Perspective Review on Municipal Solid Waste-to-Energy Route: Characteristics, Management Strategy, and Role in Circular Economy

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Abstract

The proper handling of Municipal Solid Waste (MSW) is critical due to its high generation rate and the potential to minimise environmental impacts by simultaneously reducing resource depletion and pollution. MSW utilisation for recycling is important for transforming the linear economy model into a circular one. The current review analyses and categorises MSW to energy technologies into direct and indirect approaches taking the Circular Economy perspective. The direct approach involves incinerating MSW for heat recovery. The indirect approach, including thermochemical and biochemical processes, is more complicated but attractive due to the variety of the valorised products – such as syngas, bio-oil, biochar, digestate, humus. However, consensus on the best MSW treatment approach is yet to be established due to the inconsistency of assessment criteria in the existing studies. In the case of converting MSW to energy (Waste-to-Energy – W2E), its economic indicators, such as capital, compliance, and operation cost, are important criteria when implementations are considered. In the current work, the critical characteristics of technologies for the MSW to energy routes are scrutinised. In addition, the economic characteristics and the role of MSW in the circular bio-economy is also thoroughly evaluated. Methods to advocate the industrial adoption and important assessing aspects of W2E are proposed at the end of the review to address the environmental and resource management issues related to MSW – most notably dealing with the uncertainty in composition and amounts, the energy efficiency and the resource demands of the W2E processing.

Keywords: Municipal solid waste; circular economy; energy production; environment management; waste management

Highlights

- Direct and indirect valorisation techniques for MSW are reviewed
- The economic characteristics and energy production viability of MSW are analysed
- Suggested assessment criteria for fair comparison of Waste-to-Energy technologies
- The low economic viability of Waste-to-Energy due to ignoring environmental benefits
- Methods to advocate the industrial adoption of W2E are proposed.

1. Introduction

Human society is presently plagued by two major challenges – environmental pollution and shortage of resources, resulting from the rapid urbanization and industrialization since the last decade (Hoang et al., 2021d). The fast-growing human population, which is expected to reach 10 billion people in 2057, is also regarded as another potential threat that would aggravate the current situation to a greater extent (Worldometers, 2021). Reportedly, around 2 Gt of Municipal Solid Waste (MSW) are produced and released to the environment annually (Usmani et al., 2020), of which 33 % are not appropriately collected and processed – as found in characterizing MSW in Johannesburg (Ayeleru et al., 2018), in the development of regional strategic planning for MSW (Harris-Lovett et al., 2019) and in a review on bioconversion of MSW (Yaashikaa et al., 2020).

Based on the statistics presented in **Fig. 1**, the MSW worldwide has been increasing over the years. This clearly illustrates the great pressures exerted on the energy sectors, waste management, and industrial sustainability on a global scale. Another source (Yang et al., 2021b) shows the annual generation of MSW as of 2017-2018 by countries, showing the most significant generation flows. Of those, the top five MSW generating countries are the United States (258 Mt), China (220 Mt), India (168 Mt), Brazil (80 Mt), Russian Federation (60 Mt).

While impacting the environment, the mismanagement of MSW could inflict multiple problems on the society wellbeing, affecting safety, human health, and financial aspects (Xiao et al., 2020). The constant increase of MSW, in volume and complexity, has extended the waste management challenges for current and future societies (Ye et al., 2020). This is aggravated by the increasing fossil energy use, environmental pollution, and global warming (Hoang and Pham, 2021). The depletion of natural resources is a related threat (Hoang et al., 2020a). In summary, the valorisation of MSW into energy or other useful products bears a strategic synergy potential to minimise pollution, fossil energy use, and depletion of natural resources (Amen et al., 2021).

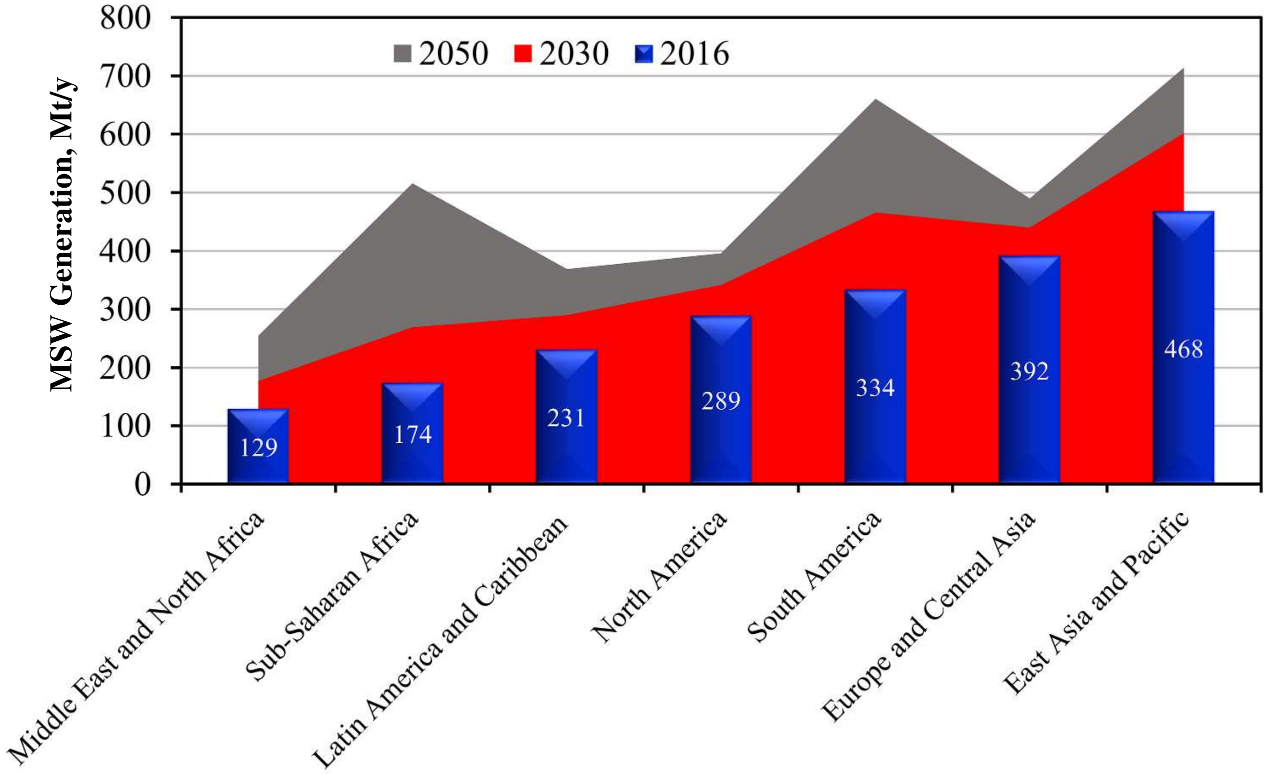


Fig. 1. The rising rate of MSW by year for some countries and areas in the world, amended after (Kaza et al., 2018)

For the achievement of societal sustainability, it is important to simultaneously improve the efficiency of energy supply, conversion, and use (Seferlis et al., 2021). Technology advancements allow the conversion of non-recyclable MSW into various energy carriers – electricity, heat, biofuel, and biogas (Beyene et al., 2018). Composting (Miller, 2020) and landfilling (Christensen et al., 2020) are conventional waste treatment technologies, while anaerobic digestion (Wang et al., 2018a), incineration (Escamilla-García et al., 2020), pyrolysis (Kwon et al., 2019), gasification (Prasertcharoensuk et al., 2019) and hydrothermal processing (Chen et al., 2020a) offer higher MSW valorisation potential into value-added chemicals and fuels. However, they meet certain implementation barriers. In particular, the technological maturity of each approach plays an important role (Farooq et al., 2021). Developed countries apply W2E technologies more widely (Chen et al., 2020b). Due to this reason, W2E presents a real potential to simultaneously solve waste and energy issues on a global scale (Skaggs et al., 2018). This could be explained that the transformation and conversion of waste into useful energy could not only reduce the pollutants released into the environment but also diversify the provided energy sources, depending on the technological characteristics of each nation, region, and locality.

To ensure the effective utilization of MSW, long-term processing technologies should be applied in well-targeted circular economy implementations (Pires and Martinho, 2019). As such, the current MSW management strategies that focus on end-of-pipe treatment have to be reconsidered. The rationale of this approach is, by following the waste hierarchy, to minimise the need for end-of-pipe treatment and maximise the economic viability of sustainable technologies for energy and material recovery (Fan et al., 2020a). In this context, MSW management should consider a broader perspective, placing W2E technologies as a vital component of the overall management strategy (Sun et al., 2018), as a means of energy valorisation only after the reuse and recycling stages. Such an evolution of the W2E paradigm would enable the authorities and related industries to adopt W2E that is more socially acceptable and economically viable.

In summary, the reviews of previous achievements – including the evolution of incineration (Makarichi et al., 2018), public perception analysis (Yuan et al., 2019), and analysis of public-private partnerships in incineration (Cui et al., 2020), have shown that the developments of the MSW to energy technologies and practices during the last decade have not been well analysed. This is especially the case in the context of the Circular Economy paradigm. A consistent critical analysis is still needed to characterize MSW processing and W2E technologies and their optimal integration into circular economy implementations.

The main objective of this study is to analyse the merits of MSW valorisation, the aspects of hazardous material management and the promotion of the circular economy pattern. The roles of waste in circular economy and energy generation are thoroughly analysed as well. The current challenges and future opportunities, along with the research gaps in the field, are also discussed at the end of the analysis. It is anticipated that our review would promote the re-utilisation and valorisation of MSW, contributing to the industrial adoption of circular economy models, as well as the well-preservation of the environment. This paper builds upon the previous review by Fodor and Klemeš (2012), discussing further advancements in the field. The scope of the considered technologies is expanded and deepened, with a discussion at the end of the waste management perspectives, within the overall strategy for building a circular bio-economy.

2. Main issues, sources, and composition of MSW

This section provides a concise summary of MSW sources and the issues resulting from the current management practices. The diversity of components and the complex origin of various MSW streams are shown together. This provides the necessary background for understanding the following review sections.

MSW is collected from diverse sources, such as industries, manufacturers, residential buildings, schools, offices, markets, and shops. There could be a variety of organic and inorganic materials in MSW, including polymers and non-renewable items, or even a mixture of all (Zheng et al., 2014). The MSW components can be categorised according to seven major groups: organics, paper/boards, plastics, glass, metals, textiles, and inert. The remainder is grouped into miscellaneous (Asamoah et al., 2016). The pie chart in **Fig. 2a** presents the distribution of these components by relative shares, following the ASTM D5231 standard. A more detailed subgrouping of MSW is illustrated in the tree diagram of **Fig. 2b.**

As mentioned, MSW composition varies, depending on the source location, economic situation, industrial structure, lifestyle, and methods applied in waste management (Rezaei et al., 2018). It is important to know the amount and characteristics of the MSW collected to not only facilitate the handling process but also to optimise the subsequent energy recovery with suitable W2E methods. The calorific value and physicochemical properties of MSW are crucial for obtaining high energy yield and harmless residue from the treatment processes. At present, most researchers are able to predict the potential emissions and performance from the properties of the MSW feedstock, but the concerns over the by-production of harmful materials from these raw materials (e.g., ash) remain an important obstacle to the adoption of the W2E processes (DOE, 2019).

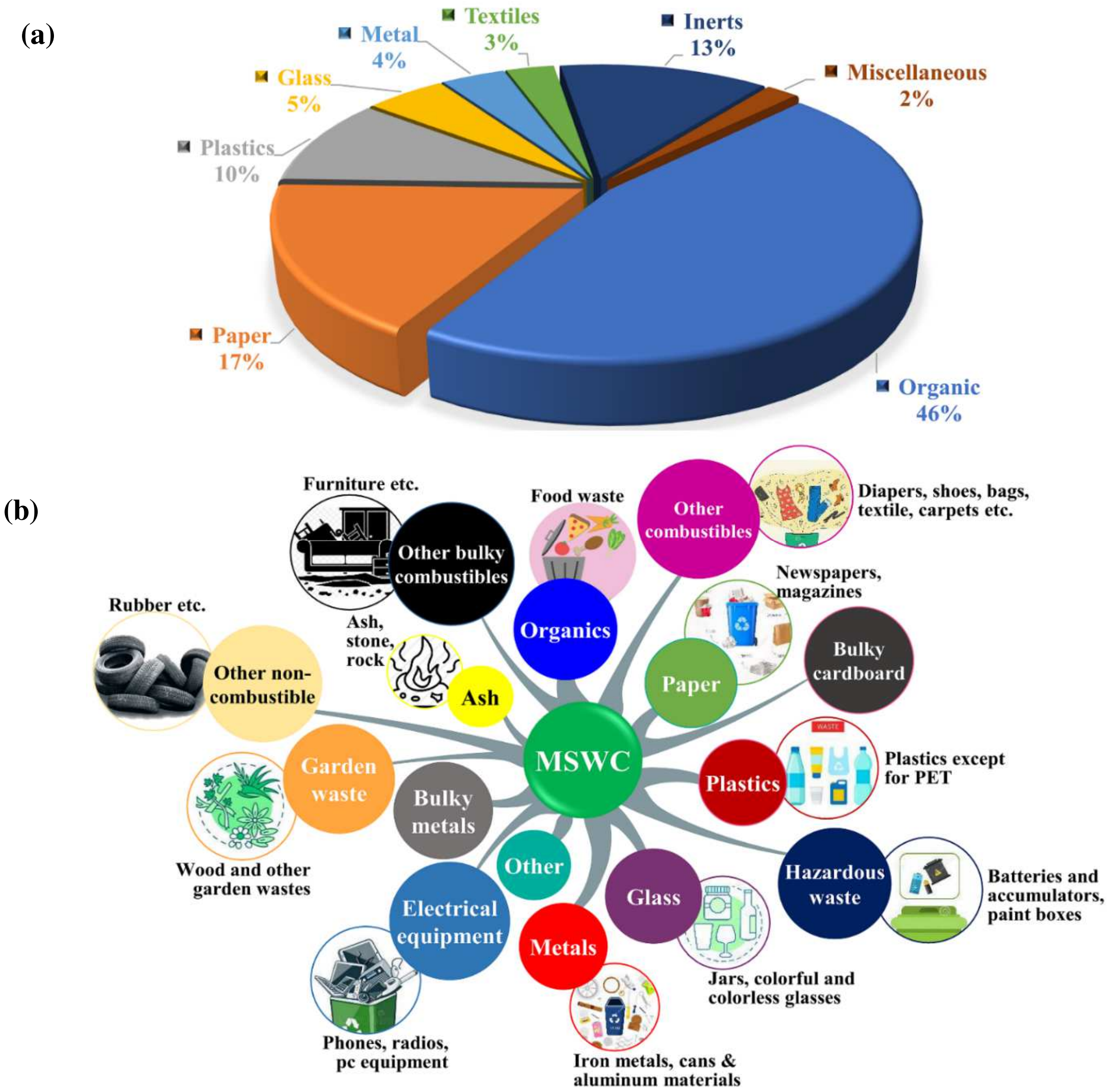


Fig. 2. MSW characterization: (a) Composition of MSW in the world based on data from (Sharma and Jain, 2020); (b) MSW Components - MSWC mapping after (Ozcan et al., 2016)

In most developing countries, households generate the highest share of MSW (55-80 %), while the commercial sector accounts for a lower share of 10-30 % (Llano et al., 2021). The MSW collected from non-residential sources is quite diverse in terms of its contents and physic-chemical characteristics (Dehkordi et al., 2020). Plastics, paper, wood, leather, fabrics, food waste, yard waste, demolition waste, etc., are some common items found in MSW. With this heterogeneity, it is extremely challenging for MSW managers to identify optimal processing and treatment methods (Ali and Ahmad, 2019). Therefore, a pre-processing sorting is essential for proper assessment and characterization, which may, in most cases, enhance the performance of the subsequent waste treatment process (Gundupalli et al., 2017). Improved public awareness, changes in consumer behaviour, and high acceptance of communities will facilitate the implementation of waste sorting and separation for the enhanced effectiveness of MSW handling (Lima et al., 2019).

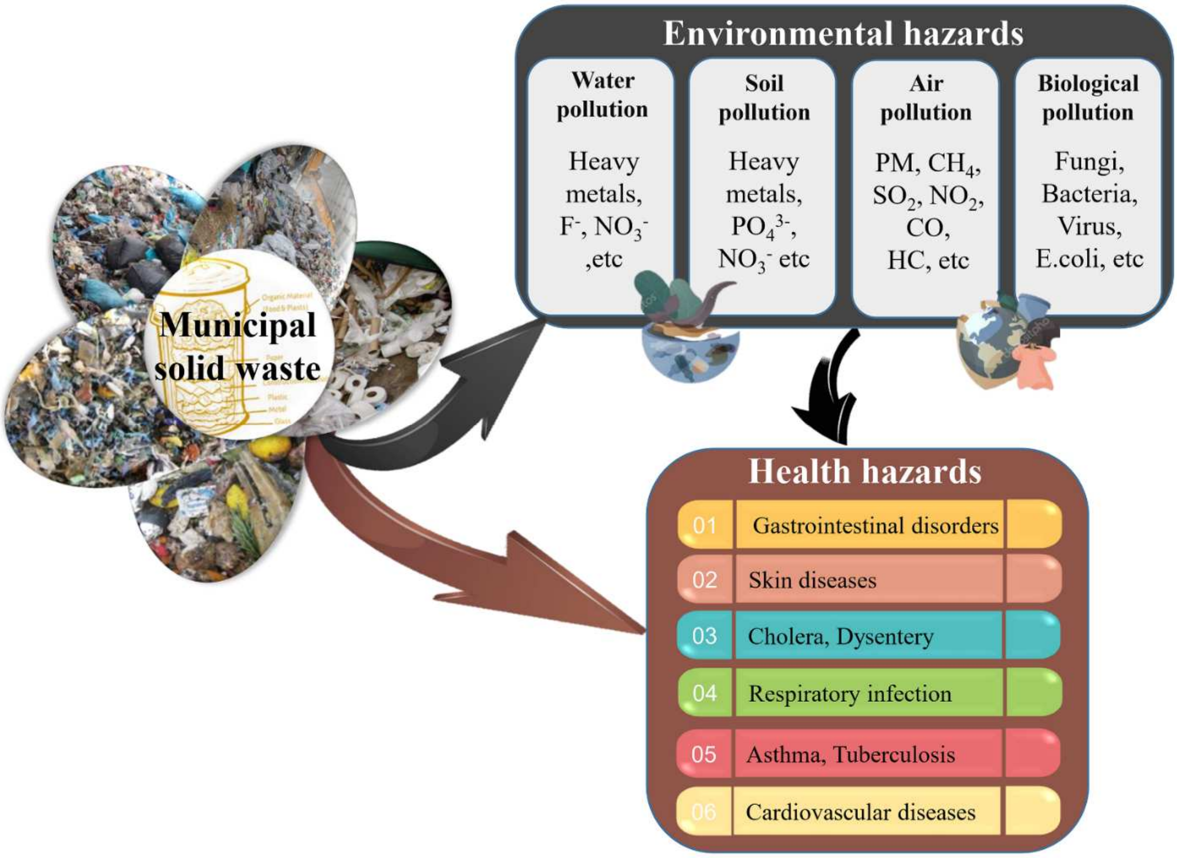


Fig. 3. Effects of MSW on human health and environment (Malav et al., 2020)

Currently, many countries have adopted various waste management practices, such as incineration, landfilling, and unregulated disposal of waste (OECD, 2019). Landfilling and – in many cases incineration, are destructive to both human health and the environment in the long run. It was found (Venna et al., 2021) in several instances that the leachate from landfills has led to soil contamination and water pollution to surface and groundwater sources. Also, the pollutants released from large-scale waste incineration would increase the rate of respiratory-related illnesses too. The insufficiency of landfilling sites poses another challenge to many urban areas. Other significant environmental and health effects associated with MSW are presented in **Fig. 3**. The mapping of the issues is based on an interpretation from (Malav et al., 2020) and based on the review of MSW practices in India (Pujara et al., 2019).

More critically, some regular household items can be hazardous, such as cleaning supplies, homecare products, electronics, motor oils, and machine lubricants. Such products, if they occur in MSW, have to be separated and treated separately from the other components and especially the energy valorisation part (Kanagamani et al., 2020). It remains difficult to obtain accurate quantitative and qualitative data on the chemical makeup of these common household items. Some chemical compounds such as phenols, chlorinated organic solvents, polycyclic compounds, benzene, toluene, or inorganic components such as sulphites, ammonium, cyanide, and heavy metals, whether existing by themselves or interacting with other substances, can pose a serious threat to humans and the environment under prolonged exposure and can be removed using biochar (Chen et al., 2022). Researchers suggest that the standardized treatment should be applied to household hazardous waste, further compelled by the desire to improve the current MSW handling (Manggali and Susanna, 2019).

In summary, the diverse MSW sources cause its composition to vary widely. While waste sorting and separate collection are practised, they are not sufficiently well implemented yet. Incineration is so far the main waste-to-energy practice. On the example of the European Union, 61Mt have been incinerated in 2020 (Eurostat, 2021) against landfilling (52 Mt) and composting (40 Mt), while good progress has been made in direct material recycling (67 Mt). Therefore, incineration implementations often need further improvement. Landfill leaching is a frequent problem causing various pollution and health risks. The limits on landfill area availability already pose challenges to urban areas.

3. Technologies for municipal solid waste-to-energy processing

W2E approaches, such as incineration, pyrolysis, gasification, anaerobic digestion, biomethanation, and landfill gas recovery, serve as effective MSW treatments while giving rise to energy valorisation (Palacio et al., 2019). These methods are intended to achieve three primary objectives:

(i) Decrease the total volume of MSW to be disposed of in landfills regardless of whether it originates from residential and commercial sectors.

(ii) Minimise the portion of biodegradables in MSW, preventing secondary environmental pollution with runaway CH_4 from potential decay of the biodegradables eventually remaining after the treatment.

(iii) Valorize the energy content of non-recyclable solid waste in the form of electricity and/or heat.

Considering technology, energy recovery through W2E can be attained via a direct or an indirect path. Direct technologies implement direct combustion of refuse-derived fuel and other waste, while indirect processing paths involve pre-treatment steps before the energy generation. Several types of thermochemical (e.g., pyrolysis, incineration, gasification, etc.) and biological processes (composting, fermentation, etc.) are involved in the latter process. This classification is used in the current review, and it is illustrated in **Fig. 4**. Some of the products, such as bio oil and biochar can be technically used for generating power. However, in the figure, they are given as generating only heat, assuming that they are more useful in the capacity of providing residential or process heat.

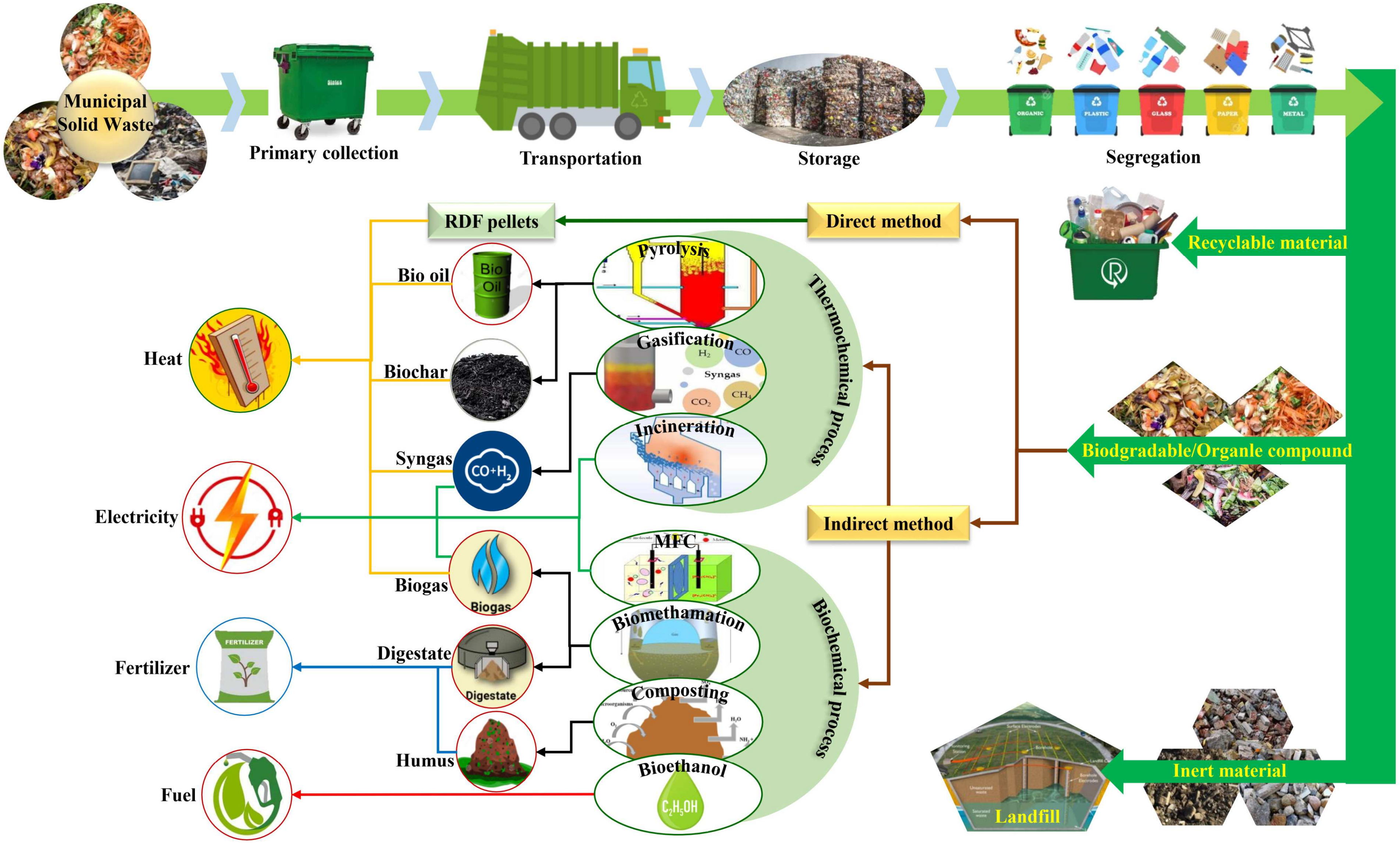


Fig. 4. Current technologies for energy production from waste

The energy and environment-based properties of W2E technologies for MSW processing are compared in **Table 1**. The data sources for the comparison in **Table 1** have been collected and analysed jointly. (Cherubini et al., 2009) considered several scenarios using the data from the municipality of Rome – landfilling without energy recovery, landfilling with biogas recovery, waste separation with follow-up energy recovery, and direct waste incineration. Munir et al. (2021) focus on the analysis of waste in New Zealand. Evangelisti et al. (2014) provide a case study on anaerobic digestion of waste with data from the United Kingdom. A similar team (Evangelisti et al., 2015) analysed advanced MSW to energy technologies – such as gasification and plasma gas cleaning, fast pyrolysis and combustion, and gasification with syngas combustion. The review (Kumar and Samadder, 2017) provides an overview and a summary of the anaerobic digestion and co-digestion of MSW with other substrates. The work by Toniolo et al. (2014) has analysed MSW incineration by comparative LCA within design and operation contexts, and (Wanichpongpan and Gheewala, 2007) analysed the energy recovery from landfill gas for MSW in Thailand. Characterization of biomass gasification was obtained in (Yang et al., 2018a), while in the work of Zaman (2010), an analysis of data on Sanitary landfills, Incineration, and gasification-pyrolysis was elaborated.

The emphasis of Munir et al.(2019a) are on sewage sludge treatment and phosphorus recovery by wet oxidation. Munir et al. (2018b) characterised hydrothermal waste treatment, while Munir et al. (2018a) deal specifically with food waste, and (Savage et al., 2010) described the use of thermochemical biomass conversion to liquid fuels and chemicals.

Table 1. Comparison of energy and environment-based characteristics for W2E process from MSW (The data sources are discussed in the text)

Energy and environment-based criteria	Incineration	Landfilling	Anaerobic digestion	Composting	Gasification	Pyrolysis	Hydrothermal carbonisation
Plant life, y	30	30	15 - 20	10 – 15	20 – 30	20	20
Ability to handle wet waste	H	L	L	L	L	L	M
Ability to handle hazardous waste	M	L	L	L	M	M	M
Energy production (kgoe/t MSW)	36 - 45	4.5 - 9	9 - 13.5	-2.7 - 3.2	36 - 80	45 - 50	-
Abiliby to reduce MSW volume	75%	60%	60%	50%	82 - 90%	84%	90%
Ability to recover value-added products	L	L	L	L	M to H	M	H
Rate of residue components	M	M	H	H	L to M	M	L
Particulate matter	20 μg/Nm^3	n.a	n.a	n.a	12.5 – 14.1 μg/Nm^3	5.7 μg/Nm^3	n.a
GHG Footprint, t CO$_2$ eq/t MSW	1.67	1.97	1.19	1.61	1.3 – 1.5	0.7 – 1.2	n.a
NO$_x$	< 400 mg/m^3	n.a	n.a	n.a	< 200 mg/m^3	< 50 mg/m^3	n.a
SO$_x$	40 μg/Nm^3	n.a	n.a	n.a	19 μg/Nm^3	35 μg/Nm^3	n.a
H- High; M - Medium; L - Low							

3.1. Direct processes

The direct processes of W2E involve mainly mass burning, Combined Heat and Power generation from waste, as well as Refuse-Derived Fuel (RDF) production and use in incineration facilities. The key parameters of the technologies are summarised in Table 2.

Table 2. Key parameters of direct W3E processes

Parameter	**Summary**	**Reference**
Share of energy recovery	Vast majority of incinerators in the EU involve energy recovery and utilisation – exceeds 80 %	(Eurostat, 2018)
Energy Efficiency	68 % as of 2015	(Saveyn et al., 2016)
RDF production	High potential for reducing the volume of landfilled waste – over 50 %	(Brew, 2018)
GHG reduction	Up to 50 % reduction of GHG emissions of a real-life W2E plant	(Brno Daily, 2021)
Emission issues	Particulate Matter (PM)	Tackled at the level of research (Di Maria et al., 2021) and industrial practice (EVECO, 2012)

Mass burning, which involves the incineration of unsorted municipal waste, is one of the popular MSW management approaches worldwide (Bandarra et al., 2021). In this context, more than 80 % of incineration facilities can be categorized as energy recovery facilities in 2015, while the remaining have only functioned as final disposal units (Eurostat, 2018). That figure is expected to increase as a result of building new W2E plants or retrofitting existing incineration facilities. Some plants, especially in Europe, could function as combined heat and power plants, which may achieve an average efficiency of 68 % (Saveyn et al., 2016). Despite its attractiveness for energy generation, one of the major drawbacks of MSW mass burning is the emission of CO_2 and other greenhouse gases. According to IPCC reports, the main contribution to CO_2 emissions from waste incineration is coming from the combustion of MSW components of fossil origin (Calabrò et al., 2015), which is indirectly confirmed in (Gómez-Sanabria et al., 2022). The release of CO_2 from the carbon stored in biomass (e.g., paper products, wood, food, and yard waste) is considered close to neutral to the global warming process. It is critical to promote source-sorting and separation, as well as recycling to lower the GHG Footprint of the incinerated MSW streams.

Some studies have reported the increase in Particulate Matter (PM) emissions, Volatile Organic Compounds (VOCs) and Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD) - (Ying et al., 2021) from the thermal co-processing of sewage sludge. A more detailed investigation (Poláčik et al., 2018), based on experiments, confirms that the concentration of PM in the products of biomass combustion exceeds the safety levels. This suggests that appropriate filtration has to be applied to the flue gases before releasing them to the ambient.

In recent decades, increased scientific consensus on the impacts of anthropogenic climate change has called for immediate and collective actions to lower global GHG emissions (Nguyen et al., 2021). Decentralised heating systems such as biomass heat stoves and coal/ natural gas boilers have been traditionally used in residential and commercial buildings. Compared to that, the supply of heat from centralised heat and power generation plants to households via district heating could significantly reduce the emissions of GHG and other air pollutants (Caserini et al., 2010). By integrating Stirling engines into existing centralised systems, these plants can simultaneously function for electricity production, in addition to heat (Bartela et al., 2018).

In situations where the use of district heating is not feasible, it has been suggested to adopt W2E for electricity generation, which is then distributed to households for direct electric heating (Kubba, 2012). Compared to district heating, direct electric heating offers a lower-investment option as it only requires the improvement of the existing electrical network and the setup of space heating equipment. Consistently, Volkova et al. (2020) also suggested higher hidden operational costs when district heating is opted for servicing larger areas with low population density, such as suburbs or rural areas. Such finding is in line with that of Giurea et al. (2017)

that unravelled the higher economic advantage of direct electric heating systems over conventional district heating systems in these aforesaid areas. When powered by renewable energy, the use of direct electric heating over conventional district heating and other types of heat stoves/boilers is further supported by the clear environmental benefits. Moreover, direct electric heating systems can utilise the electricity generated from W2E processes, which could reduce the dependence on fossil fuels while lowering the amount of solid waste being sent to landfills.

With continued progress in the research, advanced W2E technologies are equipped with the potential to emit lower amounts of air pollutants. According to Adami et al. (2020), a properly designed direct electric heating system could fulfil the residential energy demand for several small alpine communities. The authors reported that such a setup had been demonstrated by a W2E plant using residual waste and refuse-derived fuel (RDF). The results indicate that the integration of the direct electric heating system with W2E processes would reduce the potential GHG by as much as 63 % compared to coal combustion and by 3 % compared to biomass burning.

Ganesh et al. (2013) have shown that, by coupling with mechanical or biological treatment, W2E processes can convert non-recyclable solid wastes directly into useful forms of energy, known as Refuse-Derived Fuel (RDF). Such a conversion process covers several primary steps, ranging from preliminary sorting, size screening, shredding, magnetic separation, and finally, pelletizing for convenient storage and transportation (Ganesh et al., 2013). At least ten different W2E facilities have been constructed for the co-treatment of MSW and generation of RDFs. Compared to other facilities taking the direct approach to extracting energy from MSW, the RDF plants have been designed to provide a more comprehensive MSW utilisation strategy. Furthermore, the successful operation of such plants has contributed toward meeting the goal of fulfilling at least one-tenth of the region’s electricity demand via renewable energy (Adaramola et al., 2017).

The potential benefits from MSW to RDF processing are significant, as this can avoid excessive landfilling, as shown in (Gershman, 2010). The paper reports that even if RDF is to replace only 5 % of the coal consumption for electricity production, the total RDF demand is projected to reach nearly 115 Mt.

In the United Kingdom, the attention to the development of RDF-derived renewable energy has been growing. According to (Brew, 2018), over the decade preceding the publication, the processing of RDF from W2E facilities has reduced the MSW disposed of in landfills by approximately 50 %.

Similarly, RDF production from MSW is also gaining popularity in the Middle East (Emirates RDF, 2022). Though being the world's second oil producer, Saudi Arabia has invested significantly in W2E research and RDF in particular (ZAWYA, 2021). This effort is further motivated by the country's rising energy demand, which has been forecasted to reach 100 GW by 2032 (Ouda et al., 2017). Compared to the United Arab Emirates, Saudi Arabia's RDF production still lags behind their neighbouring country, whereby the construction of its first RDF plant was only started in October 2020. Such a project was initiated under a public-private initiative, which aims to convert up to 80 % of MSW into RDF (Clarke, 2020). Considering its high energy density, the RDF produced from MSW is adequate to replace coal as an alternative energy source in the cement industry while lowering potential CO_2 by at least 40 % (Rodrigues and Joekes, 2011).

In South Africa, more than two-thirds of its energy consumption relies on coal, which inflicts significant greenhouse gas emissions in the region (Joshua and Bekun, 2020). These factors further propagate the advancement of RDF production from MSW not only in South Africa (Slater, 2020) but also in Indonesia, India, and Thailand (Kubota and Ishigaki, 2018). Particularly, Indonesia, with its projected MSW generation of 150,000 t/d, presents an enormous potential for the application of such a technology (Kubota and Ishigaki, 2018). Significant efforts in finding effective solutions to MSW management have been initiated, while RDF production from it plays a key part in such initiatives.

Other major efforts include the programs taken up by the governments of India (Pandey et al., 2019) and Thailand (Srisaeng et al., 2017), which endorsed enabling policies to support the development of technologies and key infrastructures for the production of RDF from MSW, with the aim of replacing coal energy. In a relatively microscopic view of empowering the boilers, the use of RDF could eliminate issues related to ash handling, flue gas emissions, and local air pollution (Sharholy et al., 2008). The use of RDF pellets is also common in several industries such as paper pulp, wood processing, cement, and sawmills (Ouda et al., 2017).

Other types of waste, including activated sludge, agro-waste, and used tires, can be used as feedstocks for direct W2E processes too. These sources have several major drawbacks related to the emissions of fuel gases and heavy metals, especially in the case of activated sludge (Bestawy et al., 2013). Despite that, their applications in W2E are still prevailing as compared to the open mass-burning or landfilling with the energy-producing capabilities offered. Representatively, Govani and co-workers generated 8,000 kJ/kg to 14,000 kJ/kg of energy from the combustion of MSW-derived RDF pellets (Govani et al., 2019). Taking into account this high energy yield, the production of RDF pellets from MSW offers a cost-effective solution to improving current waste management practice while providing a viable source of renewable energy.

3.2. Indirect processes

3.2.1. Thermochemical conversion

The thermochemical conversion of W2E typically includes a thermal process to produce fuel or heat from MSW. The reaction conditions of selected W2E thermo-processes for energy conversion, alongside the synthesized products from MSW, are illustrated in **Fig. 5.**

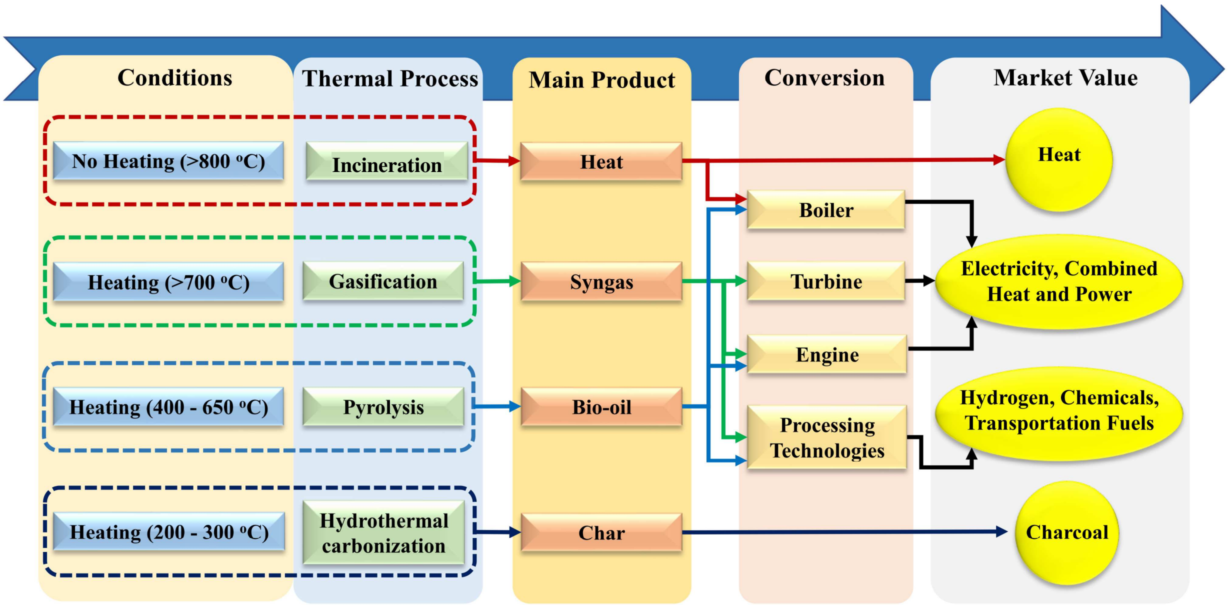


Fig. 5. Reaction conditions for energy conversion and synthesized products from W2E processes from MSW – based on (Sanlisoy and Carpinlioglu, 2017) for plasma gasification, (Makarichi et al., 2018) considering waste incineration, (Tsui and Wong, 2019) for W2E processes and especially biotechnology

Since many information sources, including some of the literature sources used in this review, use the unit “kgoe”, it is introduced here. This unit is defined as the approximate amount of energy that can be extracted from 1 kg of crude oil (Eurostat, 2022), assigned the Lower Heating Value of 41,868 kJ/kg.

3.2.1.1. Incineration

Incineration is a popular and inexpensive method to generate heat from the combustion of materials (You et al., 2016). At a temperature above 800 °C, the combustible feedstock is consumed in the presence of oxygen, resulting in heat energy in conjecture to the production of flue gases and ash. Such a process is often equipped with a regulated combustion module coupled with heat capture for steam generation, which will be utilized in driving turbine generators (Materazzi and Foscolo, 2019). In the case of MSW, a volume reduction up to 70-80 % could be prompted in its incineration process, while the released energy would be captured as heat in any feasible way. In addition to energy, the incineration of waste also yields a considerable amount of inorganic slag, which contains traces of heavy metals. A schematic diagram of a typical MSW-incineration plant is illustrated in **Fig. 6**, providing insights into its operation.

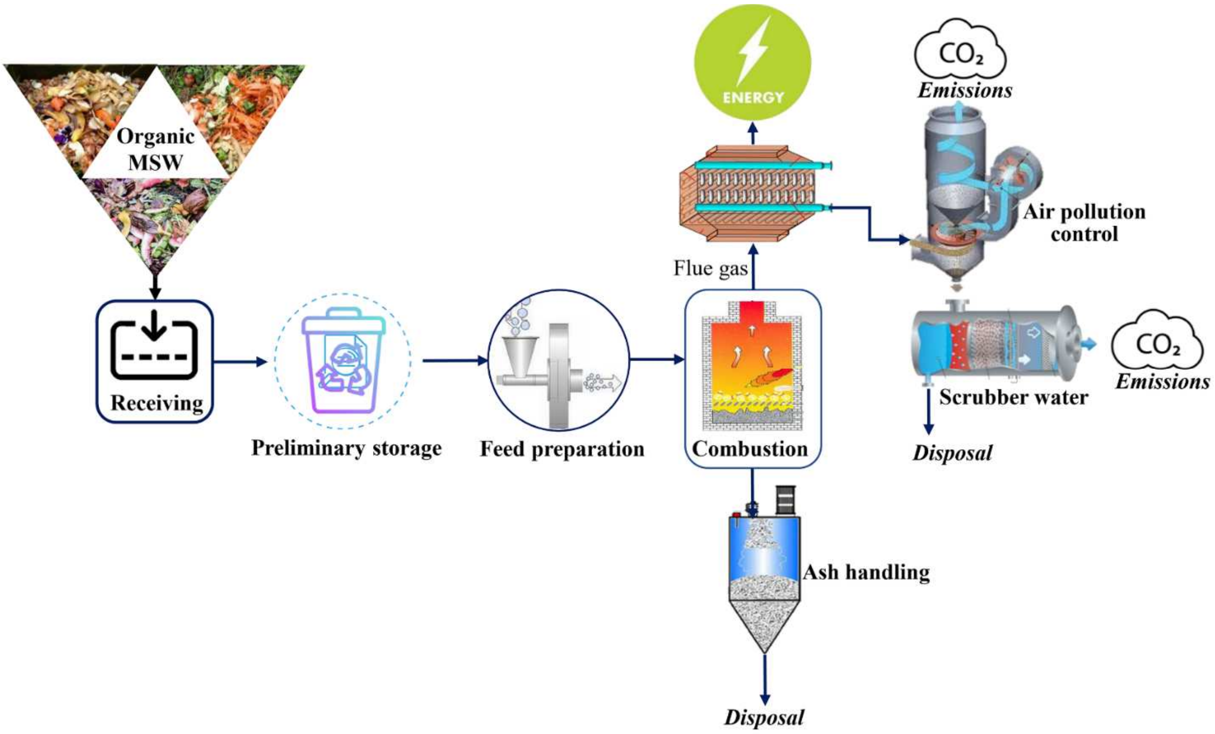


Fig. 6. Incineration for MSW-based energy conversion

Significantly, the incineration method is preferred for its high specific energy output while requiring only a small installation area for complete operation (Wang et al., 2018b). A past MSW-incinerating study even recorded 20-25 % energy efficiency, resulting in approximately 36-45 kgoe/t MSW (Kathirvale et al., 2004). Initial capital investment and compliance costs are expected to locate at a medium-high level, mainly due to the high costs of both heavy machinery (e.g., furnace) and skilled labour (Cusdjoe and Acquah, 2021). In terms of energy yield, several factors, such as density, composition, percentage of moisture, and inert compounds in the waste feedstock, are important determinants. Optimisation of these aforesaid parameters under a controlled combustion environment is the key to unlocking maximised waste removal and heat recovery. Such W2E represents a key component in the nation's energy diversification strategy, which aims to satisfy a quarter of the demand through waste-derived energy. Compared to other available alternatives, incineration is economically more attractive (Oliveira, 2014), but countermeasures need to be integrated for the co-generation of ashes, flue gas, dioxins, and acidic gases (NOx, SOx, and HCl) (Mukherjee et al., 2016). The monitoring and treatment of such combustive exhausts may induce notable costs if not handled properly.

The recent developments in the field of MSW incineration are focused on fly ash treatment, as can be seen by the first five pages of the Google Scholar (2022) search. A representative example is a review by Zang et al. (2021), where the reasons for treatment, the potential uses of this waste, and the treatment technologies are discussed. The authors point out that fly ash is considered hazardous waste because of its toxicity. At the same time, fly ash is a potential raw material for various products. The authors classified the potential technologies and sinks into stabilisation of fly ash into cement, recycling into construction materials, and resource recovery (mainly metals such as Zn, Pb, Cd, and Cu). Another type of task considered in the context of MSW incineration has been the selection of the incineration sites using a fuzzy method (Yalcinkaya and Kirtiloglu, 2020) or Particle-Swarm Optimization (Jiang et al., 2022). Other considered problems also include the identification of pollutants and impact factors from the incineration facilities (Chen et al., 2022), health risks (Bo et al., 2022), as well as Life Cycle Analysis (Sisani et al., 2022) concerning energy efficiency, Global Warming Potential, PM, ecotoxicity, resource depletion potential.

3.2.1.2. *Pyrolysis*

Pyrolysis is the process where organics are heated in the absence of oxygen and converted into bio-oil, along with charcoal and combustible gases (Nawaz and Kumar, 2021). The yield of each product is varied according to several factors, such as the types and quality of the organic feedstock, reactor construction, temperature, heating time, and so forth. Similar to other thermochemical processes, pyrolysis stands a chance in securing a great amount of energy from MSW, but with lower emissions of NO_x and SO_x due to the absence of oxygen. The pyrolysis of MSW is illustrated in **Fig. 7**.

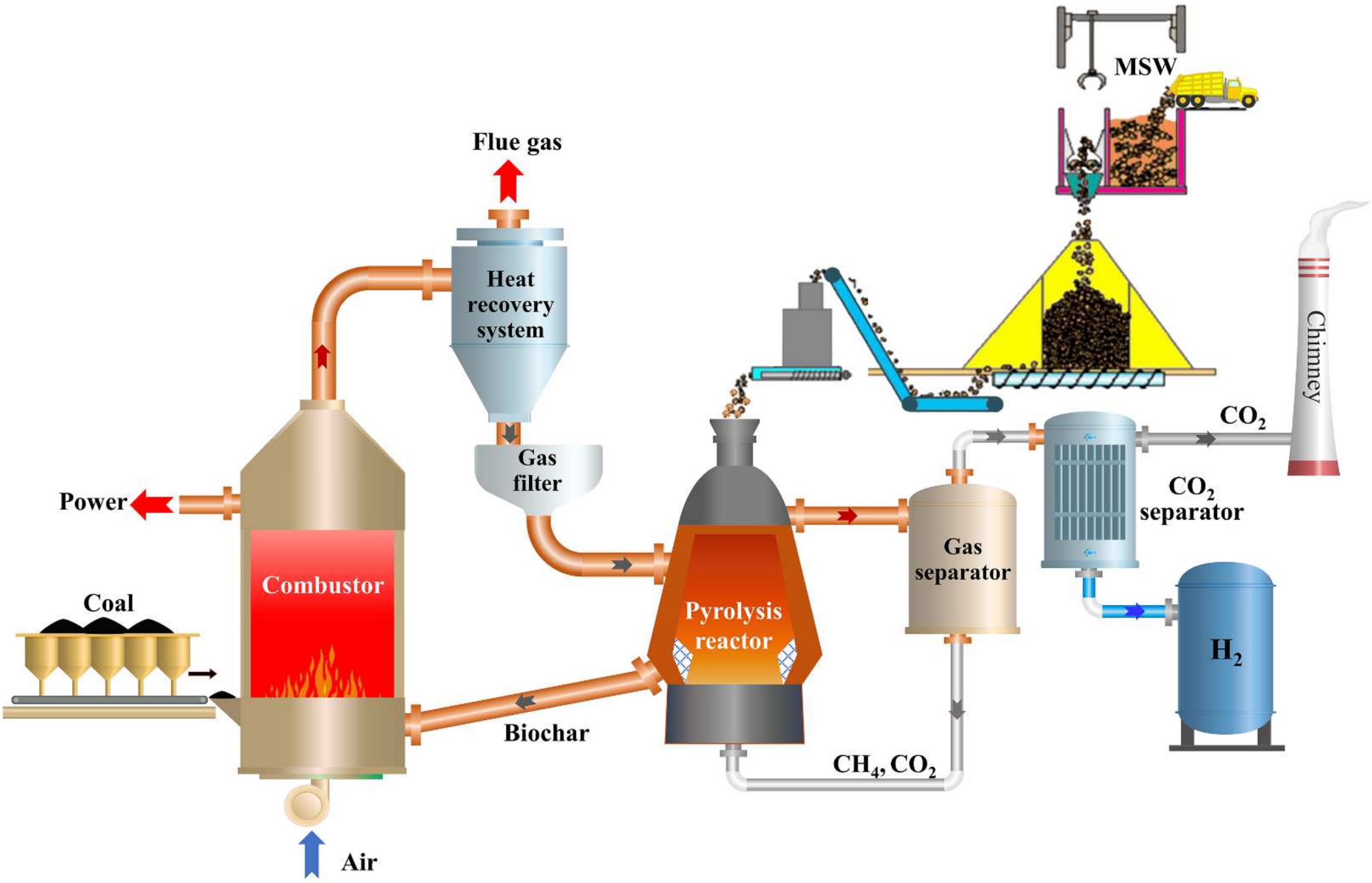


Fig. 7. Scheme of MSW pyrolysis (Yan et al., 2020)

Typically, pyrolytic temperatures fall in the range between 300 °C and 850 °C, with heat being supplied externally to initiate the process (Dabe et al., 2019). Depending on the pyrolysis conditions, the process can also yield pyro-oils, wax, and tars. On the other hand, several types of combustible gases and other compounds are typically found in the syngas, including hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and several different types of VOCs – related to CO_2 effects (Lee et al., 2020) and the need for syngas cleaning (Zhang et al., 2020a). At times, the formation of solid char is reported too, whereby its composition is rather complex, often characterized by carbon and non-combustible inorganic components. The net calorific value from syngas produced from the pyrolysis process is usually measured between 10 and 20 MJ/Nm^3 (Schmitt et al., 2012). There has been a sustained interest in pyrolysis due to its high efficiency in biofuel production (e.g., bio-oils) – as evidenced by the investigation of biomass pyrolysis products (Demirbaş, 2002) and persisting more recent straw pyrolysis study (Nawaz and Kumar, 2021). There are several different classifications of pyrolysis, including conventional, fast, and flash pyrolysis. To reduce the needed heat for pyrolysis, solar-powered pyrolysis has been found as a lucrative option in recent years (Cao et al., 2022). In this process, the pyrolysis reactor could receive the heat from solar through direct irradiance or heat transfer fluid; however, experiments associated with solar-powered pyrolysis of MSW is still very limited (Sobek and Werle, 2019).

3.2.1.3. Gasification

Gasification is a popular MSW treatment method. It offers the generation of both heat and combustible syngas that can be used for electricity generation (Wei et al., 2017). Typically, syngas contains (Chan et al., 2019) mainly hydrogen (H_2) and carbon monoxide (CO), occasionally with traces of methane (CH_4). Its production from MSW is usually pertinent to the organic and biomass portions, which are susceptible to high-temperature decomposition. The energy content measured from syngas is typically between 4 and 50 MJ/Nm^3, roughly one-third of that of the conventional natural gas (Chan et al., 2019). Syngas production from MSW is promising as it can easily take advantage of the existing natural gas infrastructure for storage, transportation, and distribution without the need for retrofitting. In addition, heat recovery from the syngas stream is possible, too, as gasification is commonly conducted at high temperatures. Further energy recovery can be prompted through the burning of syngas in gas turbines and internal combustion engines for power generation. The resulting slag from the gasification process is mainly inorganic content, which can be applied in road construction. Compared to the previous incineration method, gasification is more suitable for the processing of MSW with a substantial inorganic portion (Yong et al., 2019). Besides, it has also prevailed with the variety of its products, which covers heat, energy, and other secondary fuels, compared to incineration that only produces heat. For smaller-scale operations, the integration of gasifiers and internal combustion engine systems could yield higher energy efficiency with minimal emissions of pollutants (Teixeira et al., 2014). With the maturity of this technology, operators can choose from a wide range of gasifiers, depending on their desired operational characteristics and performance. A gasification system of MSW for energy generation is presented in **Fig. 8** for a better illustration of the technology.

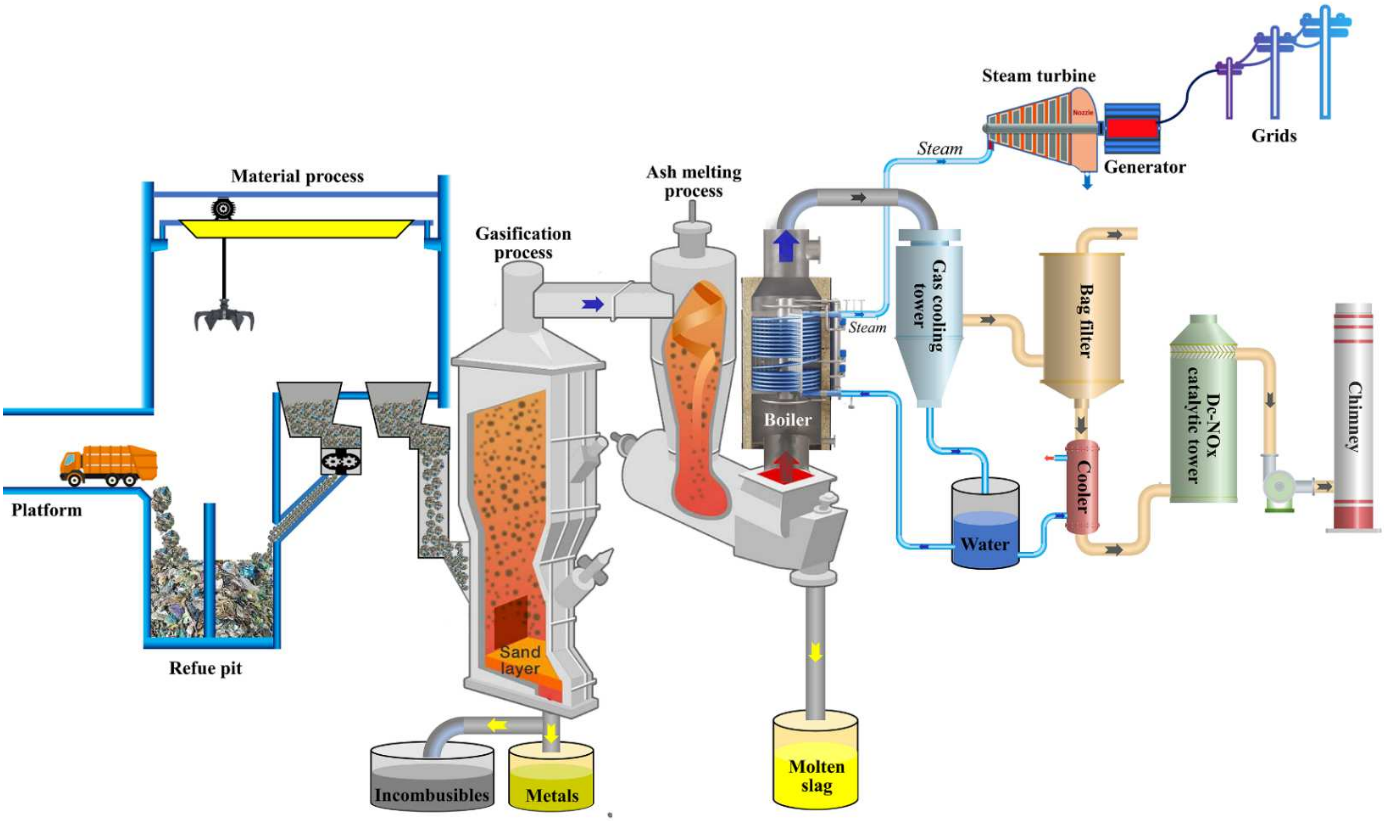


Fig. 8. Diagram of commercial gasification of MSW for integrated energy system (Zafar, 2020)

The intensification of gasification, for instance, plasma-integrated gasification, is a promising waste treatment (Munir et al., 2019b). In this process, plasma rays at extremely high temperatures of 2,000-14,000 °C are directed to the MSW (Tavares et al., 2019), which prompts the following four sequential processes onto MSW: drying for moisture removal, pyrolysis in an anoxic condition for volatiles releasing, combustion of the residue char with oxygen for energy production, and finally reduction process for syngas production (Indrawan et al., 2019). Several possible conversion pathways were examined by Mazzoni et al. (2017) to produce energy from MSW and plastic solid waste via plasma gasification. The proposed treatment yielded 38 % of energy efficiency from the mixed feedstocks that contained 70 % MSW and 30 % plastic solid waste, with pure oxygen being employed as plasma gas. However, the presence of steam (*circa* 34 %) is detrimental to the performance of such a process, reducing its energy efficiency to 21.7 % with an equal proportion of MSW and plastic solid waste in the feedstock.

The application of gasification for MSW treatment presents several important benefits. Notably, a controlled oxygen feed to the reactor is important to reduce the generation of dioxins in the exhaust gases (e.g. nitrogen oxides (NO_x) and sulfur oxides (SO_x)). Compared to the incineration and pyrolysis methods, gasification generates higher average net energy of 36-63 kgoe/t MSW (Seo et al., 2018), while its intensification with plasma could further enhance it to 63-81 kgoe/t MSW (Byun et al., 2012). Along the gasification process, an effective volume reduction of MSW, up to 80-90 %, could be achieved too in conjecture to the syngas production (Munir et al., 2021). Such syngas is useful for electricity generation through the integration of a gas turbine or fuel cell modules.

However, there are negative aspects (La Villetta et al., 2017) associated with the production of tars, ash, particulate matter, and heavy metals during the gasification process. These substances tend to accumulate within the gasifier and are considered harmful to the environment. Special care must be given to the reactions that operate at >1,100 °C as it may facilitate the tar formation, leading to blockage of the reactor (La Villetta et al., 2017). Periodic gas cleaning could be a useful strategy to prevent the aforesaid blockage issue by removing not only tar but also PMs, heavy metals, HCl, and H_2S that accumulated in the reactor (Irfan et al., 2019).

Presently, the gasification of MSW is yet to attain sufficient societal, commercial, and technology readiness for wider application, primarily due to the emissions of harmful air pollutants such as SO_x, CO, and NO_x, along with other volatile organic compounds (Vaish et al., 2019). Effective measures, such as the installation of capturing and treating facilities, should be taken to minimize the damages caused by these harmful emissions. In addition, post-process treatments for ash and other toxic residues hold critical roles too in minimizing the environmental impacts caused by improper disposal of these by-products (Luo et al., 2018).

The recent research on this technology include co-gasification of MSW with biomass (Hameed et al., 2021), analysis of the energy efficiency of heat and power generation facilities based on MSW gasification (Farajollahi et al., 2021), Life-Cycle costing of plasma gasification (Ramos et al., 2020) as well as a comprehensive evaluation of MSW utilization routes to power, heat, and fuels (Sun et al., 2021)– including identification of pollution effects.

The gasification technology, as applied to waste, needs further improvement – including a proper selection of the gasifying agent (Adnan et al., 2022), which significantly influences the yield, selectivity of components, and the heating value of the produced syngas. Such research and technology development can provide a good option for energy recovery combined with synthetic chemistry basis or a biorefinery based on waste materials.

3.2.1.4. Hydrothermal carbonisation

Hydrothermal carbonization (HTC) is a chemical process that converts organic substances to structured carbon using pressurised water heated to a high temperature (Bhakta Sharma et al., 2021). It can be served as pre-process for biomass or modified biomass with high moisture content before the main process takes place (Munir et al., 2021). Modifications, such as removal of the inorganic segment, shredding of substrate, and additional and mixing of promotional additives, could enhance HTC performance (Mayer et al., 2019). Often, a carbon-based solid, broadly known as hydrochar, would result from the HTC process that heats biomass under the condition of 180-250 °C and 1.2–2.5 MPa. The duration of treatment, on the other hand, might last anywhere between 2 to 16 h in a water phase (Kaltschmitt et al., 2016). The wet oxidative application to MSW can be examined in **Fig. 9**. There are several factors, including oxygen pressure, mixing rate, temperature, and duration of the reaction, that can influence the efficiency and outcomes of the wet oxidation process (Baroutian et al., 2018).

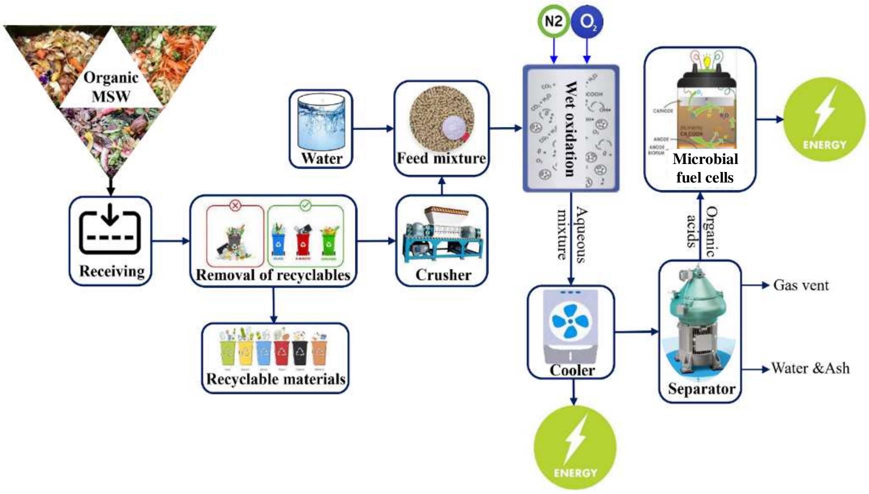
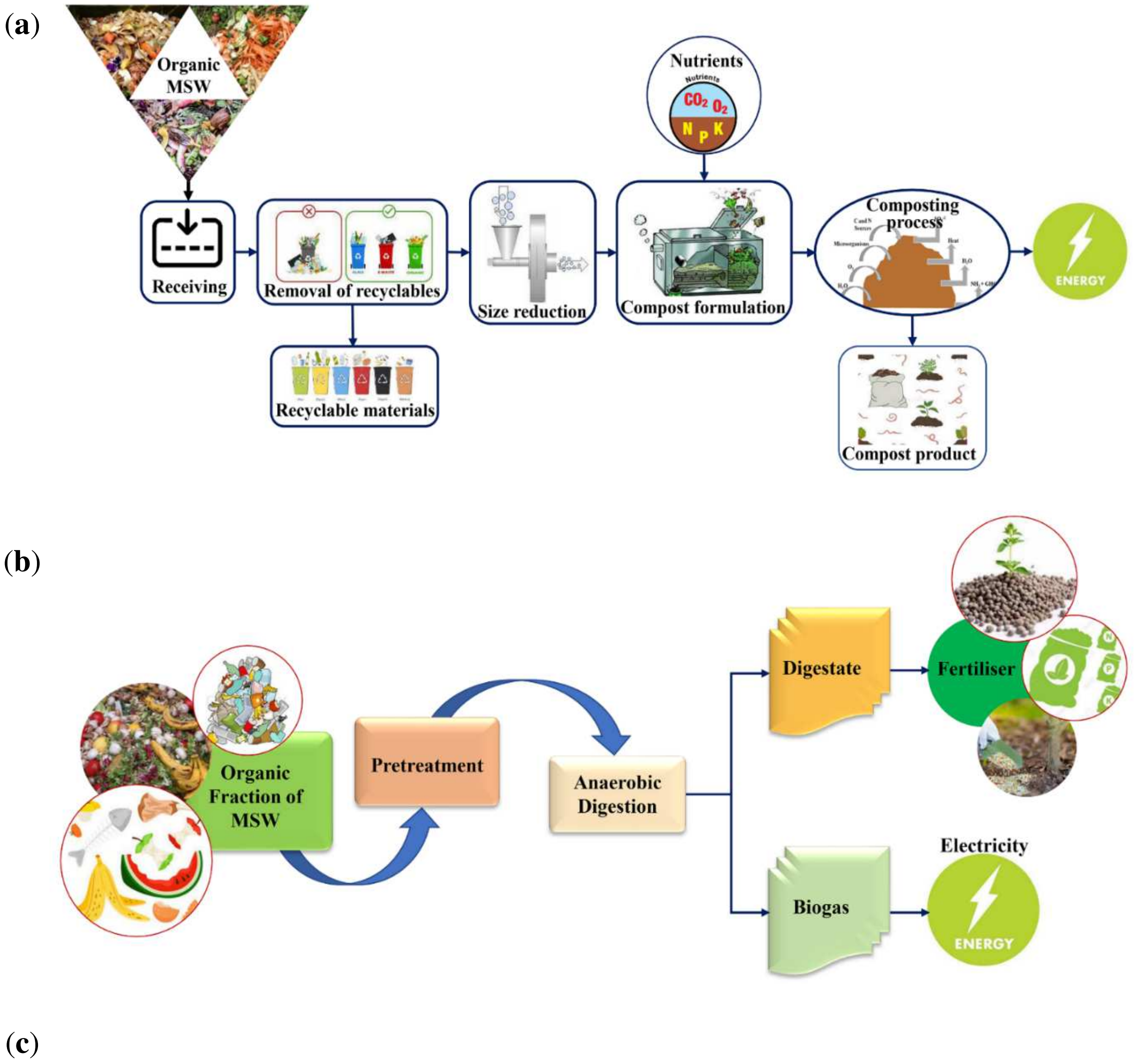


Fig. 9. Energy conversion process through hydrothermal carbonization of MSW (Munir et al., 2021)

Among the important advantages of HTC, wet biomass can be processed without the requirement for additional dehydration or drying step, which proves to be costly. HTC can also establish 90-95 % of volume reduction for MSW, which is considered a cost-effective and less time-consuming alternative to anaerobic digestion and landfilling for solid waste treatment. From the economic perspective, HTC is also favoured for its sustainable feature, judging from its potential in yielding profitable outputs (Li et al., 2020). Such technology currently has a low adoption rate, plausibly due to its low societal and technology readiness. Additional safety precautions have to be incorporated too for HTC as it often involves pressurised operation at middle-high temperatures.

3.2.2. Biochemical conversion

Biochemical conversion is an enzymatic process that can break down different types of biomass with the help of bacteria or other microorganisms (Pandey et al., 2021). Due to its low productivity, higher capital investment (e.g., larger-sized reactors) is usually needed to attain desirable throughputs. In some cases, additional bacterial enzymes and microorganisms are incorporated to increase the yield of the process (Lee et al., 2019). In such a sense, it inherited the typical sensitivity of other bioprocesses, whereby the temperature, pH, solar exposure, *etc.,* are influential to its outputs. Stringent enzymatic conditions with strict control are often required to ensure the functionality of enzymes and the success of the process. Some methods of energy production from MSW based on the biochemical conversion process could be depicted in **Fig. 10.**



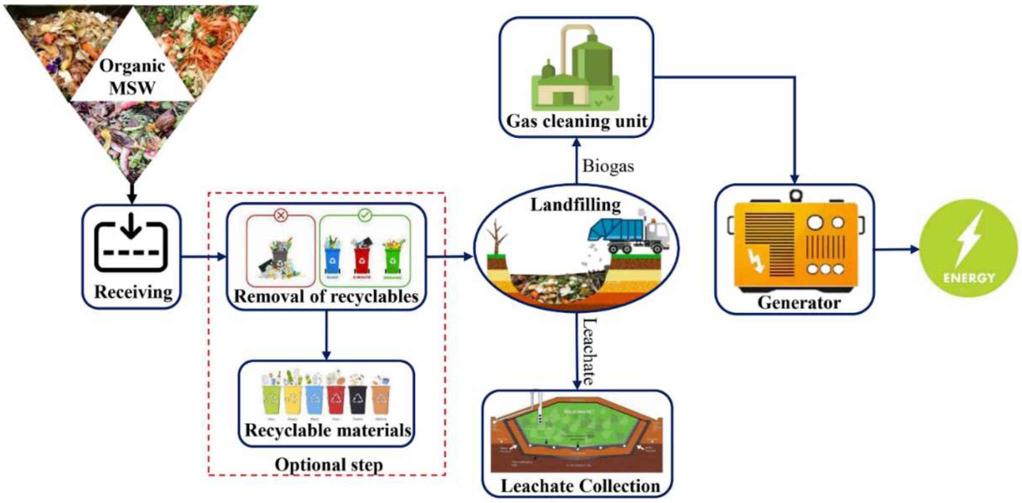


Fig. 10. Energy production by composting (a), anaerobic digestion (b), and landfilling (c) – amended after (Munir et al., 2021) with technology options from (Shah et al., 2021)

3.2.2.1. Composting

Composting is an aerobic biological process that breaks down organic waste into valuable fertilizer and manure (Song et al., 2021). Its application to organic MSW can curb greenhouse gas emissions, while the resulting fertilizer is often rich in plant nutrients (Pergola et al., 2018). **Fig. 10a** presents the major steps in a typical composting process, whereby water (H_2O), carbon dioxide (CO_2), nitrate (NO_3), sulfate (SO_4), ammonia (NH_3), organic acids may also be yielded from such process (Diaz et al., 2018). At the same time, notable compost heat would be generated along the process, which can be exploited as renewable energy too. Klejment and Rosiński (2008) reported heat generation of 3-18 MJ from each kilogram of composted organic waste. It is representative of the total energy released from the complete combustion and oxidation of each unit of organic waste. In a separate study, Irvine et al. (2010) have successfully recovered 38 % of the heat generated from their composting process. Ali et al. indicated a high decomposition rate of carbohydrates at the initial composting stage, implying its suitability over lignin, fats, and N-compounds as the raw material for composting (Ali et al., 2012).

There is a wide range of different factors affecting the composting process, including temperature, oxygen (aeration), moisture content, nutrition in terms of carbon to nitrogen ratio of the material, particle size, pH level, and compaction level, as discussed concerning the sustainability of the process (Wang et al., 2019) and in an analysis of food waste treatment (Manu et al., 2021). According to Grgić et al. (2019), an increase in the biodegradation rate of organic waste materials was detected when inoculated bacteria, including *Bacillus subtilis* and *Pseudomonas aeruginosa*, were added to the composting process. The addition of natural zeolite (clinoptilolite) is equally promotional, where it enhances the biodegradability of organics while improving the nutrient content through the increased metal uptake. Additionally, the authors also confirmed that the increased oxygen concentration, prolonged thermophilic phase, and facilitated water permeability could drive better composting performance.

Some researchers have demonstrated the positive effect of composting on nitrogen mineralization, nitrogen absorption of crops, and restoration of the topsoil, among others. The main issue of composting is the release of malodorous gases that can be extremely unpleasant, which could reduce the live quality of adjoining residentials (Lin et al., 2019). The large-scale commercial composting operation often requires adequate environmental control measures for not only enhancing the safety aspects but also minimizing its negative effects on the surroundings. When subjected to the right conditions (i.e., humidity, heat, aerobic and anaerobic environment), such a method presents a simple yet high cost-effective treatment for organic MSW such as yard waste, animal by-products, dairy waste, etc. (Abdel-Shafy and Mansour, 2018). By leveraging the advantage of the natural biodegradation of organic waste, valorized compost could be produced while co-treating the MSW. However, the conditions, as well as the functioning microbes, are the keys to access to it. There are two main categories of composting, namely aerobic and anaerobic, that can be distinguished by the presence of oxygen in the former process. Mechanical assistance is occasionally integrated to improve the yield and efficiency of the composting process (Mengistu et al., 2018).

3.2.2.2. Anaerobic digestion

Similar to composting, Anaerobic Digestion (AD) also relies on the microbes' activities for the degradation of MSW, which, however, is strictly performed under an anoxic condition (Abraham et al., 2021). The process primarily yields methane-rich biogas and digestate as outputs (Kiyasudeen et al., 2016). Conventional AD processes (without pretreatment) relying on sludge treatment have exhibited low energy cost efficiency due to the prolonged duration required for complete digestion (Zamri et al., 2021) and substrate pre-treatment often results in significant energy gains. Several pre-treatment techniques in the form of mechanical, chemical, biological, and physio-chemical means have been proposed to overcome this problem to enhance biogas/methane production and the overall higher energy outputs (Ali et al., 2018). Despite that, typical AD has a lower level of energy intensity as compared to other waste treatment methods. Rather than producing energy alone, Kumar and Samadder (2020) believed in the potential yield of digestates as both fertilizer and combustible biogas for electricity production from such technology. Furthermore, the high versatility of AD also permits the processing of a wide range of organic waste and biomass (Neshat et al., 2017). A schematic diagram of a typical AD process is shown in **Fig. 10b**.

In the absence of oxygen, AD of MSW could be attempted over the mesophile and thermophile microbes, degrading the organic portion into biogas and solid digestate. While CH_4 accounts for a significant portion of biogas (up to 55-75 %), other gas components are also present in the mixture: 30–45 % CO_2, 1–2 % H_2S, 0–1 % N_2, 0–1 % H_2 (Hilkiah Igoni et al., 2008). As reported, the four main mechanisms through which the conversion of organic MSW occurs are hydrolysis, fermentation, acetogenesis, and methanogenesis (Jain et al., 2015). The energy efficiency and performance of the AD process depend on the composition of the organic feedstock and several critical operational conditions, such as organic loading rate, nutrient content in the sense of carbon-to-nitrogen ratio, pH level, temperature, moisture content, and retention time. Provided with the optimal operational settings, the energy production of 9–13.5 kgoe/t MSW organic input could be attained (Kang and Yuan, 2017). In general, most anaerobic digesters could yield net positive energy production. The AD process is widely regarded as an energy source in various industries, especially the palm oil industry (Ng et al., 2019). In general, batch AD gives the highest net energy output with its smaller scale that facilitates precise controlling (Luo et al., 2020). There are several benefits associated with AD, including the outputs of biogas and digestate, whereby the former product could be served as a renewable energy source for electricity production. The latter usually is rich in nutrients for plants. Besides, the AD process requires minimal automation and technicality prerequisites, thereby being low in cost for its operation while being more accessible for most industries. Its high levels of societal, commercial, and technology readiness further advocated its adoption in practice (Ryue et al., 2020). On the flip side, there are still several challenges to the implementation of anaerobic MSW digestion. Though the operating costs are attractive, the initial capital investment for large-scale digesters is high. Also, several toxic components, such as heavy metals, may not be consumed in the process, and secondary treatment and disposal are still required after AD (Karki et al., 2021).

All in all, AD is still attractive for its generally low technical and operational costs, as well as its environmentally sustainable attribute that converts waste into energy. The pertinent advances in the field have significantly improved the AD process, leading to its increased implementation in various industries on a global scale. However, the costs associated with storing and handling digestate are presently important issues to be addressed. The eventual application of pre-aeration (Ahn et al., 2014) may increase methane yield but also bear a high cost for power use. Another interesting option to evaluate is the potential use of the biogas for, e.g. gasification or pyrolysis of parts of the processed waste, where the economic viability would mainly depend on the scale of the waste processing plant.

3.2.2.3. Landfilling

Landfilling is one of the most long-standing and popular methods used for MSW treatment. Similar to anaerobic digestion, biogas (also known as landfill gas in the present case) can also be collected from MSW landfills through the natural occurrence of digestion (Kumar and Sharma, 2014). Under the open environment, a fairly complex process of different biochemical reactions could be induced to degrade MSW, subsequently giving rise to the formation of landfill gas. Such degradative process may be initiated from the initial adjustment, followed by the transitional phase, acid phase, methane fermentation phase, and finally, the maturation phase (Zaman, 2009). Instead of being released free into the atmosphere, landfill gas should be captured and utilised for energy purposes. However, landfill gas is usually lower in grade due to its low methane content, further aggravated by its corrosive nature with the co-existed H_2S (Dada and Mbohwa, 2017). The utilisation of landfill gas is relatively more tedious, which can be arranged in the following operative stages: degradation of MSW, collection of landfill gas through a network of extraction wells and pipes, primary treatment, additional processing for quality enhancement, and final use as a renewable source of energy (Malav et al., 2020).

Fig. 10c gives the primary process involved in the landfilling treatment of MSW. The traditional landfilling process is described as the collection and disposal of MSW as these wastes are placed at various landfill sites while minimizing potential contamination of soil and water. Landfills can be categorized based on the type of waste being disposed of, such as MSW, industrial waste, and hazardous waste (i.e., secure landfills) (Christensen et al., 2020). Notably, the integrated process of recyclable extraction is not available at all landfill locations. Given a similar volume of input organic waste, landfilling can generate only about half of the amount of biogas (i.e., between 4.5–9 kgoe/t MSW), making it inferior to that of anaerobic digestion (Weiland, 2010). However, with their wide accessibility, landfills can potentially be located on marginal land. Compared to other MSW treatment methods, landfilling is extremely simple and does not require skilled labour for its operation. Despite the low quality, biogas captured from landfills can still be employed for energy production upon proper treatment. Other advantages of landfilling include long service life (i.e., between 30-50 y), low operational cost, as well as its medium to high levels of societal, commercial, and technology readiness. On the downside, the large space is indispensable, and MSW must be collected and sent to the designated landfill sites. More importantly, its operation is critiqued due to its low sustainability, which at the same time, encounters enormous social pressure upon the increased public awareness of green processes.

3.2.2.4. Biological conversion into bioethanol and biodiesel

Municipal biowaste or organic fraction MSW (OFMSW) makes up a significant portion of MSW, particularly in yard waste, food scraps, and organic waste from food processing factories (Salati et al., 2013). Starting from purely food waste and non-edible oils, the composition of the fatty acids plays a significant role in the quality of the biodiesel product (Hoang et al., 2020c). OFMSW mainly consists of carbohydrates (30–40 %), with proteins (5–15 %) and lipids (10–15 %) detected, too. That makes it a suitable feedstock to produce biofuels such as bioethanol, biodiesel, or value-added chemicals (Hoang et al., 2020b). In 2017, global bioethanol production reached an astonishing 85×10^9 L (WBA, 2020). Moreover, second-generation bioethanol has also evolved into a promising field of research in past decades, whereby numerous scientific efforts were invested to further extend such potential. To better explain the summarised findings among the available literature, the step-by-step method has been provided to capture the production process of bioethanol from OFMSW. **Fig. 11** illustrates the production of bioethanol from OFMSW in a comprehensive manner, which requires a pretreatment process, followed by enzymatic hydrolysis, fermentation, bioethanol recovery, and finally, the waste treatment for the residue (Barampouti et al., 2019).

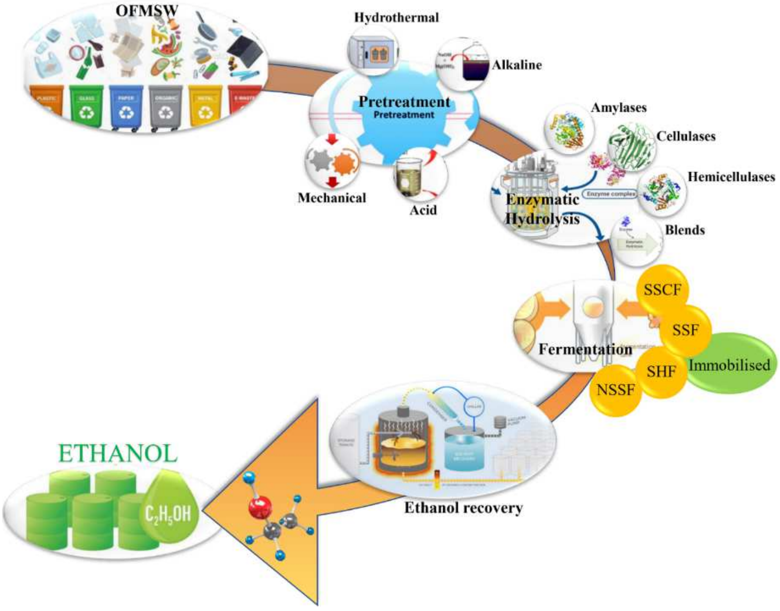


Fig. 11. Bioethanol production from MSW, amended after (Barampouti et al., 2019)

Amongst the aforesaid processes, fermentation is the key process for bioethanol generation. Unlike conventional fermentation that employed biomass as raw material, ethanol production from organic MSW does not demand the conversion of valuable farmland to grow crops for precursor acquisition (Pimiä et al., 2014). In the production of bioethanol from OFMSW, the operation frameworks are similar to that of the conventional process, in which hydrolysis (by enzymatic operations), fermentation (by microorganism use), and product purification (distillation) are all indispensable. Through these processes, Thapa et al. (2019) estimated that 329.75 m^3 of bioethanol could be produced from 11,558 t of MSW containing 50.89 % of organic and biodegradable waste on a daily basis. Hydrogen gas is another potentially valuable by-product of such bioethanol production too, which may further enhance the energy yield from such a W2E process (Battista et al., 2016). However, a significant portion of MSW is rather complex in terms of composition and could result in various issues, such as the co-production of toxic chemicals and pollutants or the deactivation of enzymatic processes. As such, the biological conversion of MSW to bioethanol and other by-products still faces significant obstacles (Rezania et al., 2019).

In addition to bioethanol, biodiesel could also be produced from the bio-conversion of MSW (Kiran et al., 2014). Significantly, the concentration of fatty acid methyl esters in the produced biodiesel is varied, depending on the characteristics of the feedstock (Karmee, 2016). Due to the high availability of medium and long fatty acids and the absence of polyunsaturated fatty acids, OFMSW makes up a good candidate for biodiesel production (Barik and Paul, 2017). Significantly, catalytic transesterification is the key process to generating biodiesel from MSW, while a pre-sorting of waste could be useful to enhance the biodiesel yield (Rodionova et al., 2017). From the literature search, basic, acidic, and enzymatic catalysts are extensively researched in biodiesel production from OFMSW. Such literature was tabulated in **Table 3**, systematically sorted according to the type of MSW employed and technological characteristics for biofuel production, alongside the yield of the desired product in each study. Similarly, the studies that examined the MSW-derived bioethanol were also sorted in the same **Table 3**. The various studies indicate wide intervals of the yield depending on the feed and process used. For bioethanol, the yield ranges from 22 % up to 90 %, while for biodiesel from 8 % to 94 %.

Table 3. Yield of bioethanol and biodiesel from various MSW types and treatment methods

Category	MSW source	Treatment method	Biofuel	Yield, %	References
Paper	Paper Waste	Enzymatic hydrolysis	Bio-ethanol	22.32	(Patra et al., 2017)
	Paper Waste	Prehydrolysis, SSF		90.8	(Nishimura et al., 2016)
	Paper Waste	Hydrolysis		40.85	(Saini et al., 2020)
Food and biomass	Retail Store	Fermentation		358 g/kg MSW	(Huang et al., 2015)
	Food waste from the restaurant	Hydrolysis		0.43 g/g	(Yan et al., 2012)
	Potato mash waste	Hydrolysis		6.18	(Chintagunta et al., 2016)
	Dry food waste	Hydrolysis		13.78	(Thapa et al., 2019)
	Soybean residue	Hydrolysis		0.42	(Salakkam et al., 2017)
	Biogenic MSW	Single pot-based hydrolysis		5.24	(Althuri and Venkata Mohan, 2019)
	Poplar Sawdust	Fed-batch, SSF		81.7	(Kim et al., 2013)
	Biodegradable fraction of municipal solid waste	Dilute Acid		85	(Farmanbordar et al., 2018)
	Hamburger	Hydrolysis		27.1	(Han et al., 2020)
Leather processing	Tannery waste	KOH catalyst	Bio-diesel	94	(Kubendran et al., 2017)
Sludge	Sewage sludge	KOH catalyst		6.8	(Wu et al., 2017)
	Sludge	In situ transesterification		8.12	(Choi et al., 2014)
	Blended sewage sludge	Two-step production		39.0	(Supaporn and Yeom, 2016)
	Municipal sludge	Acidification		90	(Olkiewicz et al., 2016)
	Municipal sludge samples	Acidification and direct liquid-liquid extraction		13.7	(Babayigit et al., 2018)
	Mixed sludge	SO_4^{2-}/Al_2O_3–SnO_2 catalyst		73.3	(Zhang et al., 2020b)
	Sludge	Ultrasonic bath and acidification		34.5	(Kech et al., 2018)
General	Landfill waste-derived oil	Acidification		25.7	(Yadav et al., 2018)

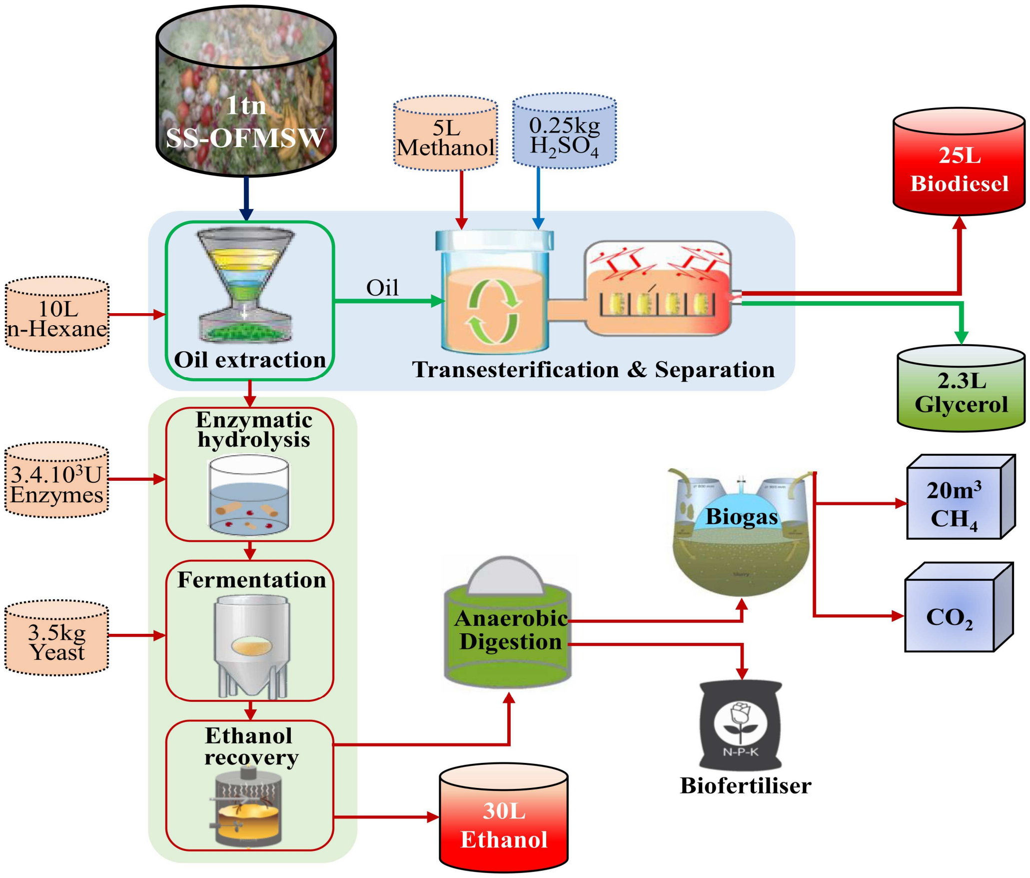


Fig. 12. The integrated production system of bioethanol and biodiesel from OFMW, amended after (Barampouti et al., 2019)

Several challenges exist in the current production of bioethanol and biodiesel, including high cost and high energy demands (Szulczyk et al., 2021), as well as environmental impacts from the use of corrosive catalysts (acidic and basic). The inefficiencies result in the potential requirement for subsidy and low GHG avoidance potential. This implies the need to improve the energy and cost efficiency of the processes. Interestingly, Barampouti et al. (2019) suggested an MSW treatment process that integrates both bioethanol and biodiesel production into a single biorefinery system, as shown in **Fig. 12**. The authors believed such a process could enhance the cost-effectiveness of the process while improving the quality of final discharge. Again, well-sort OFMSW is necessary to deliver optimum outputs.

3.2.2.5. *Microbial fuel cells*

Microbial Fuel Cells (MFC) are a coupled technology that uses both biological and electrochemical systems in producing electricity (Gebreslassie et al., 2021). Adenosine triphosphate can be generated from the oxidation of organic/inorganic compounds, which is useful in supplying the main chemical energy in MFC. There are two chambers in a typical MFC, namely anode and cathode, which are portioned off by a cationic membrane. In the operation process, microbes would metabolize the organic compounds in the anodic compartment, which then generate electron-proton pairs for electricity generation (Nawaz et al., 2020). The electrons are first transported to the anode surface, where they will be shuttled to the cathode via an external electrical circuit (Hadiyanto et al., 2022). On the other hand, the protons migrate through the electrolyte and cationic membrane to the cathodic chamber (Tiwari et al., 2019). Charge neutralization of electrons and protons will be prompted in the cathodic chamber while producing water as the major product. Along the MFC process, the current can be generated as a load is placed at the electron shuttling pathway (external circuit) (Hassan et al., 2018).

Several strategies have been proposed to improve the MFCs performance for OFMSW processing (Karluvalı et al., 2015). In particular, pivotal factors such as the incorporation of an inoculum, electrode geometry, pH level, temperature, oxygen concentration, and distance between the electrodes are often investigated for enhanced performance (El-Chakhtoura et al., 2014). Several studies have established similar conclusions, whereby a low reaction temperature (~25 °C) is benign for energy recovery in MFC application (Mohammadifar and Choi, 2019). The recent implementation of solid-phase MFC systems (SMFCs) coupled with the composting system of different biomass, such as soybean, rice husk, leaf mould, and used coffee grounds, have been successful at deriving different organic mixtures with varying C/N ratios (Chen et al., 2020c). Provided that the total OMSW by both the US and Canada amounted to 280 Mt, it is estimated to generate $3.25 \text{x} 10^{18}$ J, or equivalence of 531 MBOE (Mbbl of oil equivalent), worth of energy from this waste through SMFC technology. With a reserved assumption of 8,700 MJ/t or 2,425 kW h/t of energy output from MFC (Goud et al., 2011), nearly 190 TWh of electricity can be produced from these 280 Mt of waste. This demonstrated the feasibility of coupled SMFC-composting system for energy recovery. Similarly, Florio et al. (2019) also examined the performance of SMFC over the Dried Distiller Grains with Solubles (DDGS) that were obtained in whisky production. Laboratory results confirmed the effectiveness of MFC in DDGS treatment, while the coupling of MFC with a biohydrogen system was also proposed too to give rise to promising hydrogen production through the two-step process. Xie et al. (2021) have proposed an MFC coupled system except, in this case, it is combined with an AD system for enhanced treatment and processing of solid organic waste materials.

Another possible application of MFC is in the treatment of landfill leachate containing a high percentage of organic matter. For this particular purpose, downstream MFC components are more suitable. The future role of MFCs in solid waste management relies on the enhancement of biohydrogen and biomethane production, as well as the energy extraction from biomass, organic waste, and landfill leachate (Premier et al., 2013). The positive development of these processes will concurrently facilitate the feasibility of MFC treatment on solid waste. In addition, issues related to scaling up lab-scale investigation to the practical size, such as synthesis of the industrial-sized electrode, mass production of electrode materials, sourcing of stable feedstocks, operating conditions, and so forth, require proper solution too. Until all these issues are addressed, it is still premature to conclude the practicality of MFC technology for MSW processing and energy production. Particularly, there is a strong consensus among researchers that the energy production from MSW is far more challenging as compared to other types of agro-biomass, therefore it needs to be further improved for better practicality (Hoang et al., 2022).

3.3. Comparisons of potential W2E

The critical characteristics of W2E technologies for MSW were sorted and compared in **Table 4**.

Pyrolysis has been in the focus of Yang et al. (2018b), which provides an analysis of Combined Heat and Power (CHP) generation from MSW. The process is based on intermediate pyrolysis. The authors reported an overall CHP efficiency of 60 % and a Levelized Cost of Electricity of 0.063 GBP/kWh. The environmental performance of the technology was not included in the assessment. The pyrolysis of mixed MSW was evaluated by Chhabra et al. (2021), reporting potential economic viability as well as significant GHG Footprint avoidance of up to 989 to CO_2-eq / t MSW, compared with the practice of open landfilling.

Concerning composting, Zhou et al. (2020) have presented a domestic composter achieving a processing cost of 0.033 $/kg waste. The authors discuss the key advantages and disadvantages of the technology, starting from the prevention of methane releases and the reduction of landfill requirements. Some types of plastics are also susceptible to composting. Briassoulis et al. (2021) have analysed the composting practices for plastics based on PLA (Poly Lactic Acid) and other biopolymers. They proposed the Techno-Economic Sustainability Analysis (TESA) method for the assessment of alternative plastic waste treatment routes, considering composting as one of the treatment options. Composting treatment eliminates the material recycling and energy recovery values of waste plastics. Therefore, the authors recommended that composting should be attempted only as a third-level priority.

Landfills are commonly considered only as dumping sites, producing unpleasant odours and methane-rich Landfill Gas (LFG); for instance (Bhat et al., 2018) has considered landfill as one of the options for managing MSW in India. However, as discussed in an IEA (International Energy Agency) report (Kerr and Dargaville, 2008), the correct and efficient capture of LFG and its further use for energy recovery has been a common practice in developed countries and has a good potential for energy generation and emissions reduction also in India. The report provides a set of recommendations for developing an LFG use project in India, using various financial mechanisms for achieving economic feasibility.

Liquid biofuels have been analysed by (Nair et al., 2016) for bioethanol production, and (Kalyani and Pandey, 2014) present a wider MSW analysis considering biodiesel production as one of the options. The main observations, as summarised in **Table 4**, are that on the positive side, there are no conflicts in producing such fuels with food security, reducing the GHG, but there can be high costs for building the facilities due to machine import and for plant operation due to the eventual need for importing highly qualified operators.

Microbial Fuel Cell (MFC) variations can be used for treating MSW fractions (Budihardjo et al., 2021). The reviewed options combine Solid-Phase MFC with other processes such as anaerobic digestion to generate electricity while treating the MSW. The authors point out that this is still experimental technology, still featuring low efficiency and high cost. Further details on the technology and the underlying processes can be found in (Das, 2018).

Table 4. Critical characteristics of W2E technologies from MSW

METHODS	Advantage	Disadvantage	Related references
Direct W2E process	• Generated RDF possessing high heating value and acting as homogenous fuel; • Little production of by-product, resulting in low pollution level; • Higher efficiency due to lower required excess air; • Being used as supplement fuel for coal-fired power plants; • Easy handling because of the ability of extraction for non-combustible MSW.	• Higher cost for pretreatment process; • High cost for equipment maintenance; • Higher dangerous-level.	(Malav et al., 2020) (Paulraj et al., 2019) (Moya et al., 2017)
Incineration	• Reduction of contaminants, especially for biomedical MSW; • Reduction of 80-90% MSW volume, and reduction of the transportation cost; • Significant reduction of air pollution and the land square for MSW disposal; • Ability to recover heat for other purposes such as heating household; • Ability to destroy germs and viruses because of high-temperature operation; • Generated ash could be utilized for construction areas; • Ability to operate under every weather condition; • Ability to control odor and noise.	• High cost for installation; • Required personnel for operation and regular maintenance; • Polluted environment by flue gases, heavy metals, ash, and particulates from the incineration process.	(Malav et al., 2020) (Moya et al., 2017) (Bhat et al., 2018)

Gasification	• The high net energy of syngas, up to 10 MJ/Nm^3; • High ability to the land saving; potential application in heat/electricity production; • Availability of high-temperature working range; • Reduction of environmental pollution.	• High capital cost, and requirement of technical staff/skilled labour for operation process; • Concerns in energy recovery caused by excessive moisture of MSW.	(Malav et al., 2020) (Safarian et al., 2020) (Piazzi et al., 2020)
Pyrolysis	• Lower temperature compared to incineration; • Reduction of volume/weight of the MSW; • High rate of energy recovery and low requirement in space for the process; • Diversity of generated products and their application.	• High capital cost, and requirement of technical staff/skilled labour for operation process; • Difficulty in destroying hazardous organic compounds; • Concerns in energy recovery caused by excessive moisture of MSW.	(Malav et al., 2020) (Chhabra et al., 2021) (Yang et al., 2018b)
Composting	• Acting as a soil conditioner and organic input in agriculture; • Reduction of the burden for landfills; • Acting as organic input in agriculture	• High cost in transportation; • Low nutrient value as being used as fertilizers; • Playing as an intermediate for an infectious agent; • Requirement of a large area.	(Malav et al., 2020) (Zhou et al., 2020) (Briassoulis et al., 2021)
Anaerobic digestion	• Reduction of volatile-solid rate; • Stable, odorless, and high fertilizer-value end-products; • Smooth operation in the gaseous-fuel production; • Low capital cost and low GHG.	• High power cost of pre-aeration (Malav et al., 2020) • Poor dewaterability of sludge; • High sensitivity to the changes in temperature; • It is causing odors in the case of ineffective handling.	(Malav et al., 2020) (Moya et al., 2017) (Bhat et al., 2018)
Landfill	• 40-60% methane produced from landfills could be used for electricity generation and boilers.	• Unpleasant odour from gas produced from landfill; • Causing fire and explosion risk;	(Kerr and Dargaville, 2008) (Bhat et al., 2018)

Bioethanol/ biodiesel production	- Bioethanol/biodiesel from MSW could not cause any conflict with food security; - Reduction of GHG and climate change.	- High cost for processing and synthesis technology;	(Nair et al., 2016) (Kalyani and Pandey, 2014)
Microbial fuel cell	- Generation of electricity from various MSW without net CO_2 emissions; - Direct transformation of chemical energy into electricity, affording less energy loss; - More reliable and safer operation;	- High cost for materials of microbial fuel cell; - Low electricity power;	(Budihardjo et al., 2021) (Das, 2018)

Notably, the standards for W2E facilities used in treating MSW vary based on the national and local regulations of the specific regions. Regardless, thermochemical processes seem to be more attractive as opposed to biological processes with their higher treating rate and higher throughput (Ng, 2021). From the environmental perspective, incineration, gasification, and pyrolysis are more reliable for their capability of removing organic fractions from MSW. Compared to incineration, pyrolysis technology, with its lower operating temperature, fosters emissions reduction while retaining corrosive components, such as heavy metals and a significant portion of sulfur and chlorine in the solid residues (Chen et al., 2015). The chances of producing NO_x and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) can be minimized, too with the milder reaction conditions of pyrolytic technology. However, despite its high energy yield, pyrolysis falls short of the most environmentally sustainable strategy for MSW management due to its concurrent emission of polluting HCl, H_2S, SO_2, and NH_3 (Chen et al., 2015).

A Canadian-based survey indicated a general preference for gasification over incineration due to the cleaner nature of the former process along with the low requirement for post-processing (Shareefdeen et al., 2015). Compared to landfilling and incineration, both gasification and pyrolysis are viewed as more effective alternatives for MSW management. An LCA study based on the various US-based facilities has shown the lowest environmental impact from the fast pyrolysis compared to landfilling (Wang et al., 2015). net positive economic outcomes have been confirmed by the results of a conceptual level analysis for different MSW treatment alternatives, including gasification, fermentation, and AD (Ali Rajaeifar et al., 2015).

Interestingly, some contradictions emerged when the comparison studies were performed in different regions. For instance, a study that looks at the environmental impact assessment of different MSW management strategies for the city of Tehran has shown that biological-based AD is the most sustainable solution when coupled with incineration (Ali Rajaeifar et al., 2015). This may be attributed to the lower negative environmental effect of AD as compared to fermentation, gasification, and incineration, based on industrial ecology-based analysis (Smith et al., 2015). Meanwhile, a recent 3E analysis performed based on MSW alternatives in Malaysia indicated incineration is effective for heat and power generation while AD is generally favoured for the production of electricity alone (Tan et al., 2015). Apparently, a solid conclusion on the best MSW treatment is not attained as studies were performed in different contexts, hence, with different standards applied. For, it is necessary to establish some common basis, with a similar context of the study. Significantly, the variability of conclusions detected in this section points to the need to formulate a common basis to promote fair assessment and comparison of different technologies for MSW. In this regard, it is proposed that the common basis should include:

(a) System boundaries of the effects, i.e. fair comparisons, can be established upon standardizing the variations in Life Cycle Analysis.
(b) Selection of indicators, where an option is to use, e.g. cumulative footprints over the selected system boundaries: GHG, Water, particulates footprints (Čuček, at al. 2015). Cost, revenue, profit or loss are also important traditional criteria.

Continued research on this topic is warranted given the need for further analysis of the environmental impact and trade-off, the potential of new matrix design, solutions for improved strategic approaches, energy production performance, and overall sustainability of the MSW management.

4. Economic characteristics and role of municipal solid waste in circular bioeconomy

The rapid rate of urbanization worldwide has led to a significant rise in the demand for energy and material goods (Venkata Mohan et al., 2016). The increased consumption has induced a higher generation of waste from both residential and commercial activities. Unlike the "take-make-waste" model in a traditional linear economy, Circular Economy (CE) optimises the activities to minimise the generation and consumption of finite resources (Ellen MacArthur Foundation, 2013). In CE, the integration of renewable energy resources with the continuous recycling of resources could maximize their potential value, providing a possible mechanism to decouple economic growth from resource consumption and waste generation (Charter, 2018).

There are two key elements within a CE model – "biological nutrients" and "technical nutrients". While the latter refers to the various artificial components, the former consists of bio-based materials derived from natural ecosystems and is eventually restored to the environment (Ellen MacArthur Foundation and Granta Design, 2015). The three underlying principles of CE include:

(i) Preserving and enhancing the use of resources in such manners to regenerate the natural systems;
(ii) Maximising the yield and value of resources, materials, and components by keeping them in the economy loop through reusing and recycling;

(iii) Aiming at designing a system to eliminate the negative impacts and externalities of the commercial and residential activities that could harm the environment.

Closed-loop CE has gained considerable attention from governments, businesses, and research communities around the globe for replacing the traditional linear production (Ghisellini et al., 2016). The application of W2E processes supports the overarching goals of CE by transforming waste into useful forms of energy (Garmulewicz et al., 2018). Researchers have given strong evidence supporting W2E as a viable solution for energy production in an environmentally sustainable fashion (Kumar and Samadder, 2017). On the flip side, some W2E technologies may yield a lower economic performance if the environmental benefits are not taken into account in the financial analysis. This presents a major hurdle for the deployment of W2E technologies (Leme et al., 2014). According to McKendry (2008), the revenues generated from the sales of fertilizer and excess energy cannot be used to make up for the initial capital investment for W2E facilities. The economic case of W2E improves significantly with scaling up the operation, leading to a drop in the unit cost of energy production (Portugal-Pereira and Lee, 2016).

Statistically (EC, 2021), 250 Mt of MSW were generated by the European countries in 2005. This figure surpassed 300 and 330 Mt in 2015 and 2020, recording an alarming annual increment of 10-20 %. There is a wide range of different materials contained in the MSW generated among the EU members and characterized by its high level of diversity in the feedstock. Due to this reason, the outputs from the W2E process may vary significantly, with the properties and quality standard of the MSW stream.

Before W2E processing, sorting, screening, and milling are performed to reduce the size of the feedstock while improving its quality. Additional pre-processing stages are sometimes included for higher homogeneity of the feedstock in exchange for better energy yield. RDF is one of the energy products derived from organic materials in MSW, which presents important economic and environmental benefits through W2E technology. First and foremost, the establishment of such technologies exhibits the potential to lower emissions of common air pollutants and other greenhouse gases. The resulting RDF usually gives higher heating values compared to the energy captured from the direct combustion of MSW. More importantly, RDF can be easily stored and transported, which facilitates subsequent distribution to consumption sites. Other benefits of RDF include its lower requirement of excess air needed for combustion, as well as its enhanced physical and chemical properties as the feedstock is sufficiently homogenized.

As for fermentation technology, Solid-State Fermentation (SSF) is generally preferred over the Submerged Fermentation (SmF) with its better higher cost-effectiveness. This statement is supported by the economic analysis provided by Zhuang et al. (2007), in which these methods are assessed for bioethanol production from cellulose. The economic virtue of SSF lies in its capability in reducing the cost of cellulose from 90 $/kg to only 15.67 $/kg. While SmF exhibits a similar cost-reducing capability with its rate of 40.36 $/kg, it is still inferior to SSF upon comparing them economically. A similar result was obtained by the same group of authors (Zhang et al., 2007) in another study, where the production cost of SSF was found to be lower than that of SmF at 99.6 % of efficiency. The production of hydrolases and other similar enzymes, namely amylase, cellulase, xylanase, and protease shas been reported using *A. awamori* on babassu cake in SSF. The solid residues or fermented cake yielded from the enzyme extract process can be used as animal feed, which makes up for a portion of the total production cost (Castro et al., 2010).

On the other hand, McKendry (2008) presented a cost analysis of different UK-based W2E facilities, including incinerators, biogas plants, advanced pyrolysis, and gasification. Notably, the initial capital investment for all facilities was observed to be higher than their operational costs. Significantly, advanced treatments of MSW via pyrolysis and gasification incur the highest cost among the various facilities, plausibly due to their stringent processing conditions. By comparing direct combustion using an incinerator to the anaerobic digestion of food waste, the latter case is more attractive with its significantly lower cost. However, this is not agreed by Bilitewski et al. (2000), after examining the cost structures of W2E plants located in Germany. These authors revealed contrasting results, stating higher operational costs of anaerobic digestion plants over incineration facilities. However, the anaerobic digestion plants were observed to have significantly smaller capacities. In a separate study, an integrated solid waste management system was proposed by Sadef et al. (2016) for the treatment and processing of MSW in Lahore, Pakistan. With the application of W2E technologies, the authors expected a significant volume reduction of MSW being sent to landfills. MSW is made up of a wide range of biomass materials, including food waste, fabrics, discarded papers, woods, rubber, and plastics, among others (Pandey et al., 2016). According to Xin et al. (2016), the analysis of several W2E applications in Malaysia confirms the superiority of incineration technology over others when it comes to the case of deriving heat and electricity from MSW. The use of waste biorefinery was analyzed by

Nizami et al. (2017), showing the capability to process up to 87.8 % of MSW, leading to significant savings.

The prevailing problem of organic waste still poses significant concerns for most low and middle-income countries due to the lack of effective countermeasures. Among the available technologies, the exorbitant upfront and operational costs present the major hindrances to their implementation, in spite of the advantages offered. Hence, low-cost alternatives are often more appropriate for these developing nations.

The opportunity to enhance the economic value of the outputs while providing a source of income for the local populations, including small farmers and entrepreneurs, is another important aspect to take into account during the planning and development process. For some African countries, the cost of animal feed is a key variable in poultry production for small-scale farmers. A promising model utilizing an integrated agriculture and aquaculture approach has been successfully implemented in several countries in Africa (e.g., Malawi and Ghana) and Asia (e.g., Bangladesh and the Philippines) (Prein and Ahmed, 2000). An interesting study has examined the role of certain fly species as ecological engineers. The use of dried black soldier fly prepupae in animal feed production presents a promising potential due to their high protein and fat content. The application of dried soldier fly prepupae in animal feed is expected to yield an awarding revenue, with its annual growth of 6.1% in 2002 and 2004 on the global market. In particular, Myanmar demonstrated one of the fastest growth rates of 40.1%, followed by Vietnam (30.6 %), Iran (16.5 %), and Chile (11.2 %) (Kroeckel et al., 2012).

To achieve a more sustainable biobased economy, there is a critical need for the effective conversion of organic waste from commercial and residential activities to energy and other useful materials. This notion aligns with the basic principles of a circular economy that advocate the reusing and recycling of waste (Atabani et al., 2021). In a recycling system, waste may also serve as the feedstock for the production of biofertilizers, animal fodder, nutrients, as well as inputs for the manufacturing of recycled products such as papers, plastics, glass, metals, and textiles. Moreover, the waste products can be minimised or even eliminated by implementing systems that prioritize material reuse and waste prevention (Klitkou et al., 2020). In a circular bio-based economy, the waste hierarchy can be validated by the employment of the cascading use principle in which the high-end applications that allow for the reuse and recycling of goods and materials are given priority. According to the definition given by the European Commission (Mantau and

Allen, 2016), cascading use refers to “the efficient utilization of resources by using residues and recycled materials for material use to extend total biomass availability within a given system.” From the top of the pyramid, the highest value application includes the reuse of products and materials that are then followed by resource recycling and recovery. Two equally important strategies can be applied in the above model, including maximising the lifetime of resources (cascading-in-time) or maximising the potential added-value of resources (cascading-in-values) (Olsson et al., 2016). As shown in **Fig. 13**, the example of bio-refineries which involves the co-production of multiple bio-products perfectly adheres to the core of cascading-in-value. Particularly, the cascading use of wood can be demonstrated by its commercial application of different value-added waste wood fractions from the main manufacturing process.

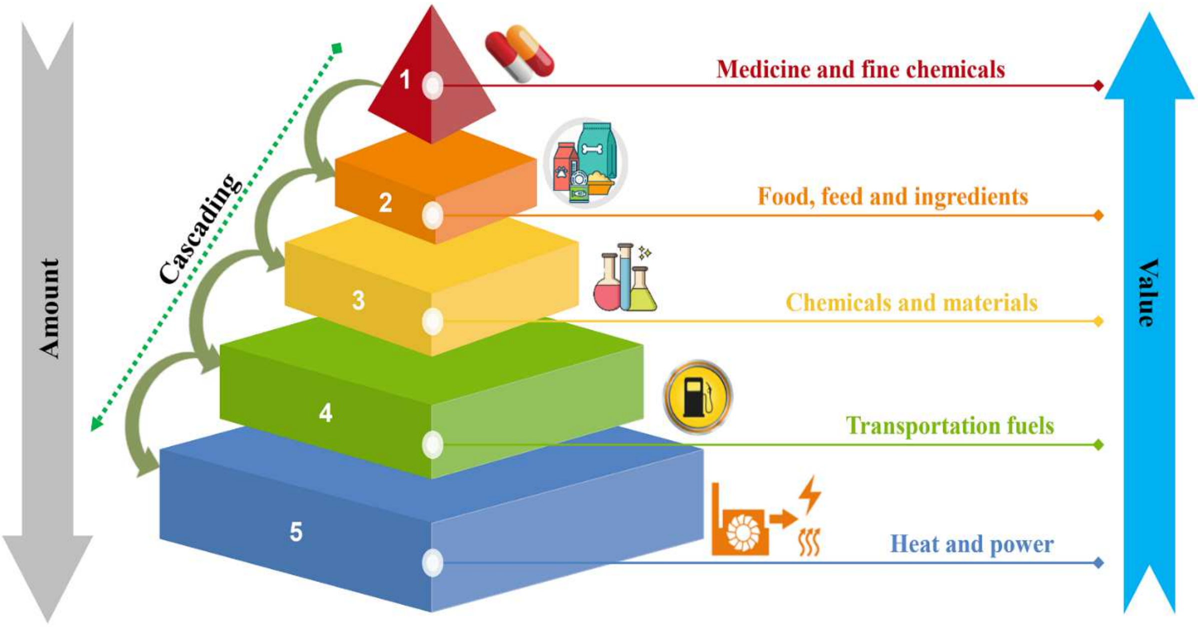


Fig. 13. The cascade-in-value role in a circular economy based on MSW (Olsson et al., 2016)

Advanced biorefinery presents a strategic element in a circular economy system. Its application permits the conversion of biomass and organic waste to a wide range of intermediate and final products. However, the successful integration of these bio-based processes into the current economy relies on the strong financial and policy incentives that support the transition toward a low-carbon-based economy (Abad et al., 2019). Significantly, OFMSW serves as a potential feedstock for biogas production via biobased-anaerobic digestion. The primary makeup of OFMSW includes mainly carbohydrates (i.e., starch, cellulose, hemicelluloses, and dissolvable sugars, for example, glucose, fructose, and sucrose), proteins, and fatty acids, and various minerals, making it an ideal candidate for bio-processing.

The application of other physical, chemical and biochemical methods has been explored and employed, too, for the manufacturing of value-added products from various sources of Food Supply Chain Waste (FSCW) (Teigiserova et al., 2020). Achieving efficient and economically viable MSW-W2E networks is a significant challenge, as shown in (Ng et al., 2014). For the technology development state as of 2014, the authors found that the resulting urban networks can be very energy efficient but with low economic viability due to the high equipment and infrastructure cost. A useful tool to use for solving cost-emission trade-offs can be found in the past work (Fan et al., 2020b), where the nexus between emission reduction and the cost is explicitly modelled and visualized, leading to the ability to select economically viable options for emission minimization.

Fig. 14 provides an example of the application of the circular economy model to MSW management. Multiple studies have proposed different approaches to convert the organic component of MSW into ethanol. Others have highlighted the potential use of the valorisation method to transform FSCW into raw materials that can be used in the production of synthetic products, intermediate compounds, biofuel precursors, and biodegradable polymers (Slorach et al., 2020). Continued enhancement to bioprocesses, such as size compression, may yield important benefits to the valorisation of MSW. To achieve significant milestones in the transition toward a fully integrated circular economy, it is critical to take into account the requirement of socio-economic structures and processes that enable the development of biorefineries and the production of energy, materials, and goods from MSW.

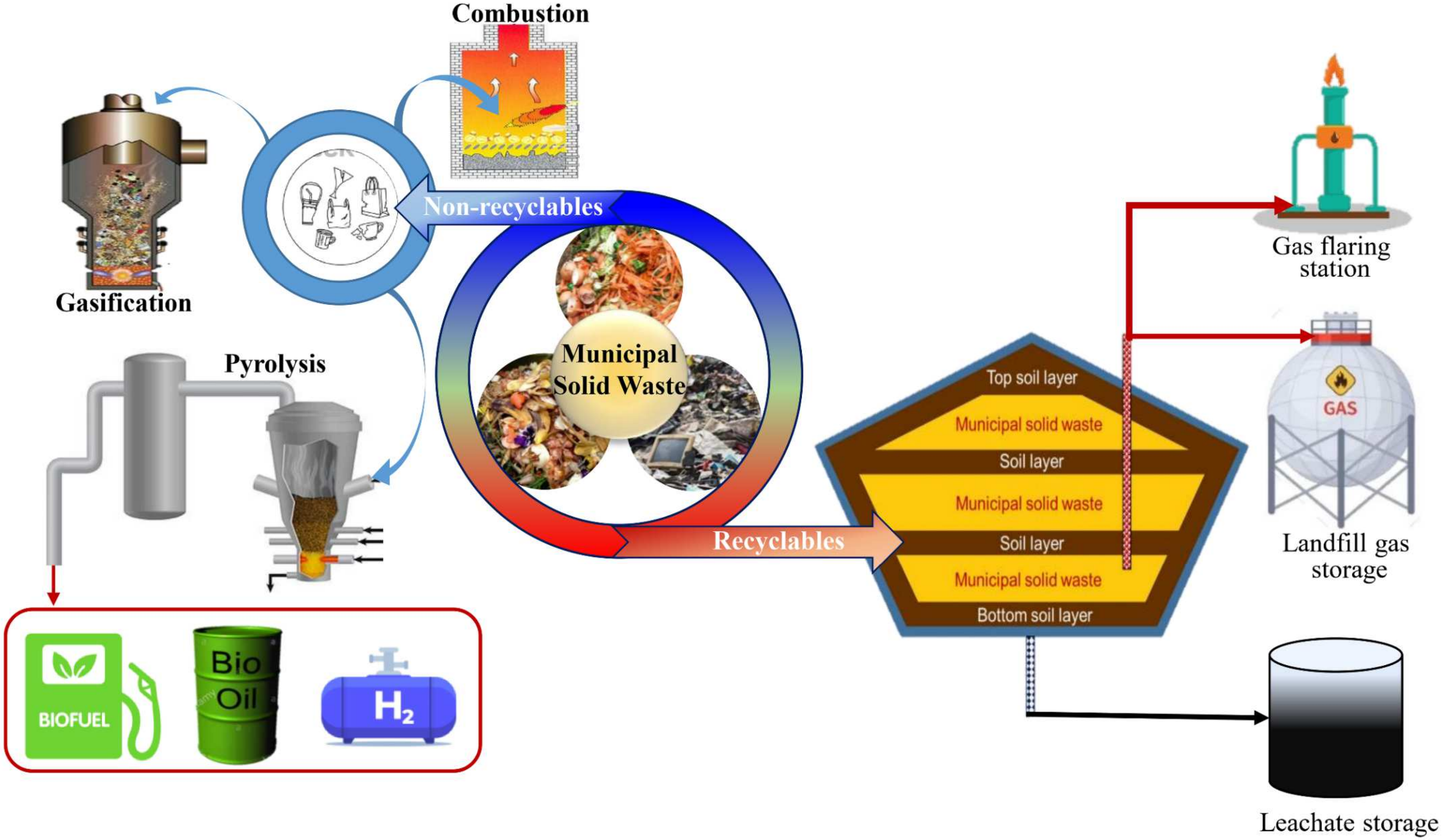


Fig. 14. **MSW management based on the circular economy model (Yaashikaa et al., 2020)**

To summarize, any stakeholders working in the waste management sector should be of interest to carry out a techno-economic study of potential W2E systems. However, it is cautioned that the comprehensive and universal economic assessments of different treatment systems cannot adequately be compared size by size due to several reasons. For instance, the variation in the regional and temporal boundary conditions, such as the differences in MSW content and characteristics of treatment plants, would lead to difficulties for fair comparisons. These uncertainties in MSW processing for energy generation have to be considered and provide an avenue for the application of stochastic techno-economic analysis (Lo et al., 2021) or data-driven and similar artificial intelligence methods (Li et al., 2021).

The stability of energy and resource costs are also contributed to the level of capital investment and fluctuation of operational costs and affect the subsequent revenue streams. More importantly, national policies and regional/local regulations with different levels of incentives and restrictions dictate the willingness of infrastructural investment. In general, the economic and social characteristics of applying the W2E process could be seen in **Table 5**. In addition to the previously reviewed sources, several more are added into this table. (Ramos et al., 2020) performed Life Cycle Costing of plasma gasification of MSW, identifying several scenarios, of which some result in economically feasible processes. In the study (Jaroenkhasemmeesuk and Tippayawong, 2015) the quantitative evaluation of a biomass pyrolysis plant was obtained, while (Chaya and Gheewala, 2007) focused on incineration and anaerobic digestion. The economic feasibility has been estimated as achievable. The authors concluded that the issues of environmental impact minimization and the maintenance of the equipment need to be developed.

Table 5. Comparison of economy and society-based characteristics for W2E process from MSW

Economic and social criteria	Various technologies-based W2E						
	Incineration	Landfilling	Anaerobic digestion	Composting	Gasification	Pyrolysis	Hydrothermal carbonization
Capital costs (M USD)	116	70	50	10	80 - 100	87	80
Compliance costs	H	L	L	M	H	M	H
Operation costs (M USD)	8.2	2	2	1	6.8 – 8.5	7.2	8
Net income (M USD)	0.5	0.5	0.5	- 0.1	3.1 – 3.2	0.5	2
Level of society readiness	L	H	M	M	L	L	L
Level of customer readiness	H	M	H	H	M	M	M
Level of technology readiness	H	H	H	H	L to M	M	L
References	(Cherubini et al., 2009) (Evangelisti et al., 2014) (Munir et al., 2021)			(Cherubini et al., 2009) (Munir et al., 2021)	(Yang et al., 2018a) (Ramos et al., 2020)	(Jaroenkhasemmeesuk and Tippayawong, 2015) (Evangelisti et al., 2015)	(Chaya and Gheewala, 2007) (Munir et al., 2021)
	Y -Yes; N - No; H- High; M - Medium; L - Low						

5. Waste management perspectives for energy production strategy in circular bioeconomy

Resource efficiency and the circular economy model are two important factors in the valorisation of wastes into high value-added products. From the perspective of enhanced waste management, MSW and its secondary waste require a wide range of complex managing activities, and its solution requires comprehensive and integrated approaches. Among the newly proposed strategies, the integrated solution-based sustainable MSW management deems promising, which enables the optimization of existing MSW processes while maximizing the environmental benefits at the lowest possible cost (Patil et al., 2018). As discussed, Solid-State Fermentation (SSF) should be adopted over preferred instead of Submerged Fermentation (SmF) for its tendency is reducing operational costs in biomass valorization. SSF, in general, manifests better performance, which facilitates a much easier and streamlined process in the subsequent stages. In this context, costs could be saved from the reduced raw materials, energy, equipment, and water consumption, particularly when the substrate costs 30-40 % of the total production costs (Cerda et al., 2017). For cities and major metropolitan areas, the current challenge in MSW management often involves its generation, collection, storage, and transportation to final disposal (Ferronato et al., 2018). Lacking an important economic driver is the key factor in compromising progress in MSW management (Okot-Okumu and Nyenje, 2011). For developing countries, the insufficient capacity in dealing with waste management issues is further compounded by the country's limited resources, which are much needed in addressing other pressing challenges. In the meantime, dealing with the serious issues related to increasing MSW generation and unsustainable disposal continues to demand attention from key national and local stakeholders. To better address the current MSW management, one should examine the socioeconomic factors that drive the generation and composition of solid wastes, including household size, average annual income, employment status, place of residence, and the number of rooms available (Pinka Sankoh et al., 2012). The type and frequency of social events held in a community might also have a direct effect on the generation and characteristics of solid waste (Yoshida, 2020). Consumption behaviours and sorting of various kinds of solid waste may also influence the makeup and amount of waste produced from residential areas. More importantly, proposals of new technologies and management strategies in dealing with MSW issues need to consider the underlying social-economic factors (Gundupalli et al., 2017), as well as the prevailing political and legal environment in the country (Yang et al., 2021a). However, catering to all factors at once is tough, particularly in developing countries, as they need to examine the issue around projected changes in demography, trends in consumer behaviour, rate of urbanization, and population growth. In recent decades, municipal governments and administrators have been grappling with solid waste management issues as they continue to search for sustainable solutions. Among the proposed strategies, an integrated solid waste management model that includes the construction, operation, and maintenance of high standard and sanitary landfills is deemed sustainable. The revenue stream obtained from the valorization and recycling of MSW could provide a viable source of income. These activities have been reported taking place in Ankara, Turkey, with almost half of the recyclables collected from all households and commercial centres, which then brought to an auspicious income of nearly 50,000 USD/d (Ali, 2002). Similar patterns were observed in Delhi, India, where it highlights the role of more than 150,000 local garbage pickers in gathering the recyclables, contributing to nearly a quarter of the total MSW generated. Consequently, such approaches to MSW management have provided cities with significant cost savings. Several means are available for the collection and separation of recyclables, including (Jouhara et al., 2017):

(i) Curbside pickup and sorting of mixed MSW;
(ii) Drop-off at collection sites or through repurchasing programs;
(iii) Deposit requirements through state and local ordinances;
(iv) A commercial operation involving the collection and separation of recyclables from identified large producers.

Reuse of products can be advocated through several approaches, such as the passing of local laws and ordinances, educational programs encouraging changes in consumer behaviour, and rewards and incentives. For a typical waste management system, the goal is to decrease the amount of waste in terms of both mass and volume (Chau et al., 2020). In this regard, the moisture and carbon emissions removals from waste are commonly performed and yielded a large proportion of CO_2 and H_2O in the emissions from waste treatment processes. The biological treatment processes, in general, contribute to lesser mass and volume reduction of the waste. Evidently, the biological-based anaerobic digestion only yields 10 wt% of mass removal as it converts the sludge into biogas (Ma et al., 2017). In certain cases, there are types of organic waste that the system cannot handle, which further deteriorates the mass and volume removal efficiency. In contrast to bio-processes, thermochemical processes, such as pyrolysis and gasification, are highly versatile when it comes to the weight and volume reduction of MSW. It is important to consider the enhancement of these methods in treating both organic and inorganic waste to achieve greater waste reduction. Similarly, open-air mass burning can be considered as a viable solution to immediately get rid of a large amount of waste too, but its emissions could induce secondary environmental issues. Regardless, the removal of pathogens from the waste stream should be carefully considered and applied to the assessment of all potential waste treatment methods. Along this line, sterilisation is a critical step that should be of interest to enhance the sanitary measures taken throughout the entire process, minimizing the presence of pathogens in the residues. Within the enhanced landfill-mining model, landfills act as the intermediate placeholders for waste while waiting for the subsequent valorization process. Two innovative concepts, namely the enhanced landfill mining and enhanced waste management, have been proposed as sustainable alternatives to conventional landfilling practices (Rich et al., 2008). The outputs from these processes can be either an energy source or valorized products, depending upon the characteristics of the waste streams and the maturity of the selected technology. Often, preventive processes will be integrated into such enhanced landfill-mining model to alleviate the emission of air pollutants, such as CO_2 and H_2S, while encompassing valorization of MSW into energy or useful materials.

The potential role of by-products should be taken into account while selecting the waste management solution for households. While compost and digestate can be sold as fertiliser, finding reliable market distribution channels for these household outputs might prove to be quite challenging. Problems associated with compost and digestate disposals could arise if there is not a viable solution, such as using them as fertilizers for backyard plants and trees. The odour from digested residue is a great nuisance to the inhabitants and their neighbours. Provided with appropriate conditions, the RDF resulted from autoclaving can be transported to incineration sites. Generally, a combined approach including pyrolysis and gasification along with combustion of the obtained products is considered the most appropriate method as it generates a relatively small amount of non-toxic and harmless residues (Akhtar et al., 2018). Furthermore, pyrolysis-based systems have demonstrated the potential to generate higher energy output compared to the amount of energy required for the operation of the plants. The obtained energy can be used in heating boilers that proves to be a reliable and financially feasible solution. The emissions of potential air pollutants and greenhouse gases from waste treatment activities play a major factor in the planning and implementation of the proposed solutions. Unregulated combustion of waste increases the emission of toxic chemical compounds, which may seriously affect public health. In developing countries, the burning of low-grade fuels is the major source contributing to the persistent local air pollution. Alternatively, the combustion of biogas can be used in residential cooking to provide a more sustainable solution with greater environmental benefits. In addition, the installation of the hydrogen sulfide filters and moisture traps would further improve the quality of the biogas, alleviating SO_x production in conjunction with the enhanced energy yield. Considering the solid waste management issues in the context of developed countries, researchers have demonstrated the interesting role of waste pyrolysis. As its operation omits the presence of oxygen, the risk of air pollution is minimal, while the resulting products are considered valuable and highly combustible in the form of solid, liquid, and gaseous fuels.

Given the substantial valuable raw materials and energy content in solid waste, the ability to efficiently extract and utilise these resources would increase the economic value of the waste management process (Fan et al., 2018). Potentially, high-value side products can be generated by processing MSW. A good example is the production of levulinic acid from MSW (Sadhukhan et al., 2016). The combined energy and chemicals production has the potential to maximize the utilization of the MSW as a resource. An evaluation model and a procedure have been proposed by Varbanov et al. (Varbanov et al., 2021) using the Exergy Profit concept. An important lesson from that work is that the energy and exergy accounting has to be performed on a Life-Cycle basis and account for the product substitution.

In addition to GHG emissions, there are other types of negative environmental externalities that are not often considered in the economic assessment and planning of waste management practices. Potential emissions of air pollutants and effluents from W2E still pose a significant risk to the environment and public health. Other factors such as noise pollution, impacts on land use, and landscape aesthetics should also be considered too. Besides the environmental sustainability aspect of proposed MSW management strategies, socioeconomic factors are also key deciding factors. These highly complex and interconnected variables can be found in **Fig. 15** (Malinauskaite et al., 2017).

Fig. 15. Critical factors affecting MSW management strategies (Malinauskaite et al., 2017)

The health and safety dimension should also be accounted for, as it contributes to the social pillar of sustainability (Klemeš, 2015). Current analysis of the trends in waste and energy flows during the pandemic showed energy demand initially dips, with a very fast rebound (Klemeš et al., 2020), while the waste generation surged (Hoang et al., 2021b). The surge concerns both packaging and medical waste. These results indicate the need to thoroughly embed the appropriate safety protocols in supply chains and other business processes. This is the necessary fundament upon which the minimization of waste generation and the maximization of material and energy recovery can be built. Without those, the waste management system may become unstable and increase the unprocessed waste.

It is realised that there is a multi-level governance structure in most existing waste management systems. The municipalities do not exist alone and typically function in symbiosis with the surrounding rural areas. The resource surpluses, demands, and secondary products from agricultural waste processing should be taken into account, as demonstrated by Foo et al. (2013) in the example of the palm-oil production waste. On the one hand, strategic visions should be realised through national policies and governmental legislation, too, with the local authorities implementing and monitoring the progress (e.g., waste collection, storage, transportation, and disposal). Supporting policy mechanisms such as tax credits and other forms of incentive provide a strong impetus for sector growth and investment in research and development (Hoang et al., 2021a). With these privileges, the business potential of W2E can be significantly improved, thereby facilitating its integration with the new circular business models. Making such policies a reality is a long process, which requires a wide debate as initiated by the series of international conferences PRES (Klemeš et al., 2017) and Splitech (2021). Meanwhile, companies would also be benefited from the aforesaid privileges as they adopt W2E technology into their business module while enhancing the organization's competitiveness. However, these strategies are simply ineffective without the general public acceptance as the issues related to waste management are highly visible and impactful to the local populace (Heffron and Talus, 2016). Overall, waste management will be ever a critical issue in modern societies as it has a large potential to affect every facet of the lives of people and the environment that we live in (Nižetić et al., 2019). Continuing the present MSW handling practices, such as landfilling, is so unsustainable that it is viewed not only as a major public health problem but also as a hidden environmental threat that contributes to the global challenge of climate change.

Taking into account the potential of resource recovery from waste material, there are always risks of output contamination in the bio-based processes. For a typical biorefinery process, it is rare and unsuitable for the direct use of mixed MSW. The circular economy principles promote the development of infrastructure to separate and recover recyclables from MSW (Bastidas-Oyanedel and Schmidt, 2018). Without such facilities, waste separation costs often outweigh the potential revenue obtained from the bio-products (Ashokkumar et al., 2019). In particular, the abilities to remove cellulose, antioxidants, amino acids, or any other contaminants are crucial components of the separation techniques. Even though conventional distillation methods have been commonly used in petroleum refineries, they are less suitable for the treatment of organic waste due to the lower volatility of the chemical components in biomass. The transition toward a sustainable bio-based economy will require the development of comprehensive waste sorting strategies to handle a more diverse and larger amount of MSW.

A potentially interesting topic comes from the technical feasibility to capture the CO_2 and other GHG from MSW to energy facilities. For waste incinerators, it has been not only demonstrated that the capture can be efficient (Fagerlund et al., 2021) but there is also a demonstration of the production of a potentially useful product using the captured CO_2 (Huttenhuis et al., 2016). The open research question in this direction is to evaluate, on a Life Cycle basis, the net GHG reduction potential of such schemes as well as their economic feasibility.

6. Conclusions and future directions in the field

6.1. Conclusions

Energy production from the organic fraction of MSW has attracted the interest of policymakers, waste management professionals, and energy researchers alike. Various W2E technologies were developed to generate energy, in the form of heat and/or electricity, from waste. In this context, the W2E applications provide a one-stop solution for the issues with energy supply and environmental pollution. The present W2E technologies are broadly categorized as following the direct and indirect approach, whereby the former involves direct combustion of waste for heat production, which is deemed to have lower energy yield in most cases. The open burning of mixed solid waste is prohibited in most countries to eliminate the risk of releasing toxic pollutants into the environment.

Indirect W2E involves a more tedious procedure to convert waste into intermediates before recovering energy from them. Technologically, most indirect W2E rely upon thermochemical or biological approaches to convert MSW into energy. Examples of indirect thermochemical processes for MSW treatment include gasification, pyrolysis, and carbonisation. Incineration is also thermal but direct treatment. Typically, the thermochemical processes are favoured for their rapid conversion process, variety of energy products (char, bio-oil, combustible gases such as syngas and biogas), and scalability. On the other hand, biological processes, such as composting, anaerobic digestion, fermentation, and MFC, degrade only the organic materials in waste releasing energy products (mainly biogas or ethanol). The application of biologically-mediated methods to MSW treatment is principally hindered by the presence of non-organic waste, which would suppress the microorganisms' activity. Hence, a comprehensively sorted MSW is critical for applying such technologies. Unfortunately, the sorting technology is presently under-developed, in which high human capital is still needed at the present stage to manually separate and sort organic waste from the others.

The economic analysis indicated that most W2E technologies are hindered by their low waste utilization and increased costs. The high costs result from waste sorting, equipment, and transportation. Novel models incorporating the benefits of energy recovery and resource recovery from waste treatment are deemed more appropriate for the assessment of these technologies.

Strategies to minimize operational costs can incorporate more efficient designs, revenue generation from the sale of valuable by-products, higher plant capacity, adoption of lean manufacturing processes, and integrated energy systems. Within this context, the apparent lesson is that waste has to be used comprehensively, with the maximum generation of all secondary products at minimal energy loss, and more efficient investments, while minimizing pollution footprints. That has to build upon the minimization of waste generation. Advancing the current levels of societal, commercial, and technology readiness provides critical momentum for the increased adoption of various W2E technologies. Provided with improved comprehension and the addition of process safety protocols, a better and more sustainable integration of W2E processes into the future circular economy can be ensured. Due to this reason, the safety protocols are crucial for minimizing simultaneously environmental pollution and the risk of propagation of toxicity, microorganisms, and related diseases.

6.2. Future directions

The application of W2E technologies in the production of energy from MSW can be assessed based on the sustainability performance in the following four areas: technology, economic/finance, environment, and socio-political. Implementation of an integrated and sustainable waste management system provides an important strategy to reduce landfilling-solid waste while enhancing the resource recovery potential. Appropriate waste sorting at the source and installation of special pre-processing plants can improve the recovery rate of recyclable materials from the waste stream, improving the overall value of the process. Overall, the minimization of generated waste should be given priority over the deployment of various waste treatment methods. In conjecture to that, the practice of sorting household waste should be promoted and implemented through municipal programs. Besides, improved public awareness can be achieved through environmental educational initiatives. Engagement and inputs of citizens should be encouraged too in the planning stages to improve the current and future waste management policies. Privileges in the form of financial incentives or subsidies should also be given to the operators to advocate the adoption of W2E through the policy mechanisms. On top of everything, continued research on W2E must be carried on to further promote its technological maturity to meet the industrial standard.

MSW can be viewed as both an environmental issue and a resource management challenge. As the latter becomes the dominant driver for more sustainable practices and countermeasures, waste treatment can no longer be analysed only from an environmental perspective but also through the lens of socio-economic factors associated with the recovery of valuable resources from waste. These discussions on the transition to a sustainable economy provide further support for the advancement of W2E technologies and an understanding of their role in the future of MSW management. As researchers continue to examine these key issues, combining W2E methods with available waste biorefinery processes provides a prominent area of critical research.

The current review focuses on the MSW treatment for energy generation. This is a highly relevant and necessary process, addressing simultaneously the issues of reducing the MSW and its environmental impact on the one hand and the need for generating renewable energy at significantly reduced GHG emissions. It is important to remember that energy valorization is only the “final resort” treatment of waste and that there are other possible processing routes – including the production of chemicals and materials. The waste hierarchy studies have also shown that the Circular Economy paths should start from the product design enabling more efficient product reuse, repurposing, and the reuse of the materials. All such processes also require the input of energy and other resources, releasing various emissions, including those of GHG. The consideration of the resource and environmental impacts of such circular processes is beyond the scope of the current review. In this context, the survey and analysis of waste management as well as Circular Economy literature and practices, worldwide and within specific countries, can bring further insights into the processing impacts and trade-offs, improving the knowledge of waste prevention and waste management.

Nomenclature

AD	Anaerobic Digestion
CE	Circular Economy
CHP	Combined Heat and Power
DDGS	Dried Distiller Grains with Solubles
FSCW	Food Supply Chain Waste
GHG	Greenhouse Gas
HTC	Hydrothermal carbonization
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis
LFG	Landfill Gas
MFC	Microbial Fuel Cell
MSW	Municipal Solid Waste
MSWC	MSW Components
NSSF	Non-isothermal simultaneous saccharification and fermentation
OFMSW	Organic Fraction of MSW
PCDD	Polychlorinated dibenzo-p-dioxins and dibenzofurans
pH	Potential of hydrogen – a measure of acidity or basicity of an aqueous solution
PEM	Polymer Electrolyte Membrane
PLA	Poly Lactic Acid
PM	Particulate Matter
RDF	Refuse Derived Fuel
SHF	Separate hydrolysis and fermentation

SMFC	Solid-phase MFC
SmF	Submerged Fermentation
SSCF	Simultaneous saccharification and co-fermentation
SSF	Simultaneous saccharification and fermentation
SS-OFMSW	Source sorted organic fraction of municipal solid waste
TESA	Techno-Economic Sustainability Analysis
VOC	Volatile Organic Compound
W2E	Waste-to-Energy

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