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Original Research Paper

Comparative Evaluation of Municipal Solid Waste Treatment Technologies: A Comprehensive Review and Sustainability Assessment Using Analytic Hierarchy Process

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Abstract
Rapid urbanization, increasing population density and changing consumption patterns have intensified municipal solid waste (MSW) generation, making sustainable treatment selection a complex multi-criteria decision problem. This study presents a comprehensive review and sustainability assessment of major MSW treatment technologies with emphasis on stream-wise treatment planning for urban local bodies. The review covers biological treatment, thermal conversion, recycling/material recovery and special urban waste streams, including vermicomposting, mechanical composting, bio-methanation, waste-to-energy, plastic recycling, construction and demolition waste processing, hazardous waste treatment, e-waste processing and biomedical waste management. The sustainability performance of treatment alternatives was evaluated using the Analytic Hierarchy Process (AHP) based on four criteria: initial cost, operation and maintenance cost, environmental positive impact and social impact. The criteria weights indicated that environmental positive impact received the highest importance, followed by operation and maintenance cost, social impact and initial cost. The consistency ratio of the AHP matrix was below the acceptable threshold of 0.10, confirming the logical consistency of the decision model. The AHP-based ranking showed that bio-methanation achieved the highest sustainability priority, followed by waste-to-energy and mechanical composting. Bio-methanation was found most suitable for segregated wet organic waste due to its energy recovery potential, digestate generation, landfill diversion and social benefits. Waste-to-energy was suitable only for dry combustible rejects or RDF after source segregation and material recovery. The study concludes that sustainable MSW management cannot be achieved through a single treatment technology. Instead, a stream-wise integrated treatment framework is required, where each waste fraction is matched with an appropriate technology based on waste characteristics, resource recovery potential, operational feasibility and environmental sustainability.
Keywords: *C&D waste; E-waste, Sustainable waste treatment; Vermicomposting; Waste to energy, AHP;*

INTRODUCTION

The UN Department of Economics and Social Affairs, and World Population Prospects (2024) projected that 68% of the global population will be expected to live in the urban areas by the year 2050 [1]. Although, in the current urban environmental challenges, Municipal Solid Waste Management (MSWM) is the most listed and concentrated issue caused due to large populations of uncontrolled urbanization, industrial growth and varying consumption patterns across the globe. The issues are not limited to the waste management but also the unsustainable treatment methods or process which affects natural environment causing air and water pollution, land degradation and climate change which ultimately impacts human health, plants and animals [2, 3]. The urban local bodies are facing the challenge to provide the services to the issue not only to manage the waste but to manage it scientifically, with less environmental impact, less emissions and no threat to human and animal life in future. Waste management outlook report 2024 shows global waste quantity increase with annual rate of 2 billion tonnes and it expected to grow 3.8 billion tons per annum till 2050 [4]. An inadequate waste management facility, lack of planning, weak regulation and enforcement of the laws are issues in the low-income group foster environmental degradation [5]. Management of MSW is largely an environment and socio-political issue [6]. In MSWM the landfill and incineration are the widely used methods which are cheapest in operation. Incineration is most popular method since it reduces waste volume and produces energy. Hence landfill management with other complementing method used as long term solution for waste management globally [6 ,7].

Waste recycling and reuse are the most common practices of waste management, further waste is treated through the process such as biological conversion, waste to energy and ultimately landfill [8, 9]. Waste collection to treatment and disposal of residue are coming under material flow in MSW. Figure 1 shows segregation at source, and processing of materials such as organic, plastic, paper, metal, and other specific flows to separate out for the reuse or recycling or going for set treatment process [10,11]. Waste management is largely practiced to recycle nutrients through biochemical conversions; non-recyclable biomass uses in thermal processes and remaining inert material is landfilled are shown in the following sections in a diagrammatic flow [12].

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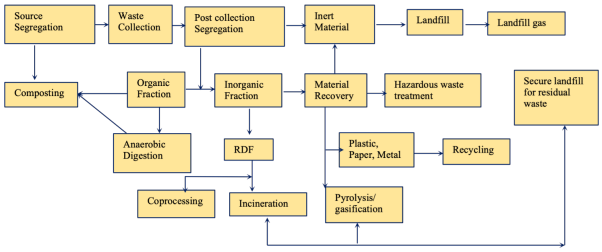


Figure 1: Overview of material flow in MSW treatment

Various environment and waste management related goals are set under the Sustainable Development Goals (SDG 2030) includes clean water and sanitation, responsible consumption and production, climate action, life below water and life on land [13]. An integrated approach for MSWM has been suggested and recommended in the Asian countries [14]. It includes national policies and legal frameworks, institutional arrangements, appropriate technologies, operational and financial management, public awareness and participation etc. However, the criteria for measuring the sustainability of waste management through any methods are like processing waste quantity, compliance requirement, time taken for composting, complexity and skill required, demand for final products, initial investment, operating cost, land requirement and also the impacts such as odour, water contamination, dust and air pollution etc. [15]. Solid waste treatment is the most crucial and essential part for MSWM. Prior to the regulations on MSW the waste was largely removed and disposed in landfill areas of cities due to concern of public health issues. Post the rules of SWM and knowing the waste hazards various disposal techniques are evolved for the urban areas. The modern technologies are largely focusing on the material recovery and energy production from the wastes [14]. However, there are no ideal or specific waste treatment process for the waste, because different waste type needs different methods. Similarly, the climate, geography, culture, capital for technology implementations are essentials for the treatment. In case of India, though the collection efficiency has reached around 70-90% the treatment efficiency has not above 28%. Also due to large waste quantum waste management is difficult for various cities [15]. Considering such issues, present study is envisaged to understand various treatment methods and sustainability parameters amongst various waste treatment methods adopted and applied globally for MSWM.

Recent studies indicate that municipal solid waste treatment selection cannot be treated as a single-technology decision because waste composition, source segregation efficiency, organic fraction, land availability, energy recovery potential, capital cost, emission-control requirements and social acceptance vary from one city to another. Therefore, multi-criteria decision-making methods such as the Analytic Hierarchy Process (AHP), fuzzy AHP, TOPSIS and hybrid MCDM approaches have been increasingly applied for MSW treatment planning. Previous studies have evaluated landfill site selection, incineration facility planning, composting, recycling, anaerobic digestion and integrated waste management scenarios. These studies confirm that AHP is useful for comparing alternatives under conflicting technical, environmental, economic and social criteria. However, most earlier studies focus either on landfill/incineration facilities or on specific local management scenarios. The present review differs by comparing biological treatment, thermal treatment, material recovery and special urban waste streams under a common sustainability hierarchy for Indian urban MSW planning. Thus, the study provides a decision-support framework to identify suitable treatment pathways according to waste type and sustainability priority. The novelty of this study lies in developing a stream-wise sustainability assessment framework for MSW treatment technologies in the Indian urban context. Unlike previous AHP/MCDM studies that mainly focus on landfill site selection, incineration facility planning or a limited number of disposal alternatives, this study compares biological treatment, thermal treatment, material recovery and special urban waste stream management under one sustainability hierarchy. The proposed framework clarifies that sustainable MSWM cannot be achieved by selecting a single universal technology; instead, each waste fraction must be matched with an appropriate treatment pathway based on environmental performance, cost feasibility, operation and maintenance requirements and social impact.

1. LITERATURE STATUS

A structured literature review protocol was followed to identify relevant studies, reports, guidelines and policy documents related to MSW treatment technologies and sustainability assessment. The literature search was conducted using academic databases and institutional sources such as Scopus, Web of Science, ScienceDirect, SpringerLink, Google Scholar, CPCB, MoHUA, UN-Habitat, UNEP and World Bank reports. The keywords used for searching included “municipal solid waste treatment,” “MSW sustainability assessment,” “AHP in waste management,” “bio-methanation of MSW,” “waste-to-energy,” “mechanical composting,” “vermicomposting,” “plastic waste recycling,” “C&D waste management,” “hazardous waste treatment,” “e-waste management,” and “biomedical waste management.” Studies published mainly after 2010 were prioritized to capture recent technological, policy and sustainability developments, while older foundational studies were retained where they provided basic concepts or established methods. The inclusion criteria were: studies focused on municipal solid waste or urban waste treatment, peer-reviewed articles or recognized institutional reports, studies discussing environmental/economic/social performance, and papers applying AHP, MCDM, LCA or sustainability assessment in waste management. The exclusion criteria were: papers unrelated to MSW, studies without treatment relevance, duplicate records, non-technical opinion articles and sources without sufficient methodological or policy relevance. The final literature

pool was categorized into composting, bio-methanation, waste-to-energy, plastic recycling, C&D waste, e-waste, biomedical waste, hazardous waste and sustainability assessment.

Table 1. Suggested Literature Screening Summary

Screening Stage	Description	Suggested Count
Records identified	Journal papers, reports, guidelines and policy documents identified from databases and institutional sources	160
Records after duplicate removal	Duplicate and repeated records removed	135
Records screened	Titles, abstracts and document relevance screened	120
Full-text documents assessed	Full articles/reports checked for treatment and sustainability relevance	105
Final documents used	Studies and official documents finally included in review and AHP justification	100

To synthesize literature on waste treatment processes various documents on MSW, peer-reviewed journals, policy and research documents, government reports etc. were assessed and scrutinized with different category of treatment as listed in Fig 2. Hence a systematic identification and evaluation of different research literature is made to understand global approach of sustainable waste management [16]. Keyword basis data had searched to get specific research articles in similar domain. The articles studied were largely published after 2010 onwards focusing changing technology and adopting new concepts or methods for waste treatment process. It also includes case studies, policy analysis, empirical data etc.

In this review current ongoing global level waste treatment processes are examined considering sustainability criteria. Hence, basic and advance technology for each category of waste is enlisted and the overview of the technology and its process is discussed to understand its long-term use in the context of sustainable MSWM. The current technologies used globally for MSWM are vermi-composting, mechanical composting, bio-methanation, waste-to-energy, plastic recycling, construction and demolition waste processing, treatment for hazardous waste, bio-medical waste, e-waste etc. A common waste treatment articles, case, guidelines, reports etc. segregated for the review have shown in the Figure. 2

Researches available on sustainability aspects are focusing largely on the methods of vermicomposting and technology such as waste to energy, CNG, plastic recycling etc. However, there are limited researches which are directly linked to the sustainability approach and most of them are covering environmental pollution aspects, emissions reduction, lifecycle assessment, or social aspect include stakeholder involvement for reduce, reuse and recycling of waste etc. The methods for defining sustainability are present basically with theoretical approach of social, environmental and economic aspects and no particular method to assess the sustainability of waste treatment available. Therefore, this review has deliberated use of the analytic hierarchy process in ascertaining sustainability parameters with the waste treatment.

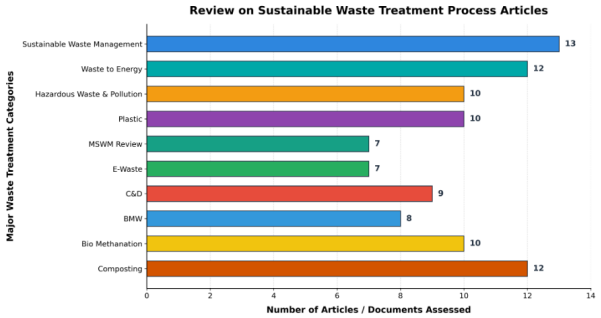


Figure 2: Domain specific articles, case study, guidelines, report, rules etc.

Evaluating sustainable waste treatment methods using Analytical Hierarchy Process (AHP): AHP is a multi-criterion-decision making model used to assess the sustainable method for waste management [17]. In AHP, identifying a problem statement and structure it for making a decision hierarchy is the first step and further the Saaty's scale (1–9) is applied, this gives priority weights and lastly validate it by calculating the consistency ratio. In this multicriteria decision model we used four criteria i.e. C1- Initial Cost, C2- Operation and Maintenance cost, C3- Environmental Positive Impact and C4-Social Impact, which are compared to the pillars of sustainability i.e. economic, environment and social.

Table 2: Previous AHP/MCDM Studies on MSW Treatment Selection

Author /Year	Method Used	Alternatives / Scope	Major Finding	Gap Addressed by Present Study
Sun et al. (2020)	AHP	Sustainable MSW management options for Bangkok	AHP was used to prioritize MSW options using sustainability criteria.	Present study applies the sustainability hierarchy to multiple MSW treatment streams in the

Author /Year	Method Used	Alternatives / Scope	Major Finding	Gap Addressed by Present Study
				Indian context.
Gunamantha et al. (2023)	AHP	Organic waste processing alternatives for small cities	Organic waste technology selection depended strongly on environmental and technical criteria.	Present study expands beyond organic waste and includes thermal, material recovery and special waste streams.
Gaur et al. (2022)	Fuzzy TOPSIS / MCDM	Landfill, incineration, biomethanation, composting and recycling scenarios	A combined biomethanation and landfill scenario performed better than single-treatment options.	Present study uses AHP to build a broader stream-wise sustainability ranking.
Mallick et al. (2021)	GIS + Fuzzy AHP + MCDA	Municipal landfill site suitability	AHP-based weighting improved landfill suitability mapping and decision support.	Present study focuses on treatment technology selection rather than only landfill siting.
Coelho et al. (2017)	Critical review of MCDM applications	Solid waste management decision problems	MCDM helps decision-makers handle multiple conflicting waste management criteria.	Present study applies this decision-support concept directly to treatment alternatives.
Gutierrez-Lopez et al. (2023)	Systematic review of MCDM and sustainability indicators	Solid waste management frameworks with social indicators	Social aspects and stakeholder involvement remain limited in many MCDM waste studies.	Present study includes social impact and livelihood opportunity in the AHP criteria.

The literature review shows that AHP and other MCDM methods are widely used in solid waste management; however, a large number of studies are restricted to landfill site selection, incineration facility planning or individual waste treatment technologies. Limited studies compare multiple treatment streams under a single sustainability framework that includes environmental benefit, economic feasibility, operation and maintenance requirements, and social impact. This gap is important for Indian urban local bodies because MSW generally consists of organic wet waste, dry recyclables, combustible rejects, inert residues and accidentally mixed special waste streams. Hence, the present study develops a stream-wise AHP-based sustainability assessment to compare treatment alternatives and support practical decision-making for integrated MSWM.

2.1 Research Gap

The reviewed literature confirms that AHP and other MCDM methods are widely used in waste management decision-making; however, most existing studies are limited to landfill site selection, incineration planning, organic waste treatment or city-specific alternatives. Few studies provide a combined framework that compares biological treatment, thermal treatment, recycling, material recovery and special waste streams

under a common sustainability hierarchy. This gap is important in the Indian context because MSW is often heterogeneous and contains wet organic waste, dry recyclable materials, combustible rejects, inert residues and occasionally mixed hazardous or biomedical components. Therefore, a stream-wise AHP-based sustainability assessment is required to support technology selection according to waste characteristics rather than treating all waste fractions through one common route.

2. VARIOUS TREATMENT APPROACHES

2.1 Vermicomposting

Vermicomposting is a process of non-thermophilic action of earthworms and other bacteria to produce fertilizer from the organic waste called compost or vermicompost. While in decomposition process earthworm aerates the soil, fragments the surface of organic waste residue and the microbes further increase the surface area hence speeds up the decomposition process.

The nutrient rich manure formed during the process helps plant for its growth. Vermicomposting is an alternative for solid organic waste from urban areas and converting it into useful resource for agriculture sector and one of the eco-friendly or natural method of composting [18 19]. The process of vermicomposting is shown in Figure 3. An effective waste management practice involves negligible environmental impact and minimum cost of operations. Vermicompost is the natural by-product of worms and helpful for soil as it retains soil moisture and holds the nutrient for long period [20]. Considering the environmental issues and the waste management norms vermicomposting is an appropriate solution for organic fractions of municipal solid waste (OFMSW) includes food waste, paper, garden waste. However, the use of compost generated from earthworm is recommended for the use of agriculture purposes [21]. Vermicomposting method has large advantages over the conventional method since it produces high quality fertilizer for agriculture [22].

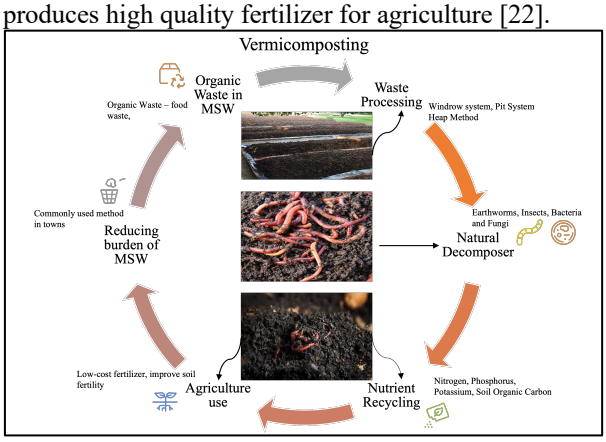


Figure 3: Vermicomposting process for organic waste

For the sustainable waste disposal of compost generated is essential part because it is evident that the compost produced in urban areas is not utilized at larger scale and dumped as it is. However, the vermicompost made using the earthworm has high market demand due to the essential nutrients present in it. The urban local bodies are investing in innovative technologies for the organic waste where the use of vermi-compost is largely a cost effective and sustainable solution as it recycles and reuse nutrients in environment, keeping human health (safety in processing of waste) and food security by using it as fertilizer [23]. In MSW the increase of organic waste and its accumulation is evidential in one side whereas the need for bio-fertilizers like vermicompost, reducing soil quality are other issues in agriculture sector. A balance can be achieved by use of the vermicompost for regaining the quality of soils and reducing burden of organic waste disposals from city areas [24].

Vermicomposting methods are generally of two types small scale and large scale, the small models are cylindrical, or square 2/3 units used at household level while large models are windrow, bio-reactor, outer-bin or plane system etc. these are commercial models of composting techniques used at the municipal level. In few cases earthworm is used for treating the organic sludge, where the researcher mentioned the beneficial aspects such as no mechanical or electrical equipment, less maintenance, and minimum operation and maintenance cost. However, the constraints are requirements of land (high compared to mechanical processing plants), maintaining the external conditions and process understanding etc. [25].

2.2 Mechanical composting

It is an appropriate method for areas where population size exceeding 0.5 million [26]. Mechanical composting process is a two-step process where conventional practice uses at initial level and in second stage particle size, separation, removal of inorganic content and lastly packing of finished product is carried out. In Indian cities composting is largely practiced for organic waste management, Indore model, Bangalore model, INORA these are examples set in composting field. A mixed method of vermicomposting and bio-inoculum used for experimenting the post-consumer waste such as artificial paper banana leaf waste shows addition of bacillus species increase the rate of degradation of waste and recovery of high nutrient value [27]. Process under mechanical composting has been shown in the figure 4.

Composting is largely used method for waste management since it is a low-cost technology for high volumes of organic waste. Most of the cities in India such as Hyderabad, Bangalore, Mumbai, Faridabad has been using the composting technology for the municipal organic waste disposal [28, 29].

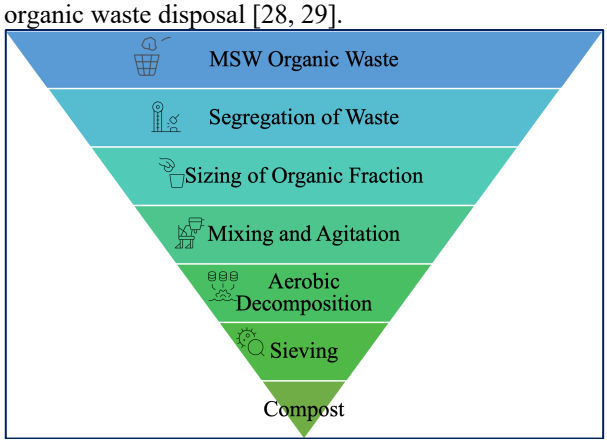


Figure 4: Mechanical composting process for organic waste

The presence of multiple waste component such as organic or inorganic and degradable or non-degradable in the municipal solid waste becomes difficult to manage hence the process of mechanical composting applies at various municipal waste treatment plants. In such processes large objects remove at the primary stage and mainly organic material feeds into to the machinery for further process. The large volumes of waste moved and processed through large machinery on plants to enhance composting process. The waste is kept moistened, turned for aeration, grind or crushed to reduce particle size, spraying of bacterial culture for fast process are mandatory steps of mechanical composting [30]. Composting is an attractive and less expensive method of treatment.

2.3 Bio-methanation

Bio-methanation is the most suitable methods for the rural and urban household waste management [31]. It is a promising eco-friendly solution for the organic waste to produce bio-energy and a fuel for the food/dairy industries or MSW where large proportion of biomass is generated. This method of waste processing captures the GHG emissions as well. Hence, it resolves issue of organic waste and a sustainable energy source for the future [32, 33, 34]. Figure 5 shows Bio-methanation process flow.

Challenges of bio-methanation such as high initial cost, maintenance cost, skilled work force, continuous supply of waste, regulations and safety etc. The operational challenges are disposal of bio-solids and slurry water, no market for compostable products, odour etc. [35]. These issues can be resolved when plant runs on high quantity and commercial scale. A case of Indore where successfully 20TPD plant run by private agency utilizing gas for the automobiles and it gets higher price than compost. Similarly, In Canada, and Sweden it has seen from the economic models for quantification of cost benefit analysis where for the process capacity of 10000 Kg /day the payback period is 2.2 years comparing the use of commercial LPG rate [36]. A sustainable waste management practices for Bangalore city highlights the three pillars of sustainability. Various studies showed that the potential of waste to bio-methanation under decentralize system are more profitable [37].

Bio-gas can be tapped by purification or without purification for energy purposes. Non-purified gas can be used directly for cooking needs, electricity generation etc. However, considering the need and potential of biogas generated it is compressed to methane CBG or converted to CNG after purification. Technology has improved further to store the carbon-dioxide and use for other purposes like fire extinguisher, beverages, refrigeration and cold storages. A smart city model proposed at the Delhi Municipal corporation uses two step approach with centralize and decentralize bio-methanation plant installations. In this approach at first stage centralize bio-gas installed which produce bio-gas and bio fertilizers. In the second step mainly the demand points or the decentralize plants are established and the bio-gas transported through the pipeline to the centralize one and in third step purification of gas is made to make CNG and bottling can be done similarly, CO_2 is separated and bottled for industrial applications [34, 38].

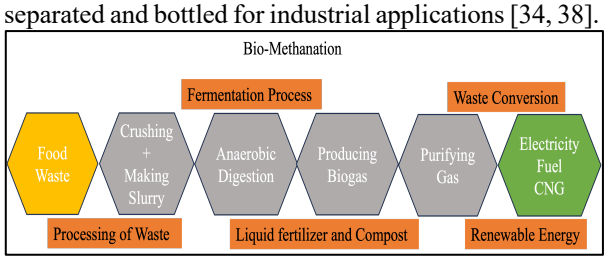


Figure 5: Bio-methanation process flow

Technologies such as membrane separation, water scrubbing, pressure swing adsorption and chemical scrub use for purification of bio-gas, removal and collection of gases etc. [39]. The government of India has published the guidelines and BIS standards for the specification of bio gas and its process for various substrates include MSW and it is considered under orange category of industries [40]. The promotion of CBG plants, subsidies, guidelines etc. is showing the positive impacts of CBG plants on energy sector, agriculture benefits (fertilizer production), waste management sector and overall economy of the region or country. Hence the use of bio-methanation plants will be a sustainable solution in long run for various sectors including municipal solid waste.

2.4 Waste to Energy (WtE)

In developing countries waste hierarchy and circular economy altogether can bridge the gap between waste management and energy demand [41]. Global researches on waste management have shown that there is increase in waste generation in developing countries and causes are rapid urbanization and changing lifestyle. This changing trend demands more energy for the fast economy, industry and urban settlements. Waste to energy is a midway for managing the waste and produce energy in the form of electricity. There are number of technologies producing energy from the waste include incineration, gasification, pyrolysis, biogas, landfill gas recovery etc as shown in Figure 6. About 800 Waste to Energy (WtE) plants operated globally till 2011. Incineration is the conventional treatment for recovery of heat in the form of electricity and it is the most preferred method for treating of MSW [35, 42, 43, 44]. Incineration differs from pyrolysis and gasification as it largely related to chemical value recovery, however combined process of pyrolysis gasification and combustion is more suitable for energy recovery from the waste [45]. Thermochemical conversions can covert waste biomass into various products range include Electricity, Methanol, Hydrogen, DME, Petrol and Bio-diesel [46].

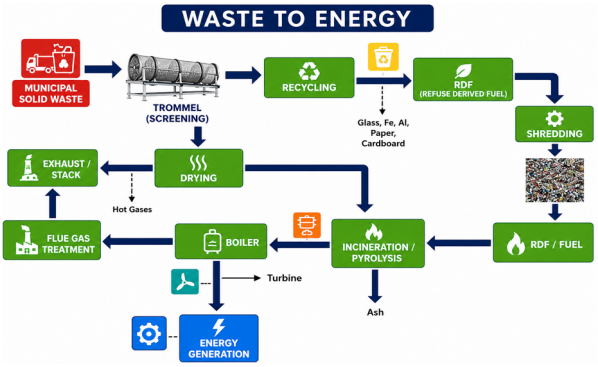


Figure 6: Waste to energy process flow chart

A comparison of waste to energy thermochemical process shown by Karmakar (2023) where the key parameters are operating temperature, pressure, environment, energy use efficiency, type of waste used etc. [47]. However, the different thermochemical technologies are incineration, gasification, pyrolysis and biochemical waste to energy processes are Anaerobic digestion and ethanol fermentation. The limitations and application/benefits of each technology vary based on the key parameters. In India, 1.5GW waste to energy plant potential available but only 2% of it is captured [48, 49]. Pre-processing of waste is done for MSW in Indian plants compared to UK. Whereas, the emission norms are stricter in European countries compared to India. The major challenge to operate the plant there is lack of financial support to operate the plant, policy gaps for waste to energy plant.

The calorific value of waste is low in India i.e. 1411-2150 kcal/kg as compared to Sweden, Norway, Germany and USA i.e. 1900-3800 kcal/kg [50]. Various parametric studies on incineration technology shows that power and energy ratio are largely depending on the incineration temperature. In similar way the parameter such as road infra, industry, climate, rainfall, population and population density, electric grid are also determining the success ratio of waste to energy plants [45]. Incineration helps to save land use, reduce leachate production as waste dumping reduces and minimizes environmental impacts as cleaner energy solution [35]. Though large benefits of economic and environment achieved through waste to energy plants, there are various challenges include regulation and technical standards, no suitable business model, lack of local technology and development, fly ash treatment and management, skill labour. Higher capital investments and lack of viable flue gas treatment technologies however, the local available energy cost is comparatively low. The technology is not applicable in all geographies. Considering these facts use of technology recommended in areas where operation and maintenance is possible i.e. availability of finances [44]. Waste to energy in hybrid mode i.e. anaerobic digestion along with the gasification technology is viable.

The success of waste to energy plant are largely governed through its operational, environmental, legal, and economic aspects. In the operational aspect along with technology a dedicated team of manager, engineer and technicians with proven capacity is important. Treating flue gases, dust and reducing air polluting parameters is an utmost requirement under environment aspect. The energy recovered is a carbon neutral as it made from the biomass in MSW. The legal binding of industrial or pollution control norms as per the state or nation can maintain the regularities in the operation of the plant. Economic aspect is the most important criteria of sustainability this include the capital investment, operational cost and the revenue generated from waste to energy plant [12].

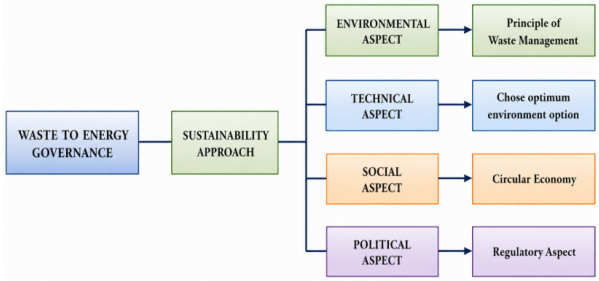


Figure 7: An approach of waste to energy novel model in developing countries

Figure 7 is showing an approach of waste to energy novel model that suggest overall sustainability aspects. In this approach environmental aspect focusing on use of economic instruments and polluter pay principle whereas the technology aspects are recommending optimum environment options i.e. resource recovery and best technical solution for waste treatment. Social aspects deal with the research, education and awareness and increasing social involvements to boost circular economy and last the most important political aspect to regulate policies by mandatory audit, promoting international cooperation, emission control and monitoring.

2.5 Plastic waste management

Plastic and its different forms in the environment can affect the land, water and air quality. Poor disposal of waste affects animal and human health due to its toxic effects [51, 52]. The Swachh Bharat Mission (Urban) 2019 reports that about 60% plastics can be recycled whereas remaining becomes the waste in the environment, it is also mentioned that the 70% of packing products made from plastic are becoming waste in shortest span of time [53]. In addition to these various municipal authorities are lacking the technical skill to manage such hazardous waste, less infrastructure for handling, recycling and recovery of waste, awareness and rules lacking makes to increase the waste loads at the management sites [54]. Solid waste is not a disposal strategy it requires administrative, economical and societal efforts to resolve the problem using appropriate technology and better environment friendly solution. The scientific efforts to handle the issue is referred as waste management [55]. In 2022, the global plastic production measured around 400.3 million Tonnes, and the main drivers for increasing plastic are urbanization, economic development and population growth. Plastics being highly stable and durable it is not easily degraded in the natural environment [56]. High consumption and production of polymers is the major issue of plastic

waste globally. In MSW plastic waste is generally 11% of the total waste quantity. It has been observed that petroleum-based plastics emits 1781 Mt CO_2 during its life cycle in year 2015 and it may emit 6500 Mt CO_2 in year 2050 if the trend continues [52].

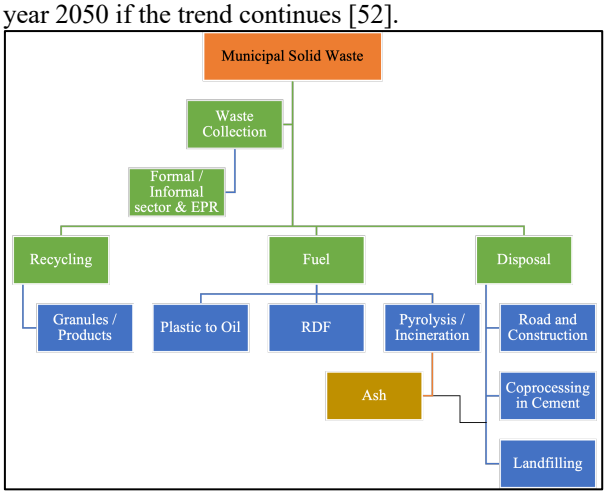


Figure 8: Flow chart for plastic waste management

Incineration, pyrolysis, bio-remediation, landfill are few of the methods applied for disposal of plastic waste [51, 52]. A new way for plastic waste management is like use of microwave / plasma assisted conversions, super critical water conversion, photo reforming, compatibilization etc. as shown in Figure 8. Similarly, applications of plastic waste in different sectors include construction industry, concrete production, electrode material, metallic ceramic reinforcement, liquefaction, road construction and tar, waste water treatment and various other value-added product making [52, 57, 58]. Classification of plastic is based on various methods whereas the internationally accepted standards are classification is like Polyethylene Terephthalate (PETE), High Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low Density Polyethylene, Polypropylene (PP), Polystyrene (PS) and other types of plastic [56]. The sustainable plastic waste management practice primarily includes recycling of the plastics. It is seen that virgin plastics can be recycled 2 or 3 times since the quality and life span of such plastic gets deteriorates after recycling. Reduce, Reuse and Recycle i.e. 3R principal is the best policy for controlling its use, reuse multiple times and recycle to make other products. Recycling being a sustainable way of plastic waste management in which various methods used are like chemical depolymerisation to get monomers from PET and the output product can be a liquid refuse derive fuel RDF and use as fuel in cement industry.

Segregation of plastic waste using mechanical means such as near-infrared scanners which can easily categorised waste are most efficient methods. For segregated waste further process in mechanical recycling involves shredding of plastics, washing, melting, remoulding etc. Recycling reduces dependency on virgin raw material however the cleanliness and purity of input material is basic parameter for recycle product quality [59, 60]. Conversion of plastic to fuel is another method where using thermal decomposition i.e. pyrolysis the plastics can be converted into oil and fuel. For disposing the biomedical, hazardous and polymeric plastic plasma pyrolysis technology is used which burns the waste at about 8500 °C it converts organic waste into non-toxic gases of CO_2 and H_2O and kills all bacteria and pathogens at high temperature [53]. In India various approaches are used to manage the waste and the guiding documents are the policy framework i.e. Municipal solid waste management rules (2000) and (Amendment 2016), Plastic Waste Management and Handling Rules 2011 etc. At the same time approach or models include extended producer responsibility (EPR), bye back model (Buy Back), PRO professional organization entrusted for responsibility etc. [45, 61].

2.6 Construction and demolition (C&D) waste

C&D waste is producing form construction, renovation and demolition activities having varied percentage of inert materials along with steel, wood, brick, asphalt, shingles, concrete, hazardous and non-hazardous inert waste [62, 63]. Rapid urbanization leads to growth in construction sector and it is estimated around 7 to 8% in coming 10 years, where India will be third largest in the world. At the same time quantum of C&D waste is around 100 million tons per annum in 2018 [64]. In case of C&D waste only 5% waste is recovered and rest can be landfilled, dumped, disposed illegally on river banks and water bodies etc. [65]. Such practice affects land and water resources in particular areas.

There is an acute shortage of natural resources used for the construction activities such as aggregates, limestone, and materials like sand and soil etc and their demolition process are illustrated in Figure 9. In urban peripheral areas agriculture activities affected from the brick industry as it uses the soil as basic resource. A study by Ray (2024) shows satellite imageries are helpful in mapping the increase or decrease in settlement areas which can be used as reference source to understand increasing or decreasing percentage of C & D waste in particular area [62]. As per the National Institute of Urban Affairs (NIUA - 2020) management of the C&D waste in a scientific manner helps economically, environmentally and socially in different ways as follows; Economic impact – Reduction in expenses by minimizing the trips since there is high fees for tipping the C&D waste due to its weight, recycling of the waste to useful construction material, reduce load on dumping grounds.

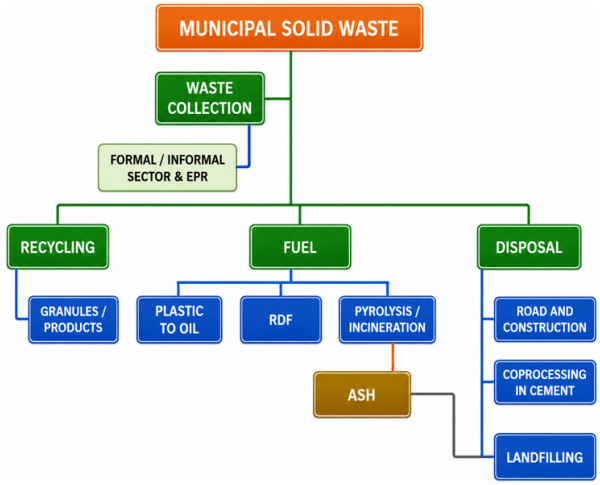


Figure 9: Construction and demolition waste process flow

Environment – prevent flooding and maintain hydrologic system associated with eco-system since the uncontrolled dump on waterways leads such issues, reducing air pollution and restrain contamination of soil and groundwater from hazardous residues in waste, reduce GHG emission as environment friendly products of building material can be used in construction activities, recycling of material reduces pressure on natural resources like sand, trees, stones etc. Social – increase jobs for the non-skilled workers and also market for the eco-friendly/recyclable product making industry [66], saves open public spaces and improve aesthetics. For the management of C&D waste government implemented various policies and actionable steps at ULB level however the stakeholder attitude and behaviour change to use recyclable materials is the most important strategy for C&D waste management. At the same time there are several barriers exists in C&D waste management practices include governance (regulatory), operational, technical, stakeholder engagement and management, market, economic and social etc. [67, 68]. From sustainability point of view, schedule II under the CDWM Rules 2016 [69], the applications of the products made from construction and demolition waste plant are given, is a regulatory mechanism prepared by government of India. The treatment process of C&D comprises of heavy-duty machinery for screening, crushing, handling, washing, thickening of products developed at an industrial scale which can be marketed as eco-products. Shahidan (2017) has tested the strength of the aggregates of various sizes in concrete such as tensile test, compressive strength test and the absorption of water test showing quality of the products matches to the required quality [70].

2.7 Hazardous waste:

The category of hazardous waste (HW) in MSW includes various components like batteries, paints, cleaning agents, electronic waste, fluorescent lamps, expire medicines, academic or institutional laboratory waste, sanitary napkins, pesticide bottles and organic pollutants etc. [71, 72]. The unmanaged and mixed hazardous waste can be toxic to human health and pollution soil, air and water. The groundwater contamination from the heavy metals around the landfill areas is the best example of hazardous waste pollution and its spreading. High COD and positive corrosivity test of groundwater sample is indication of pollution load in the leachate [73, 74]. Similarly, the air emissions from unmanaged waste dump sites pose to serious health issues largely respiratory diseases, reproductive disorder, also the occupational hazards in people handling the waste etc. [75, 76]. Low-income countries face various challenges in managing hazardous waste are started from public awareness, insufficient infrastructures, lack of funding, weak implementation and law enforcement, safety and other risk aspects [77]. Hazardous waste management in sustainable way means safe disposal of waste, clean and eco-friendly practice. The sustainable technologies to treat hazardous waste are composting, incineration, pyrolysis, hydrothermal treatments, physico-chemical treatments, biological treatments and landfill [78]. For the higher level of destruction to the persistent pollutants the technologies used are plasma treatment and encapsulation (Sharma and Jain 2021). A new and advance technologies for tracking of hazardous waste have been started using public and private partnership project which have improved the collection and processing infrastructure [79]. Under chemical and capsulise treatment the waste is stabilise or solidifies, neutralize, precipitate and remaining contaminated waste like ash or leachate are landfilled similar methods used under ISWM systems in cities like Singapore and Toronto [80]. Waste residues from MSWM are generally landfilled in the designed landfill sites having liners, leachate collection systems, recovery of methane and other toxic gas whereas separate units are made for treatment of HW containing heavy metals and asbestos [81].

2.8 E-Waste:

Under solid waste management the e-waste is categorically not directly associated with MSWM but part of the same is coming directly or indirectly into the MSW. Electronic waste is basically the product needs electric energy to run such as mobile phones, computers, television, and other electronic goods and kid toys etc. The global e-waste production measured to be around 53.6 million metric tons in year 2020, and it is expected to increase by 2.5 million tons annually [82]. E-waste is having large recycling market and in contrast it comes under hazardous waste category since it has embedded materials like lead, mercury, cadmium etc. as shown in Figure 10.

Segregation of waste is the key parameter from management perspective in the low-income countries. The unsegregated e-waste disposal and non-scientific mechanism of disposal creates environmental contaminations. The materials like printed circuit boards, batteries and cathode ray tubes are having heavy and toxic chemicals which otherwise affects human health and contaminates the environment [83]. A large work force in this sector is always facing the risk due to associated activities and direct exposure [75]. For management of e-waste, the government authorities

publish timely guidelines on E-waste management through the MSW Rules. However, the first step is the segregation at source, second is public awareness, implementing regulations such as extended producer responsibility etc. A separate collection drive, door to door collection and drop off system applied in Francisco and Seol observed to be more efficient for managing e-waste [84]. Non-recyclable items and hazardous waste mainly the batteries need specialized treatment include secure landfilling. Stabilization and encapsulation reduce chances of leachate contamination. Also burning through incineration with appropriate air pollution controlling devices and separate mechanism for treating plastic components are required for treatment of the waste [84].

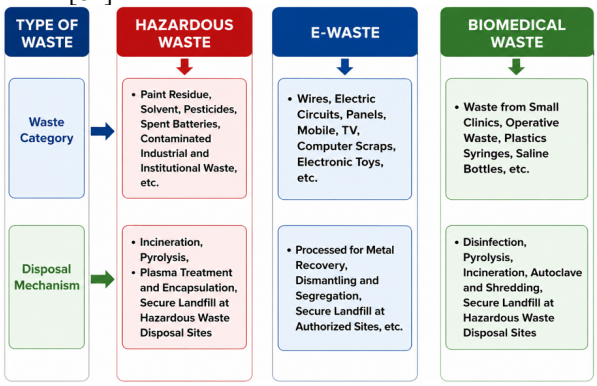


Figure 10: Hazardous Waste, E-Waste and Biomedical Waste in MSW

A separate system for the material recovery and pre-processing for e-waste is the most useful steps before dismantling and mechanical shredding. Through material recovery the e-waste containing valuable metals like gold, copper, aluminum etc. are recovered [86]. Countries like Japan and Switzerland are recovering significant number of metals through e-waste known as urban mining [87]. The advance systems of block chain, AI, circular economy are now-a-days used in segregation and recovery of the useful materials from the waste.

2.9 Bio-Medical waste:

Healthcare demands in urban areas are increasing as per the population growth and need. Hence, there is quantitative increase of bio-medical waste (BMW) and its handling affect the municipal solid waste management [88]. Waste generated from healthcare facilities are hazardous in nature, if it is not managed well can become harmful since it carries pathogens, bacteria and toxic chemicals in the environment. Improper waste disposal leading to risks of health and infections as well as environment contamination [89]. Mainly in the small towns and growing urbanized areas in developing countries the small clinics, diagnostic laboratories and hospitals are disposing the syringes, bandages and cytotoxic waste, drugs etc. into regular solid waste [90]. Unmanaged solid waste containing BMW can generate leachate on landfill sites, it may produce GHG's and pose threat of vector borne disease spread. Unaware waste collecting workers on the landfill site are exposed to such waste and easily affect since they are not even using any protective equipment's [91]

To manage BMW India is having cradle to grave approach which primarily includes waste characterization, quantification, storage, transport and treatment etc. [92]. Segregation is the key aspect of managing BMW as per the rules, it provides specific color coding to the waste for identification and disposal of the waste in a scientific manner. The categorization of BMW is infectious, sharp, pharmaceutical and general waste etc. [93]. In recent time the use of barcode and GPS enabled collection vehicle tracking systems are used for efficient mechanism and timely treatment of waste [94]. BMW can now a day treated on site as it contains infectious waste to avoid entering in MSW a practice of sustainable waste management. The methods like autoclave, microwave, chemical treatment are applied for disinfection [95] Energy recovery from BMW is one important aspect of incineration for waste disposal, similarly plasma arc gasification and pyrolysis are used requires high end technology for emission control and dust control [96].

3. ASSESSING MSW TREATMENT METHODS

Waste treatments at global level mainly Open Dump and Landfill which are highly preferred in the developing countries of regions such as Latin America, Africa, East Asia and Pacific, and South Asia. However, composting and recycling are the common technologies used for treatment of municipal solid waste. It can be seen that the Incineration method is least preferred in countries of East Asia and Pacific and in Europe and Central Asia. Table 2 presented the hierarchy of waste treatment methods.

Table 2: Waste treatment methods percentage at global level

Waste treatment method	East Asia and Pacific	European and Central Asia	Latin America and Caribbean	Middle East and North Africa	North America	South Asia	Sub-Saharan Africa
Open Dump %	18	25.6	26.8	52.7	54.3	75	69
Landfill %	46	25.9	68.5	34		4	24
Composting %	2	10.7	1	4	0.4	16	1
Recycling %	9	20	4.5	9	33.3	5	6.6
Incineration %	24	17.8	--	1	12	--	--

Source: [97]

The various MSW treatment methods, its challenges and benefits are shown in Table 3. It highlights the different treatment method, economic and environment benefit, limitations and challenges mainly investment cost, operation and maintenance cost, skill operator and trainer need etc. This assessment helps in identifying suitable technologies for integrated and sustainable solid waste management planning at the Urban Level Bodies (ULB) mainly for the large towns and cities in developing nations.

Table 3: MSW Treatment methods, challenges and benefit

Treatment Methods / Reference	Limitations / challenges	Environmental Benefits	Economic Benefits	Operations and Handling
Vermi-composting Gade and Reddy (2009), Supriya et al., (2023)	Special Care of Earthworms, Need large space, Composting period is high	Vermi Compost Vermi Wash Liquid fertilizer Negligible / zero emissions	Low cost of operation and maintenance	Easy, Cost effective
Mechanical Composting MoHUA; Viswanathan and Glawe (2006); Csaba et al., (2022	High electricity Consumption Requires additives	Bio-fertilizer Less time, Less Space Less emission	Maintenance cost (Electricity, oil, parts of machine etc.)	Require skill / trained personnel
Bio-methanation CPCB (2020-2021); Bhattacharya and Nath (2022); Singh and Kalam dhad (2022);	High capital, Skill Labor, Slurry disposal, Seasonal impact on gas production,	Bio-gas / methane / CNG / CBG etc. Solid / Liquid Fertilizer Generate Renewable energy, Reduce GHG	Produce Fuel has high demand and value	High O&M, Require skill / trained personnel
Waste to Energy GIZ (2017); Sharma et al., (2024); UNDP; Nixon et al., (2017); CSE India	High capital cost, Fly ash treatment and disposal, Maintaining Emission Standards	Electrical and Thermal energy, Produce Renewable Energy Reduce waste volumes	Energy produces at low price	Skill Labor High O&M Pre-processing for Waste material Stringent guidelines
Plastic waste Recycling Maitlo et al., (2017); Hopewell et al., (2009); Niti Ayog and UNDP (2021)	Mixed waste, Emissions during	Pellets, Fuel or Plastic to oil Reducing plastic pollution	Low-cost raw material for other industries	Skilled / Trained workers
Construction and Demolition Waste Chung and Carlos (2003); Baharet et al., (2017);	High investment, Stakeholder Awareness, Dust Control	Eco product for infrastructure industry Reduce pressure on natural resources	Self-run business model	Skill Labor, Trained staff, High maintenance cost

Treatment Methods / Reference	Limitations / challenges	Environmental Benefits	Economic Benefits	Operations and Handling
C&D Rules (2016); Shahidan et al., (2017)				
Hazardous Waste UNEP (2020); Siddiqua et al., (2022); Wilson et al., (2012); Kumar et al., (2023)	High investment Fly-ash disposal	Reduce contamination of air, soil and groundwater, Reduce health hazards, Recover energy in case of incineration	No economic benefits to ULB's except scientific disposal of the waste	High operational cost Stringent regulations and documentation work
E-Waste UNEP (2019); Sharma and Jain (2021); Yoshida et al., (2016)	Collection and segregation Disposal of heavy metals	Metals recovery, Reduce contamination of air, water and soil	Recovery of precious metals, Create circular economy, Known as urban mining	Safety Aspects in handling
Bio-medical Waste WHO (2022); Bagwan (2023); Patil and Shekdar (2001); Windfeld (2015); PCMC-ESR (2025)	High capital investments,	Extraction of thermal energy, Reduce public health risk	Energy generation can recover operational cost only	High operational cost for fuel, collection and segregation, Health and Safety concerns

4. SUSTAINABILITY IN WASTE TREATMENTS

4.1 Sustainability of waste treatments

The optimal utilization of resources, reduction in waste, recycling of materials, managing construction and demolition waste, providing space for recyclables are basic common method for waste management However, use of new and other alternate methods in the hierarchy i.e. Reduce-Reuse-Recycle/Compost-Recover-Disposal shows relative sustainability. Reducing number of landfill sites due to regulation and policies, scarcity of disposal land areas, and high resource value for waste are rational parameters of sustainable waste management [6, 98]. The pillars for sustainability stand for as per three aspects: social, environment and economics. Figure 11 illustrated the sustainability assessment for various treatment process and their impact. The analytic hierarchy process AHP model for sustainability assessment shows highest rank to alternative of waste management as mechanical biological treatment for organic waste to be composted, incinerating refused derived fuels in waste to energy and remaining fractions to be landfill [15]. Hence, proportion of waste to landfill will be reduced in long run and minimizing environment impact.

Though the research discussion is on municipal solid waste management the home composting aspect cannot be neglected since it is the most essential component of sustainability. The home composting system is better in performance compared to vermicompost or mechanical compost process, unmanaged organic waste otherwise producing impacts through landfill include Global Warming, Human Toxic via soil and water. Home composting is an important alternative for Organic Household Waste. Requirements of home composting are less (for e.g. Material/tools for treatment, transport, disposal etc.) hence less impact on environment. Use of compost material is conservation of nutrient in soil mainly the phosphorus which otherwise not recycle in MSW or waste to energy plants [99].

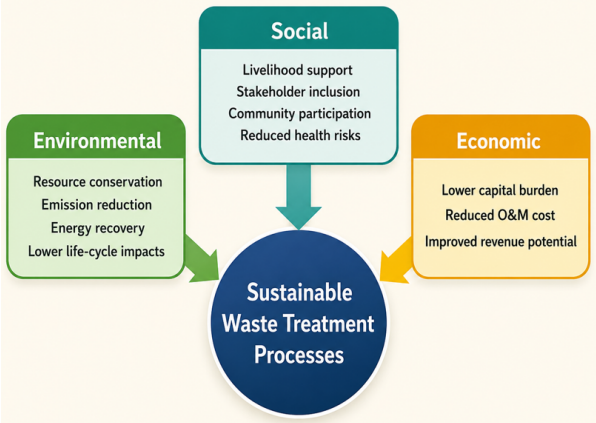


Figure 11: Sustainability assessment framework

Sustainable waste management practice is requiring knowledge and understanding of waste streams, material balance and stakeholder willingness. In consideration to this the life cycle assessment (LCA), Waste Characterization, Capacity Building and bridging the gap are four major keys of sustainable SWM [15, 38] Waste stream and material balance can be assess through LCA and characterization of waste where the life cycle assessment is an inventory of product (for all stages must include energy utilized during production process), potential impact on environment and resources and to identify alternate product or process to improve the environment. Whereas the waste characterization helps in planning the treatment and resource optimization for the required treatment process etc. Through material balance one knows the point of detachment as like the LCA where gaps can be identified. Lastly capacity building: for the stakeholders such as municipal authorities, administration, corporate bodies, non-government organizations (NGO) and educational institutes etc. capacity building plays a vital role in developing skills and educate to resolve the issues related to SWM. Similarly, the knowledge helps in creating awareness for the sustainable landfilling, implementing polluter pay principle, identifying gaps, recycling of waste, energy recovery, efficient operation and maintenance etc.

4.2 Social sustainability

It includes upliftment of social and vulnerable groups working in the sector of MSW. Inclusion of marginalized communities, gender and inclusiveness makes the sector socially sustainable. However, increasing economic status of the people and providing livelihood opportunities helps to measure social sustainability. For eg. in Bio-methanation plant at least 2 persons get livelihood from one-ton waste processing and producing the energy. In case of composting plant minimum 1 person per ton of waste management gets livelihood etc. The marketing sector for selling of byproducts such as compost, bio-CNG, energy, etc. and other aligned activities generates livelihood for long term.

4.3 Environmental sustainability

It can be measured on the basis of GHG emissions scale. Hence, the reduction in the GHG emission by applying suitable methods like composting, bio-methanation, waste to energy etc. to avoid open dumping as well as reducing waste for dumping impacts positively since less GHG emissions in the environment. The conversion of waste to useful products and by products, recycling of waste etc. helps natural ecosystem and reduce burden on it. The fuel produced through bio-methanation, energy produced from waste to energy plant are the alternate energy sources from MSW which reduces emissions. Countries like India and China are setting up waste to energy plant as one of sustainable alternative to landfills [46].

4.4 Economic Sustainability

The operation and maintenance cost of the plants are most essential in accounting economic sustainability of the MSWM. Since in management of MSW, cost is basically required for transportation, segregation, treatment and disposal. Decentralize system or centralize system to be selected for operation considering cost of operation may help to determine economic sustainability. Hence, a structure on fees for consumer, operation agencies and its cost, similarly, models like revenue and profit sharing, monitoring mechanism for overall MSWM brings the economic sustainability in solid waste management sector. The new and advanced technologies, operations which are based on Public Private Partnership PPP model are highly successful and sustainable in long run. This review shows various benefits of sustainable waste treatment process include reduction in waste disposal cost, space requirement for disposal, greenhouse gas emissions as the energy either less energy requirement or energy production etc. However, the challenges to achieve sustainable waste treatment processes are inadequate budget, high cost on operation and transport, lack of trained staff etc. [98].

5. ANALYTIC HIERARCHY PROCESS FOR TREATMENT METHODS:

The Analytic Hierarchy Process (AHP) was used in this study to evaluate the sustainability priority of different municipal solid waste treatment methods. The selection of an appropriate MSW treatment technology is a multi-criteria decision problem because no single treatment method can satisfy all environmental, economic, operational and social requirements. Therefore, AHP was applied to convert qualitative sustainability judgments into quantitative priority scores. The decision hierarchy was structured into three levels. The first level represents the overall goal, which is the selection of a sustainable MSW treatment method. The second level represents the evaluation criteria, and the third level includes the treatment alternatives considered in this review. The four criteria selected for AHP evaluation were: C1: Initial cost, C2: Operation and maintenance cost, C3: Environmental positive impact and C4: Social impact. These criteria were selected because sustainable MSW treatment must not only reduce waste quantity, pollution and landfill burden, but also remain economically feasible, operationally manageable and socially beneficial. The treatment alternatives considered were bio-methanation, waste-to-energy, mechanical composting, plastic

recycling, e-waste recycling, natural composting/vermicomposting, C&D waste processing, hazardous waste treatment and biomedical waste treatment.

6.1 AHP Decision Hierarchy

The AHP hierarchy used for the present study is shown in Figure 12. The top level consists of the objective, which is to identify the most sustainable treatment method for municipal solid waste management. The second level consists of the four sustainability criteria, namely initial cost, operation and maintenance cost, environmental positive impact and social impact. The third level consists of the treatment alternatives. In this study, C&D waste, hazardous waste, e-waste and biomedical waste are considered as special urban waste streams associated with MSWM, not as direct substitutes for mixed MSW treatment. Therefore, the final interpretation emphasizes stream-wise treatment selection rather than one universal treatment method for all waste categories.

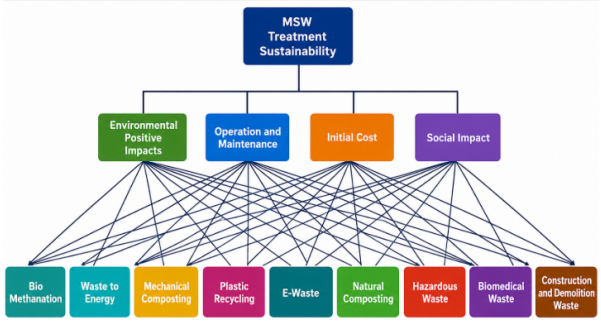


Figure 12: Analytic hierarchy process for MSW treatment methods

6.2 Pairwise Comparison of Criteria

The criteria were compared using Saaty's relative importance scale. The pairwise comparison matrix was prepared based on sustainability relevance identified from the reviewed literature. Environmental positive impact was given the highest importance because the primary purpose of sustainable MSW treatment is to reduce landfill dependency, air pollution, leachate generation, greenhouse gas emissions and resource loss. Operation and maintenance cost was assigned the second priority because high O&M cost, skilled manpower requirements and technical failure are major constraints in MSW treatment plants. Social impact was considered next because waste treatment systems also influence employment generation, safety of workers, public health and livelihood opportunities. Initial cost was assigned relatively lower importance because high capital investment can be justified when long-term environmental and operational benefits are significant.

Table 4: Pairwise comparison matrix for AHP criteria

Criteria	C1 Initial Cost	C2 O&M Cost	C3 Environmental Impact	C4 Social Impact	Geometric Mean	Normalized Weight
C1 Initial Cost	1	1/3	1/4	1/2	0.452	0.098
C2 O&M Cost	3	1	1/2	2	1.316	0.286
C3 Environmental Impact	4	2	1	2	2.000	0.434
C4 Social Impact	2	1/2	1/2	1	0.841	0.182
		Total			**4.609**	**1.000**

The normalized AHP criteria weights indicate that environmental positive impact received the highest weight of 0.434, followed by operation and maintenance cost with 0.286, social impact with 0.182 and initial cost with 0.098. These weights show that the sustainability performance of MSW treatment technologies is governed mainly by environmental benefits and long-term operational feasibility.

6.4 Consistency Check of AHP Matrix

The consistency of the pairwise comparison matrix was checked to ensure that the assigned criteria weights are logically acceptable for decision-making. In AHP, inconsistent judgments can lead to unreliable priority values. Therefore, after calculating the criteria weights, the weighted sum vector was obtained by multiplying the pairwise comparison matrix with the normalized weight vector. The maximum eigenvalue was then calculated using the following expression:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i} \quad (1)$$

where λ_{max} is the maximum eigenvalue of the pairwise comparison matrix, A is the pairwise comparison matrix, W is the normalized criteria weight vector, and n is the number of criteria used in the AHP model.

For the present study, the calculated maximum eigenvalue was:

$$\lambda_{max} = 4.046$$

The consistency index was calculated using the following equation:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (2)$$

Substituting the values:

$$CI = \frac{4.046-4}{4-1} \quad (3)$$

$$CI = \frac{0.046}{3} \quad (4)$$

$$CI = 0.015$$

The consistency ratio was calculated using the following equation:

$$CR = \frac{CI}{RI} \quad (5)$$

For four criteria, the random index value is:

$$RI = 0.90$$

Therefore, the consistency ratio was calculated as:

$$CR = \frac{0.015}{0.90} \quad (6)$$

$$CR = 0.017$$

The calculated consistency ratio is 0.017, which is lower than the acceptable limit of 0.10. Hence, the pairwise comparison matrix is considered consistent and suitable for AHP-based sustainability assessment. This indicates that the assigned relative importance among initial cost, operation and maintenance cost, environmental positive impact and social impact is logically acceptable for the present MSW treatment evaluation.

6.5 Rating Scale for Treatment Alternatives

After determining the criteria weights, each treatment alternative was evaluated using a five-point rating scale. For the cost-related criteria, namely initial cost and operation and maintenance cost, reverse scoring was applied. Therefore, a higher score represents lower cost, easier implementation and better operational feasibility. For environmental positive impact and social impact, a higher score represents stronger sustainability benefit.

Table 5: Rating scale used for AHP evaluation

Score	*Interpretation for Initial Cost and O&M Cost*	*Interpretation for Environmental and Social Criteria*
1	Very high cost or very difficult operation	Very low benefit
2	High cost or difficult operation	Low benefit
3	Moderate cost or moderate operation	Moderate benefit
4	Low cost or good operational feasibility	High benefit
5	Very low cost or very easy operation	Very high benefit

The total weighted score of each treatment alternative was calculated by multiplying the rating score of each alternative with the corresponding AHP criteria weight. The weighted score was calculated using the following equation:

$$S_i = \sum_{j=1}^{n} W_j \times R_{ij} \quad (7)$$

where S_i is the total weighted score of the i^{th} treatment alternative, W_j is the normalized weight of the j^{th} criterion, and R_{ij} is the rating score of the i^{th} treatment alternative under the j^{th} criterion.

The normalized priority value of each treatment alternative was calculated using the following equation:

$$P_i = \frac{S_i}{5} \quad (8)$$

where P_i is the normalized priority value of the i^{th} treatment alternative, S_i is the weighted score, and 5 is the maximum possible score in the adopted rating scale.

6.6 AHP-Based Weighted Scoring and Ranking of Treatment Alternatives

The weighted scoring results of the MSW treatment alternatives are presented in Table 5. The scoring was developed based on the reviewed literature, treatment process characteristics, environmental benefit, cost requirement, operational complexity and social relevance of each technology. The criteria weights used for the weighted score calculation were: initial cost = 0.098, operation and maintenance cost = 0.286, environmental positive impact = 0.434 and social impact = 0.182.

Table 6: AHP-based weighted scoring and ranking of MSW treatment alternatives

Treatment Alternative	**C1 Initial Cost Score**	**C2 O&M Cost Score**	**C3 Environmental Score**	**C4 Social Score**	**Weighted Score**	**Priority Value**	**Rank**
Bio-methanation	3	3	5	5	4.233	0.847	1
Waste-to-energy	1	2	5	5	3.751	0.750	2
Mechanical composting	3	3	4	4	3.616	0.723	3

Treatment Alternative	C1 Initial Cost Score	C2 O&M Cost Score	C3 Environmental Score	C4 Social Score	Weighted Score	Priority Value	Rank
Plastic recycling	3	3	4	3	3.434	0.687	4
E-waste recycling	2	2	4	3	3.050	0.610	5
Natural composting / vermicomposting	5	2	3	3	2.911	0.582	6
C&D waste processing	2	2	3	2	2.434	0.487	7
Hazardous waste treatment	1	1	3	2	2.050	0.410	8
Biomedical waste treatment	1	1	2	2	1.616	0.323	9

The AHP results indicate that bio-methanation is the most sustainable treatment alternative, with the highest priority value of 0.847. This result is technically justified because bio-methanation is suitable for segregated organic MSW and provides multiple benefits such as biogas generation, compressed biogas production, electricity generation and digestate recovery. It reduces the biodegradable fraction going to landfill and helps control methane emissions from uncontrolled decomposition. Although the initial cost and operation requirement are moderate, the environmental and social benefits are high because the technology supports renewable energy generation, local employment and organic manure production. Waste-to-energy ranked second with a priority value of 0.750. This technology provides high environmental benefit in terms of waste volume reduction and energy recovery from combustible waste or refuse-derived fuel. However, the initial cost and operation and maintenance scores are low because WtE plants require high capital investment, continuous feedstock supply, emission-control systems, skilled operators and proper ash management. Therefore, WtE should not be recommended for mixed wet MSW. It is more suitable for dry combustible rejects after source segregation, recycling and organic waste separation.

Mechanical composting ranked third with a priority value of 0.723. It is suitable for large-scale processing of organic municipal waste and has moderate initial and operation requirements. It provides environmental benefits by stabilizing biodegradable waste and producing compost. However, its effectiveness depends strongly on source segregation, contamination control and market acceptance of the final compost. Plastic recycling ranked fourth because it contributes to circular economy and reduces demand for virgin plastic material. However, its success depends on segregation efficiency, cleanliness of input material and market value of recycled products. E-waste recycling ranked fifth because it supports valuable metal recovery and prevents toxic materials from entering the mixed MSW stream. However, it requires specialized dismantling, trained workers and safe processing systems. Natural composting or vermicomposting ranked sixth. It has low initial cost but requires more land, longer treatment time and careful process control, especially at municipal scale. Therefore, it is more suitable for decentralized or small-scale organic waste treatment rather than high-volume urban MSW processing.

C&D waste processing, hazardous waste treatment and biomedical waste treatment ranked seventh, eighth and ninth, respectively. Their lower ranking does not mean that they are unimportant. These waste streams require separate and authorized treatment systems because they are not direct mixed-MSW treatment alternatives. C&D waste needs crushing, screening and recycled aggregate production. Hazardous waste requires secure handling, chemical treatment, stabilization, incineration or secure landfill. Biomedical waste requires segregation, disinfection, autoclaving, incineration or other approved treatment methods. These processes are compliance-driven and involve higher technical control, cost and operational safety requirements. Overall, the AHP analysis confirms that sustainable MSW treatment should follow a stream-wise integrated approach. Bio-methanation should be prioritized for segregated wet organic waste, mechanical composting may be used where compost quality and market demand are available, plastic and e-waste recycling should be used for dry recoverable fractions, WtE should be restricted to non-recyclable combustible rejects or RDF and secure landfill should be used only for inert and residual waste. Therefore, the study does not recommend one single treatment method for all wastes. Instead, it supports an integrated MSW management framework based on waste characteristics,

resource recovery potential, operational feasibility and environmental sustainability.

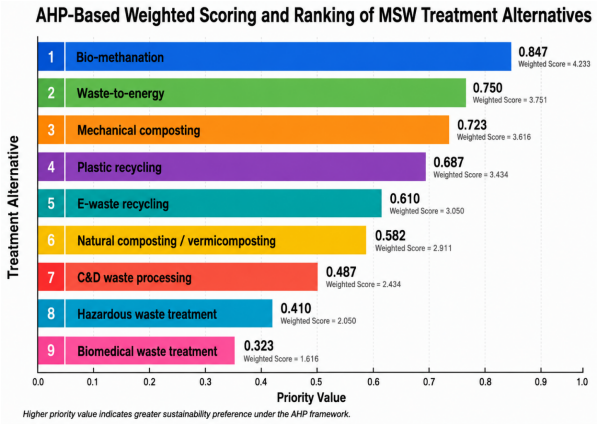


Figure 13: AHP based hierarchy for sustainable Municipal Solid Waste Treatment

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6. DISCUSSION

The AHP-based sustainability assessment demonstrates that the selection of municipal solid waste treatment technology must be guided by waste characteristics, environmental performance, operational feasibility and social benefits rather than by a single economic or technical factor. The criteria weighting clearly shows that environmental positive impact is the most influential criterion, followed by operation and maintenance cost, social impact and initial cost. This ranking is appropriate for MSWM because treatment technologies are expected to reduce landfill dependency, control emissions, recover useful resources and protect public health. Bio-methanation achieved the highest priority value because it directly treats segregated organic MSW and produces useful outputs such as biogas, compressed bio-gas, electricity and digestate. It also reduces uncontrolled methane generation from landfilled biodegradable waste and supports decentralized waste-to-energy systems. Waste-to-energy ranked second due to its ability to reduce waste volume and recover energy from dry combustible

rejects; however, its sustainability is restricted by high capital cost, high O&M requirement, feedstock quality dependence, emission-control needs and ash management. Mechanical composting ranked third because it is suitable for large-scale organic waste stabilization, but its performance depends strongly on source segregation and compost market acceptance.

The results further indicate that sustainable MSWM should not be interpreted as choosing one best technology for all waste types. Plastic recycling and e-waste recycling ranked after biological and thermal options because they are essential for circular economy and material recovery, but their success depends on separate collection, clean feedstock, organized recycling markets and safe processing systems. Natural composting or vermicomposting remains useful for decentralized organic waste treatment, although its lower priority is associated with longer processing time, land requirement and process sensitivity. C&D waste processing, hazardous waste treatment and biomedical waste treatment received lower AHP priority values, not because they are unimportant, but because they are specialized waste streams requiring separate regulatory compliance, authorized facilities and technically controlled handling. Therefore, these streams should not be mixed with ordinary MSW treatment alternatives. The overall discussion supports a stream-wise integrated treatment framework in which wet organic waste is directed to bio-methanation or composting, dry recyclables to material recovery, combustible rejects to RDF-based WtE or co-processing, and inert residues to sanitary landfill. This approach can help urban local bodies improve environmental performance, reduce disposal burden, recover resources and develop a more sustainable and practical MSW management system.

7. CONCLUSION

This study concludes that sustainable municipal solid waste treatment cannot depend on a single universal technology because MSW contains heterogeneous fractions such as wet organic waste, dry recyclables, combustible rejects, inert materials and special waste streams. The AHP-based sustainability assessment showed that environmental positive impact is the most influential criterion, followed by operation and maintenance cost, social impact and initial cost. Among the evaluated alternatives, bio-methanation ranked highest due to its suitability for segregated organic waste, renewable energy generation, digestate recovery, landfill diversion and potential livelihood benefits. Waste-to-energy ranked second because it supports energy recovery and waste volume reduction, but it should be applied only to dry combustible rejects or RDF after proper segregation and material recovery. Mechanical composting ranked third and remains useful where organic waste quality, compost demand and operational control are ensured. Recycling-based options are essential for plastic and e-waste fractions because they support circular economy and resource recovery. C&D waste, hazardous waste and biomedical waste should be managed through separate authorized systems rather than mixed MSW treatment routes. Overall, the study recommends a stream-wise integrated MSW treatment framework in which wet waste is treated through bio-methanation or composting, dry recyclables through material recovery, combustible rejects through WtE or co-processing, and inert residues through sanitary landfill. Future work should include city-specific waste characterization, expert-based AHP validation, sensitivity analysis, life cycle assessment and techno-economic evaluation.

8. LIMITATIONS AND FUTURE RESEARCH SCOPE

The present study provides a literature-based AHP sustainability assessment of municipal solid waste treatment technologies. However, the ranking of treatment alternatives may vary depending on city-specific waste composition, source segregation efficiency, land availability, financial capacity, market demand for recovered products and local regulatory conditions. The AHP scores were developed using reviewed literature and process characteristics; therefore, future studies should validate the framework using expert opinions from municipal officials, plant operators, environmental consultants and academic researchers. Further research can also apply fuzzy AHP, TOPSIS, life cycle assessment and techno-economic analysis to reduce uncertainty and improve decision accuracy. Field-level validation using real operational data from composting, bio-methanation, material recovery and waste-to-energy plants would make the framework more applicable for urban local bodies. Future work should also include sensitivity analysis to examine how changes in environmental, economic and social criteria affect the final ranking of MSW treatment alternatives.

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COMPETING INTEREST

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DATA AVAILABILITY STATEMENT

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