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Waste-to-energy technologies: a sustainable pathway for resource recovery and materials management

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The huge generation of municipal solid waste along with the reliance on natural resources to meet the ever-increasing demand of energy has stimulated the world towards the exploration of novel methods for the recovery of energy and resources by using the generated waste. Despite the numerous advantages of waste-to-energy (WtE) technologies, these techniques are not widely implemented. The review has summarized the various aspects of WtE techniques including advantages and limitations, techno-economic analysis, challenges and prospects, framework and implementation. The review has identified that the WtE techniques are more efficient than conventional waste management practices. The characteristics of municipal solid waste (MSW) vary with geographical conditions, living standards, socio-economic conditions, *etc.* Therefore, no particular WtE technique is equally feasible for the treatment of MSW. The strict environmental strategies, policies, and guidelines can assist in selecting the best WtE practice. The thermal treatment methods can effectively reduce the volume of generated waste by up to 90%. Techno-economic analysis has revealed that WtE techniques are economically feasible with suitable measures. The life-cycle assessments have found that WtE techniques can recover up to 27.40% of energy. The food and agriculture waste constitutes 50–56% of the generated waste stream in developing countries thereby highlighting the significance of anaerobic digestion. The implementation of WtE techniques can considerably reduce the emission of greenhouse gases and is beneficial to environmental health. The potential of WtE techniques for effective waste management and promotion of sustainability is underscored. The review contributes to the implementation of more effective measures for MSW management and promotes a circular economy.

1. Introduction

The global population is increasing rapidly at a rate of 1.05% per year and is anticipated to surpass 10 billion by the year 2057. Consequently, this increases the accumulation of municipal solid waste.[1] Moreover, economic growth and rapid urbanization have stimulated the generation of municipal solid waste (MSW) which is anticipated to increase speedily along with the growing population and urban areas causing a shift in routines. The generation of municipal solid waste is anticipated to reach 9.5 billion tons per year by the year 2050.[2] Out of the total generation of municipal solid waste, approximately 33% remains unmanaged which is creating a serious challenge for environmental sustainability and necessitates the development of strategies for the effective management of MSW.[3,4] Moreover, the quantity and composition of the waste pose risk to human health and the ecosystem and therefore efficient management of the generated waste is crucial for improving the environmental health and conservation of natural resources.[5] There is an urge for an affordable source of energy; besides, the emission of carbon remains a major concern and the production of energy by using municipal solid waste can effectively deal with the issues of waste management and energy crises.[6,7]

There are various techniques available for the treatment of municipal solid waste to reduce landfilling, and each technique has its perspectives and consequences.[8] The transformation of

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waste into electrical energy is an effective approach to overcome the issue of increasing waste generation and it promotes the production of sustainable energy.[9] The improvement in energy efficiency and reduction in the emission of toxic contaminants from gases are the current anxieties. Gasification, incineration, pyrolysis, and digestion are the alternative approaches for the generation of electricity in urban areas, with each approach requiring specific methods for the generation of electricity.[10] The research community is dealing with these problems by finding economically feasible techniques to decrease the liability of urban waste.[11] Thermal treatment including pyrolysis, gasification, incineration, and plasma gasification is the most commonly employed technique for the generation of energy in different forms and waste-to-wealth creation.[12] In terms of energy and resource recovery capacity, pyrolysis is recognized as a more promising alternative when compared to incineration.

Combined heat and power (CHP) is commonly employed as an alternative source of energy with a good energy conservation rate and is generally employed in incineration or anaerobic

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digestion plants.[13] The feasibility of incineration and gasification for the conservation of energy through a stable source has recognized incineration as an effective approach to transforming urban waste into electrical energy by using a steam turbine. Consequently, the generation of solid waste and air pollution due to combustion are critical issues.[14] To reduce the emission of harmful gases from the incineration of waste, several post-treatment processes like carbon capture are employed with waste-to-energy facilities.[15] The relatively high efficiency, ability of quick startup and shutdown, and economy of combustion processes have made them a popular choice. The operating condition, structural design, and rate of fuel consumption are the factors that influence the generation of power. The gas turbine and micro gas turbine are employed for the generation of electricity from municipal solid waste.[16] The gas turbine utilizes combustion as a stable source to heat the compressed air, which improves the efficiency of energy production by the inlet gas. The micro gas turbine utilizes the syngas produced by the gasification of municipal solid waste with a high caloric value in the inlet gas. Biodiesel derived from different discarded oils can be a suitable alternative to petroleum-based diesel as a fuel for engines.[17] Besides combustion, fuel cells are a source of power generation from urban waste but their sensitivity to impurities like chlorides, sulfides, and particulates within syngas generated by municipal solid waste requires a purification system to maintain the service and life of the fuel cell.[18] Due to their low sensitivity, matching operating conditions and favorable operating environments solid oxide fuel cells (SOFCs) have drawn attention. The microbial fuel cell relies on the anode of respiring bacteria allowing the production of electricity by using organic waste.[19] Through their metabolic action, these bacteria release electrons from organic waste, and these electrons then flow through a circuit to the cathode and generate electricity leaving behind water and CO_2 as the by-products. Although the technique is less polluting and reduces the issue of organic waste, it is still not commercialized. Moreover, the hybridization of solar panels and wind turbines in a hybrid microgrid system can improve trustworthiness and efficacy by giving numerous energy sources.[20]

The recycling and reuse of feedstock, and the elimination of waste in landfills are the prerequisites for an ideal circular economy. The waste-to-energy sector provides various business opportunities when strict pollution standards are being enforced by the governments.[21] Despite the low energy recovery efficiency of incineration, there are many feasible pathways for the recovery of energy through incineration.[22] Although not every conversion technique is economically feasible, optimum pathways depend on the characteristics of the local supply connection. The wastes are collected, transported, sorted, pre-heated, and finally transformed into a value-added product or energy, and the by-products are disseminated and eventually disposed of. An optimized supply chain can reduce the impact on the environment and cost incurred in the recovery of energy while increasing the income from sales.

A smooth flow of products, waste, and by-products between supply points is of paramount importance.[23] Techno-economic aspects considering technical viability and cost-effectiveness can be evaluated. An evaluation of the technical performances of different processes can assist in identifying a suitable technology for the attainment of higher return and efficiency.[24] Therefore, the economic feasibility and technical performances are combined for a complete assessment of WtE techniques. In general, the environmental considerations of the waste-to-energy process cannot be ignored, particularly with the growing focus on global carbon neutrality.[25] Global warming is one of the primary indexes to qualify the influence of greenhouse gases against carbon dioxide. The waste-to-energy conversion of MSW is crucial for the attainment of net-zero pledges as it addresses the increasing rate of waste generation associated with economic growth.[26] There are different economically feasible approaches available for the recovery of energy having less environmental impact for each type of municipal waste.

The literature presents considerable work on the management of MSW and less work is available on WtE techniques while there is an absolute dearth of work dedicated to the techno-economic analysis, prospects, and limitations of waste-to-energy techniques. The present work is aimed at providing an overview of the different aspects of waste-to-energy techniques. The novelty of the review stems from the thorough analysis of the environmental impact and economic feasibility of WtE conversion plants across different regions of the globe. The review explores different aspects of municipal solid waste including techno-economic analysis, benefits and limitations of waste-to-energy techniques, generation of solid waste, implementation of waste-to-energy techniques, *etc.* Moreover, the review summarizes state-of-the-art municipal waste-to-energy techniques, aiming to identify future research prospects rather than delving deep into a single aspect. The study highlights the prospects of municipal solid waste for energy recovery by implementing waste-to-energy techniques. The review emphasizes the positive impact of energy recovery of promising waste-to-energy recovery techniques. This work is crucial to overcome the detrimental effects of municipal solid waste. The work is significant for the recovery of energy through waste and the implementation of the circular economy. The review will assist the decision makers and policymakers to advance towards the attainment of the sustainable development goal. The review findings are intended to function as a scientific framework to deliberately allocate resources to the WtE pathways.

The remaining part of the review is organized as follows: Section 2 gives the status of municipal solid waste and treatment methods. Section 3 discusses the waste-to-energy conversion techniques in detail. Techno-economic analysis is provided in Section 4, while Section 5 discusses the framework for waste-to-energy techniques. Section 6 is dedicated to the challenges of waste-to-energy techniques. The discussions on prospects of waste-to-energy techniques in terms of energy, environment, economy, and society are provided in Section 7. Section 8 is the conclusion section where concluding remarks are provided, and then finally, in Section 9 the outlook of the work is presented.

2. Status of municipal solid waste and treatment methods

Economic development and rapid urbanization are the factors responsible for the generation of municipal solid waste.[27] The generation of municipal solid waste in major countries of the globe indicates that the quantity of waste generation varies with regions. The maximum waste is generated by Maldives while Nepal generates the minimum waste. The per capita generation of waste by India is about 0.57 kg (Fig. 1). The global generation of municipal solid waste is estimated to be 2.01 billion tons, out of which 33% has been dumped unanswerably which is creating several challenges for the environment. Therefore there is an urge to utilize the generated municipal solid waste for the recovery of energy.[28] The characteristic of the generated municipal solid waste indicates that biomass occupies a major portion of the generated municipal solid waste, being at about 57%; therefore the implementation of techniques to recover energy from biomass is significant (Fig. 2). The increasing rate of industrial waste having different composition is challenging for the management of the generated solid waste.[29] In addition, the improper management of municipal solid waste is endangering the community and environment.[30,31] Furthermore, the dependency on municipal solid waste is a major concern for humanity, raising health, financial, and security issues.[32,33] The mismanagement of municipal solid waste is a collective issue in emerging nations like India. The management of solid waste in India is still in its embryonic stage and is evolving over the years; the fraction of waste processed yearly in India is comparatively low in comparison to the developed countries.[34,35] The problem due to the mismanagement of solid waste is becoming more critical due to the increased amount of waste resulting from the growing population. The management of municipal solid waste, including its assortment, transportation, and storage, is deteriorating and requires immediate attention.[36,37] It is inferred that there are multiple factors responsible for the monitoring of solid waste in developing countries.[38,39] Additionally, developing countries are facing the problem of waste collection at the doorstep and lack of an effective recycling technique.[40] Only a small fraction of municipal solid waste is treated whereas the remainder is dumped unanswerably in the landfill. The facilities available for the treatment of municipal solid waste are not sufficient to effectively treat the generated waste.[41] The dumping of municipal solid waste contaminates the water and air which is endangering humans, animals, and plants. Consequently, there is a pressing need to implement robust waste management techniques with less dumping.[42,43]

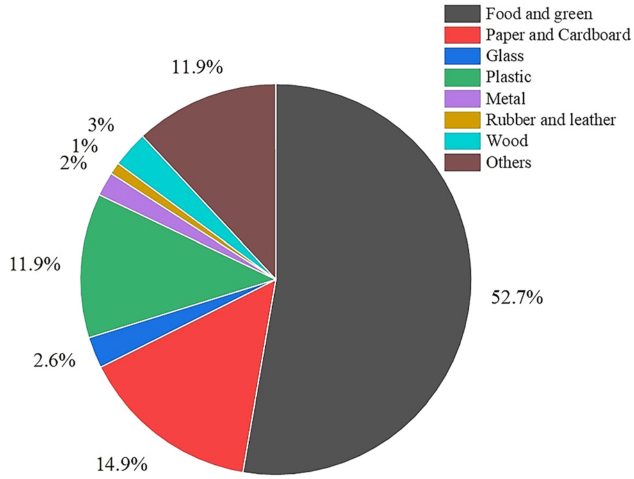

Fig. 2 Characteristics of municipal solid waste.[44]

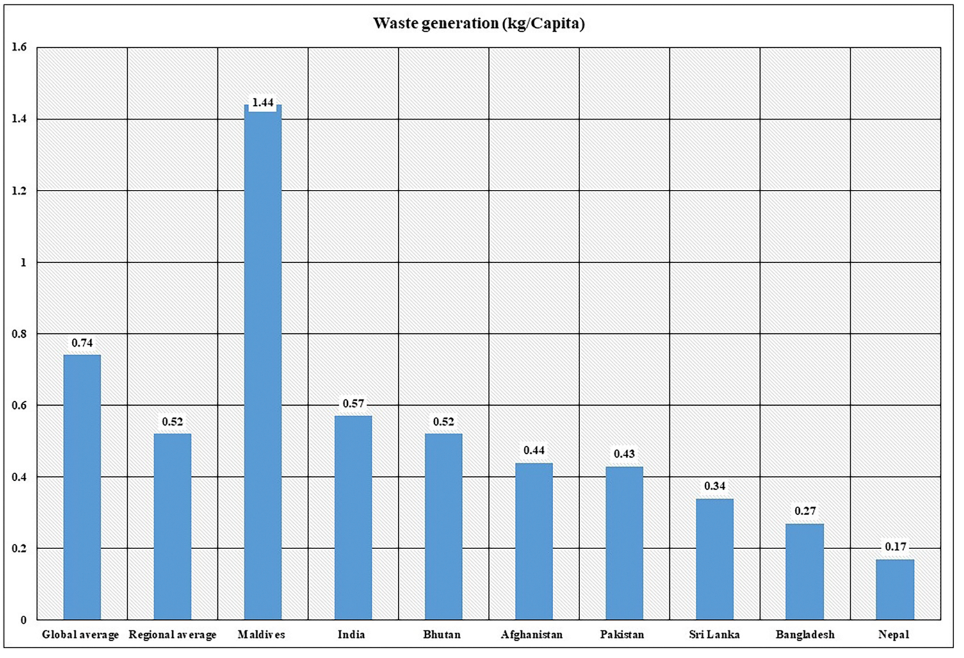

Fig. 1 Solid waste generation in different regions of the world.[44]

To overcome the issues of municipal solid waste management, it is essential to advance an eco-friendly method for the management of municipal solid waste. Recycling, landfill gas recovery, and waste-to-energy techniques have gained considerable attention for minimizing municipal solid waste.[45] The different waste-to-energy methods are the most beneficial as they reduce the reliance on fossil fuels and mitigate associated emissions. The waste-to-energy technologies can assist in the promotion of a circular economy.[46] The waste-to-energy methods are influenced by environmental, location-related, geographical, and socio-economic considerations.[47] A thorough analysis of the waste-to-energy techniques is required for the large-scale implementation of waste-to-energy techniques in developing countries.[48] The advantages and limitations of the waste-to-energy technique must be discussed before adopting any waste-to-energy technique as different WtE techniques have their benefits and limitations (Table 1). Municipal solid waste can be used in different ways and therefore can be considered as a source of resources for the conservation of energy.[49] A few of the methods based on the quality and composition of the waste can offer several opportunities. The collection of waste is a critical step before the treatment and utilization of waste. The collection and transportation of municipal solid waste constitute a considerable part of the overall waste management.[50] The model for solid waste management indicates that a part of the collected waste is utilized in the generation of energy and recovery of material and the remaining is directly disposed of in a landfill (Fig. 3).

Nowadays, the methods for storage and separation of waste, such as door-to-door collection, drop-off points, storage in mixed waste, *etc.*, are performed without separation.[51] It is observed that in the door-to-door collection of waste, people put their recyclable waste in non-recyclable plastic bags which creates difficulties in the separation of waste and restricts the implementation of the techniques.[52] In the curbside system for collection of waste, the waste is placed in the container placed at a certain distance generally 50 to 100 (meters) apart.[53] Besides, at the drop-off points the people deposit the waste in big containers placed at intervals of 500 to 1000 (meters) at the side of the street.[54] In the mixed collection, the municipal solid waste is kept in a container without any separation; the separation is performed later at a recycling facility where the person involved separates the waste, which is then transported to a transfer station and finally to a disposal center.[51] The present system of waste collection is classified as formal, informal, and formalized modalities. In the traditional method of waste collection, the separation of waste is performed by the citizens while the collection is carried out by the standard private or municipal personnel, whereas in the informal model, the separation of waste is performed by the recyclers and there is no formalization; the formalized model is the combination of the formal and informal models.[55] Different strategies have been employed to enhance the separation and collection of waste. The economic and technical aspects in the collection of municipal solid waste including waste generation, financial parameters, composition settlement structure, database for infrastructure nature, *etc.* have been improved by the different mathematical models and life cycle assessments.[56] The different factors such as the number of bins and houses, cycle for waste collection, vehicle trips, seasonal variations, and working hours have increased the complexity of the model.[57] The artificial intelligence system, mathematical programming, and geographic information systems have been employed to optimize the collection of municipal solid waste.[58] Nowadays, the replacement of manual sorting of waste by a robot with artificial intelligence has facilitated the automation of municipal solid waste.[59] The subway collection of waste by a vacuum-assisted system is another emerging solution for the collection of municipal solid waste.

Several waste management systems are developed by using the Internet of Things such as pello, recycling robots, solar power compactors, and pneumatic waste pipes besides some government initiatives. Pello is a novel technology that has been developed to assist in the efficient management of waste and decrease the environmental impact. The system monitors the level of trash cans and generates real-time information on the location; therefore the system can alert users regarding the contamination of the container. Recycling robots can be programmed for a rapid and accurate response to differentiate the materials. The implementation of recycling robots allows for an efficient sorting of waste and decreases landfills. Pneumatic waste pipes can directly deliver the waste to the processing centers and eliminate the requirement of waste collection thereby minimizing the harmful emissions and overflowing of the waste. Furthermore, solar-powered trash compactors compress the trash to increase the capacity of the bin. They consist of sensors that can transmit data on the fill level of the waste bin which facilitates scheduling pickups and streamlining the collection of waste. There are several recycling apps available to assist the individual in developing a sustainable and circular economy.

3. Waste-to-energy conversion techniques

Municipal solid waste (MSW) contains energy that can be used for different purposes. Energy extraction processes are considered waste-to-energy extraction technologies. The various techniques are helpful in dealing with the problem of municipal solid waste disposal and decreasing the quantity of waste disposal. Based on its composition and characteristics, municipal solid waste can be converted into energy by using biochemical and thermochemical methods.[70] Preprocessing and pretreatment of solid waste before it is transferred to waste-to-energy conversion plants can increase the efficiency and effectiveness of these plants.[71] The heterogeneity of municipal solid waste requires different segregation methods which requires additional energy and operational costs.[72] Popular techniques such as anaerobic digestion, pyrolysis, and gasification are implemented for homogeneous solid wastes containing non-flammable, recyclable, and sluggish materials.[73] Gasifiers and pyrolysis reactors can decrease particle size and surface area to maintain homogeneity in the solid waste, resulting in better yields.

3.1. Thermochemical conversion technique

The thermochemical conversion process is a well-known technique that is generally used to decompose carbonaceous

Table 1 Benefits and limitations of waste-to-energy techniques

Feedstock	Treatment	Target	Power generation technology	Description and power capacities	Benefits	Limitations	Ref.
MSW	Combustion	Steady heat source	Steam turbine • Organic ranking cycle	>250 kW	Integrated power generation	MSW contains various kinds of wastes and a high content of moisture	60 and 61
Biomass and MSW	Combustion or gasification (rarely)	Stable heat source	Stirling engine	A flue gas flow of 730 g s^{-1} and temperature of 980 °C corresponding to 24.5 kW of power generation Electric efficiency ≈ 30%	Appropriate for constant, small- to medium-scale power generation by utilizing biomass and MSW	Combustion and gasification of biomass and MSW face challenges such as operational conflicts and complex emission control requirements.	62
Biomass and MSW	Gasification	Syngas	Internal combustion engine (ICE), spark ignition engine (SIE), compressed ignition engine (CIE)	Efficiency is prominently influenced by the type of fuel and the equivalent ratio 0.5–5.8 kg kW^{-1} h^{-1}	Flexibility in utilizing dissimilar forms of internal combustion engines for power production	The efficiency is highly adjustable, and largely influenced by various fuel and equivalent ratios	63
Biomass and MSW	Gasification	Syngas	Gas turbine	Efficiency up to 65% in combined cycle configurations	Attain high efficacy	The system complications and cost increase significantly	64
Biomass and MSW	Gasification	Syngas	Micro gas turbine (MGT)	25 kW to 2 MW Efficiency of 26–33%	Appropriate for an extensive range of uses	The comparatively low efficacy of 26–33% may hamper its effectiveness	5
Biomass and MSW	Gasification and purification	Hydrogen	Fuel cell	Electric efficiency of 35–65%	It promotes the production of clean energy	Variations in electric efficacy (35–65%) may influence the overall steadiness	65
Biomass	Gasification	Syngas	Hybrid SOFC/MGT cogeneration	Electric efficiency of 35% and cogeneration efficiency of 88%	High efficacy combined system	The system's performance is dependent on the efficiency of both SOFC and MGT	66
Organic waste	Microorganisms	Hydrogen	Microbial fuel cell	The MFC capability could reduce up to 95% of food waste degradation efficiency	Proficiently transform organic waste into hydrogen	Inadequate due to the specific conditions and effectiveness of the microbial processes involved	67
Organic waste	Microorganisms	Hydrogen	Microbial fuel cell	Generated more energy (24.47 mW m^{-2})	Higher power density	Integrated WTP system	68

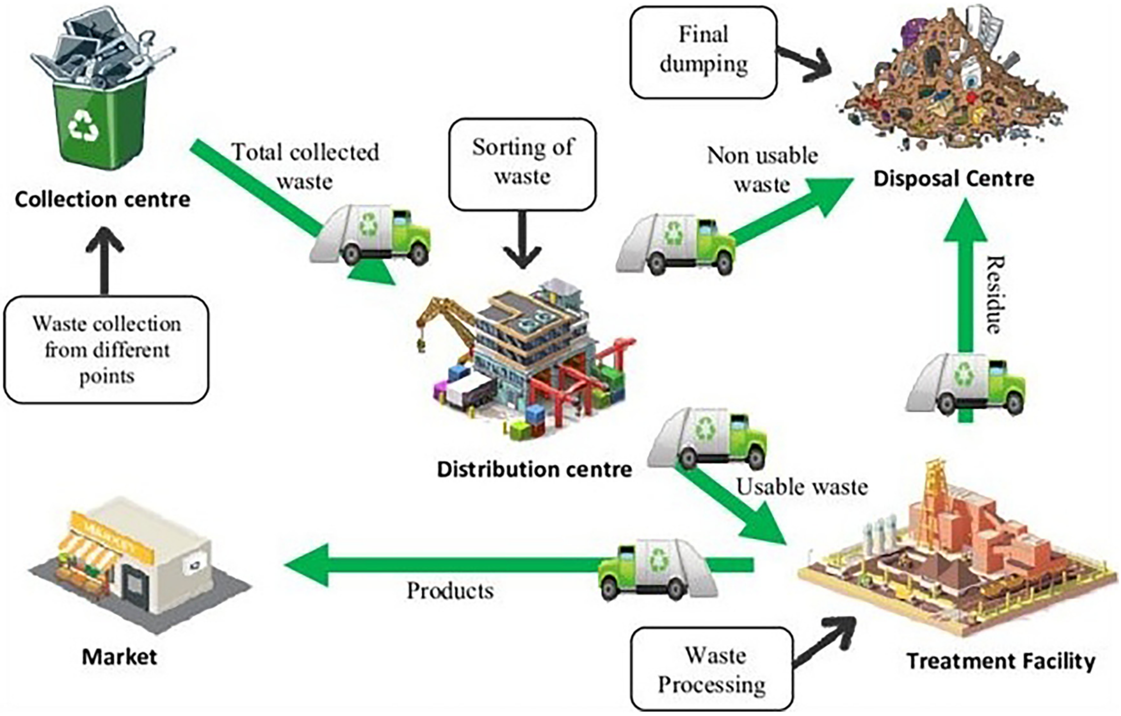

Fig. 3 Model for municipal solid waste management.[69]

organic matter at an elevated temperature for the production of heat energy, oil or gas, and charcoal.[74] This approach includes techniques such as incineration, pyrolysis, and gasification. Solid waste with low density and low moisture can be utilized under the thermochemical process for waste-to-energy conversion.

3.1.1. Incineration. Incineration is the burning of discarded materials at elevated temperatures which is used for the management of solid waste. This approach is generally employed for carbon-based (organic) fuels such as coal, biomass, or MSW.[75] This operation results in the reduction of waste quantity and the destruction of contaminants. The different types of waste such as municipal solid, medical, and hazardous waste can be treated by incineration.[76] This process involves waste preparation, combustion, control of air pollution, recovery of energy, and disposal of the product. This process allows the direct burning of municipal solid waste in a sufficient supply of oxygen in a furnace at elevated temperatures of 800–1000 (°C). The municipal solid waste is ultimately converted into carbon dioxide, water vapor, and ashes.[77] The incineration process is applicable when the lower heating value matches the specific conditions such as the type of waste and temperature.[78] The pre-drying phase is performed for municipal solid waste which improves the incineration of MSW and reduces the emission of harmful gases. One of the techniques that may be adopted in this process is flue gas recirculation which increases the effectiveness of incineration.

The advantages of incineration are as follows: (i) it can reduce the quantity of waste by 80% to 90% and mass by nearly 70% to 80%; (ii) it can reduce the landfill spaces significantly; (iii) it is helpful in mitigating the hazardous substances due to elevated temperature; (iv) even low-technique and low-skilled manpower may be sufficient to minimize the mass and volume for any type of waste through the incineration process; (v) incineration produces hot fuel gas as a by-product which can be useful to produce steam in a boiler; and (vi) the extracted energy can be used for various purposes to meet the energy requirements of a community. However, the advantages of incineration are not feasible as the incineration of solid waste promotes the formation of dangerous carcinogenic complexes such as dioxins, furans, particulate substances, and acidic gases such as SO_2, HF, and NO_x which produce waste containing plastics.[79] The extracted fuel gases are a combination of gases and compounds of heavy metals. The control and mitigation of hazardous emissions require intricate and expensive pollution controller technologies. The incineration is performed under high temperatures and produces corrosive gases which can damage the equipment and lead to costly maintenance. The incineration waste disposal method leads to various public health issues.

3.1.2. Gasification. Gasification is a thermal treatment process that decomposes solid waste (carbon-enriched fuel) into three different forms such as gaseous, liquid, and solid matter. The process takes under a controlled supply of insufficient oxygen through thermochemical reactions.[80] Based on the source of heat for the ignition, gasification is categorized as auto-thermal and allo-thermal.[81] This process exhibits high potential due to its flexibility and releases a limited number of dioxins and other pollutants. Depending upon the parameters and reactors, the conversion efficiency of gasification varies from 70% to 90%.[82] Gasification produces syngas which consists of hydrogen (H_2), carbon (C), carbon monoxide (CO), nitrogen (N_2), carbon dioxide (CO_2), and a limited amount of moisture.[83] Some parameters are decisive in the gasification method such as temperature and oxidants. A case study was conducted in China, where the effect of temperature and oxygen demand was analyzed on syngas collection. Gasification temperatures were varied from 550 °C to 650 °C for the different oxygen demands such as 0.25%, 1.25%, 2.5%, 3.75% and 5%. It was observed that the optimal syngas is achieved at 1.25% O_2 concentration at 650 °C.[62] In another study, the gasifier's efficacy was increased by adjusting the mass of air and pre-heated temperature.[84] Syngas is a by-product that can serve as an alternative source for fuels, chemicals, and fertilizers, and can also replace natural gas in various applications.[85] Some of the impurities such as particulates, tar, alkali-based metallic elements, chloride, *etc.* may create harmful effects making it inappropriate for downstream uses such as electrical power and heat-energy production.[86] The syngas must be purified for the protection of equipment and prevent harmful emissions. Syngas is a useful product for numerous applications such as boilers, steam turbines, inner combustion engines, and solid oxide fuel components.[87] Cleaning of syngas can be performed by using dry and wet processes; the dry process does not require water, and it can be performed by using methods such as cyclones, fabric filters, and thermal cracking of tars.

The gasification method can be adopted for homogeneous carbon-based organic materials having a high heating value. The pre-treatment with densification homogenizes the MSW which improves the efficiency of energy recovery.[88] The various gasifiers such as fixed bed, fluidized bed, entrained-flow, moving grate, and plasma are useful for solid waste gasification.[80] To fulfill the requirement for gasification a commercial MSW gasification plant is required in large numbers. The gasification method exhibits low emission when compared to conventional combustion and converts biomass gas into synthesis gas which is generally recognized as an environmentally friendly source of energy.[89] The process requires a limited supply of oxygen, thereby reducing the development or reformation of dioxins and furans. It is potentially useful for low-cost applications and efficient for green hydrogen production. Gasification technology is efficient for the removal of fine metal particulates which promotes the formation of dioxins and furans.[90] Syngas is considered a resource by the manufacturing sector. It can be an alternative source to produce electricity through graded composting which is an acceptable economic solution. The efficiency of the gasification process depends on the treatment of MSW and its characteristics and handling. The requirement of sophisticated equipment for high heat transfer efficacy is the limitation of the gasification process. Advancements in the design of the gasification process and the use of catalysts are important for the future advancement of the MSW disposal methodologies.[91]

3.1.3. Plasma gasification. Plasma gasification is a popular gasification technique as it provides a sustainable energy retrieval technology at higher temperatures above 5000 °C.[92] The syngas is extracted from MSW by utilizing a heat source such as an AC or DC plasma torch. The municipal solid waste breaks down inside the plasma gasification furnace at high temperatures, producing chemical substances comprising highly energetic radicals, electrons, ions, and excited molecules. A plasma torch is used as an energy source to convert feedstock into syngas.[93] At high temperatures in the reactors, the chemical substances degrade into electrons, ions, and excited molecules.[94] The formation of tar in plasma gasification from MSW is prevented by using a higher plasma power and gasification temperature.[95] Lower emission of CO_2, better plant efficiency, and higher quantity of H_2 in the syngas are constraints in the plasma gasification of municipal solid waste. The feed of steam at high temperatures increases the yield of syngas and decreases the demand for air. The energy losses in plasma gasification mainly occur due to the chemical energy, functional heat from syngas, and system heat loss.[5] Various types of waste such as MSW, hazardous, industrial, and medical waste can be processed by using plasma gasification. The technique produces a high-quality syngas having a high content of hydrogen that can be effectively used in different applications.[96] The large quantity of H_2 has demonstrated its suitability in fuel cell and clean energy technologies. The technique suffers due to the technological complexity, requirement of special equipment, and the need for skilled workers for operation and maintenance of the plants. The plasma gasification has demonstrated an energy conversion and carbon conversion efficiency of 48.83% and 100%, respectively. Also, the generation of 1 kg of syngas requires about 1.78 kW h of electrical energy.[97] Moreover, the efficiency of the technique is influenced by the feedstock characteristics, and moisture content decreases the quality of the input waste.[98]

3.1.4. Pyrolysis. Pyrolysis is the thermochemical decomposition of biodegradable materials without oxygen or an inert atmosphere at a temperature of 300–600 °C. It is one of the most favorable alternatives to incineration.[99] The process is initiated by the thermal decay of MSW at 300 to 400 °C in an oxygen-deficient or oxygen-free atmosphere. The temperature is further increased to yield products of pyrolysis such as biogas, biofuel, bio-oil, and biochar. The products of pyrolysis can be used as fuels, for production of heat, and as fertilizers (Fig. 4). Pyrolysis is influenced by the rate of heating, temperature, type of reactor, and time of residence.[100] Researchers have evaluated the performance of unsegregated municipal solid waste in tubular and fluidized bed reactors.[37] The influence of slow pyrolysis, fast pyrolysis and co-pyrolysis of municipal solid waste on the yield stability and composition of the end product was evaluated.[101] The municipal solid waste was found to be not suitable for pyrolysis and required a pre-processing step for eliminating metals, glass, and inert materials before processing. The high moisture content in waste increases the energy requirement in pyrolysis, therefore decreasing the efficiency and increasing the overall cost.[102] A specific and homogeneous waste is most suitable for pyrolysis. The gas produced from pyrolysis can be used for the generation of electricity by employing suitable energy recovery devices.[103] Due to its lower emission, pyrolysis is more environmentally friendly than incineration and

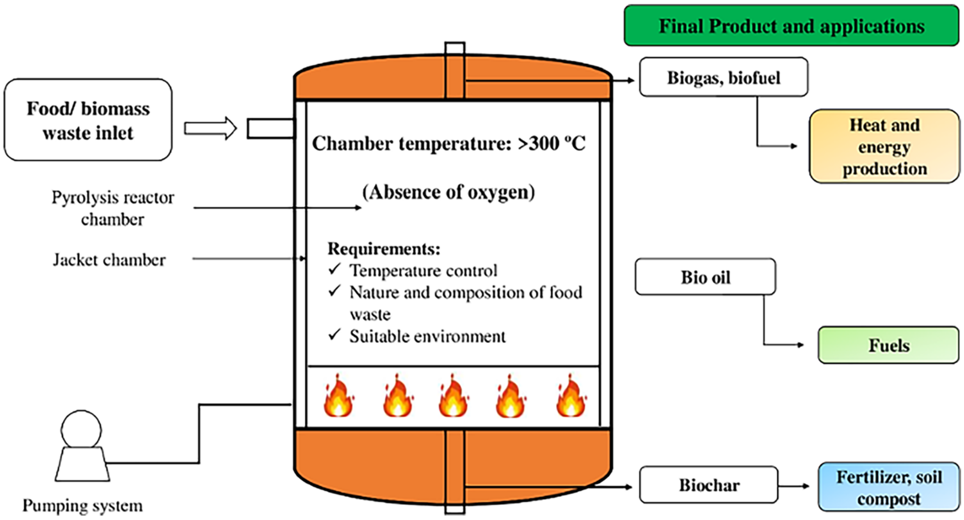

Fig. 4 Mechanism of the pyrolysis process and products (with permission from Elsevier, copyright 2021).[106]

also less noise is produced in a pyrolysis plant as compared to incineration.[51] Pyrolysis can effectively convert organic waste into valuable products such as char, bio-oil, and syngas. Pyrolysis can effectively convert 60–80% of the waste plastics into liquid fuels, and the yield can be enhanced up to 85% with fast pyrolysis.[104] The by-products of pyrolysis can be utilized as fuels, chemicals, or soil amendments which provide various pathways for the retrieval of energy.[105] Pyrolysis takes place in the absence of oxygen which significantly decreases the formation of dangerous pollutants, making it a cleaner solution for the management of waste. The quality of products obtained through pyrolysis depends on the characteristics of the feedstock.[99] Pyrolysis is challenging in terms of its effectiveness and efficiency, particularly when adopted on a large scale. The small-scale systems could be more effective but less economical.

3.1.5. Hydrothermal carbonization. Hydrothermal carbonization is a thermochemical process of converting waste biomass into biochar. The process operates at a temperature below the pyrolysis temperature with a varying residence time of 0.5 to 8 hours.[107] The process is advantageous in recovering the raw material containing a high fraction of organic waste and no pre-heating is required for the treatment of municipal solid waste.[108] The study has revealed that approximately 40 to 48% of water can be recovered at 200 °C by employing a biogas digester.[30] The water in municipal solid waste acts as heat media in hydrothermal carbonization. The material in solid form is dried to get biochar and the liquid is recirculated in the process. Dehydration, hydrolysis, and decarboxylation are the most common reactions in hydrothermal carbonization and carbon dioxide is generated by gas emissions. Due to the low-temperature requirement in hydrothermal carbonization, high biochar production is mainly found in the ranges of 37.68 to 70.37%.[109] The optimal energy production of the hydrochar was 86.47% under the hydrothermal carbonization temperature of 160 °C for a liquid/solid ratio of 10 : 1 and a time of reaction of 2 hours.[110] Hydrothermal carbonization consumes less energy and is eco-friendly; therefore it has gained considerable importance in urban development.[58]

Biochar shows promise as a cement replacement to advance the structural characteristics of concrete and building materials.[111] Hydrothermal carbonization can efficiently process the waste having high moisture content and no pre-drying is required. The process is beneficial for the treatment of organic waste which is normally wet.[112] The process yields biochar which can be utilized as a soil amendment to enhance the fertility of soil, carbon sequestration, and water retention. The biochar is a valuable material for application in water treatment as a carbon-rich material. Hydrothermal carbonization faces challenges in optimizing and scaling up the process due to the need for control of pressure, temperature, and reaction time.

3.2. Biochemical conversion process

Biochemical conversion involves breaking down biodegradable MSW through microbial activity, either in the presence or absence of oxygen, resulting in the production of various useful products.[113] The process is preferred for the treatment of waste having a high content of biodegradable matter and moistness which supports microbial activity. Anaerobic digestion, landfilling, and composting are a few of the biochemical processes.

3.2.1. Anaerobic digestion. Anaerobic digestion is a process of converting waste into methane-rich biogas due to the decomposition of organic waste and it involves four consecutive stages such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Fig. 5).[114] Hydrolysis is the primary step in digestion where complex organic molecules like starch, proteins, and fats are broken down into soluble organic molecules like glucose, fatty acids, and amino acids. The rate of hydrolysis is limited due to the formation of volatile fatty acids which can be compacted by the pre-treatment of the organic matter of wastes before being supplied to the digester.[115] Acidogenesis, also known as the fermentative phase, breaks down the product obtained in hydrolysis to yield fatty acids, ethanol, hydrogen,

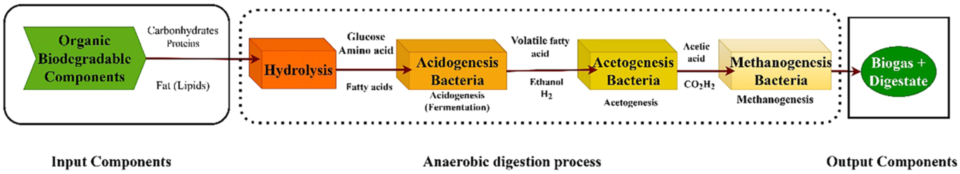

Fig. 5 Consecutive stages of anaerobic digestion (reproduced with permission from Elsevier, copyright 2021).[106]

and carbon dioxide. Acetogenesis is the third stage where the organic compounds are converted into hydrogen, carbon dioxide, and acetic acid. Methanogenesis is the last stage where biogas is produced besides some other gases.

Biogas is mainly composed of methane (CH_4) and carbon dioxide (CO_2) at about 55–75 vol% and 25–45 vol%, respectively.[116] Biogas requires the removal of CO_2 through physical absorption by using caustic soda, silica gel, and activated carbon before being supplied to internal combustion engines for the generation of electricity or can be used as a fuel in automobiles by using combined heat and power generation.[117] Digestate is an additional valuable product of anaerobic digestion that can be utilized as a soil conditioner or an organic amendment.[118] The production of biogas, methane content, and stability of the digestion are influenced by operating factors like pH value, carbon–nitrogen ratio, operating temperature, and substrate composition.[119] The biodegradable ingredients are the appropriate raw feed for the generation of biogas in an anaerobic breakdown process. The plant biomass and manure are commonly used in biogas plants in rural areas, while food waste and sewage sludge are the feedstock for the production of biogas in municipality areas.[120] Although anaerobic digestion is an important technique for the treatment of waste and favors sustainability and carbon neutrality, the process has limitations of high-capital investment and requires safety regulations and maintenance.

3.2.2. Landfilling and landfill gas recovery systems. Landfilling is the final disposal of waste and is the most predominant method for the global disposal of waste particularly in emerging nations. It is stated that around 90% of the waste in Africa, Latin America, and the Caribbean is disposed of in landfills and open dumps (UNEP, 2019). It is reported that about 74%, 90%, and 80–90% of the waste in Nigeria, South Africa, and Malaysia, respectively, are dumped in landfills.[121,122] Despite the economic viability of landfilling, landfilling is deteriorating the atmosphere due to the release of harmful gases into the environment. Landfilling occupies a large amount of land and could cause the explosion of methane besides a huge loss of resources and available agricultural land. The environmental implication of landfilling begins with the large amount of methane gas emitted from the landfills. It is reported that around 30–70 million tons of methane is expelled due to the landfill into the environment.[123] The effectiveness of methane in causing climate change is 28–36% higher than that of carbon dioxide over a period of about 100 years.[124] Landfilling is not considered a sustainable method of municipal solid waste management due to environmental risks.

The shortage of land is a challenge for the allocation of new dumpsites in advanced nations. Landfill gas recovery technology (LFGR) can be employed by using an internal combustion engine for the generation of electricity by utilizing the gas emitted from landfills.[125] Energy recovery from landfills offers a chance to generate income by selling electricity and earning credits in carbon markets. The generation of methane is influenced by biodegradation which is affected by the requirement of moisture for bacterial growth. The implementation of bioreactors has accelerated the degradation of waste in the landfill and enhanced the production of landfill gas.[126] The biodegradation of waste in a bioreactor landfill is increased by the recirculation and distribution of aqueous effluent. The biocell technology of is an advanced method for the optimization of biogas recovery from landfills.[127] It is an upgraded bioreactor landfill process in which biological breakdown takes place in three consecutive stages: anaerobic, aerobic, and mining. In the first stage, landfill gas is produced by recirculating the leachate as in a bioreactor and after that air is pumped into the solid matrix to facilitate compost formation. In the last stage, the biocell recovers materials that can be recycled and creates space for reuse and therefore is considered an important source of wealth for sustainable growth.

4. Techno-economic analysis

The techno-economic investigation provides a comprehensive linkage between the economic and technical performance of waste conversion techniques.[128] Production, process efficiency, and feedstock conversion are considered as the parameters for assessing technical performance, whereas the net profit value, return rate, payback period, cost of raw materials, and selling price are considered as the economic factors.[129] Techno-economic analysis is a method for evaluating the economic and technical performance of a technology. In the work that analyzed the potential of landfills and anaerobic digesters for the production of biogas in the Brazilian States of Minas Gerais and Sao Paulo, it was found that the waste generation varies directly with the gross domestic production.[43] The generation of electricity from biogas reduces a considerable amount of CO_2 emissions. The energy requirement in urban areas and issues of waste management can be successfully addressed through waste-to-energy techniques.[130] The implementation of waste-to-energy practices with digitalization can reduce the environmental impact of conventional waste management practices and shift towards cleaner energy. A mathematical model can anticipate the quantity of waste generation based on the population.[131] The production of biogas from the waste stream is assessed by using the rate of decay parameters considering the collection efficiency of 55.5%. The estimation of yield power was made by considering the lower heating value (LHV) of methane, combustion efficacy of methane (33%), and methane percentage in biogas (55%). The fraction of methane can be increased from 24% to 40% by the incorporation of sludge, leaches, and wastewater in the digester.[31] The creation of biogas from an anaerobic digester is estimated by considering the fraction of organic waste in municipal solid waste assuming a methane content of 65% and a collection efficiency of 90%. An economic examination gives the levelized cost of electricity (LCOE) for municipal solid management using biogas. For landfill gas, LCOE was found to vary from 85 to 93 US$ per MW h denoting a decent potential for the generation of electricity from landfill gases (LFG). The LCOE for biogas by anaerobic digestion varies from 106 to 254 US$ per MW h. The results suggest that the anaerobic digesters are cost-efficient, but the cost of production of biogas is high. Recently, the concentration of CH_4 was increased by 36.3% by adding 10% slag, which reduced the acidity of the environment making it favorable for methanogens.[35,132] The comparison of the LCOE between the landfill gas recovery and anaerobic digestion in Nigeria found the anaerobic digester as the most cost-efficient pathway, with anaerobic digester LCOE varying from 0.0681 to 0.0336 US$ per kW h.[32,114]

A techno-economic analysis of the generation of biogas from organic municipal solid waste was conducted by considering six different scenarios including plant size, upgrading methods, digester type, and the addition of biogas from the treatment of wastewater. Aspen Plus® was employed for the simulation of the process. The evaluation of the economic performance was performed by using the Aspen process economic analyzer. The economic feasibility and technical performances of six (06) different circumstances for the generation of biogas from municipal solid waste in Boras, Sweden, were assessed by varying the cost of municipal solid waste between −200 and 200 US $ per ton. Scenario 6 provided the optimum profit in terms of economic performance, energy efficiency, and consumption. The minimum price of compressed biogas for the base scenario and scenario 6 was 1.15 and 0.76 (US$ per L), respectively. It was concluded that utilizing upgraded methods with increased capacity will produce greater profits. Municipal solid waste has a significant influence on the economy, but there exists an uncertainty in the cost of collection and conveyance. The techno-economic analysis of municipal solid waste in Brazil has identified biogas from landfills and incineration of municipal solid waste as the primary two scenarios for the generation of electricity.[133] Electricity is generated by using biogas from landfills by passing it through an internal combustion engine. Initially, the biogas having equal fractions of CH_4 and CO_2 is purified and then it is passed into the incineration unit where it is burned at a high temperature of about 870–1200 (°C) and a high pressure is created in the incinerator which drives the gas turbine to generate electricity.[134] The net profit value, cash flow, and internal rate of return are the indicators of the economic feasibility of municipal solid waste. Besides, the consumption of municipal solid waste is related to the energy indicator CH_4. The different waste-to-energy techniques such as incineration, anaerobic digestion, and landfill gas recovery are the most prominent methods for the management of solid waste. The advancement of WtE techniques has led to an improvement in efficiency and reduced the environmental impact with the progression of years (Table 2). The implementation of waste-to-energy techniques has reduced the dependency on fossil fuels in developed countries whereas in developing countries these practices are not effectively performed.[88] The inadequate technical expertise and lack of funding have hampered the widespread adoption of waste-to-energy conversion practices. Despite the challenges developing countries are facing to produce sufficient energy, the waste is dumped instead of being transformed into a valuable form.

The recovery of energy systems for households having three (03) inhabitants was put into perspective by using economic indicators. Considering a population of 100 000, a negative net profit value and an internal revenue rate of 0.4% were calculated. The zero net profit was obtained at the selling price of 82.60 US$ per MW h. Besides, the net positive value was 3 004 678 US$ and 8 793 264.25 US$ for a population of 500 000 and 1 000 000, respectively. It is observed that all the situations have a negative net profit and as a result decreased economic feasibility. In Brazil, the techno-economic analysis of electricity generation by using gasification was carried out.[144] The net profit value, yearly rate of interest, internal revenue rate, and net profit value are the economic indicators, whereas power, efficiency, and generation of electricity are considered as the technical indicators. The generation of electricity is influenced by the size of the population. A decision model for techno-economic analysis of waste-to-energy conversion techniques from municipal solid waste was developed.[145] A suitable model for the municipalities can assist in making decisions on the conversion of waste into useful energy. Composting is the cheapest way to generate energy, and the cost of conversion is about 77 US$ per ton. The integration of gasification with composting generates electricity which requires an amount of 42–72 (US$ per ton) for the waste generation of 50 000–150 000 tons per year.[146] The sensitivity analysis of gasification has observed the selling price of biofuels and electricity as the dominating factor impacting the feasibility of the technique.[147]

The generation of energy by using municipal solid waste through pyrolysis has been identified as an intermediate step for the conversion of solid waste into fuel gas and organic oil. The efficiency of the combined heat and power is estimated to be 60% for a plant having a processing capacity of 5 tons per h and capital investment of 27.61 million pounds at an efficiency of 0.063 lb per kW h.[148] The energy created from the gas and diesel engines and the data were collected from the pilot experiments of the plant. The profitability of the plant was influenced by the capital cost, feedstock cost, energy productivity, and plant maintenance. The thermo-socioeconomic

Table 2 Advancement in waste-to-energy techniques

Year	Method	Electricity generation	Cost	Environmental impact	Remark	Sources
2019	Anaerobic digestion and incineration	4165 GW h per year	—	Reduces the GHG emissions by 1.7 Mt per year	New South Wales produces 5.9% of the overall power	135
2018	Incineration	1471 GW h per year	—	Emits 0.18 kg per s of CO_2	Improves the waste management in Jitabarang	136
2018	Combustion	277.17 GW h per year	—	—	Reduces the dependency on oil and other non-renewable energy sources. Decreases the emission of GHG to minimize the global warming and eliminates the contamination of water and air	137
	Gasification	177.39 GW h per year	—	—		
	Anaerobic digestion	—	—	—		
2013	Combustion	8500 GW h per year	—	Reduces the emission of CO_2 by 11 Mt per year	The results of the simulations indicate the potential to meet 0.5% of the electricity requirement in Turkey by 2023	138
2017	Incineration	113 GW h per year	150 USD per MW h	—	Optimizes the powder generation through wastes	139
2017	Landfill, anaerobic digestion and composting	1229 GW h per year	10 USD per ton	Reduces the emission of CO_2 by 1.8 Mt per year	Decreases the emission of greenhouse gases	140
2020	Incineration	11 681 GW h per year	128 827.11 USD	—	Produces 4.3% of the power requirement of the country. Decreases the challenges of environmental pollution	141
2013	Landfill	1.5 GW h per year	250 000 USD per month	—	Production of energy by using landfill is the economical way, good quality fertilizers can be produced.	142
	Incineration	2 GW h per year		—	Transmission of diseases can be prevented by sanitary landfills	
2022	Incineration	170 GW h per year	2.36 million USD per year	—	A systematic waste to energy practice transfers 20 MW of energy to the network	143

assessment was performed by studying the thermo-kinetics of municipal sewage sludge through pyrolysis. The comparison of the production of biogas, biochar, and bio-oil through pyrolysis shows an optimum performance due to a higher internal revenue rate, return on investment, and net profit value considering the social and economic aspects.[149] The researcher has studied the environmental and economic aspects of the valorization of municipal solid waste by taking seven different conventional waste processing units and found that the least-cost solution reduces the cost and greenhouse emissions by 26%. The plasma gasification process has shown feasibility under higher electricity prices.[150]

The techno-economic analysis of municipal solid waste for supercritical and critical Indian coal was carried out.[151] The co-combustion of municipal solid waste can overcome the issues of low calorific values of municipal solid waste. It is demonstrated that the combustion of municipal solid waste and coal in a ratio of 1 : 3 has a lower levelized cost of energy of 73.47 US$ per MW h and 69.7 US$ per MW h for high and low ash coal, respectively, when compared to that for the municipal solid waste at 80 US$ per MW h. Thermal economic analysis of a novel mechanical–biological treatment system that generates heat, power and hydrogen from municipal solid waste was performed.[152] In mechanical–biological treatment, the mechanical sorting of the municipal solid waste is performed and then it is converted into wet organic fractions for the generation of electricity and heat while the remaining part of the waste is disposed of as a landfill. However, the discarded material can be effectively converted into some valuable products by a gasification unit.[153] The integration of three techniques of waste-to-energy techniques including pyrolysis, anaerobic digestion, and solar PV has generated an annual revenue of $41.6 million. The commercial waste-to-energy plant can process about 1000 tons of waste plastics daily and generate about 19.7 MW of electricity. The capital investment and annual operating cost are $102.2 million and $12.2 million, respectively.[154] The investigations of the three different scenarios of the production of electricity and fuel have shown that the generation of electricity and fuels has attained a net profit value of EUR 13 million and a payback period of 12 years. Therefore, hybrid systems have gained great interest and thermal economic analysis plays an important role in selecting a suitable waste treatment method.

5. Framework for solid waste management

The waste-to-energy practice when incorporating renewable energy sources is gaining considerable interest. A crucial step in waste-to-energy techniques is the conversion of waste into energy, which significantly impacts municipal solid waste management. The community must invest in the development of waste-to-energy facilities. A well-defined approach for constructing a waste-to-energy system is essential to initiate a massive undertaking (Fig. 6). The study of feasibility, designing

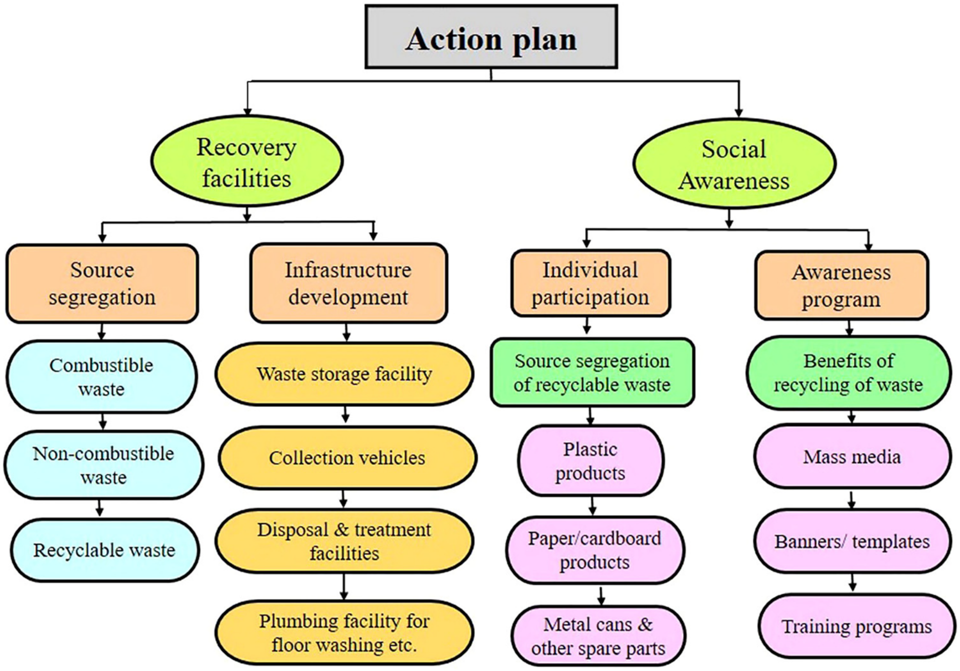

Fig. 6 Strategies for effective municipal solid waste management.[167]

a construction phase, and operational phases are included as the different phases of the project. The feasibility study is the first step in the development of a waste-to-energy facility; here the scope and aim of the project are outlined.[155] The economic, technical, social, environmental, and legal feasibility are the elements of a waste-to-energy facility. The economic viability of the waste-to-energy techniques includes several factors such as analysis of cash flow incurred in the design of the project, construction cost, maintenance cost, operating cost, and annual income.

Global energy developers and consultants, countries experienced in waste-to-energy techniques, literate, global financial institutions, *etc.*, are the sources of data for the revenues and expenses of waste-to-energy techniques.[25] The approaches for economic analysis such as present value, reimbursement time, and international rate of yield can be used in the development of waste management approaches. A thorough analysis of the initiatives for financial needs and earnings is required.[156] The evaluation of the present status of the waste-to-energy technique and the prediction of the characteristics of municipal solid waste are performed through technical evaluations.[157] The identification of the most efficient and appropriate waste-to-energy techniques considering both prospects and limitations can be performed by comparing the different waste-to-energy techniques which can be done through an intangible but inclusive design that assesses the rational cost and project timeline for various waste-to-energy techniques.[158] The assessment of the cogeneration potential and heat generation is essential to optimize the energy yield.[159] The technical feasibility is evaluated by estimating the quantity of recycled waste, suitability of thermal treatment of wastes, efficiency of the technology, and the time required for the operation of the facility.[160] The environmental assessment will be performed for the selected waste-to-energy technique by collecting the different ecological baselines for this process such as information on the ecological and geographical area.[161] An assessment of the potential contamination of noise, air, soil, surface, and groundwater must be carried out.

A list of potential solutions must be developed and estimations of the time and cost must be determined.[162] A social assessment is important for assessing the social context of the project, ensuring its success. The recycling of municipal solid waste and the construction of plants must be carried out in proper time. The conventional and non-conventional waste-to-energy techniques must be favored for the recycling of materials while landfilling must be minimized.[163] The anaerobic digestion and composting are followed for organic waste, whereas the non-recyclable waste can be processed by hydrothermal technologies and gasification. Decentralized waste-to-energy facilities can be a feasible approach for a continuous supply of municipal solid waste.[164] The handling of solid waste must be performed carefully, and a huge amount of municipal solid waste can be treated instead of landfilling which is not a viable approach for waste treatment. To make non-conventional waste-to-energy methods more cost-effective, facilities should be equipped to produce valuable by-products such as organic acids, syngas, and pyrolysis-derived materials.[165]

Hydrogen, fuels, and chemical compounds are the valuable end products. The improvement in the capacity of plants by feeding by-products such as slag in plasma gasification, development of methodology of lean manufacturing, and assimilating energy to reduce energy costs are the cost-cutting techniques that can be implemented for waste management.[166] There is a need for the feasibility analysis of vital processes and design configuration. The generation of products and the economy of the process must be improved by effective process design, critical decision, optimization, and modifications in the technological stages. These investigations are significant before their implementation at the industrial level and must be performed with the support of academia and industry at the pilot and laboratory scales. It is essential to support a range of stakeholders such as industry, local governmental bodies, and investment corporations for the acceptance of waste-to-energy systems by the customers and community.

6. Challenges for waste-to-energy techniques

There has been an exceptional increase in the global generation of solid waste with a significant portion being generated from the developed countries. Moreover, factors such as population growth, urbanization, and technological advancements have significantly contributed to a surge in the generation of municipal solid waste.[168] Besides the generation of electricity, the gap between the demand and supply of energy is another problem arising due to the increasing population, particularly in developing countries. Fossil-based resources like oil, coal, and natural gases are a central part of conventional energy production. To fulfill the current energy demand, approximately 84% of the global energy is supplied from fossil fuels.[169] The usage of fossils for the production of power is not considered environmentally friendly due to their environmental issues. Public apathy and lack of awareness are some of the social challenges for waste management in developing countries. The community is facing the issues of implementing recycling activities and waste segregation. These issues are more severe in developing countries due to the limited resources and growing population. There is still a lack of awareness of environmental and public health risks associated with mismanagement of waste.

The current practices of waste management are ineffective due to the high quantity of waste production. It is reported that nearly 30–90% of the waste is disposed of in landfills, with Latin America, Africa, and the Caribbean as the leading generators.[170] Due to the emission of greenhouse gases, the improper collection and disposal of waste is a major threat to the environment; besides, urbanization and industrialization are creating problems for the available land. The valorization of waste is an effective approach that can effectively deal with the issues of energy crisis, climatic changes, and available land, thereby ensuring effective waste management. Moreover, the strategy can reduce the emission of toxic gases from landfills and mitigate health-related issues that arise due to the contamination of soil, air, and land.[171] The majority of the developed countries have successfully implemented waste-to-energy management techniques, but the financial, technical, logistics and socio-eco-technical constraints are still hampering the implementation of waste-to-energy techniques in emerging nations (Fig. 7).[48] The lack of waste segregation, poor logistic support, and insufficient waste collection facilities are the challenges to the adoption of waste-to-energy techniques in emerging nations.

The physical and chemical nature of waste is crucial for estimating the calorific value of municipal solid waste. Insufficient knowledge about the characteristics of waste results in an improper selection of equipment and techniques and eventually a waste of time and effort.[163] The waste-to-energy techniques are expensive and require sophisticated equipment; also the developing countries are facing the problem of initiating investigations on the process of waste-to-energy conversion.[88] The cost of construction and maintenance of incineration facilities may be uneconomical and unreasonable for emerging nations; *e.g.* the high maintenance cost suspended incineration in Malaysia.[172] The financial incentives can promote investment in waste-to-energy sectors, making waste-to-energy technologies more attractive. The policies and regulatory framework must be introduced through legislative action to motivate the public–government partnership in the waste-to-energy sector.[173] The availability of feedstock is decisive for the effective execution of waste-to-energy systems. The authorities at regional and national levels across the countries must enforce strict penalties and sanctions on waste disposal as landfilling to

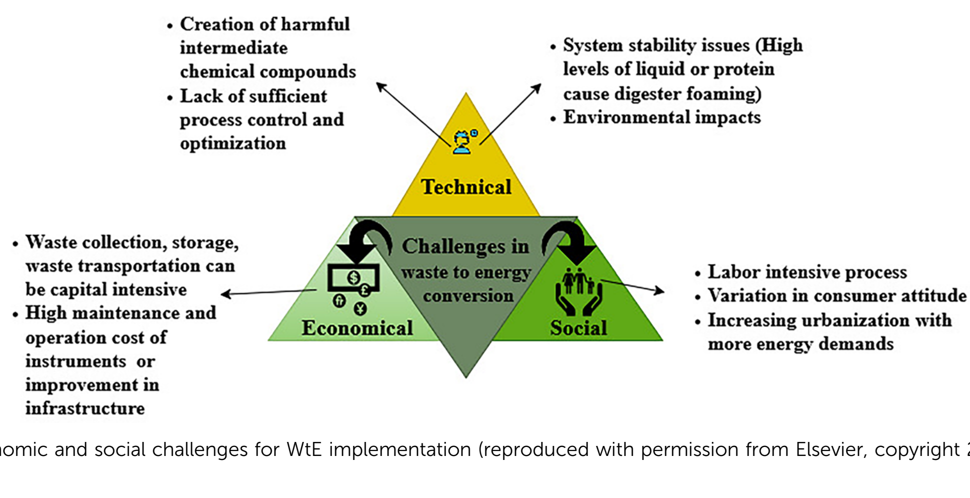

Fig. 7 Techno-economic and social challenges for WtE implementation (reproduced with permission from Elsevier, copyright 2021).[106]

maximize waste diversion from landfills and ensure the availability of feedstock for the implementation of waste-to-energy techniques.[174] The separation of waste can increase the calorific value and require less operating cost in comparison to the mixed waste type. The separation at source can ensure homogeneity in wastes and increase the practices of waste management at the community level and the cost-effectiveness of the waste-to-energy techniques.[175] The adoption of sustainable waste management practices through the implementation of waste-to-energy techniques is facing numerous challenges. The challenges arise from the different aspects of waste to energy chain, method of energy recovery, power generation, energy analyses, and techno-economic analyses.[176] The challenges associated with waste-to-energy techniques must be effectively addressed to promote a sustainable circular economy.

The shift towards a viable circular economy where the generated thrash is regarded as a valuable resource denotes a considerable footrace. A comprehensive waste management system is required to recover the recyclable and reusable materials from the generated waste.[177] The initiatives, policies, and government regulations are important factors in the establishment of waste-to-energy facilities.[25] However, these initiatives often face social restrictions due to public concerns. Siddiqi *et al.* have highlighted the challenges in the estimation of waste-to-energy chains to integrate economic and social benefits.[178] Thermal treatment methods such as pyrolysis, incineration, and gasification for municipal solid waste treatment are encountering several environmental challenges. Although incineration is a widely adopted technique, it suffers due to the low efficiency and high emissions which lead to the generation of toxic pollutants. Additionally, managing pollution effectively remains a major challenge in the incineration process.[179] However, pyrolysis and gasification are more effective and less polluting but they necessitate a primary investment and precise control of the condition to optimize the quality of syngas and minimize the production of tar.[180] Despite the potential of plasma gasification to treat the generated waste, its implementation is restricted due to operational cost and energy consumption, and the requirement for advanced material for handling extreme conditions.[181]

Rajendran *et al.* have discussed the economic barriers to the implementation of waste-to-energy technologies.[155] The uncertainty in economic returns, particularly within the public sector, is intensified due to the limited monetary support and the inadequate risk distribution mechanisms, posing major challenges to capital investment.[153] The environmental implications of the traditional waste-to-energy conversion technique are also a cause of concern. The researchers have demonstrated that the waste-to-energy technique significantly contributes to greenhouse gas emissions.[51] The effectiveness of waste-to-energy technologies in improving environmental conditions depends on the local conditions and specific processes; therefore, no particular waste-to-energy technique can be established as the standard.[182] The high moisture content in municipal solid waste poses a challenge for stable heat production, and blending it with high-heating fuels like coal can reduce this issue, but it increases the emission of toxic substances and air pollution.[183] The work has demonstrated that the integration of innovative technologies such as plasma gasification and chemical looping combustion presents implementation challenges.[184]

7. Prospects of waste-to-energy techniques

The authorities must improve the guidelines and offer incentives to inspire the adoption of waste-to-energy technologies. The formation of a supporting framework that promotes public–private partnerships and attracts investment from the private sector can assist in overcoming the financial risks and burdens.[25] Public awareness is important for the acceptance of waste-to-energy techniques. A comprehensive framework that integrates social, economic, and environmental considerations must be adopted to ensure efficient and sustainable resource utilization. The different waste-to-energy techniques are influenced by the techno-eco-socio and environmental factors (Table 3). The challenges in waste-to-energy techniques can be overcome by improvement in the preparation of feedstock and advanced sorting technologies.[174] Public participation in the segregation of waste can enhance the feedstock quality. The investigation into cleaner incineration technology like selective catalytic reduction systems and flue gas recirculation can reduce emissions and enhance the recovery of energy.[51] The optimization of the process parameters and implementation of a robust control system can maximize the quality and yield of the product in gasification and pyrolysis.[185] A better heat recovery system in support of plasma gasification in a cost-effective way can improve the viability of the process. The economic feasibility of these advanced waste management techniques can be increased by government incentives. Finally, the encouragement of industrial collaboration can enhance the sustainability and efficiency of the thermal treatment processes. A comprehensive analysis to select efficient and economic waste-to-energy technology for various regions and waste composition is important. The promotion of public–private partnerships can reduce the financial burden and risks associated with waste-to-energy projects. The government should offer support schemes and incentives to private sector ventures encouraging the commercialization of optimal pathways.[186]

WtE techniques offer several benefits for resource recovery and materials management by the transformation of waste into energy, decreasing the landfills, and supporting circular economy while lowering the environmental impacts. The advantages of WtE include the following: (i) decrease landfill reliance: WtE technologies, such as incineration and anaerobic digestion, can significantly reduce the landfill and therefore can conserve valuable land resources; (ii) energy recovery: WtE technologies can recover usable heat, electricity or fuel from waste materials and therefore provide an alternative source of energy and decrease the reliance on fossil fuels; (iii) resource recovery: WtE techniques facilitate the recovery of valuable

Table 3 Socio-eco and environmental implications of the waste-to-energy technique[187,188]

Parameters	Waste-to-energy technique				
	Anaerobic digestion	Landfill gas recovery technology	Incineration	Landfill gas	Pyrolysis
Waste type	Organic fraction	Mixed waste	Mixed waste	Homogeneous waste	Homogeneous waste
Technical					
Technology maturity	Very high	Very high	Extremely high	Emerging	Emerging
Waste volume reduction	45–50%	Low	75–90%	75–90%	50–90%
Technology complexity	Low	Low	Low	High	High
System efficiency	50–70%	10%	50–60%	70–80%	70%
Residence time	15–30 days	Years	2 s	10–20 s	Seconds to weeks
Labor skill requirement	Low	Low	Low	High	High
Land requirement	Large	Very large	Small	Small	Small
Pre-treatment	Required	Not required	Not required	Required	Required
Future potential	High	High	Moderate	High	High
Economic					
Capital cost	Medium-high	Low	Medium-high	High	High
Operation and maintenance costs	Medium-high	Low	Medium-high	High	High
Pre-treatment cost	Medium	None	None	High	High
Social and environmental					
GHG emissions	Least	High	Extremely high	Low	Low
Dioxin and furan emission	Extremely low	Extremely low	Very high	Very low	Very low
Social opposition	Very less	Less	Extremely high	High	High

resources and therefore promote circular economy; (iv) environmental benefits: WtE techniques assist in the minimization of carbon and methane emissions from landfill as well as soil pollution; (v) circular economy: WtE techniques support circular economy by transforming waste into a valuable resource and as a result reduce the generation of waste and promote resource efficiency; (vi) production of sustainable energy: by transforming waste into energy, WtE techniques contribute to the production of sustainable energy and reduce the environmental impact of traditional practices of waste management. WtE techniques enable the recovery of resources and energy, reduce waste, and create economic benefits. The techniques that divert the waste from landfilling reduce the environmental impact and are favorable for the recovery of energy and resources. The WtE techniques generate electricity and heat which provides an alternative source of energy. Moreover, the techniques can create jobs in the waste management sector and therefore provide economic benefits. The technique integrates a circular economy for a closed-loop system where the waste is recognized as a valuable resource, reducing the extraction of new resources.

Life cycle assessment (LCA) has emerged as a useful tool to estimate and associate the environmental impacts of waste-to-energy technologies and assist in the optimization of the parameters to decrease greenhouse emission and carbon footprints. Technological and environmental factors significantly

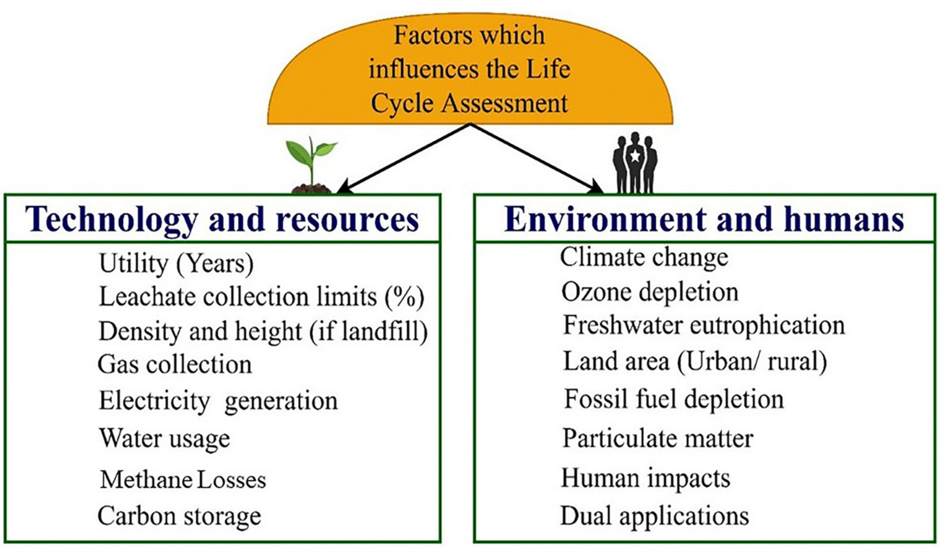

Fig. 8 Factors that affect the life cycle assessment (reproduced with permission from Elsevier, copyright 2021).[106]

Table 4 Summary of life cycle assessments

Source	Dong *et al.*[51]				Demetrious and Crossin[198]		
WtE technology	Incineration	Pyrolysis	Gasification	Gasification with ash melting	Landfill	Incineration	Gasification–pyrolysis
Feedstock	Residual MSW	MSW, industrial sludge, sewage sludge	Solid refuse fuels	MSW	Mixed paper and mixed plastics		
Feedstock LHV	10.307 GJ per ton				Mixed paper: 14.1 MJ kg^{-1}; mixed plastics: 30.8 MJ kg^{-1}		
Primary product/output	Electric power				Electricity		
Net electricity recovery efficiency	17.70%	17.70%	27.40%	16.70%	35%	15.84%	32%
System boundary	Waste pre-processing, thermal transformation, energy capturing, air pollution control (APC), and solid residue management				Waste processing, electricity production, and disposing byproducts/waste		
Functional unit	Thermal treatment with electricity recovery of one (1) ton MSW				Thermal treatment with electricity recovery of one (1) kg MSW		
Additional information	—				Mixed paper: 10% newspaper and 90% packaging paper containing an average moisture of 11.2%, carbon composition of 40%, nitrogen composition of 0.3% and sulfur composition of 0.1% Mixed plastics: average moisture of 15.3%, carbon composition of 63%, nitrogen composition of 0.6% and sulfur composition of 0.1%		
LCA software	Gabi 8.0	SimaPro 8.0.4					
Life cycle impact assessment method	CML 2001 method	—					
GWP (kg CO_2 eq. per unit)	172	151	104	422	Mixed paper: 1.56 Mixed plastics: 1.51	Mixed paper: 1.03 Mixed plastics: 8.98	Mixed paper: 1.02 Mixed plastics: 1.87

Source	Khoo, H. H.[199]							
WtE technology (% of total waste)	Material recovery: 7% incineration: 93%	Material recovery: 11% incineration: 89%	Material recovery: 7% incineration: 89% pyrolysis: 4%	Material recovery: 7% incineration: 84% gasification: 9%	Material recovery: 7% incineration: 80% pyrolysis: 4% gasification: 9%	Material recovery: 10% incineration: 77% pyrolysis: 4% gasification: 9%	Material recovery: 10% incineration: 83% pyrolysis: 7%	Material recovery: 11% incineration: 71% gasification: 18%
Feedstock	Mixed plastic waste							
Feedstock LHV	—							
Primary product/output	Electricity							
Net electricity recovery efficiency	—							

Table 4 (*continued*)

Source	Khoo, H. H.[199]							
System boundary	Waste production and centralized collection, circulation of plastic wastes to various recycling and WtE options, and byproducts/waste disposal							
Functional unit	Thermal processing with electricity recovery of one (1) kg MSW							
Additional information	Mixed plastic waste composition: 40% PE, 17% PVC, 12% PP, 4% PS, 4.8% PET, and 22.2% other mixed fractions							
LCA software	GaBi							
Life cycle impact assessment method	ReCiPe							
GWP (kg CO_2 eq. per unit)	0.940	0.921	0.929	0.911	0.900	0.866	0.902	0.872

Source	Maghmoumi *et al.*[182]				Ramos and Rouboa[156]		
WtE technology (% of total waste)	Incineration: 100%	Landfilling: 100%	Incineration: 50% landfilling: 30% material recovery: 20%	Incineration: 30% landfilling: 50% material recovery: 20%	Incineration	Gasification	Plasma gasification
Feedstock	MSW				MSW		
Feedstock LHV	8.4 MJ kg^{-1}				—		
Primary product/output	Electricity				Electricity		
Net electricity recovery efficiency	21%				—		
System boundary	—				MSW processing, gas cleaning, power production, waste/byproduct disposal		
Functional unit	Treatment with electricity recovery of one (1) tonne MSW				Thermal treatment with electricity recovery of one (1) tonne MSW		
Additional information	GHG emanations was calculated using the IPCC method and complete mechanical treatment analysis				Waste composition (wt%): organic (37.57%), paper (10.47%), plastics (12.10%), metals (2.45%), glass (5.53%), textiles (16.46%), others (15.42%)		
LCA software	—				GaBi		
Life cycle impact	—				CML 2001		
GWP (kg CO_2 eq per unit)	−85.67	41.42	−97.98	−72.56	−170.9	27	−31

Source	Dastjerdi *et al.*[41]					
WtE technology	Landfilling	Incineration	Food waste: anaerobic digestion Combustible and non-combustible: landfilling	Food waste: anaerobic digestion combustible: incineration Non-combustible: landfilling	Food waste: anaerobic digestion combustible: incineration plastic waste: recycling Non-combustible: landfilling	Food waste: anaerobic digestion combustible: gasification plastic waste: recycling Non-combustible: landfilling

Table 4 (*continued*)

Source	Dastjerdi *et al.*[41]					
Feedstock	Residual MSW					
Feedstock LHV	8.91 MJ kg^{-1}					
Primary product/output	Electricity					
Net electricity recovery efficiency	—					
System boundary	Residual MSW treatment, electricity production, and byproducts/waste disposal					
Functional unit	Treatment with electricity recovery of one (1) tonne residual MSW					
Additional information	—					
LCA software	OpenLCA 1.9 and by employing Ecoinvent V3.5					
Life cycle impact assessment method	ReCiPe 2016 midpoint and endpoint hierarchist methods					
GWP (kg CO_2 eq per unit)	+	–	+	–	–	–

Source	Zhao *et al.*[181]				
WtE technology	Rotary kiln incinerator	Pyrolysis incineration	Plasma melting	Steam sterilization	Microwave sterilization
Feedstock	Medical waste				
Feedstock LHV	—				
Primary product/output	Electricity				
Net electricity recovery efficiency	—				
System boundary	Medical waste treatment, flue gas purification, energy recovery, and byproducts/waste disposal				
Functional unit	Disposal of one (1) tonne medical waste (MW)				
Additional information	Electricity consumption: 172.10 kW h per ton MW	Electricity consumption: 151.91 kW h per ton MW	Electricity consumption: 539.64 kW h per ton MW	Electricity consumption: 539.64 kW h per ton MW	Electricity consumption: 127.88 kW h per ton MW
LCA software	—				
Life cycle impact assessment method	—				
GWP (kg CO_2 eq per unit)	420	187	686	165	135

affect the LCA of WtE techniques (Fig. 8). The integration of LCA into policy-making confirms that the consideration of the environment is prioritized in the planning and implementation of waste-to-energy projects (Table 4).[189] The estimation of carbon emission by additive-subtractive integrated hybrid manufacturing (ASIHM) has found a reduction in carbon emission by 80% in comparison to the conventional subtractive manufacturing technique.[190] The pretreatment of municipal solid waste decreases the moisture content thereby improving the combustion properties. The exploration of alternative methods for power generation such as fuel cells and gasification can decrease the dependency on coal and fossil fuels.[183] The implementation of hybrid power generation arrangements that integrate numerous technologies can decrease emission and improve overall efficiency.[191] To identify the improvement and optimization a detailed analysis of the energy and exergy for the different waste-to-energy technologies is important.[184] The investigation of the integration of technologies in waste-to-energy systems offers the implementation of best practices and improves the efficiency of waste-to-energy facilities. The LCA system boundary is the interface between the environment and the waste management system. The life of any product ends up being a waste once the product is discarded. The mechanical-biological treatment systems that generate refuse derived fuel (RDF) offer renewable energy sources and reduce landfills. The ash produced in thermal treatment is dumped in a landfill. Material recovery allows for the extraction of various reusable materials, reducing the amount of waste that ends up in landfills (Fig. 9). The sensitivity analysis and cost–benefit analysis can be carried out for LCA.[192] A systematic and comprehensive approach consisting of financial incentives, regulatory support, technological advancement, and regulatory support is essential to address the challenges in waste-to-energy systems. The communities, governments, and private sectors must work together to form a sustainable framework that can effectively optimize waste management practices and offer economic and environmental advantages of waste-to-energy technologies.[193]

Integrating technologies such as biopolymer production, large-scale biomass conversion, and waste-to-energy systems can be an effective approach to treat municipal solid waste for the generation of electricity.[194] The development of biorefineries for the recovery of municipal solid waste is an essential aspect of sustainability.[195] The waste-to-energy method provides a feasible approach for municipal solid waste; and offers various environmental and economic advantages. The waste-to-energy system minimizes the volume and mass of disposal of municipal solid waste by 90% and 80%, respectively.[196] The waste-to-energy system offers sustainability through the recovery of energy and reduces the fraction of landfills.

8. Conclusions

Due to the cumulative amount of municipal solid waste, environmental pollution, economic sustainability, *etc.*, there is a global concern for the management of solid waste. The work has comprehensively summarized the different aspects of the WtE systems and highlighted the potential of WtE techniques for energy recovery and reducing the detrimental impact of different types of municipal solid waste. The disposal of municipal solid waste in a cleaner way is crucial to overcoming

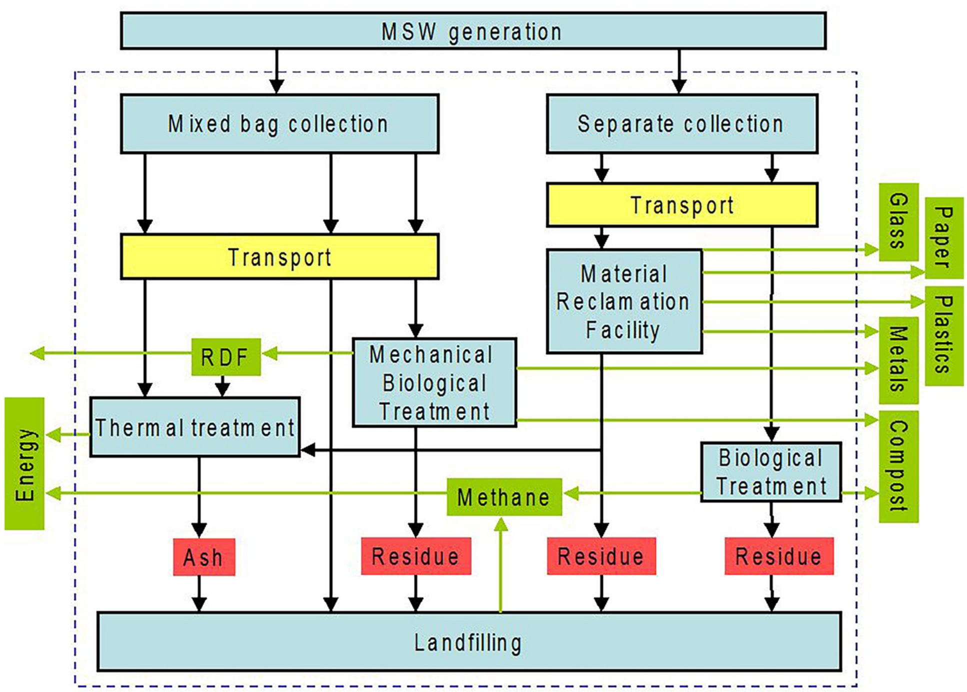

Fig. 9 Life cycle assessment of municipal solid waste.[197]

the issues due to the mismanagement of solid waste. Biomass occupies about 57% of municipal solid waste, highlighting the significance of biomass for energy recovery. WtE techniques generate employment besides reducing the landfill and emission of methane and environmental pollution. The incineration of plastic waste is an economical way of managing waste but suffers due to the emission of various toxic substances and low-conversion efficiency. The implementation of thermal treatment can reduce the volume of generated waste by 90%. The lack of economic feasibility is an obstacle to the large-scale implementation of various waste-to-energy techniques. The involvement of the private sector could provide a more optimal pathway for energy conversions. The high organic content is a primary concern, and its appropriate disposal is important. The generated plastic waste is a sustainable source of energy. The support from the government, local bodies, and public participation can promote WtE practices. In lower-income countries, food waste occupies a considerable fraction; therefore biochemical techniques are preferred to produce biofuels and fertilizer. Recycling is the preferred way for the management of waste plastics. The gasification of the organic municipal solid waste to generate hydrogen is more favorable for the hydrogen economy. To meet the increasing demand for biofuels, the yield of biofuel by the pyrolysis process is significant. The combination of waste-to-energy conversion techniques can increase the overall efficiency of the plant operating with different proportions of MSW feedstock. The authorities must implement policies and provide incentives to attract the different sectors for the investigation of WtE projects. Moreover, the integration of the socio-economic and environmental aspects in WtE is pivotal for a comprehensive evaluation of waste-to-energy techniques. The introduction of advanced techniques for segregation and sorting to enhance the quality of feedstock, exploration of novel pathways for different wastes, implementation of techniques for tracking wastes, and development of community-based programs to enhance public participation in the recovery of energy are critical steps. These initiatives will favor the circular economy and reduce environmental pollution. The life cycle assessment has demonstrated that the WtE method can recover up to 27.40% of energy.

The review suggests that advanced thermochemical techniques particularly combined with recycling increase the volume of energy recovery besides reducing landfilling. Sustainability in waste management can be achieved without any dependency on incineration. The work has provided insight into the qualification of waste management practices. The effectiveness of waste management practices can be demonstrated by the recovery of the resource, decreased landfilling, and enhanced production efficiency. The review has provided vital information to assist in the development of more sustainable practices of management waste and paves the way towards a circular economy to potentially increase the recovery of energy.

9. Future scope

The work for the implementation of novel and efficient WtE practices and optimization of the economic viability of the current waste management practices is the future scope of waste management. Future work should focus on the scaling of these practices and exploration of their practical implications. Additionally, the social and environmental impact of waste-to-energy practices through regular monitoring along with the in-depth examination of the public dynamics in the areas hosting WtE facilities must be explored. Furthermore, future research should investigate the ramifications of this combination for logistics, the economy, and the environment. The long-term performance and scalability of WtE are not effectively demonstrated, which can be an area of future research. Future studies should also examine the long-term environmental and social effects of WtE implementation. This calls for ongoing observation as well as a thorough analysis of community dynamics in areas where WtE plants are located. More research into the scalability and reproducibility of effective models as well as an examination of new WtE technologies can help create waste management plans that are more resilient and flexible.

Abbreviations

ASIHM	Additive-subtractive integrated hybrid manufacturing
CHP	Combined heat and power
CIE	Compressed ignition engine
ICE	Internal combustion engine
LCA	Life cycle assessment
LCOE	Leveled cost of electricity
LFGR	Landfill gas recovery technology
LHV	Lower heating value
MGT	Micro gas turbine
MSW	Municipal solid waste
MW	Medical waste
RDF	Refuse derived fuel
SIE	Spark ignition engine
SOFC	Solid oxide fuel cell
WtE	Waste-to-energy

Author contributions

Ashish Soni: conceptualization, drafting-original draft, visualization, writing – original draft, formal analysis; Sonu Kumar Gupta: writing – original draft, writing – review & editing, visualization; Natarajan Rajamohan: writing – review & editing; Mohammad Yusuf: writing – review & editing, formal analysis, supervision.

Data availability

Data sharing is not applicable as no data were created in this article.

Conflicts of interest

There is no personal or financial conflict of interest among the authors in this work to declare.

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