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REVIEW

# Transformation of municipal solid waste to biofuel and bio-chemicals – a review

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## Abstract

Globally, the generation of municipal solid waste is increasing at an alarming rate due to rapid population growth, urbanization, industrial evolution, etc. The natural decomposition of these wastes leads to the generation of methane, which is several times more potent as a greenhouse gas than $CO_2$ and thus leads to several health hazards and other socio-economic concerns. The conversion of these huge amounts of waste into energy offers a remedy for environmental concerns like greenhouse gas emissions and waste handling, contributing to the creation of an environmentally friendly setting while fostering economic growth concurrently. This review provides detailed sustainable techniques available for the conversion of waste into bioenergy, along with comprehensive deliberation of sources and compositions of municipal solid waste. The thermochemical routes include incineration, liquefaction, pyrolysis, gasification, and combustion while biological conversion routes include landfilling, composting, aerobic and anaerobic digestion, etc. Anaerobic digestion and thermochemical conversion processes face limitations in extracting energy from municipal solid waste due to their intricate processes and challenges related to the diverse composition of municipal solid waste. Addressing these issues is essential before successfully implementing these methods on an industrial scale. Moreover, the article broadly reviewed the physicochemical properties of various bioenergy products including bio-oil, biogas, biochar, and heat obtained from different conversion methods, and discussed their possible applications. A thorough evaluation is conducted on the present condition of municipal solid waste management, encompassing efficient disposal, and diversion, while examining the opportunities and challenges associated with encouraging the redirection of solid waste away from being deposited in landfills towards utilization in biorefineries.

**Keywords** Municipal solid waste · Thermochemical conversion · Anaerobic digestion · Bioenergy · Waste management

## Abbreviations

| | |
|---|---|
| MSW | Municipal solid waste |
| MT | Million ton |
| PW | Plastic waste |
| SWM | Solid waste management |
| OSW | Organic solid waste |
| WCG | Waste Concern Group |
| WtE | Waste to Energy |
| GHG | Greenhouse gas |
| LFG | Landfill gas |
| AD | Anaerobic digestion |
| ZSM-5 | Zeolite Socony Mobil-5 |
| HTC | Hydrothermal carbonization |
| HTL | Hydrothermal liquefaction |

## Introduction

The increasing population density, industrialization, economic growth, and migration from rural to urban regions, are producing enormous quantities of waste, leading to significant economic, social, and socio-demographic challenges. Rapid industrialization and urbanization along with population growth cause two major environmental challenges including pollution and energy crisis. The world population is around 8.1 billion in 2023 which is expected to rise in 9 billion and 10 billion in the years 2037 and 2058,

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respectively (Worldometers 2023). This demographic rise in population causes the necessity of other essential items of human beings including food, clothes, shelters, energy, etc. Fossil fuel is the main source to meet up the growing energy demand which usually contributes around 84% of global energy needs. However, the dependency on fossil-based fuels causes several environmental challenges including greenhouse gas (GHG) emissions, $CO_2$ emissions, ozone layer depletion, climate change, rise in sea level, etc. Therefore, the world is looking for an alternative source of energy to meet the energy demand and replace fossil-based fuels.

This growing population, higher living standards, and sophisticated lifestyle play a significant role in consumption patterns and the generation of waste. Waste materials can be solid or liquid and include various categories such as municipal solid waste, industrial waste, agricultural waste, radioactive waste, medical waste, and chemical waste. Municipal solid waste (MSW) is solid waste discarded by the people, which poses a negative impact on environmental sustainability. It has been reported that around 2.01 billion tonnes of MSW are generated worldwide annually among which approximately 33% is handled in an environmentally sustainable manner (Worldbank 2023). Moreover, the generation of MSW across the globe is projected to increase by 70% and reach 3.40 billion tonnes by 2050 (Statista 2023). This growth rate is more than twice the projected rate of population increase during the same period. It has been reported that on average, approximately 0.79 kg of solid waste is generated per capita per day (WorldBank 2020). However, the effective management of this huge amount of waste is always expensive and in limited practice. Among the total waste collection, around 19% is recycled while more than 70% is thrown for landfilling and 11% is used for various energy recovery processes.

Improper or open disposal of waste creates several environmental crises, threatens community safety, causes societal and economic issues, human health as well as financial aspects (Xiao et al. 2020). The amount and complexity of MSW have been steadily rising, which has made waste management more difficult for communities today and in the future. Figure 1 represents the typical steps of managing MSW. Sorting or separation is crucial before processing the waste for conversion as it contains both biodegradable and non-biodegradable materials. The primary goals for recycling MSW are to save landfill space, save a large portion of expense from handling MSW, and protect the environmental quality because few portions of MSW, such as plastics or polythenes are not degradable, so these materials should be recycled again instead of dumping. The waste that can neither be recycled nor be treated to recover energy, is disposed of as landfill. Most of the time, landfilling is done by open dumping without maintaining any proper procedure. The act of open dumping has the potential to be a notable contributor to the release of greenhouse gas (GHG) emissions into the atmosphere (Ngwabie et al. 2019), which is also responsible for the contamination of air, water, and soil. Moreover, landfill gas (LFG) is also produced from this process, which consists of 55% of methane gas ($CH_4$) and around 40% of carbon dioxide gas ($CO_2$) (Sendilvadivelu et al. 2022).

To address the issues related to socioeconomic and environmental impacts of MSW mismanagement, sustainable and environmentally friendly processing of MSW has been deemed essential. Composting, incineration, energy recovery, waste minimization, controlled landfills, recycling, sanitation, open dump, and improving the recovery of landfill gas, are the common possible solutions for managing MSW to reduce environmental impact (Fig. 2). According to Fig. 2, landfilling is mostly used for waste management followed by incineration and open dump. Around 13.5% of waste is recycled while 5.5% is composted. Among these, the Waste-to-Energy (WtE) approach is the most promising approach, as it provides a potential energy source while minimizing emissions and land use. Furthermore, the efficient management of MSW and conversion into energy is aligned under Sustainable Development Goals (SDGs) Goal 7 (Affordable and Clean Energy), Goal 11 (Sustainable Cities

**Fig. 1** Typical steps of managing MSW

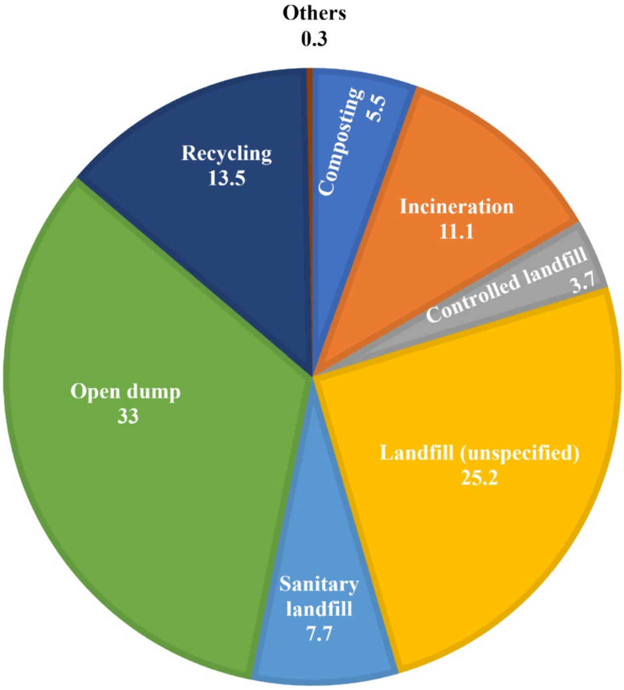

**Fig. 2** Global treatment and disposal of waste

and Communities), and Goal 12 (Responsible Consumption and Production) (United Nations 2018). Transformation of MSW into energy, fuels, or other value-added products can be economically feasible and environmentally sustainable to harness energy from left-over materials, generating fuel, heat, and electricity, reducing pollution, replacing fossil fuels, and cutting off the depletion of natural resources.

There are several routes for the transformation of waste into energy such as thermochemical and biological processes (Fig. 3). Pyrolysis, carbonization, liquefaction, and gasification are common in thermochemical routes while biological conversion techniques include anaerobic digestion, fermentation, etc. Bio-oil, synthesis gas, and biochar are some of the key products of thermochemical conversion processes while biogas, bio-slurry, ethanol, butanol are the products of biological conversion processes. There are no standardized methods for evaluating the environmental effects and efficiency of various waste-to-energy (WtE) conversion technologies. The properties of MSW are essential for determining its suitability for various conversion technologies. For instance, biological conversion (anaerobic digestion, composting, etc.) and hydrothermal conversion techniques (liquefaction, supercritical/ subcritical gasification) are

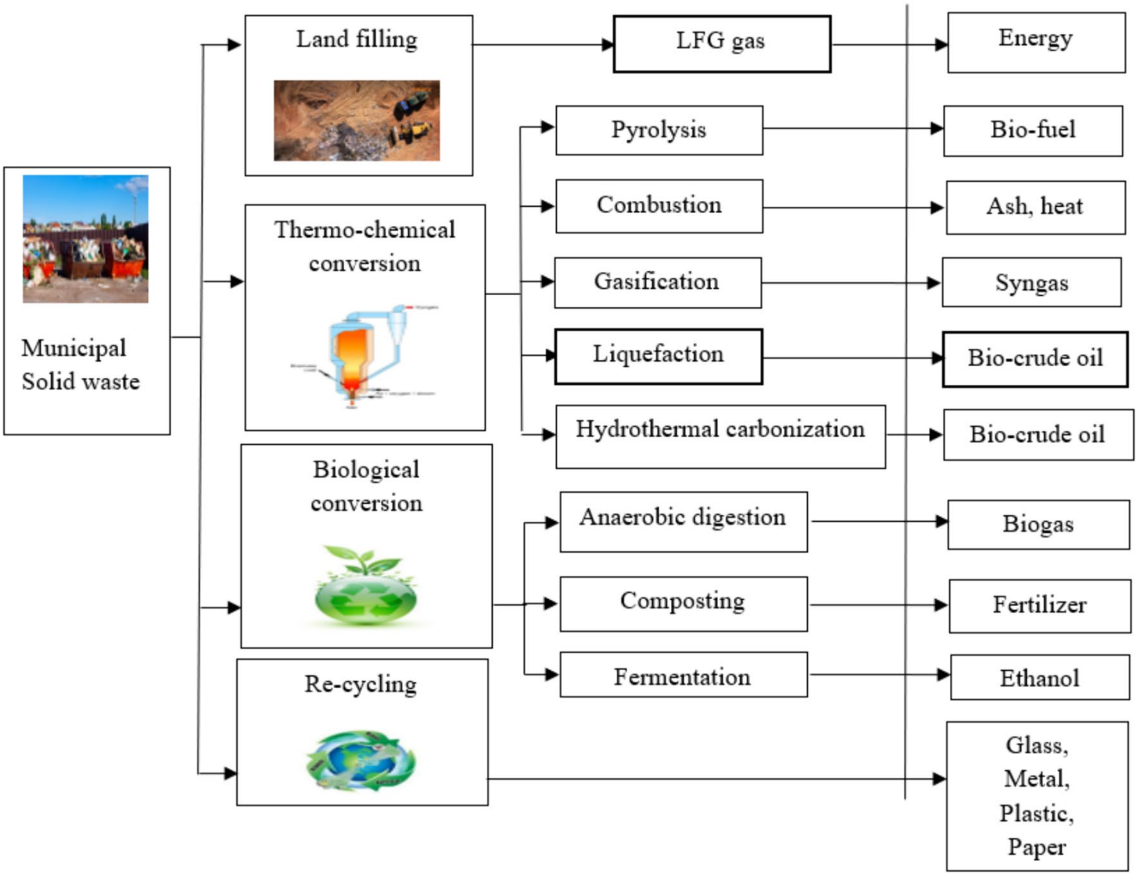

**Fig. 3** Conversion process of Municipal Solid Waste

more appropriate for MSW that contains high percentages of moisture for example kitchen waste, yard waste, and food waste. While in the case of thermochemical conversion methods (pyrolysis, carbonization, and gasification) dry material including non-biodegradable organics (such as plastics, rubber, and polymers), and paper waste (such as packaging trash, cardboard boxes, and paper), are better suited.

There is an increasing interest in the efficient and safe handling of MSW along with its effective utilization. Long-term processing technologies ought to be used in well-planned circular economy implementations to guarantee the efficient use of MSW. Despite the substantial generation of MSW on a global scale in both developing and developed nations, there is a deficiency in the transfer of technology between countries. Moreover, a thorough critical analysis is required to characterize MSW and identify the most suitable WtE technologies for energy production. Therefore, this paper seeks to extensively investigate MSW as a viable resource for global alternative energy production. The primary emphasis of this review is to comprehensively explore diverse thermochemical and biological conversion approaches. The range of the technologies under consideration is broadened and explored in greater depth, culminating in a discussion on waste management perspectives as part of the overall strategy for developing a circular bio-economy. The technical assessment of these MSW treatment technologies is intended to recognize opportunities, challenges, and obstacles to successfully adopting sustainable waste management. This review also discussed the challenges associated with biofuel generation from MSW and its future prospects.

## Sources and compositions of MSW

MSW is gathered from various sources, including businesses, factories, residences, offices, marketplaces, and retail establishments. According to Zheng et al. (2014), MSW may contain a combination of organic and inorganic materials, including polymers and non-renewable goods. It has been reported that around 40–60% of total solid waste generated is biodegradable and the remaining is non-biodegradable (Lave et al. 1999). MSW can be classified into seven key categories: organics, paper/boards, plastics, glass, metals, textiles, and inert while the remaining items fall under miscellaneous or other categories (Asamoah et al. 2016). Table 1 presents various kinds of MSW along with their origins. According to the ASTM D5231 standard, the distribution of these components by relative shares is shown in Fig. 4. The composition, amount, and nature of MSW vary based on the source area of collection, lifestyle, industrial structure, waste management methods used, economic condition, geographical location, and the culture of living people, etc. MSW is a resource that necessitates quick attention to appropriate waste management procedures. Furthermore, it represents a valuable, renewable, and cost-effective resource of waste that can be used to produce useful fuels including solid, liquid, and gaseous to augment rising energy needs. The composition and management of MSW differ greatly between municipalities and nations. However, the amount of MSW generation along with its composition is vital to facilitate the waste management process as well as to identify the most suitable WtE conversion methods and to optimize the process.

In many developing nations, the majority of MSW, ranging from 55 to 80%, spawned from household activities, while the commercial sector contributes only 10 to 30% (Llano et al. 2021). MSW gathered from non-residential sources has a wide range of contents and physicochemical properties (Dehkordi et al. 2020). As mentioned earlier, MSW generally contains plastics, paper, wood, leather, textiles, food waste, yard trash, demolition waste, and other materials. It is very difficult for MSW managers to discover effective processing and treatment approaches in the face of such heterogeneity (Ali and Ahmad 2019). Consequently, pre-processing or sorting or separation of non-biodegradable material becomes necessary for accurate assessment and characterization, which, in many cases, enhances the efficiency of the system. Sometimes, MSW may contain hazardous materials, for example, homecare products, lubricants, motor oils, etc. which need to be separated first and treated separately to produce value-added products. Accurately obtaining quantitative and qualitative data on the chemical composition of common household items remains challenging. Certain chemical compounds, such as phenols, chlorinated organic solvents, polycyclic compounds, benzene, toluene, and inorganic components like sulfites, ammonium, cyanide, and heavy metals, whether alone or interacting with other substances, can pose significant risks to humans and the environment with prolonged exposure. Moreover, upgraded public knowledge, community acceptance and changes in consumer behavior will make garbage sorting and separation easier to improve the efficiency of MSW handling processes (De Morais Lima et al. 2019).

Recently, numerous developed and developing countries have implemented diverse waste management approaches, including incineration, landfilling, and unregulated disposal techniques to efficiently manage this massive volume of waste. This study focuses on various thermochemical and biological conversion techniques that can be applied to the generation of various value-added products from different sorts of MSW. As mentioned earlier, the suitability of conversion techniques highly depends on the characteristics of MSW, therefore, this review concentrated on the conversion of biodegradable MSW via biological conversion pathways while thermochemical routes are greatly dedicated to non-biodegradable or complex MSW. For example,

**Table 1** Various type of MSW with their originated sources

| Category | Originated sources | Amount (%) |
|---|---|---|
| Organic waste | Agricultural residue | 46 |
| | Wood waste | |
| | Kitchen waste | |
| | Yard waste | |
| Paper | Newspaper | 17 |
| | Magazine | |
| | Scrap paper | |
| | Paper bags | |
| | Packaging boxes | |
| | Books | |
| | Cardboard | |
| | Wet wipes | |
| | Wrapping paper | |
| | Tissue paper and napkins | |
| | Parchment paper | |
| Inert | Construction materials | 13 |
| | Ashes | |
| | Renovation wastes | |
| | Demolition | |
| | Drywalls | |
| | Discarded furniture | |
| Plastics | Plastics bottles | 10 |
| | Boxes | |
| | Containers | |
| | Caps or lids of bottles and container | |
| | Ziplock bags | |
| | PVC pipes or other plastic pipes | |
| | Clear wraps | |
| | Polyethylene bags | |
| | CDs, DVDs and vinyl records | |
| | Polystyrene | |
| | Cable wire | |
| Glasses | Jars | 5 |
| | Bottles | |
| | Broken glassware | |
| | Colorful and colorless glasses | |
| | Light bulbs | |
| | Utensils | |
| | Broken window | |
| | Mirror | |
| | Decorative items | |
| Metal | Cans and tins | 4 |
| | Aluminum materials | |
| | Aluminum foils | |
| | Iron metals | |
| | Utensils | |
| | Cookware | |
| | Various appliances | |
| | Container lids | |
| | Railings | |
| | Bicycles | |

**Table 1** (continued)

| Category | Originated sources | Amount (%) |
|---|---|---|
| Textiles | Wastes clothes | 3 |
| | Leather | |
| Miscellaneous | Broken appliances | 2 |
| | Electronic waste (e.g. thrashed computers, monitors, tablets, phones, watches, batteries and other electronic goods) | |
| | Cosmetics | |
| | Health care products | |
| | Rubber | |
| | Pet litter | |
| | Personal hygiene products | |
| | Pharmaceuticals | |

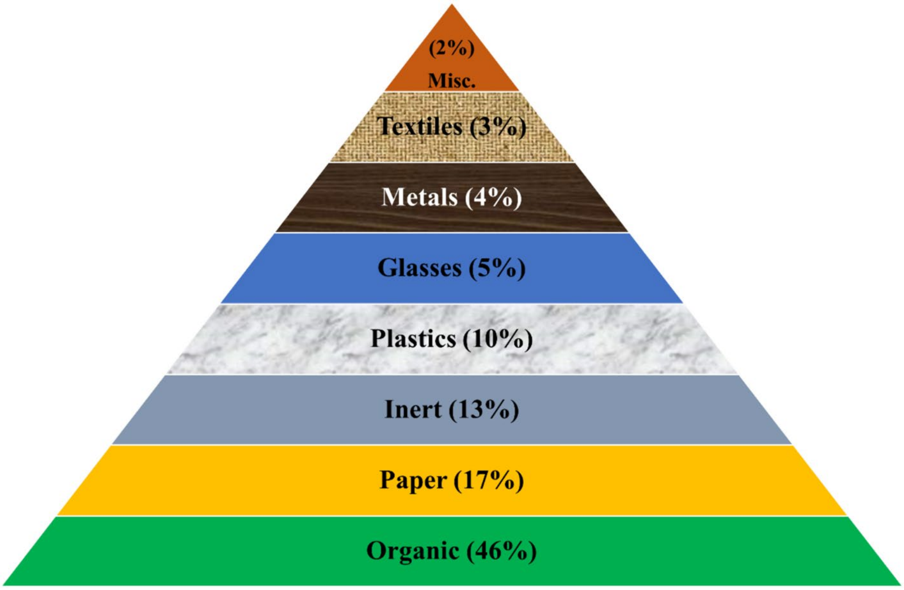

**Fig. 4** Composition of MSW across the Globe

biodegradable materials are more suited for the biological conversion process, and they require various microbes to decompose the organic fraction of MSW for alteration into biomethane, biogas, biohydrogen, compost, and digestate. In order to prepare the feedstock for biological conversion, it is necessary to take into account various factors such as moisture, dry solids, volatile solids, carbon/nitrogen (C/N) ratio, organic content, and the presence of micro- and macronutrients for microorganisms. Additionally, any contaminants, such as pesticides, insecticides, disinfectants, antibiotics, pharmaceuticals, and inert materials like glasses, plastics, and metals, must be avoided. The most suitable biological conversion routes (composting, anaerobic digestion, biophotolysis, dark fermentation, and photo fermentation) are identified based on the metabolism of the relevant microorganism. Non-biodegradable organic materials are suitable for thermochemical conversion therefore, elemental properties, thermal stability, bulk density, proximate composition, particle size, and biopolymeric composition are important to know before conversion as they help to identify the appropriate thermochemical conversion routes.

## Conversion of municipal solid waste

There are several ways to convert solid waste into biofuels such as biological conversion methods and thermochemical conversion routes. The method of biological conversion involves the use of bacteria or fungi to decompose the organic material and convert it into liquid or gaseous fuel. The biological conversion process includes anaerobic digestion (AD), composting, fermentation, etc. On the contrary, thermochemical conversion methods require heat to degrade the waste into energy or fuels. These methods include pyrolysis, liquefaction, hydrothermal carbonization, gasification, etc. Table 2 presents various ways of managing MSW.

**Table 2** Different technologies used for MSW management

| Name of the technology | | Energy production description | References |
|---|---|---|---|
| 1. Landfilling | Sanitary landfills | Engineered land disposal sites where waste is spread in thin layers, compacted, and covered with soil daily | (Das et al. 2019) |
| | Bioreactor landfills | Landfills designed to accelerate the decomposition of organic waste by enhancing microbial activity | |
| 2. Incineration | Waste-to-energy plants | Incineration of MSW to generate electricity and/or heat. Advanced systems capture pollutants to minimize environmental impact | (Jones et al. 2009) |
| 3. Recycling | Single-stream recycling | Collection of recyclables in a single bin, which are then sorted at recycling facilities | (Kouloughli and Kanfoud 2017) |
| | Material recovery facilities (MRFs) | Facilities equipped with machinery and conveyor belts to sort and process recyclable materials | |
| | Composting | Decomposing organic waste into nutrient-rich compost for agricultural use | |
| 4. Biological treatment | Anaerobic digestion | Bacterial breakdown of organic waste in the absence of oxygen, producing biogas and nutrient-rich digestate | (Mihai et al. 2019) |
| | Vermicomposting | Using earthworms to decompose organic waste into high-quality compost | |
| 5. Mechanical–biological treatment (MBT) | Mechanical sorting | Utilizing conveyor belts, magnets, and screens to mechanically sort recyclables from mixed waste | (Velis et al. 2009) |
| | Biological treatment | Employing biological processes like composting or anaerobic digestion to treat the organic fraction of waste | |
| 6. Waste minimization | Source reduction | Encouraging the reduction of waste at the source through methods like better product design and consumer education | (John Pichtel 2005) |
| | Reuse programs | Promoting the reuse of products and materials to extend their lifespan before they become waste | |
| 7. Advanced technologies | Nanotechnology | Utilizing nanomaterials for waste treatment, including waste remediation and pollution control | (Lacy Peter 2016) |
| | Robotics and automation | Implementing robots and automated systems in sorting facilities for more efficient and accurate waste separation | |
| 8. Smart waste management | IoT sensors | Implementing sensors in waste bins to monitor fill levels, optimizing collection routes and schedules | (Ali et al. 2020) |
| | Data analytics | Using data analysis to optimize waste management processes, predict waste generation patterns, and enhance overall efficiency | |

## Biological conversion

**Anaerobic digestion (AD)** Anaerobic digestion (AD) is known as a biological conversion process that alters organic materials, such as MSW, into biogas and nutrient-rich organic residues in the oxygen-deficient environment in which a series of biochemical reactions take place where bacteria or other micro-organisms break down the organic matters of any substrate into a gaseous mixture like $CH_4$, $CO_2$, $H_2$, $H_2S$, etc. A wide variety of feedstocks are suitable for AD such as MSW, animal manure, poultry waste, agricultural residues, industrial by-products, etc. Recently, AD has gained widespread adoption in rural regions of developing nations due to the abundant availability of feedstock materials, its cost-effectiveness, minimal need for human labor, low maintenance requirements, reduced land area and infrastructure demands, and the potential for utilizing biosludge in agriculture to enhance soil fertility. AD is one of the technologies that may be used to transform this garbage into a usable source of energy (Jain et al. 2015). As there is a presence of higher organic fraction and water content in MSW, the AD process is very suitable for energy conversion. According to Cecchi et al. (1990), the changes in concentration of the substrates, microbial populations, and products during the digestion process is the first step for AD. AD process of MSW requires several crucial phases. First, organic waste is gathered from a variety of sources and cleaned up by eliminating impurities. Then, the prepared feedstock is fed into the digestion chamber along with the required amount of water. This prepared waste is broken down by anaerobic microorganisms in the digestion chamber, yielding useful biogas that are high in methane. The biogas that has been collected can be utilized to produce energy, and the digestate that is still full of nutrients can be used as fertilizer. In general, AD diverts organic waste from landfills or incineration, provides renewable energy, and helps to create a more sustainable waste management system.

During AD, the organic fraction is decomposed through four steps as shown in Fig. 5. In the hydrolysis process, insoluble complex components such as carbohydrates, fats, and proteins undergo degradation, breaking their chemical bonds and transforming into smaller soluble components and sugar monomers. This stage is carried out by hydrolytic or facultative anaerobes and anaerobes, as noted by (Gerardi 2003). The most popular hydrolytic enzymes used in AD are amylases, cellulose, hemicellulases, lipases, and proteases. Commonly utilized bacteria for biomass hydrolysis in this context encompass Erwinia, Acetivibrio, Streptomyces, Bacillus, Clostridium, Cellulomonas, Ruminococcus, Microbispora, and Thermomonospora. The operating conditions including temperature, organic loading rate, $P^H$ significantly influence the hydrolysis process. The next step is acidogenesis, where simpler molecules especially volatile fatty acids (VFA) are produced from monomers, sugars, and amino acid by means of acidogenic bacteria which breaks down in stage III. Stage III is acetogenesis, where $H_2$, $CO_2$, $CH_3$ gases are produced from volatile fatty acids. Microorganisms including Clostridium, Acetobacterium, Ruminococcus, Eubacterium, and Sporomusa are accountable for acidogenesis and acetogenesis. Finally in last stage, methane-producing microbes (methanogens) eat $H_2$ and convert acetate into biogas ($CH_4$ and $CO_2$) by methanogenesis (Sendilvadivelu et al. 2022). Methanobacterium, Methanococcus, Methanobrevibacter, Methanoculleus, Methanogenium, Methanofollis, Methanocorpusculum, Methanopyrus, Methanomicrobium, Methanosarcina Methanoregula, and Methanosaeta, are a few methanogenic bacteria that perform actively during methanogenesis reaction to produce biogas. In comparison with other known methanogens, Methanosarcina sp. has a high potential for creating biomethane since it is rather resistant in responding to various impairments (De Vrieze et al. 2012). Acetate produces on average 70% of methane through acetoclastic methanogens, while the remaining 30% is generated from hydrogen and carbon dioxide via redox reactions with hydrogenotrophic methanogens.

Concerning the microbiological dimension, various types of microorganisms contribute to AD process, such as saccharolytic bacteria, proteolytic bacteria, lipolytic bacteria, and methanogens. Maintaining a delicate balance among these microorganisms is crucial and requires careful attention. Failure to sustain this balance adequately can result in diminished methane yields and a decline in the overall efficiency of the process. However, AD is often used as a sustainable and environmentally friendly way to manage and treat organic waste while also generating renewable energy. The process of how AD works for the conversion of municipal solid waste is presented in Fig. 6.

The overall biogas production, gas quality, and process stability are dependent on several factors for example temperature, retention time, volatile fatty acids (VFA), $P^H$, organic loading rate (OLR), C:N ratio, total solid content, mixing, inoculum, etc. Elevated temperatures enhance bacterial activity, leading to higher growth rates, faster metabolism, and increased nutrient demand. Conversely, a drop in temperature below an optimal range result in reduced bacterial metabolism, leading to decreased methane production or a complete halt, accompanied by a rise in $CO_2$ levels.

Typically, most digesters are operated at mesophilic (35 °C) or thermophilic (55 °C) temperatures. Long retention times and a low-temperature inoculum are required for successful digestion at psychrophilic temperatures (as low as 10 °C). Nevertheless, the mesophilic operation appears to be the most desired due to the ability to manage temperature changes (which is not feasible with ambient temperature operation) and the higher energy expenditures associated with thermophilic digestion. However, thermophilic AD with a retention duration of 10–12 days, has become a very efficient treatment for pathogen reduction. The optimum pH for hydrolysis and acidogenesis ranges from 5.5 to 6.5. $P^H < 6.5$ can restrain the growth rates of methanogenic while high pH can disrupt granule structure. VFA is another

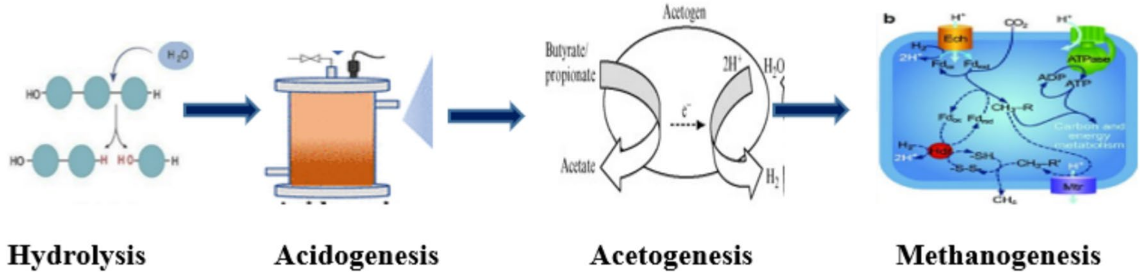

**Fig. 5** Steps involved in anaerobic digestion process

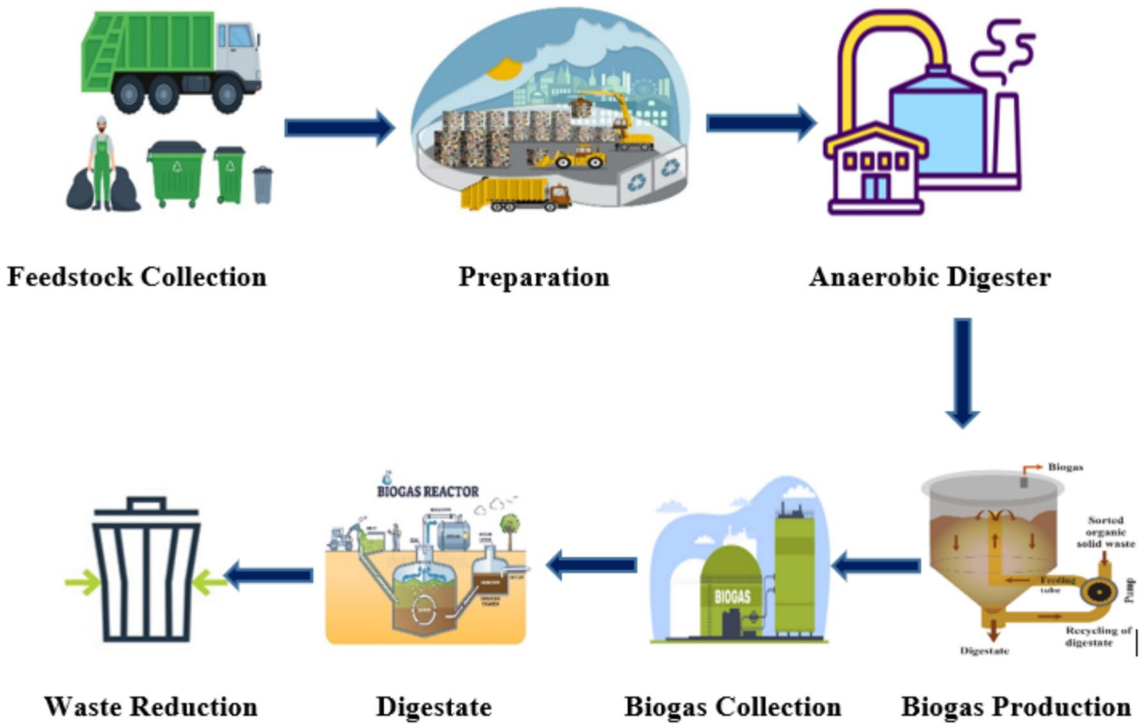

**Fig. 6** Overall process of anaerobic digestion of MSW

crucial factor that has a great impact on biogas generation. Moreover, high OLR allows for the treatment of larger amounts of waste, making the process more productive, however, it does not always result in optimum biogas outputs if the materials are partially decomposed during leaving the reactor. Table 3 presents recent studies on AD of MSW.

Fang et al. (2018) reviewed numerous approaches and stages involved in AD of MSW including pretreatments, post-treatments, digestion process, waste collection, and transportation in order to optimize the biogas quality and quantity while all the stages were evaluated in terms of requirements of energy, and carbon emission footprint. They identified thermal hydrolysis pretreatment as less suitable for MSW, however, the efficiency can be improved by two stages (separate hydrolysis/acidogenesis and methanogenesis) digestion system. In addition, the separation of waste at source can highly contribute to AD of MSW. They also suggested that microwave pretreatment is more effective for AD of MSW, with the drawback of increased energy consumption while post-treatment based on chemical, and membrane requires less energy for upgrading of biogas.

Pera et al. (2021) assessed the efficiency of an industrial AD facility through a two-year examination of the treatment of organically preprocessed waste fractions sourced independently from municipalities in the Calabria region of Southern Italy. The plant, with a capacity of 40,000 tons per year, operated under mesophilic conditions at 40 °C, with a hydraulic retention time of 22 days. Their observation depicts that on average the plant produced around 860 $m^3$ and 191 $m^3$ of biogas per tonne of total volatile solid and organic material input, respectively while the methane concentration in biogas was 59.09%.

The main product of AD is biogas, which is a mixture of $CH_4$, $CO_2$ and $H_2$. Typically, biogas contains 40–70% methane ($CH_4$), 30–60% carbon dioxide ($CO_2$), and other gases (1–5%) such as nitrogen ($N_2$), hydrogen sulfide ($H_2S$), carbon monoxide (CO), ammonia ($NH_3$), and vapor ($H_2O$). The produced gas requires less cleaning as it mostly contains methane, which can easily be transported in rural areas for cooking, heating, and generation of electricity. Biogas with higher methane concentrations ($>90\%$) possesses an increased heating value and can be utilized as a fuel for transportation, fed into the national gas grid, or employed for electricity generation**.** Moreover, the by-product of AD is bio-slurry which is rich in nutrients, especially N, P, and K, therefore it is widely used in agricultural operations as a fertilizer. However, AD takes time (around 20–40 days) and emits a sickening foul stench near the digesters. Nonetheless, incorporating intermittent addition of various feedstocks (such as cattle dung, poultry litter, municipal solid waste, and plant debris) to the digester offers a straightforward waste management and volume reduction solution. Additionally, utilizing feedstocks having high moisture for AD contributes to reducing the capital costs associated with

**Table 3** Recent studies on AD of MSW for energy conversion

| MSW | Parameters | | | Energy | Yield | References |
|---|---|---|---|---|---|---|
| | Temperature °C | Organic loading rate | Solids content | | | |
| MSW | 48–52 | 4.6 kg VS/m$^3$ day | 148 tons/day | Biogas & Methane | 0.535 & 0.350 m$^3$/kg, VS | (Goa et al. 2021) |
| Residual MSW | 35 | – | 5.11 tons/hour | Bioelectricity | 493.6 kW | (Ng et al. 2021) |
| OFMSW | 55 | 9.0 kg VS/m$^3$ day | 20.5 tons/day | Biogas | 0.693 m$^3$/kg | (Mavridis and Voudrias 2021) |
| Cattle manure | 36 | 1.2 g-VS/L day | 70% | Methane | 603 LCH$_4$/kg VS feed | (Marañón et al. 2012) |
| OFMSW | 36 | – | 80% | Methane | 196 NmL/g-VS | (Nielfa et al. 2015) |
| Cattle manure | 36 | 1.2 g-VS/L day | 70% | Methane | 603 mL/g-VS | (Zhang et al. 2013) |
| SSMOW | 54 | 2.0 g-VS/L day | 90% | Methane | 365 NmL/g-VS | (Tsapekos et al. 2018) |
| OFMSW | 37 | 4.0 kg COD/m$^3$ d | 60% | Biogas | 0.22 m3/kg COD | (Bernat et al. 2021) |
| WAS | – | 0.20 g COD g/TSS/d | 0.09 kg/kg TSS/d | Methane | 296 ± 15 mL/g VS | (Guo et al. 2020) |
| MSW | 37 | – | 10 kg | Methane | 409.5 L/kg. VS | (Ge et al. 2016) |
| Food waste | 55 | – | 55% | Biomethane | 310.77 mL/g COD | (Wongthanate and Mongkarothai 2018) |
| Waste peach pulp | 39 | – | 45.59 gTS/L | Biohydrogen | 123.27 mLH$_2$/gTOCo | (Argun and Dao 2017) |
| OFMSW | 55 | 2.5 kgVS/m$^3$/d | 35% | Biogas | 0.45 m$^3$/kg | (Valentino et al. 2019) |
| OFMSW | 38 | 2.0 kg COD/m$^3$ | d 20.67 ± 1.9% | Biogas | 400.2 L/kgVS | (Bacab et al. 2020) |
| Mixed organic wastes | 36 | – | 30% | Methane | 13.28 mL/gVSS0d | (Cheng et al. 2020) |

biomass pretreatment, resulting in a significant decrease in the overall cost of AD for municipal solid waste and organic waste.

In the single anaerobic digestion of MSW produced 37 m$^3$ of methane per ton of dry waste (Macias-Corral et al. 2008). 200 Nm$^3$ or 150 kg of methane can be generated from one tonne of wet MSW that contains 40% water and 60% organic matter via AD (Scarlat et al. 2015). 1 m$^3$ of biogas produced from AD of MSW can provide 6 kW h of heat energy and can create 2 kW h of electricity, as reported by AQPER (Association Qu'eb'ecoise De La Production D″energie Renouvelable, 2020). Furthermore, the use of organic waste in the production of biogas is expected to account for around 25% of the total budget allocated to renewable energy sources (Holm-Nielsen et al. 2009).

Though AD of MSW has certain benefits, it still requires some automation and advanced technicality to make the process fascinating to most industries. The capital investment for large-scale digesters is still too high, which needs attention. Additionally, a secondary treatment process is necessary to digest various toxic compounds or heavy metals that may not be consumed during AD. Moreover, handling and storage of digestate currently poses significant challenges that need to be addressed. Preaeration might enhance methane yield but comes with high power costs. Another promising option is using biogas for gasification or pyrolysis as part of the processed waste, where the economic feasibility would largely depend on the size of the waste processing facility.

**Composting** Composting is a naturally occurring and eco-friendly method that transforms organic materials, including MSW, into a nutrient-rich soil conditioner known as compost in the presence of moisture or air by live microorganisms, insects, worms, and the enzymes they secrete. All over the world, around 46% of solid waste is organic waste (Hoang et al. 2022). Composting can be an effective way if it can be dealt with properly. Compost from MSW is considered worldwide as an organic fertilizer for plants, agriculture, horticulture, gardening as well as landscaping due to having high nutrient content. Moreover, compost can also be used as fuel for direct combustion, gasification or pyrolysis as it contains a major amount of combustible materials (Vasileiadou et al. 2020). The composting process is very important, especially in terms of its ability to recycle nutrients, reduce waste, and recover energy with the least amount of environmental impact (Kumar 2011).

Composting is a traditional, cost-effective, and simple approach to managing and enhancing the value of organic waste, both at a local level (such as domestic trash) and on a larger scale (such as centralized communal waste). While manual composting is practiced in rural areas, urban areas, and municipalities employ mechanical composting plants. Composting has gained popularity in developing nations, especially in tropical regions where environmental conditions are conducive to the natural decomposition of waste. The overall process of composting MSW is shown in Fig. 7. Municipal solid waste composting is a methodical eight-step procedure. Organic materials like food scraps and yard garbage are first separated from non-organic waste at the source. Then, after being collected, organic waste is sent to composting facilities where it is shredded and mixed to promote microbial activity. Microorganisms like bacteria and fungi drive the process of aerobic decomposition, which takes place in the presence of oxygen. A curing and maturation phase is followed by circumstances that are carefully monitored and managed by facilities to maximize the process yield. The completed compost is supplied for agricultural, and landscaping uses after quality assurance and screening, enhancing soil health and plant growth.

There are a wide variety of parameters that affect the process of composting such as temperature, moisture content, aeration, pH, porosity, carbon to nitrogen ratio of feedstock, particle size, compaction level, etc., which attempts to establish appropriate conditions for microbially catalyzed organic waste breakdown. Fungi are important in the humification process. The water content is crucial in this context because dissolved organics serve as a vital energy source, but an excess of water can lead to unfavorable anoxic conditions that hinder the growth of fungi. The favorable water content and aeration rate is 40–65% and 3.25 L/kg DM initial/min, respectively for safeguarding appropriate maturity and N adaptation compost.

Bacteria engaged in compositing can be classified based on soil temperature as psychrophilic (i.e. 12–20 °C), mesophilic (i.e. 20–38 °C), or thermophilic (i.e. 45–71 °C) (Nanda and Berruti 2021). Initially, bacteria play a key role in hydrolyzing complicated organic matter into straightforward forms, followed by actinomycetes and fungi, which predominantly break down cellulose, lignin, chitin, and proteins. Composting bacteria encompass a variety of species, such as Alcaligenes faecalis, Arthrobacter, Brevibacillus brevis, Bacillus circulans, Bacillus licheniformis, Bacillus megaterium, Bacillus pumilus, Bacillus sphaericus, Bacillus subtilis, Clostridium thermocellum, Flavobacterium sp., Pseudomonas sp., and Thermus sp. etc. Actinomycetes species involved in garbage composting include Streptomyces sp., Frankia sp., and Micromonospora sp. Fungi renowned for their composting capabilities include Aspergillus

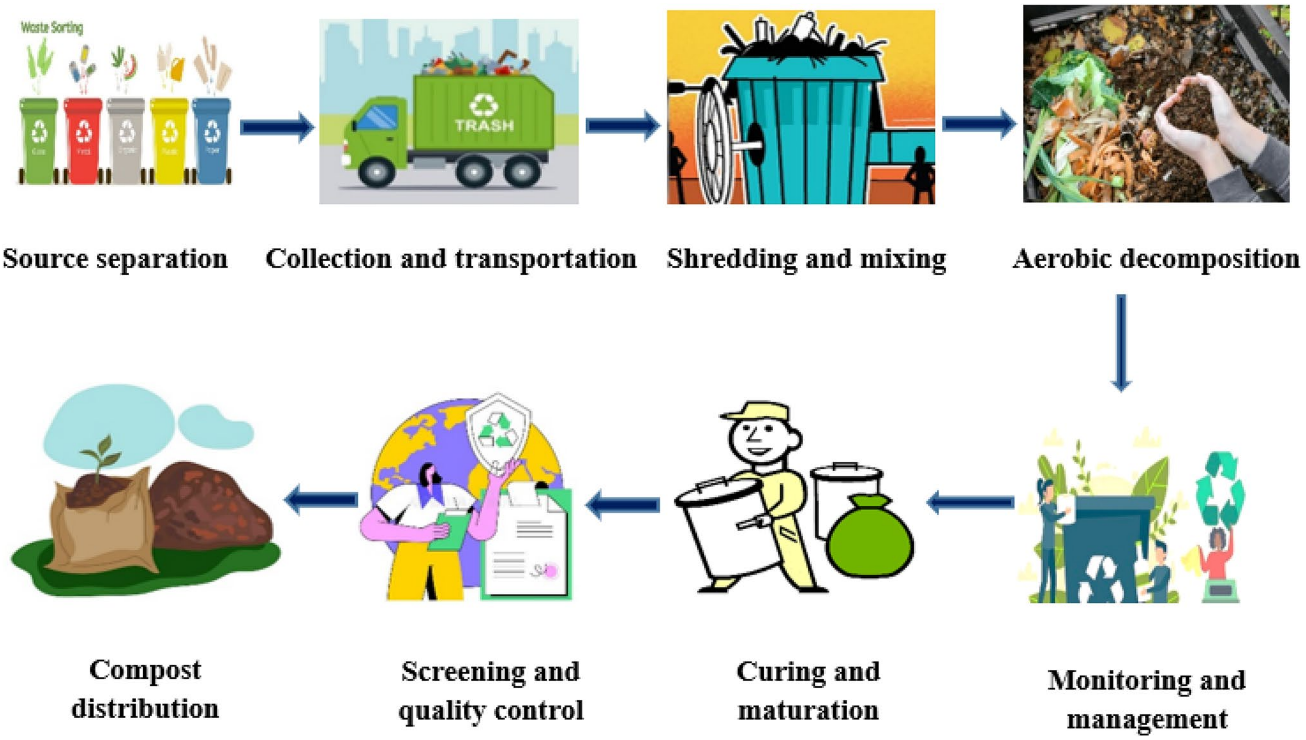

Fig. 7 Process of composting of MSW

fumigatus, Basidiomyces sp., Humicola grisea, Humicola insolens, Humicola lanuginosa, Mal-branchea pulchella, Myriococcum thermophilum, Paecilomyces variotii, Papulaspora thermophilia, Penicillium sp., Scytalidium thermophilum, etc.(Composting 2020).

Cataldo et al. (2022) mentioned compost of MSW as an environmental and agronomic resource while assessing the merits of using compost prepared from organic MSW for the growth of vineyards. They used four different fertilizer doses (municipal solid waste compost at 40 tons/ha, 15 tons/ha, 2.5 tons/ha and no compost (CTRL) to investigate the vine balance (equilibrium of productive and vegetative growth). Their results indicate that MSW compost choices are predicted to alleviate water stress, increase vine performance, and promote long-term organic matter recirculation. The application of MSW compost advances soil structure and workability, reducing the energy needed for ploughing and additional tillage, decreasing the energy required for irrigation, and promoting soil aggregation, thereby reducing soil loss caused by erosion.

Machado et al. (2021) investigated the impact of MSW compost supplemented with inorganic N on soil physicochemical parameters, nitrate content, plant development, and antioxidant activity in spinach. They used four doses of fertilizer in neutral and acidic soil and the results reveal that the addition of compost enhanced the $p^H$ and organic matter content of both type of soils. Application of compost with N enhanced the dry weight of shoot and yield of spinach by about 109%. The production increased in both type of soils with the maximum compost rate (70 t/ha) and 43% of N added. Compost and N applied together could significantly replace inorganic P and K fertilizers. The combination of MSW compost with pine bark is very effective in enhancing water retention and plant productivity compared to manure (Paradelo et al. 2019).

Though composting has several benefits, the major challenge with composting is the emission of foul-smelling gases, which can significantly decrease the quality of life for nearby residents. Large-scale commercial composting operations often require robust environmental control measures to enhance safety and mitigate negative impacts on the surrounding area. Under optimal conditions (humidity, heat, aerobic and anaerobic environments), composting offers a simple yet cost-effective method for treating organic MSW like yard waste, animal by-products, and dairy waste (Abdel-Shafy and Mansour 2018). By utilizing the natural biodegradation process of organic waste, valuable compost can be produced while co-treating MSW. However, the conditions and the microbes involved are crucial for success.

**Fermentation** It is the most important process for producing bio-fuel like bio-ethanol, and bio-butanol from the organic fraction of MSW especially from paper waste or cardboard, yard waste, food scraps as well as residues generated in food processing plants. The organic portion of MSW basically comprises carbohydrates (30–40%), lipids (10–15%), and proteins (5–15%) which ultimately makes it suitable for the generation of biofuels including biodiesel, bioethanol, or other value-added chemicals. Figure 8 demonstrates the process of bioethanol generation from MSW in a complete style, which involves a pretreatment stage, followed by enzymatic hydrolysis, microbial fermentation, product recovery and ultimately the management of residue or by-products.

There are several crucial phases involved in the conversion of MSW by microbial fermentation. Firstly, organic waste is gathered and cleaned of impurities and the trash is pre-processed in order to break it down, depending on the final product that is sought. Pre-treatment of MSW is usually carried out to improve the efficiency of hydrolysis. Enzymatic hydrolysis is preferred for breaking the carbohydrate polymer into monomers. After that yeast is added to the sugar to produce ethanol. However, fermentation is the most crucial step in the production of bioethanol. As mentioned earlier, the operating frameworks to produce bioethanol from the organic fraction of MSW closely resemble those of the traditional process. This involves essential stages such as

**Fig. 8** Flow diagram for the fermentation process of MSW conversion

hydrolysis through enzymatic actions, and fermentation utilizing microorganisms.

Some water is produced in this stage which can be removed by distillation. Under anaerobic conditions, microbes metabolize organic materials to produce a variety of products, including biofuels (like ethanol or biogas) or useful compounds. Following fermentation, the product is separated and refined, and any residual residues might be used again or put through additional processing. This strategy offers a flexible and environmentally friendly technique to turn organic waste into useful resources while minimizing its impact.

Thapa et al. (2019) investigated ethanol production from MSW in Nepal and India and stated that MSW can generate 329,756 L and 13,414 L of ethanol per day from 11,558 t of feedstock in Delhi in India and Nepal, respectively. Along with bioethanol, biodiesel might be created by the bio-conversion of MSW. The organic fraction of MSW is an excellent option for biodiesel synthesis because of having long fatty acids, high availability of medium, and the deficiency of polyunsaturated fatty acids (Barik and Paul 2017). Moreover, catalytic transesterification is the primary process for producing biodiesel from MSW, whereas trash pre-sorting may be beneficial to aggregate biodiesel output (Rodionova et al. 2017). Various catalysts, including basic, acidic, and enzymatic types, have been extensively studied for biodiesel production from MSW. Based on literature (Hoang et al. 2022), the yield of biodiesel generation from the organic portion of MSW lies between 8 to 94% whereas bioethanol production is a little bit higher around 22 to 90%.

## Thermo-chemical conversion

The term “thermo-chemical” indicates the involvement of thermal or heat and/or chemical for treating biomass or waste materials. This treatment process includes pyrolysis, combustion (incineration), gasification, liquefaction, hydrothermal carbonization etc.

### Pyrolysis

Pyrolysis is a thermal cracking method that occurs in the absence of air at a higher temperature generally from 300–700 °C and produces solid material, gas, and liquid products (Islam et al. 2010). Solid products mainly contain carbon known as biochar, while the liquid part is called bio-oil whereas the gaseous fraction includes hydrogen, methane, carbon dioxides, and so on. It is a well-established method for obtaining bio-oil, biochar, and syngas from MSW. On the basis of heating temperature and heating rate pyrolysis process can be classified as slow, intermediate, fast and flash pyrolysis. Fast pyrolysis occurs at 400–900 °C temperature in less than 2 s and produces approximately 60–75% bio-oil, 10–25% biochar and 10–30% non-condensable gases ($H_2$, $CH_4$, CO, $CO_2$) while slow pyrolysis occurs at 300–500 °C temperature for more than 30 min and produces roughly 20–50% bio-oil, 25–35% biochar and 20–50% gas. Intermediate pyrolysis occurs at 400–600 °C for 10 min which produces 35–50% bio-oil, 25–40% biochar, and 20–30% gas while flash pyrolysis takes place at temperature 800–1000 °C for less than 0.5 s with heating rate of 1000 °C/s (Nanda and Berruti 2021).

The key product of the pyrolysis process is bio-oil, but a remarkable amount of biochar and gas are also generated while the gases comprise mainly $H_2$, $CH_4$, CO, and numerous distinct types of volatile organic compounds (VOCs) – related to $CO_2$ effects. Moreover, a trace amount of wax and tars are also produced from the pyrolysis of MSW. MSW exhibits a diverse composition that includes various inorganic metals, including alkalis. These metals, along with sulfur, play a significant role in processes such as melting of ash, formation of fly ash, emission of aerosol, and corrosion of reactors when MSW is employed as a feedstock.

Pyrolysis in high temperatures causes dehydration and depolymerization of organic materials in MSW, resulting in volatile constituents. Condensation of volatile components generates bio-oil. The amount and characteristics of bio-oils are influenced by the quenching process and the period during which volatile vapors reside. Bio-oils, which are oxygenated liquid derivatives, are formed through the thermal decomposition of cellulose, hemicellulose, lignin, lipids, fats, carbohydrates, and organic remnants found in MSW.

Acids, alcohols, aldehydes, esters, ethers, furans, ketones, sugars, and mixed oxygenates are produced during the pyrolysis of cellulose and hemicellulose while lignin pyrolysis creates catechols, guaiacols, phenols, and syringols (Nanda and Berruti 2021). Bio-crude is also produced from pyrolysis which contains organic and aqueous phases. The organic fraction is mainly composed of heavy oil, phenolics, tar, and carbonyls while the aqueous phase includes acids, aldehydes, ketones, alcohols (such as phenol, methanol, and ethanol), ethers, and esters. The oil generated from the pyrolysis of MSW contains high moisture and oxygen which lowers its energy density, thermal stability, and heating value; therefore, it requires further processing steps to be used as fuel or in biodiesel production. The hydrodeoxygenation of bio-oil encompasses various sub-reactions, including decarboxylation, decarbonylation, dealkoxylation, dealkylation, hydrocracking, hydrogenation, hydrogenolysis, and methyl transfer (Nanda et al. 2023).

The product yield of pyrolysis depends on several factors, such as mode of heating, process temperature, reaction time, heating rate, types and compositions of feedstock, type of reactor used, etc. Among all these parameters, temperature is the most influential factor that affects the pyrolysis efficiency and product yield followed by reaction time, and heating rate. The reactor can be a muffle furnace, two-stage fixed bed reactor, tubular reactor, fluidized bed and two-bed reactor, etc.

The mode of heating also plays a vital role in energy consumption and the overall efficiency of the process. The most efficient and fast method for heating is considered microwaved heating. In traditional heating, the heat is transferred from the surface to the center of feedstock while the mechanism of microwave heating is reverse where microwaves reach the center and are transferred throughout the entire volume of feedstock (Sarangi and Nanda 2020; Sarker et al. 2024b). The wavelength of microwave radiation has a range of 300 MHz to 300 GHz. Microwave-assisted pyrolysis has a faster, quicker, uniform, and consistent heating rate and has high energy recovery (Sarker et al. 2022a).

Ma et al., (2019) investigated the pyrolysis behavior of MSW including PVC, cotton fabric, paperboard, sawdust, and vegetables using Py-GC/MS and TG-FTIR. They noticed that the benzenoid compounds are high in PVC (65.03 wt%) followed by paperboard (32.9 wt%) and vegetables (21.91 wt%). The kinetic study showed that vegetables (82.85 E/(kJ·mol$^{-1}$) require low activation energy while high activation energy is required for cotton fabric (178.59 E/kJ·mol$^{-1}$) and PVC (114.57 E/(kJ·mol$^{-1}$).

Quesada et al., (2019) conducted pyrolysis of MSW (plastic film) to produce liquid fuel. The pyrolysis operating conditions varied as follows: temperature (450 ºC to 550 ºC, at 50 °C intervals), residence time (40 to 120 min with 40 min intervals), and heating rate (20 ºC/min, 35 ºC/min and 50 ºC/min). The oil obtained from pyrolysis has pH: 5.9, a specific gravity of 0.812, and a density of 0.809 g/cm$^3$, which were quite similar to those of commercial fuels (diesel and gasoline).

Sometimes catalysts like zeolites, metal oxides, dolomites, bimetallic, and metal hydroxide are used in the reactor depending on the types of raw material to boost up the product yield (Li et al. 2020b). (Miskolczi et al. 2013) investigated the influence of several catalysts including Y-zeolite, β-zeolite, and H-ZSM-5 on the pyrolysis of MSW at a temperature of 500 °C with a reaction duration of 72 to 85 min in a batch reactor. The addition of catalysts remarkably enhances the oil and gas yield and lowers the char yield. Moreover, a high yield of aromatic oil is also generated due to having high surface area and acidity. (Gandidi et al. 2018) examined the effect of zeolite catalysts on the yield and quality of bio-oil obtained from pyrolysis of MSW, biomass, rubber, paper, textile, and plastic while conducting pyrolysis experiments in a fixed bed vacuum reactor. They noticed both gas and liquid yield increased from 21 to 50% (wt) and 15 to 48% (wt), respectively compared to thermal pyrolysis.

Fang et al. (2018) explored co-pyrolysis of MSW with paper sludge at ratios of 10, 30, and 50 wt% with MgO as additive. They concluded that the addition of paper sludge by 30 wt% with MgO additive as the optimum ratio for the co-pyrolysis as paper sludge noticeably reduced pollutants and the amount of aliphatic hydrocarbons.

Besides these $V_2O_5$, $MnO_2$, $Al_2O_3$, and CaO are also used as important catalysts. Among these, $V_2O_5$, and $MnO_2$ are valuable and not easily producible on a large scale. In contrast, $Al_2O_3$ and CaO are cost-effective and can be readily synthesized in large quantities (Li et al. 2011). Catalytic pyrolysis enhances the isomerization rate, reduces residence time, and improves product (oil) quality, though the degree of improvement depends on the type of catalyst used.

Though pyrolysis of MSW has promising potential, several challenges such as high capital cost, high cost of the reactor, cost of heat, air pollution, etc. hinder the widespread adoption and leave commercial-scale implementation in its early stages. Effective air pollution control is essential, requiring efficient filtration and purification methods for the potential pollutants in pyrolysis products. Integration of solar power into pyrolysis to heat the reactor can be a lucrative option to reduce the cost of heating. Despite current issues such as initial costs and air pollution control, ongoing research, strong government support, collaborative initiatives, and market development efforts are expected to elevate pyrolysis to a key role in reliable and feasible MSW management and energy production. Looking to the future, continuous research is necessary for the advancement of commercial-scale pyrolysis of MSW into energy and valuable resources.

## Hydrothermal carbonization (HTC)

Hydrothermal carbonization (HTC) is a thermo-chemical conversion process that uses heat to convert wet feedstocks to hydrochar. These feedstocks can be food residues, industrial wastes, crop residues, forest wastes, sewerage sludges, municipal solid waste, etc. Biomasses with high moisture content and heterogeneous composition, such as the organic fraction of municipal solid waste, tend to pollute the environment more than other types of biomasses. Thus, hydrothermal carbonization can be a suitable option to lessen this impact (Ischia et al. 2021).

Typically, HTC is conducted at temperature ranges 180–250 °C for 0.5 to 8 h under automatically generated (autogenous) pressure of 1.2–2.5 MPa. During HTC, water is added to the reactor because it is a good medium for heat transfer. Gases (mainly $CO_2$) and aqueous slurry are produced from the reactor. This slurry is centrifuged to separate the liquid from the solid (wet cake). The wet cake is dried to produce a carbon-rich material known as hydro-char and the liquid is transformed into bio-crude which ultimately generates bio-oil via purification (Sarker et al. 2024a).

The alteration, for example, size reduction, the removal of inorganic portions, and the addition and mixing of promotional chemicals could improve the performance of the HTC process. However, numerous elements such as temperature, reaction duration, oxygen pressure, mixing rate, etc. can affect the efficiency, product yield, and distribution of the wet oxidation process (Sarker et al. 2024a).

Among the many advantages of HTC, one of the main benefits is the ability to process wet biomass without the need for an expensive additional dehydration or drying phase. HTC can attain a volume reduction of 90–95% for MSW, presenting a more economically viable and time-efficient option compared to both anaerobic digestion and landfill disposal for solid waste management. Additionally, HTC is economically advantageous due to its potential for generating profitable outputs over the long term (Li et al. 2020a). Such technology currently has a low acceptance rate, which is most likely owing to a lack of sociological and technological maturity. HTC requires additional safety considerations since it frequently involves pressurized operation at medium–high temperatures.

Berge et al. (2011) investigated the environmental impacts of HTC on municipal waste streams, including the analysis of gas and liquid products. The study aimed to assess the physical, chemical, and thermal attributes of the generated hydrochar and to compute the carbonization energetics for each waste stream. Findings from batch carbonization tests indicate that 49.75% of the original carbon content is preserved in the char, while 20.37% and 2.11% of the carbon are transferred to the liquid and gas phases, respectively. The features of the resultant hydrochar imply that both dehydration and decarboxylation processes take place during carbonization, leading to the formation of aromatic compounds.

Aragon-Briceño et al. (2022) optimize the HTC process to retrieve water from the digestate of MSW by varying temperature from 180–230 °C with 30–120 min of residence duration. HTC treatment enhanced water recovery (40–48%) throughout the dewatering process in comparison with the original feedstock (18%). The process model demonstrated a favorable energy balance of 110 kWh/tonne of MSW digestate processed, achieving 23.9% electrical efficiency.

HTC has appeared to be a profitable and economically feasible process in the past for converting solid waste and biomass into high-value end products. In comparison with other thermochemical conversion techniques, HTC requires minimal investment, low operational cost, and simple safety measures. HTC allows precise control over the physiochemical properties of the feedstock, which is essential for subsequent biochemical processes, especially when dealing with highly heterogeneous solid waste. This is particularly important for managing incoming solid waste with varying characteristics. Additional safety measures must be implemented during HTC operation as it operates at moderate temperature under pressure. Nonetheless, acceptance of the technology is currently low because society is not yet ready for such technologies.

### Liquefaction

Liquefaction is another thermo-chemical process that converts biomass or solid residues into energy-dense high-quality bio-oil at a moderate temperature of 200–370 °C under high pressure of 4–20 MPa. The reaction mechanism first starts with breaking down the biomass into smaller monomers such as sugars by hydrolysis process. Then, by cleavage and decarboxylation process, monomers turned into smaller compounds. Finally, the smaller compounds recombined into new compounds via condensation, and polymerization reaction. Hydrogenation and liquefaction reactions, aided by hydrogen gas and catalysts, convert the volatile gases into a liquid product known as bio-oil or synthetic oil. This liquid product can be further refined to create biofuels or chemicals.

When liquefaction is conducted in the presence of water then the process is referred to as hydrothermal liquefaction (HTL) which usually takes place at a pressure of 10–25 MPa and 280–370 °C temperature where water acts as a reaction medium (Sarker et al. 2021). There are various advantages of using hydrothermal liquefaction over alternative biomass-to-liquid conversion processes. The utilization of feedstocks that contain high amounts of water especially, algae, MSW, sewerage sludge, aquatic biomass, and cow manure is one such benefit because those feedstocks do not need to be dried to apply in HTL, as the reaction medium is water, thus, reduces the operating costs considerably.

Besides water, some other solvents for example ethanol, and subcritical water are also used in liquefaction. These solvents are important for breaking the cellulose, hemicellulose, and lignin of biomass into volatile matter and form tar and watery phases. The watery phase basically contains water or solvents and bio-chemicals which are recycled further and reused again as solvents during liquefaction. The primary output of this process is bio-crude which needs further upgrading to be used as fuel or blended with diesel as it contains low oxygen contents, more hydrocarbon yield, and flowability. The solid char or ash residue left behind can find various uses, such as construction materials or soil improvement. To meet environmental standards, WTL facilities incorporate emission control systems to minimize pollutants released into the atmosphere, employing methods like gas cleaning, scrubbing, and particulate filtration. A viable strategy to lessen greenhouse gas emissions from the municipal and transportation sectors is the transformation of MSW into vehicle fuels.

Katakojwala et al. (2020) studied HTL of the organic fraction of MSW at temperature of 200 °C under 100 bar pressure (sub-critical conditions) into biocrude. They found that biocrude contains a significant amount of middle oil as well as $C_6$–$C_{22}$ chemicals while the presence of reducing sugars, sotolon, and furfurals was detected in the aqueous phase. The composition of biochar revealed the highest carbon component, followed by hydrogen and oxygen.

Mahesh et al. (2021) conducted HTL of nonhomogeneous MSW by varying temperature from 300–350 °C for 15–45 min at 8 wt% solid loading where the solvent was water and a mixture of water and glycerol. Their observation showed that the biocrude quality was comparable to tetralin when glycerol was used as a solvent while the predominant components in the bio-crude were phenolic compounds and cyclo-oxygenates. The products achieved a maximum energy recovery of 95%, and the energy consumption ratio for the bio-crude was 0.43, demonstrating the energetic viability of the process.

High initial investment, complex equipment, and infrastructure are the most common hindrances for pilot-scale commercialization. Aqueous phases of HTL sometimes contain toxic compounds, therefore, handling and disposing of by-products from the process may require additional treatment steps. Integration of anerobic digestion for the byproducts of HTL with the HTL process can make the overall process attractive and economical.

### Gasification

Gasification is a process that transforms carbon-containing materials, whether organic or fossil-based into syngas (CO, $H_2$, $CO_2$, $CH_4$) with the help of a gasifying agent such as air, oxygen, steam, nitrogen, etc. This process required a high temperature around 700–1400 °C. During gasification, a significant amount of heat is also generated along with gas. Various value-added products such as biofuel and biochemicals can be obtained by additional processing of syngas including Fischer–Tropsch synthesis. The byproducts of the gasification process are biochar, a carbon-rich material, and tar which is rich in organic fractions. This biochar can be used for soil amendments, production of cosmetics, wastewater treatment, etc. while tar can be processed to produce bio-oil (Sarker et al. 2022c).

There are various types of gasification like thermal gasification, hydrothermal gasification, steam gasification, $CO_2$ gasification, plasma gasification, etc. Thermal gasification uses heat at a very high temperature around 800–1200 °C to decompose the organic fraction of MSW. However, hydrothermal gasification uses subcritical and supercritical water as solvents to break down the feedstocks which is performed at moderate temperature ranges from 400–700 °C. Subcritical water is present at temperatures below the critical temperature (374 °C) and pressures below the critical pressure (22.1 MPa), while supercritical water is found at temperatures above the critical temperature and pressures exceeding the critical pressure (Sarker et al. 2022b). The major advantage of hydrothermal gasification over other types of gasification are suitability to use high moisture content biomass or MSW without the necessity of drying (Sarker et al. 2022d).

Steam gasification has become popular because the produced gas from this gasification can be directly used as an intermediate product for producing fuels and chemicals on large scale (Zhang 2010). The steam will break the cell structure of biomass and finally produce $H_2$, CO, $CO_2$, $CH_4$, and other hydrocarbons (Lamb et al. 2020). Because of using steam, the production of $H_2$ formation is enhanced, and it produces valuable heating gas without any nitrogen. Although it is a very costly and energy-consuming process, there is no need for an expensive gas separation method in this process (Parthasarathy and Narayanan 2014). Another kind of gasification is $CO_2$ gasification which is used for minimizing $CO_2$ emissions and relieving the energy shortage (Cheng et al. 2016). The main advantage of $CO_2$ gasification is no requirement of external energy for vaporization, moreover, the gasification efficiency increased. For producing syngas from coal, $CO_2$ gasification has been used which has also reduced $CO_2$ pollution (Irfan et al. 2011). In the case of energy recovery of waste to energy technologies, such as gasification, one ton of MSW may typically provide about 600 kW/h of electricity.

There are various phases involved in the gasification of organic waste. When the biomass is subjected to heating at 500 °C, it releases water vapor and volatile constituents such as polysaccharides (including cellulose, hemicellulose, and starch), lignin, lipids, fats, proteins, and pectin. The decomposed components undergo reactions, resulting in the formation of phenolics, aromatics, aliphatics, aldehydes, and olefins within the temperature range of 500–600 °C. In the third stage (600–900 °C), the intermediate degradation products are further disintegrated to produce permanent gases (such as $H_2$, CO, $CO_2$, $CH_4$, and $C_{2+}$) and tertiary products (including benzene, naphthalene, anthracene, pyrene, and phenanthrene).

Shafiq et al. (2021) conducted steam gasification of MSW and optimized the conditions in order to attain maximum gas yield using Aspen plus. They noticed that hydrogen gas yield increased with the augmentation of steam to MSW ratio. The simulation results suggested that the optimum condition for gasification is 680 °C with 1.3 steam to MSW ratio where a maximum yield of hydrogen gas (79.8%) is obtained.

Fu et al. (2022) developed an Aspen Plus model for the conversion of MSW into syngas via steam gasification by varying temperatures ranging from 750 to 900 °C with steam flow rates of 0.138–0.312 kg/h. Their results indicated that the gas yield augmented by 29.8% with the increment of temperature from 750 to 900 °C because of improved endothermic reactions while the tar yield decreased due to thermal cracking at higher temperatures. Moreover, the application of steam in gasification contributes to the augmentation of $H_2$ gas generation by encouraging the water–gas shift reaction and tar cracking reactions.

Recently, gasification of MSW has been conducted with other feedstock, which is known as co-gasification. The purpose of co-gasification is to minimize the black tar formation and improve the gasification efficiency. Compared to conventional gasification, co-gasification has demonstrated improved performance for gaseous products, carbon conversion, and cold gas efficiency. Bhoi et al. (2018) gasified MSW with switchgrass at three different ratios of 0, 20, and 40% in a commercial scale downdraft gasifier of capacity 100 kg/h and noticed that the calorific value of syngas, as well as cold gasification efficiency, increased with the rise in co-gasification ratio. Saravanakumar et al. (2024) designed a downdraft gasifier of 100 kg/h capacity to gasify heterogeneous feedstock with an air supply rate of 150 kg/h. They used MSW and tamarind wood to gasify and obtained the maximum calorific value (1250 kcal/$Nm^3$) of syngas for a 50:50 ratio (by mass). Co-gasification of MSW has not been studied exclusively, therefore, extensive performance studies involving diverse combinations of raw materials and MSW are mandatory to optimize the process for commercialization.

Plasma pyrolysis has been gaining attention recently because of its promising performance. This method employs a plasma torch, powered by either alternating or direct current, as a thermal source to decompose solid waste into synthetic gas (Prajapati et al. 2021). The plasma torch generates thermal energy by passing an electric current through a gas. Mazzoni and Janajreh (2017) explored a number of potential conversion routes to generate energy from MSW and plastic solid waste using plasma gasification. Their proposed treatment achieved 38% energy efficiency from a mixture of 70% MSW and 30% plastic solid waste, with pure oxygen used as the plasma gas. Plasma gasification is more efficient and suitable WtE technology among others.

Gasification of MSW conversion offers multiple advantages, including efficient energy generation through clean-burning syngas, waste volume reduction, resource recovery from char or ash residues, reduced greenhouse gas emissions compared to landfilling, and the potential for chemical and biofuel production using the syngas as a feedstock. These benefits make gasification a promising and environmentally friendly approach to MSW management and resource utilization. Compared to incineration, these methods allow for a 95% reduction in waste production and require less thorough cleanup of combustion gases. Moreover, gasification produces a higher average net energy of 36–63 kgoe/t MSW in comparison to pyrolysis and incineration (Munir et al. 2021). Because of its potential for energy recovery and its influence on the environment, gasification technology is preferable to solid waste incineration technology.

However, the problems associated with gasification are the formation of ash, particulate matter, and heavy metals during gasification which pose negative environmental impacts after accumulation. Reactions occurring above 1,100 °C require special attention, as they can promote tar formation, potentially blocking the reactor (La Villetta et al. 2017). Periodic gas cleaning can help to prevent blockages by removing tar, particulate matter, heavy metals, HCl, and $H_2S$ that accumulate in the reactor.

The selection of a proper gasifying agent has a substantial influence on the gas yield, energy content of syngas, selectivity of components, etc. Research and the advancement of technology in this area offer a viable solution for energy recovery, either through a synthetic chemical approach or the establishment of a bio-refinery using waste materials.

### Combustion

Combustion or incineration is a widely used waste treatment process that deals with the burning of organic waste materials. The heat produced by waste incineration can potentially be utilized to create electricity. Opting for MSW incineration has become a favorable alternative to landfills, which are unattractive, occupy significant space, and vie for residential or agricultural land areas. Incineration typically results in an 80–85% reduction in the weight and a 95–96% reduction in the volume of the original MSW.

The properties (microscopic and macroscopic) of MSW determine the quantity of heat generated during burning. Thermal analysis, minerals, and chemical kinetic research are examples of microscopic properties whereas heterogeneity, particle size, heating value, ultimate and proximal analysis, bulk density as well as ash fusion are common in the macroscopic features. The thermal properties of MSW, particularly thermal conductivity, specific gravity, specific heat, and volatile emissions, are substantially influenced by combustion temperature, moisture content, and thermal degradation magnitude. Moisture, light hydrocarbons, $CO_2$, CO, $H_2$, $CH_4$, volatile organic carbons (VOC), polycyclic aromatic hydrocarbons (PAH), dioxins, furans, and tars are among the volatile matter emissions from incineration. The yield of gas generation, ash formation as well as heat production greatly depends on various parameters such as temperature, mineral matter, heating rate, inert compounds, and inorganic compounds present in MSW.

MSW can be converted into energy, saving more precious fuels while reducing the amount of waste that needs to be disposed in landfills and preserving energy and natural resources. Waste-to-energy facilities utilizing combustion follow a structured process. First, municipal solid waste is collected, prepared, and sorted to remove non-combustible materials. Then, it is fed into a combustion chamber, ignited, and undergoes combustion in three zones. The heat generated is used to produce electricity via steam turbines or for direct industrial heating. Emission control technologies are employed to reduce pollutants. Finally, the remaining ash and non-combustible materials are managed, often being disposed of in landfills or repurposed for construction materials. This process enables energy recovery, waste reduction, and control of emissions while handling municipal solid waste.

Combustion for MSW conversion offers several benefits, including energy recovery for electricity generation, waste volume reduction, resource recovery from ash residues, and a potential reduction in greenhouse gas emissions compared to landfilling due to the avoidance of methane emissions from organic waste decomposition.

### Challenges in biofuel production

The production of biofuels from MSW poses several techno-economic challenges that must be addressed for the successful commercialization of MSW-to-biofuel technologies.

**Feedstock variability**: MSW is a heterogeneous feedstock, which means that its composition varies from one location to another and even within the same location over time. This variability makes it difficult to design and optimize biofuel production processes. It can also affect the quality and quantity of biofuels produced, which can impact their economic viability.

**Process efficiency**: The efficiency of biofuel production processes from MSW is generally lower compared to other biomass feed-stocks due to the high moisture content and low energy density of MSW. This can result in higher production costs and lower yields of biofuels. Improving the efficiency of the conversion process is critical in reducing production costs and increasing the economic viability of MSW-to-biofuel technologies.

**Capital costs**: MSW-to-biofuel technologies require significant capital investments in equipment, infrastructure, and facilities. The capital costs associated with these technologies can be unaffordable, particularly for small-scale facilities. These high capital costs can make it difficult for MSW-to-biofuel technologies to compete with traditional fossil fuels.

**Operational costs**: The operational costs associated with MSW-to-biofuel technologies are also high due to the need for pre-processing, sorting, and cleaning of the waste feedstock. These processes can be labor-intensive and energy-intensive, which adds to the overall production costs.

**Regulatory challenges**: Biofuel production from MSW is subject to a complex regulatory environment that can impact its economic viability. Regulatory challenges include permitting requirements, environmental regulations, and incentives for renewable energy production. Meeting these regulatory requirements can add to the production costs of biofuels from MSW (Centi and Perathoner 2020).

### Future Prospects

Despite the challenges, the production of biofuels from MSW holds promise as a sustainable source of renewable energy. To overcome the techno-economic challenges associated with MSW-to-biofuel conversion, several strategies can be adopted, including:

**Integration with other renewable energy sources**: MSW-to-biofuel conversion technologies can be integrated with other renewable energy sources, such as wind and solar, to improve their economic viability. This integration can help to offset some of the variability and intermittency associated with renewable energy sources.

**Use of advanced technologies**: Advanced technologies, such as artificial intelligence and robotics, can be used to optimize the MSW-to-biofuel conversion process. These technologies can help to reduce operational costs and improve the efficiency of the conversion process.

**Policy support**: Policy support in the form of incentives, subsidies, and mandates can help to overcome the economic barriers to the adoption of MSW-to-biofuel technologies. These policies can equalize the competition with traditional fossil fuels and enhance the competitiveness of MSW-to-biofuel technologies. (Sipra et al. 2018).

## Conclusion

Waste to biofuel production will be an alternative way in the future for producing energy for the growing population. Embracing MSW as a plausible source for generating alternative fuels not only diminishes reliance on fossil fuels but also originates opportunities for environmentally sustainable remediation. MSW can be converted into biofuel through biological conversion methods including anaerobic digestion, and composting, on the contrary, the thermochemical conversion techniques involve pyrolysis, gasification, liquefaction, hydrothermal carbonization as well as incineration and combustion of fuel.

Anaerobic digestion generates biogas and bio-slurry while composting is a cost-effective technique of transformation of the organic components in MSW into nutrient-rich compost that has a wide application in agricultural operations. Pyrolysis and liquefaction of MSW typically end up with energy-dense bio-oil which can be used for generation of various chemicals, biodiesel, and so on, whereas gasification generates $H_2$ rich syngas. Along with those methods, HTC generates a carbon rich material known as char which can be utilized for enhancing soil, capturing carbon, adsorption, or manufacturing specialized materials with diverse applications. The product yield and quality of products of all thermochemical processes are affected by the operating conditions of the process including temperature, heating rate, pressure, reaction time, feed concentration, and the type and amount of catalyst. The incineration of MSW and the combustion of various fuel products like bio-oil, syngas, or biogas can be utilized for combined heat and power or undergo catalytic upgrading to produce synthetic transportation fuels.

The benefits of a circular economy include reducing the disposal of MSW in landfills and boosting recycling rates. Effectively designed and strategic approaches to MSW processing, along with centralized systems for promoting the final products and by-products, have the potential to achieve zero cash flow and remove financial barriers in waste management. Additionally, conducting lifecycle analysis to assess environmental and techno-economic analysis for various MSW management and recycling alternatives is crucial for a thorough assessment of the numerous advantages and risks linked to landfilling compared to waste diversion. By thoroughly assessing the advantages and drawbacks of each method, local authorities can make well-informed choices that align with their energy objectives and environmental concerns.

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## Declarations

**Conflict of interest** The manuscript was prepared originally and not submitted elsewhere for publication. 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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