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Advances in Municipal Solid Waste Valorization and Energy Recovery: A Comprehensive Review of Thermochemical, Biochemical, and Integrated Biorefinery Approaches

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Abstract:- Municipal solid waste (MSW) management is emerging as one of the key global sustainability challenges. The increasing waste generation rate—driven by rapid urbanization, industrialization, and population growth—poses severe environmental, economic, and social pressures. Conventional landfilling and open dumping practices result in greenhouse-gas (GHG) emissions, groundwater contamination, and loss of valuable resources. Waste-to-energy (WtE) conversion provides a viable pathway for transforming waste into useful forms of energy and materials, aligning with circular-economy and net-zero objectives. This review synthesizes progress in thermochemical (incineration, gasification, and pyrolysis) and biochemical (anaerobic digestion and composting) technologies and highlights recent developments in integrated MSW bio refineries. Comparative analyses of energy efficiency, environmental performance, and techno-economic viability are presented. The study identifies research priorities such as hybrid reactor design, advanced catalysts, digital optimization, and policy instruments that promote sustainable resource recovery.

Keywords*: Municipal solid waste; waste-to-energy; pyrolysis; gasification; anaerobic digestion; biorefinery; circular economy; sustainability.*

1. Introduction

Global solid-waste generation has surpassed 2 billion tonnes per year and is projected to exceed 3.4 billion tonnes by 2050 [1]. Rapid industrialization and changing consumption patterns are creating increasingly heterogeneous waste streams, containing high fractions of organic matter, plastics, paper, and metals. Traditional disposal methods, dominated by landfilling, consume valuable land, emit methane, and offer no material recovery.

Waste-to-energy (WtE) conversion represents a strategic shift from waste disposal to resource utilization. By combining energy generation with material recycling, WtE contributes directly to United Nations Sustainable Development Goals 7, 11, and 12 (clean energy, sustainable cities, and responsible production). Figure 1 illustrates the current and projected distribution of global MSW treatment methods, emphasizing the opportunity for valorization technologies.

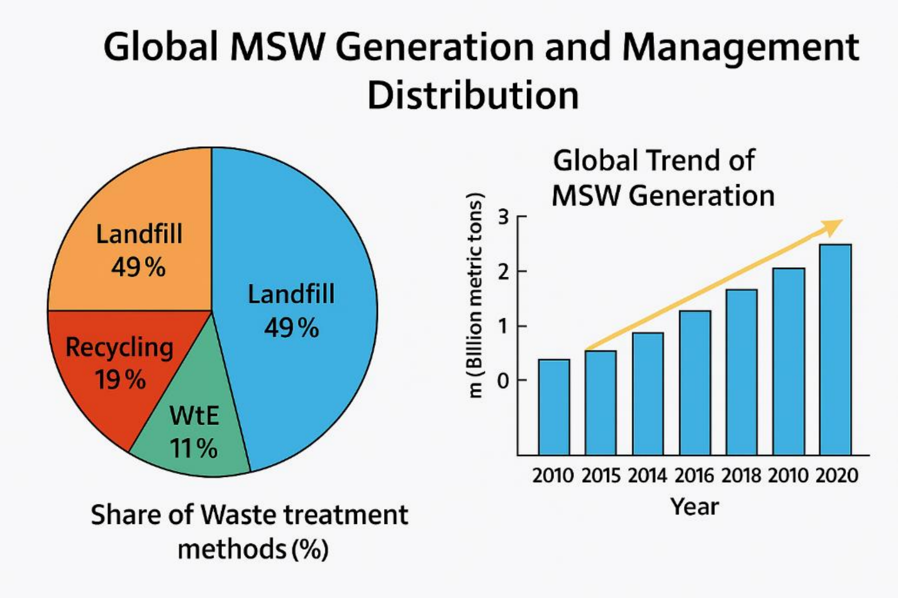

Figure 1. Global MSW generation trends and treatment distribution (landfill, recycling, WtE, composting).

2. Composition and Characteristics of Municipal Solid Waste

The composition of MSW depends on regional economic status, cultural behavior, and climatic conditions. In developing nations, the organic fraction often exceeds 50 % of total MSW; in high-income countries, packaging waste such as paper and plastics predominates [2].

Table 1. Typical Composition and Calorific Value of Municipal Solid Waste

Component	Low-income (%)	High-income (%)	Moisture (%)	LHV (MJ/kg)
Organic waste	55	38	55	6.0
Paper and cardboard	8	27	8	15.0
Plastics and rubber	10	14	2	30.0
Metals and glass	5	10	2	0.0
Inerts	22	11	5	1.0

3. Thermochemical Conversion Technologies

Thermochemical processes operate at elevated temperatures to break down organic matter into energy carriers. They are categorized into incineration, gasification, and pyrolysis [3–5].

3.1 Incineration

Incineration involves complete oxidation of waste at 850–1100 °C, reducing volume by 70–80 %. Modern plants use moving-grate or fluidized-bed furnaces coupled with heat-recovery boilers and flue-gas-cleaning systems. Efficiency can reach 30 % in combined heat-and-power (CHP) mode. Fly-ash and bottom-ash management, together ≈ 10 % of input mass, is critical for environmental compliance.

3.2 Gasification

Gasification partially oxidizes waste to form synthesis gas ($CO + H_2 + CH_4$). Operating at 700–1000 °C, the process provides higher electrical efficiency (≈ 35 %) and lower emissions than incineration [6]. Syngas upgrading enables production of methanol, Fischer–Tropsch fuels, and hydrogen.

3.3 Pyrolysis

Pyrolysis thermally decomposes organic fractions in an oxygen-free environment (400–800 °C) to yield bio-oil, gas, and char. Catalytic variants (using zeolites, dolomite, or Ni-based catalysts) increase syngas yield and reduce tar. Char can be valorized as a carbon-sequestering soil additive. Table 2 gives the comparison of Thermochemical waste to energy processes and Figure 3 gives the flow diagram of thermochemical conversion routes

Table 2. Comparison of Thermochemical Waste-to-Energy Processes

Process	Temperature (°C)	Main Products	Efficiency (%)	Advantages	Limitations
Incineration	850–1100	Heat, Power	25–30	Mature, reduces volume	High emission control cost
Gasification	750–1000	Syngas	30–35	High efficiency, flexible feedstock	Tar formation
Pyrolysis	400–800	Bio-oil, Gas, Char	20–30	Product diversity	Requires pretreatment

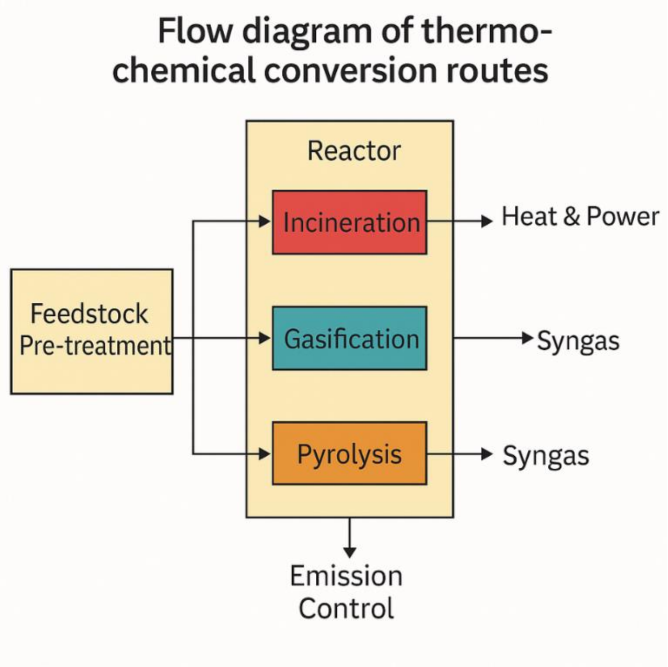

Figure 3. Flow diagram of thermochemical conversion routes

4. Biochemical Conversion Technologies

Biochemical routes rely on microbial consortia to convert organic waste into biogas and compost [7, 8]. The comparison of Biochemical Conversion Processes is given in Table 3.

4.1 Anaerobic Digestion (AD)

AD proceeds via hydrolysis, acidogenesis, acetogenesis, and methanogenesis. It produces biogas containing 60–65 % CH_4 and digestate rich in nutrients. Optimum parameters: temperature 35–55 °C, pH 6.8–7.2, C/N 20–30. Methane yield typically 0.45 m^3 CH_4 kg^{-1} VS. Co-digestion with sewage sludge or food waste improves microbial balance and yield.

4.2 Composting

Composting aerobically decomposes organic waste into humus. Maintaining 50–60 °C and 40–60 % moisture ensures rapid biodegradation and pathogen kill. The product is a stable soil amendment used in agriculture.

Table 3. Comparison of Biochemical Conversion Processes

Process	Conditions	Output	Yield	Advantages	Limitations
Anaerobic Digestion	35–55 °C, pH 6.8–7.2	Biogas + Digestate	0.4–0.5 m^3 CH_4/kg VS	Renewable energy, nutrient recovery	Long retention time
Composting	50–60 °C, aerobic	Compost	60–70 % mass loss	Low cost, soil conditioner	No direct energy recovery

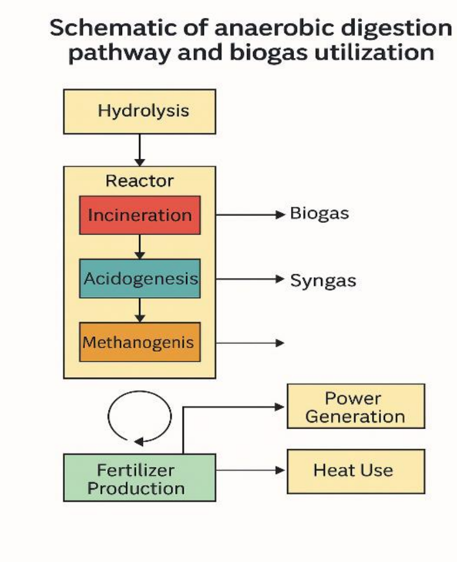

Figure 4. Anaerobic digestion process and biogas utilization pathways.

5. Integrated Biorefineries and Circular Economy

The concept of the integrated biorefinery extends the WtE approach by merging thermochemical and biochemical conversion processes within a single, synergistic system. The main goal is to utilize all waste fractions, ensuring that no potential feedstock remains unused.

Figure 5 presents a schematic of a modern MSW biorefinery. The facility typically includes preprocessing units for sorting, drying, and size reduction. The organic fraction is sent to anaerobic digesters, while plastics, paper, and other combustibles are directed to gasification or pyrolysis reactors. Heat and power generated from syngas combustion sustain process energy demand, while CO_2 from biogas upgrading can be recycled to promote microalgal growth or methanation reactions.

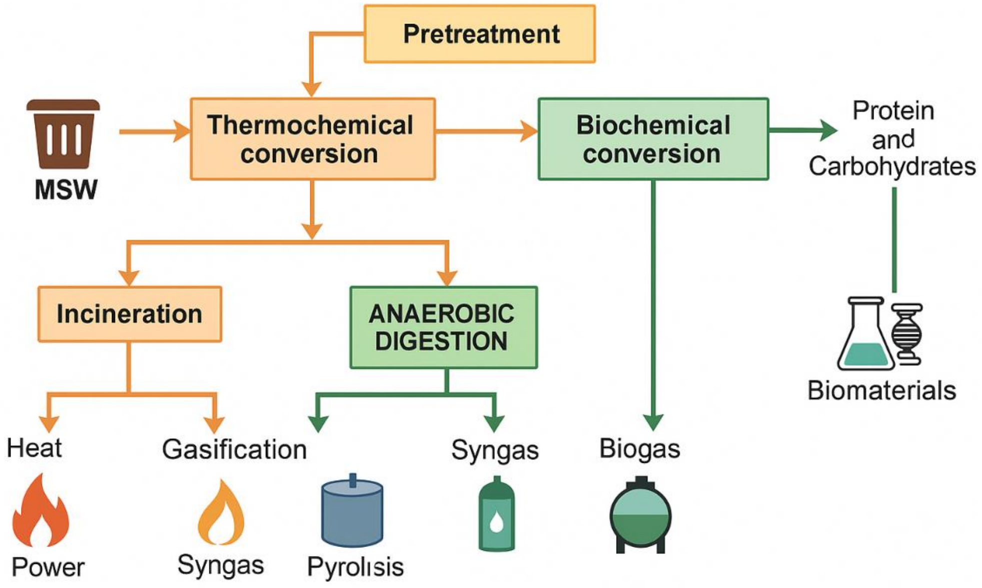

Figure 5. Conceptual flow diagram of an integrated MSW bio refinery

5.1 Process Synergies

The coupling of biochemical and thermochemical processes yields multiple synergistic benefits:

- Enhanced Resource Utilization: Digestate residues can be pyrolyzed to produce biochar, which enhances AD stability and nutrient recovery.
- Energy Integration: Waste heat from gasification units maintains optimal digester temperature, improving overall energy balance.
- Emission Reduction: Carbon-neutral CO_2 utilization within the system significantly lowers lifecycle emissions.

5.2 Circular Economy Perspective

Integrated biorefineries represent a cornerstone of the circular economy, in which waste streams are continuously revalorized to generate new materials and energy. Biochar can serve as a carbon sink; recovered metals can enter manufacturing loops; and composted residues can enrich soil fertility, reducing dependence on chemical fertilizers.

Table 4. Major Outputs and Their Utilization in an Integrated MSW Biorefinery

Output	Origin Process	Utilization	Circular Benefit
Syngas	Gasification	Electricity, Fuels	Renewable energy source
Biogas	Anaerobic Digestion	Heating, CHP	GHG emission reduction
Biochar	Pyrolysis	Soil conditioner, carbon sequestration	Long-term carbon storage
Compost	Composting	Agriculture	Nutrient recycling
Metals / Glass	Sorting / Incineration	Manufacturing feedstock	Resource recovery

6. Environmental and Techno-Economic Assessments

To evaluate sustainability and feasibility, life-cycle assessment (LCA) and techno-economic analysis (TEA) are indispensable. They provide insights into greenhouse gas mitigation, energy efficiency, and investment performance [9–12].

6.1 Life-Cycle Assessment (LCA)

LCA considers all stages—collection, transportation, conversion, and disposal. Studies indicate that incineration with energy recovery reduces net CO_2 emissions by 30–40 % compared to landfilling. Gasification and AD further enhance reductions when co-products like digestate and char are valorized [12-15].

6.2 Exergy and Energy Efficiency

Exergy analysis identifies where energy degradation occurs within conversion systems. Typical results show:

- Incineration: 8–10 % exergy loss in combustion chambers.
- Gasification: 15–20 % exergy destruction in heat exchangers.
- AD: 25 % chemical-exergy destruction during methanogenesis.

Integrating thermal and biological units can raise overall system efficiency to 70–75 % (energy + material recovery) [15-16].

6.3 Techno-Economic Analysis (TEA)

Financial assessment considers capital cost, operation, and payback period. Table 5 presents comparative economic data for key valorization routes [16-20]

Table 4. Techno-Economic Comparison of MSW Valorization Technologies

Process	Capital Cost (USD/t/day)	Payback (years)	Products	ROI (%)
Incineration	80,000	8–10	Power, Heat	9
Gasification	100,000	7–9	Syngas, Hydrogen	12
Pyrolysis	85,000	6–8	Oil, Char, Gas	14
Anaerobic Digestion	45,000	4–6	Biogas, Compost	11

7. Conclusions

This review establishes that the integration of thermochemical and biochemical technologies can transform MSW from an environmental burden into a renewable resource. Thermo chemical processes provide rapid energy recovery, while biochemical systems offer stable treatment for organic waste. Combining these within integrated biorefineries maximizes energy output, reduces emissions, and supports circular-economy principles. LCA and TEA results demonstrate environmental superiority and financial viability under optimized operating conditions.

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