enzymes. The composting process results in the formation of a semi-solid matter called compost (or humus) that has high agricultural values. Compost is rich in highly plant-available nutrients and is used through mulching in agriculture, gardening, horticulture and landscaping as an organic fertilizer. Composting is a traditional, cheapest and simplest way of treating and valorizing the organic wastes both at small-scale (i.e. household waste) and large-scale (i.e. centralized community waste). While in rural areas, manual composting is practiced, the urban centers and municipalities use mechanical composting plants. The composting process has gained popularity in developing countries, especially tropical countries, where the climatic conditions favor the natural decomposition of wastes.

The day-to-day wastes such as vegetable and food waste, yard waste, plant residues and cattle manure are allowed to decompose in a controlled or open environment ensuring proper aeration and water content. The materials are mixed routinely and conditioned with water, which allows bacteria, fungi and actinomycetes to decay the organic components. The growth and movement of worms, insects and maggots within the decomposing materials also help create aeration. Unlike, anaerobic digestion, composting requires aerobic conditions and a sufficient supply of oxygen for bacterial and fungal growth. The organics are mostly oxidized to produce organic carbon, heat energy, CO_2, NH_4 and essential plant nutrients. The ammonium ions (NH_4^+) are either utilized by the plants or converted by bacteria into nitrates (NO_3^-) through nitrification. The compost or humus produced is usually non-odorous and free of pathogens. Composting can potentially reduce the volume of wastes by 80–85% (Sarkar and Chourasia, 2017).

Depending on the soil temperature, bacteria involved in compositing can be categorized into psychrophilic (i.e. 12–20 °C), mesophilic (i.e. 20–38 °C) and thermophilic (i.e. 45–71 °C) groups. Bacteria that tend to hydrolyze the complex organic matter into the simpler forms are succeeded by actinomycetes and fungi that mostly degrade cellulose, lignin, chitin and proteins. A few bacteria responsible for composting are *Alcaligenes faecalis*, *Arthrobacter*, *Brevibacillus brevis*, *Bacillus circulans*, *Bacillus licheniformis*, *Bacillus megaterium*, *Bacillus pumilus*, *Bacillus sphaericus*, *Bacillus subtilis*, *Clostridium thermocellum*, *Flavobacterium* sp., *Pseudomonas* sp., *Thermus* sp. and *Vibrio* sp. (Carry on Composting, 2020).

A few actinomycetes species involved in composting of wastes include *Streptomyces* sp., *Frankia* sp. and *Micromonospora* sp. Besides, some fungi known for composting are *Aspergillus fumigatus*, *Basidiomycetes* sp., *Humicola grisea*, *Humicola insolens*, *Humicola lanuginosa*, *Malbranchea pulchella*, *Myriococcum thermophilum*, *Paecilomyces variotii*, *Papulaspora thermophilia*, *Penicillium* sp., *Scytalidium thermophilum*, *Termitomyces* sp. and Trichoderma sp. One gram of compost can typically contain up to 10^9 bacterial cells, 10^8 actinomycetes cells and 10^6 fungal

cells (Carry on Composting, 2020). The factors affecting composting include substrate properties (e.g. porosity, particle size, texture and organic matter), moisture, oxygen and aeration, nutrients (i.e. C/N ratio), pH, temperature and time (Kazemi et al., 2016).

Since microorganisms change the chemistry of decomposing materials, they are considered as biological decomposers. On the other hand, soil organisms such as ants, beetles, earthworms, flatworms, centipedes, millipedes, mites, nematodes, rotifers, snails, springtails, sowbugs, slugs and termites are considered physical decomposers because they mechanically decompose the organic matter by grinding, tearing and chewing into smaller particles. These soil faunae perform composting by feeding on the organic matter and decomposing them in their digestive tract. The involvement of microorganisms and macroorganisms in composting leads to carbon and nitrogen cycling in the soil.

Vermicomposting is a type of composting where the decomposition and stabilization of organic waste occur with the synergistic relationships between earthworms and aerobic microorganisms. The primary decomposition of biodegradable wastes occurs through extracellular enzymatic activities by microorganisms (Carry on Composting, 2020). Earthworms that feed on partially decomposed materials and decomposing them in their gut and excreting vermicast fulfill the secondary decomposition of wastes. The vermicast result from particle size reduction and digestion of the organic matter in the worms' guts. It is a granular and usually odorless product saturated with essential water-soluble soil nutrients and contains lower levels of contaminants. The vermicast can act as an organic fertilizer and green manure in agriculture. Earthworms can daily consume organic matter almost five-times their body weight and weigh 100–1000 lbs/acre. Their mobility inside the soil–organic matter mixture creates channels, which increase infiltration and aeration for the activity of aerobic microorganisms. Vermicomposting has gained a lot of attention in Asian countries where local earthworm species such as *Eisenia fetida*, *Eudrilus eugeniae*, *Lampito mauritii*, *Perionyx ceylanensis* and *Perionyx excavatus* have been used (Paul et al., 2011).

The concentrations of heavy metals, especially Zn and Pb in the MSW-derived compost are relatively higher than that of the soil. However, the complexation of heavy metals in MSW-derived compost with organic matter is higher, which limits their solubility and bioavailability in soil (Yu et al., 2018). In terms of metal complexation, Pb has a strong affinity, Ni has the weakest, and Zn, Cu and Cd have intermediate sorption properties. Composts produced from MSW and sewage sludge are characterized by their strong metal sorption properties, which tend to be beneficial for the application in remediation of heavy metal contaminated soils (Nanda and Abraham, 2013). Compost from certain MSW streams can also have high salt concentrations, which can increase the salinity of soil and inhibit plant growth (Meena et al., 2019). Excessive amounts of MSW compost application can cause heavy metals and to permeate the soil column and pollute groundwater. Composts from MSW also contain high carbon and nitrogen levels, thus their amendment into agricultural soils can supplement C/N ratio.

The heavy metals in MSW compost tend to become concentrated in the amended soil with time as microbial decomposition, oxidation and dehydration release carbon and water from the compost. MSW contains certain levels of organic contaminants such as polynuclear aromatic hydrocarbons (PNA), polychlorinated biphenyls (PCB), polychlorinated dibenzodioxins (PCDD) and polychlorinated dibenzofurans (PCDF). Although no evident literature is available, it is believed that these pronounced mutagenic and carcinogenic contaminants could remain persistent in the environment upon MSW composting and soil amendment (Chen et al., 2018).

Hamoda et al. (1998) evaluated the kinetics of MSW composting and determined that the degradation of organic matter follows a first-order kinetic model. The effects of temperature (i.e. 20–60 °C), moisture content (i.e. 45–75%), substrate particle size (i.e. 5–40 mm) and C/N ratio (i.e. 15–30) were investigated. The temperature of 40 °C was found optimal for the growth of thermophilic microorganisms, which resulted

in maximum organic matter decomposition in a short time. The moisture content of 60% was found optimal because high water content prevented oxygen diffusion through the compost bed. The larger substrate particle size of 40 mm was favorable for composting as the voids between the particles were bigger allowing better access to oxygen for microbial degradation. A higher C/N ratio of 30 led to greater total organic carbon (TOC) removal.

Elango et al. (2009) studied the thermophilic composting of MSW using *Bacillus megaterium* and *Pseudomonas fluorescens*. The thermophilic bacteria accelerated the composting of MSW causing a volume reduction of 78% in 40 days. Proper mixing of the substrates during composting reduced odor emission, compost maturation phase, as well as minimized the requirement of high C/N ratio and moisture content. During early composting phases, the pH of the substrate is lowered due to the formation of organic acids by microbial hydrolysis. As the acids were converted to CO_2 due to microbial fermentation, the pH became neutral. Furthermore, NH_3 was formed during the maturation phase, which increased the pH of the compost.

Paul et al. (2011) performed vermicomposting of MSW with cow dung using *Perionyx ceylanensis* earthworm for 50 days. Cow dung enhanced the vermicomposting of MSW with a high decomposition rate of 78% and a reduced C/N ratio of 15.4. Vermicomposting also increased the availability of plant-essential nutrients i.e. NPK (nitrogen, phosphorus and potassium) and the population of essential bacteria, fungi and actinomycetes. The degradation rate of cellulose and lignin also reached 37% and 12%, respectively with earthworm assisted-composting of MSW and cow dung.

Arafat et al. (2015) performed environmental impact assessment and lifecycle analysis of different MSW streams and treatment processes with potential energy recovery. The MSW investigated includes food waste, yard waste, waste paper, wood, plastics and textile waste, whereas the treatment processes studied are anaerobic digestion, bio-landfills, composting, incineration and gasification. According to this assessment, it is sustainable to recycle paper, wood and plastics through thermochemical conversion technologies. On the contrary, it is optimal to anaerobically digest the food and yard wastes, whereas textile wastes are optimal for incineration. Composting had the least environmental impacts, whereas anaerobic digestion and gasification revealed higher environmental benefits.

4. Conclusions and perspectives

The adoption of MSW as a candidate feedstock for alternative fuel production can not only reduce the dependency on fossil fuels but also provide new ways for their eco-friendly remediation. Table 3 summarizes the advantages and disadvantages of different WtE technologies potentially applied to MSW. Pyrolysis and liquefaction of MSW can produce energy-dense bio-oil, whereas gasification results in H_2-rich syngas. Char, a solid residue from pyrolysis and gasification, is rich in stable aromatic carbon that can be used for soil amendment, carbon sequestration, adsorption or manufacturing of specialty materials with diverse applications. However, the quality and quantity of bio-oils, char and gases depend on the operating conditions of these thermochemical processes such as temperature, heating rate, pressure, reaction time, feed concentration as well as catalyst type and loading. Co-firing of MSW with coal can also significantly mitigate the emissions of GHGs, SO_x and NO_x as well as reduce fly ash and bottom ash production. On the other hand, anaerobic digestion of MSW occurs under controlled anaerobic conditions to produce biogas and active sludge. Composting of MSW is a cost-effective method to transform the organic compounds in MSW to carbon and nutrient-rich compost for use in agriculture. Incineration of MSW and combustion of the fuel products such as bio-oil, producer gas, syngas or biogas can produce combined heat and power or catalytically upgraded to synthetic transportation fuels.

The four important criteria, namely reduce, recycle, reuse and recovery can lead to a win-win-win scenario for societies, municipalities

Table 3

Notable advantages and disadvantages of municipal solid waste (MSW) conversion technologies.

Process	Advantages	Disadvantages
Conventional incineration	• Widely used technology for MSW conversion. • Mature technology with established industrial infrastructures. • Converts MSW to combined heat and power, electricity and steam. • Commercially viable. • Low operating costs. • Fast process than biological conversion.	• Generates massive amounts of greenhouse gases and pollutants. • Heavy metals from MSW are retained in fly ash, bottom ash and flue gases, which require expensive sequestration techniques. • Non-combustible ash may generate clinkers and corrode incinerator walls, thus increasing the maintenance cost.
Hydrothermal incineration	• Clean technology due to the involvement of supercritical water for the hydrothermal flame generation. • Aids in the remediation of highly recalcitrant, complex and hazardous pollutants in MSW. • Results in the near-complete conversion of pollutants to energy. • Generates massive amounts of energy. • Applications can be extended to extraterrestrial organic waste remediation. • Fast process than biological conversion.	• Requires high-temperatures and high-pressures to maintain supercritical conditions. • Corrosion of reactor from salts and metals present in MSW. • Issues in the recovery of waste heat. • Lack of literature due to the new technology and requires more research.
Pyrolysis	• Converts MSW to bio-oil, biochar and producer gas. • Biochar can be used for soil application, activation, pollutant adsorption, carbon sequestration and several other environmental application. • Bio-oil can be catalytically upgraded to synthetic transportation fuels. • Bio-oil can be used as a precursor for the recovery of biochemicals. • Moderate operating cost. • Fast process than biological conversion.	• Metals present in MSW can either catalyze or retard the pyrolysis process affecting product yields. • Product yield depends on operating conditions (e. g. temperature, heating rate, vapor residence time, reaction time, reactor type and MSW properties). • MSW properties greatly influence the chemistry and fuel properties of bio-oil. • MSW requires drying to enhance the energy content of bio-oil. The drying step can add to the overall process expenditures.
Thermochemical and hydrothermal liquefaction	• Converts MSW to bio-crude oil. • Adding acid and base catalysts can enhance product yields. • Liquefaction-derived bio-crude oil has superior fuel properties and energy density compared to pyrolysis-derived bio-oil. • Bio-crude oil serves as a precursor for biochemicals. • Moderate operating cost. • Hydrothermal liquefaction operates in subcritical water. Hence,	• Metals present in MSW can either catalyze or retard the liquefaction process affecting product yields. • Product yield depends on operating conditions (e. g. temperature, heating rate, feed concentration, reaction time, catalyst type and loading, reactor type and MSW properties). • MSW properties greatly influence the chemistry and fuel properties of bio-oil.

Table 3 (*continued*)

Process	Advantages	Disadvantages
Thermochemical and hydrothermal gasification	the drying of MSW is optional. • Faster process than biological conversion. • Converts MSW to H_2-rich syngas and char products. • The presence of combustible gases (i.e. H_2, CH_4 and CO) in the syngas can enhance its heating value. • Hydrothermal gasification operates in subcritical and supercritical water. Hence, the drying of MSW is not required. • Results in the enhanced dissolution of organics, paper and plastics in MSW. • H_2 present in MSW-derived syngas can be used as an energy carrier or energy vector and has applications in fuel cells, bio-oil upgrading and production of hydrocarbons and chemicals. • Faster process than biological conversion.	• Requires high-temperatures and high-pressures to maintain supercritical conditions. • Corrosion of reactor from salts and metals present in MSW. • Issues in the recovery of waste heat. • Tar and char may cause the plugging of the reactor. • Product yield depends on operating conditions (e. g. temperature, feed concentration, heating rate, reaction time, catalyst type and loading, reactor type and MSW properties).
Anaerobic digestion	• Clean technology requiring methanogenic bacteria. • The presence of undesired microorganisms is restricted due to the anaerobic environment. • Low operating costs and less maintenance. • Mature and traditional technology. • Potential to boost the rural economy with self-sustained and integrated bioenergy and MSW-management infrastructure. • Biosludge can be used for agricultural applications to enhance soil fertility and carbon content. • Biosludge can be diverted to thermochemical conversion for energy generation.	• A time-intensive process requiring days to weeks due to slower microbial metabolism. • Requires strictly anaerobic conditions. • Biogas (CH_4) is considered as a potent greenhouse gas. • Created foul and obnoxious odor in case of leakage of the bioreactor. • The presence of inhibitory compounds in MSW can inhibit microbial growth and impact methanogenesis.

and waste management facilities. A circular economy is opportunistic by reducing the MSW disposal in landfills and substantiating the amounts used for recycling. In such a regenerative system, the tapering of energy and material loop, the resource input as well as waste residues, by-products, gas emissions and energy leakage can be minimized. Efficiently planned and strategic approaches for MSW processing integrated with consolidated processes for marketing the end products and by-products could aid in zero cash flow and exorcize the financial obstacles encountered in waste management. Furthermore, lifecycle analysis, environmental impact assessment and techno-economic analysis of different MSW management and recycling options are highly necessary for holistic evaluation of the many benefits and risks associated with either landfilling or diverting the wastes. These qualitative investigations can determine the strengths, weaknesses, opportunities and threats (SWOT) to utilize the highly heterogeneous MSW at a global

scale for energy and product recovery. This can also help the policy-makers and enforcement authorities to understand the lessons from the past, current status, prospects and barriers involved in a sustainable and cost-effective MSW management.

CRediT authorship contribution statement

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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