

# Valorization of Municipal Solid Waste Through Chemical Pathways

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## ABSTRACT

*The escalating generation of municipal solid waste (MSW), primarily driven by rapid urbanization and population growth, has become a global critical environmental and management concern. In India alone, municipal solid waste production has reached approximately 160,000 tonnes per day. Chemical valorization presents a promising pathway to transform this waste into valuable products such as fuels, chemicals, and materials, aligning with the principles of a circular economy. According to the Ministry of New and Renewable Energy, the energy recovery potential from urban solid waste in India is estimated at 1,247 MW. This review systematically examines recent developments in chemical valorization strategies, including pyrolysis, gasification, and catalytic upgrading. It also explores the integration of advanced technologies such as plasma-assisted conversion, bio-electrochemical systems, and machine learning-driven process optimization. Despite the establishment of six operational waste-to-energy plants in India with a cumulative capacity of 66 MW, challenges persist, particularly the heterogeneous nature of municipal solid waste, process scalability, and economic feasibility. This review aims to provide a comprehensive resource for researchers, industry professionals, and policymakers pursuing sustainable and technologically advanced approaches to municipal solid waste management.*

**Keyword :** - MSW, Valorization, Pyrolysis, Gasification, Catalytic, Waste to energy.

## 1. INTRODUCTION

The accelerating trends of urbanization, industrial expansion, and population growth have significantly contributed to the surge in municipal solid waste (MSW) generation worldwide. As reported in the *Handbook of Solid Waste Management*, global MSW production is expected to double by 2025, thereby intensifying the environmental, economic, and operational challenges associated with sustainable waste management. Conventional disposal methods such as landfilling and incineration, while widely practiced, are increasingly criticized for their detrimental impacts, including environmental pollution, depletion of natural resources, and substantial greenhouse gas emissions.

In recent years, the focus of waste management has transitioned from traditional disposal methods toward resource recovery, in alignment with circular economy principles. Chemical valorization of municipal solid waste (MSW) presents a viable strategy for converting heterogeneous waste fractions into high-value products such as fuels, platform chemicals, and advanced materials. This approach facilitates both the reduction of waste volume and the recovery of embedded energy and carbon resources [1]

Among the various chemical transformation routes explored for municipal solid waste (MSW) management, pyrolysis, gasification, and catalytic conversion have emerged as the most extensively studied and scalable technologies [2]. Pyrolysis entails the thermal decomposition of organic fractions in the absence of oxygen, yielding bio-oil, syngas, and gasification, on the other hand, involves partial oxidation of carbonaceous materials in the presence of a controlled amount of oxygen or steam to produce syngas—a versatile energy carrier comprising primarily carbon monoxide (CO) and hydrogen (H<sub>2</sub>). These thermochemical pathways offer distinct advantages over conventional waste treatment methods, including higher conversion efficiencies, reduced pollutant emissions, and compatibility with diverse feedstocks. [3] further highlight critical aspects such as economic viability, feedstock variability, catalyst performance, and process optimization. This review provides a comprehensive analysis of the key chemical valorization pathways for MSW, emphasizing their technological potential, implementation challenges, and applicability within the Indian context

## 2. PYROLYSIS

Pyrolysis is a thermochemical conversion process carried out in the absence of oxygen, wherein the organic fraction of municipal solid waste (MSW) is transformed into value-added products such as bio-oil, syngas, and char. As a sustainable alternative to traditional waste disposal methods like landfilling and incineration, pyrolysis holds significant potential, particularly in developing countries like India, where waste streams are largely heterogeneous and poorly segregated.

The raw materials utilized in the cited studies underwent proximate and ultimate analyses to assess their physical and elemental properties. [4] provided a comprehensive characterization, demonstrating a notable resemblance between the representative MSW sample and a binary mixture predominantly comprising biomass and plastics. Such correlations support the development of targeted conversion strategies. Among emerging technologies, microwave-assisted pyrolysis has shown considerable promise due to its rapid heating capabilities and enhanced product selectivity. [5] emphasized its applicability to Indian MSW, citing improvements in process efficiency, waste volume reduction, and the recovery of energy-dense outputs. In parallel, [6] explored biorefinery-based valorization approaches, wherein biodegradable MSW fractions are transformed into high-value bio-based chemicals. These integrated pathways support the principles of a circular economy by enabling simultaneous energy recovery and chemical production.

Building upon these findings, numerous review articles have offered in-depth perspectives on the diverse approaches to MSW valorization. [8], [7] systematically analyzed thermochemical and biochemical conversion technologies, particularly in the context of India’s municipal waste management systems. In parallel, [9] highlighted the potential of bioenergy pathways, whereas [10] explored the regulatory, technological, and operational challenges associated with managing hazardous fractions within solid waste streams

**Table -1:** Recent Advances in Technologies

Technology / Strategy	Ecological Impact	Energy Efficiency & Output	Material Recovery Potential	Scalability / Maturity
<b>Plasma Gasification</b>	Low emissions; stabilizes hazardous waste; converts MSW into inert slag and syngas.	High energy output (up to 816 kWh/ton); efficient for high-calorific-value MSW	Slag reusable in construction; potential recovery of metals from fly ash	High CAPEX but commercially applied in Japan and, USA
<b>AI-Controlled Gasification</b>	Enables optimal control, reducing emissions and process variability	Optimizes feed rate, temperature, and airflow for maximum syngas quality	Improves consistency for downstream separation and material recovery	Emerging; integration ongoing
<b>Metal Recovery from MSW Ash</b>	Prevents leaching of heavy metals into soil and water	Moderate; energy depends on extraction technique (hydrometallurgy, bioleaching)	Recovers Zn, Cu, Pb, etc.; supports circular economy	Medium; widely tested in the EU and China
<b>Sustainable Catalysts (e.g., Ni-Zn, zeolite)</b>	Reduces environmental burden of conventional tar-cracking catalysts	Enhances tar removal, boosts H <sub>2</sub> /CO yield	Improves gas purity; indirectly benefits syngas-to-chemical conversion	Low to medium; lab-scale success, industrial trials ongoing
<b>Hydrothermal Liquefaction (HTL)</b>	Converts wet organic MSW to bio-crude; avoids drying step	Efficient for wet feedstock (20–40% energy recovery)	Organic-only; limited metal recovery	Pilot scale; promising for food and green waste
<b>Syngas Fermentation (Bio-refinery)</b>	Utilizes syngas (from gasification) to produce ethanol, acetic acid, etc.; biologically mediated	Lower energy than thermochemical upgrading; less heat-intensive	Converts carbon in MSW into value-added chemicals	Under development; some industrial demo plants (e.g., LanzaTech)

### 3. GASIFICATION

Gasification of municipal solid waste (MSW) represents a promising thermochemical conversion technology that enables the production of synthesis gas (syngas), primarily composed of hydrogen (H<sub>2</sub>), carbon monoxide (CO), methane (CH<sub>4</sub>), and carbon dioxide (CO<sub>2</sub>). This approach serves as a sustainable alternative to conventional incineration and landfilling by facilitating efficient energy recovery while minimizing environmental pollution [11]. Optimal gasification performance is achieved within the temperature range of 700–850 °C, wherein the Boudouard reaction (C + CO<sub>2</sub> ⇌ 2CO) is thermodynamically favored over the water-gas shift reaction, thereby promoting higher CO yields and enhancing the overall efficiency of the process [12].

[7] provided an extensive overview of gasification technologies tailored for Indian MSW streams, highlighting their integration with combined heat and power (CHP) systems and the production of value-added chemicals such as methanol, hydrogen, and ammonia. The selection of gasifier design is influenced by operational scale and feedstock characteristics: fixed-bed gasifiers are well-suited for small-scale applications with uniform feedstock; fluidized-bed gasifiers offer better temperature uniformity and flexibility for heterogeneous inputs [11]

while plasma gasifiers, though capital-intensive, deliver superior energy efficiency (up to 816 kWh/tonne) with minimal emissions [13]

#### 4. CATALYTIC

Zeolite catalysts, notably HZSM-5, have been extensively reported to substantially improve the yield of aromatic hydrocarbons during biomass pyrolysis, attributed to their distinctive shape-selective characteristics and strong acidic sites. Additionally, metal-modified zeolites, such as Ni/ZSM-5, have demonstrated enhanced syngas production alongside significant tar reduction in gasification processes [14]. Various catalytic materials, including zeolites, metal oxides, and activated carbon, are widely employed to increase product selectivity and overall conversion efficiency in both pyrolysis and gasification technologies.

**Table -2:** Types of Catalyst

Catalyst Type	Description	Applications	References
<b>Zeolites (e.g., HZSM-5)</b>	Microporous aluminosilicate minerals with high surface area and acidity, offering shape selectivity.	Enhancing aromatic hydrocarbon production in biomass pyrolysis.	<a href="#">Energy &amp; Fuels, 2020</a> [14]
<b>Metal Oxides (e.g., NiO, ZnO)</b>	Metal oxides that can act as active catalysts or supports, often used in combination with other materials.	Catalytic reforming and tar reduction in gasification processes.	<a href="#">ACS Omega, 2022</a> [15]
<b>Biochar-Based Catalysts</b>	Carbon-rich materials derived from biomass which can be modified with metals to enhance catalytic properties.	Pollutant degradation, bio-oil upgrading, and as supports for metal catalysts in various reactions.	<a href="#">ScienceDirect, 2023</a>

#### 5. ECONOMIC FEASIBILITY AND SCALABILITY

Economic evaluations of chemical valorization technologies reveal a balance of promising opportunities and inherent challenges. For example, the implementation of Waste Integrated Gasification–Gas Turbine Combined Cycle (WIG-GTCC) technology in Chile required a capital investment of approximately USD 111.8 million, yet generated annual revenues of up to USD 24.1 million. The projected payback period of 12 to 17 years underscores the potential economic feasibility of such large-scale systems (MDPI, 2023).

A case study on municipal solid waste management in Mumbai, India, demonstrated that a hybrid strategy combining composting and landfilling emerged as the most cost-effective solution, incurring a disposal cost of INR 531 per tonne. This method also led to a 79% reduction in global warming potential when compared to open dumping practices (SAGE Journals). On a broader scale, a global economic review of waste-to-energy technologies underscored the necessity of coupling environmental impact assessments with techno-economic evaluations. While the upfront capital investment for advanced valorization systems may be considerable, long-term advantages include energy recovery, resource efficiency, and reduced costs associated with environmental remediation.

**In summary**, chemical valorization technologies present substantial environmental advantages over conventional waste disposal methods. However, for successful and sustainable implementation, it is critical to adopt integrated approaches that balance economic viability with environmental performance.

**Challenges and Future Directions-** In the context of municipal solid waste valorization, several critical challenges persist. These include the heterogeneity and irregular availability of feedstock, scalability issues in transitioning from laboratory-scale to pilot and industrial-scale operations, underdeveloped markets for valorized products, and the lack of integration with existing waste segregation and collection infrastructures. Future research should prioritize the development of hybrid technologies (such as the integration of pyrolysis with fermentation), formulation of supportive policy frameworks including carbon credit mechanisms, and the application of artificial intelligence for process optimization alongside comprehensive life cycle assessment (LCA) models.

#### 6. CONCLUSIONS

Chemical valorization of municipal solid waste (MSW) represents a promising approach for achieving sustainable waste management, resource recovery, and environmental protection. Despite notable advancements in laboratory-scale and pilot-scale studies, the successful integration and upscaling of these technologies within existing waste management frameworks remain significant challenges. Effective implementation will require coordinated efforts among industry, policymakers, and academia, alongside supportive regulatory and financial mechanisms.

Among the various valorization routes, gasification has emerged as a sustainable and energy-efficient technique for converting MSW into syngas and other valuable fuels, while simultaneously minimizing environmental impacts. However, widespread adoption hinges on further technological refinement and economic feasibility.

Catalytic interventions, particularly the use of zeolites and metal-doped catalysts such as Ni/ZSM-5, have demonstrated the ability to enhance product selectivity and yield during pyrolysis and gasification. These catalysts also play a pivotal role in suppressing tar formation, thereby improving process efficiency and operational stability.

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