Review Article

A Review of Modern Waste to Energy Recycling Technologies: Between Innovation, Challenges, and Circular Economy Prospects

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Abstract | The world is witnessing a continuous increase in the quantities of municipal, industrial, and agricultural solid waste, which imposes escalating environmental, economic, and social challenges and calls for sustainable solutions for its management. Waste-to-energy (WtE) technologies represent a strategic option for reducing dependence on fossil fuels and lowering greenhouse gas emissions within a circular economy framework. This review presents global trends and recent developments in the main thermal and biological technologies, including direct incineration, pyrolysis, gasification, and anaerobic digestion, in addition to plastic and electronic waste recycling using advanced chemical pathways and hybrid technologies. The study also discusses quantitative performance indicators such as energy conversion efficiency, operating and maintenance costs, and the levelized cost of electricity production, alongside the different dimensions of economic feasibility. Furthermore, the review highlights technical, environmental, regulatory, and societal acceptance challenges, while exploring prospects for integrating these technologies into smart waste and energy management systems supported by digitalisation and artificial intelligence, in a way that enhances the transition toward more sustainable production and consumption models.

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Introduction

The world is experiencing rapid growth in the production of municipal, industrial, and agricultural solid waste due to rapid demographic and industrial development. This has led to environmental, economic, and social pressures that require innovative, sustainable solutions for managing these large volumes of waste (Hoang *et al*., 2022; Rasheed *et al*., 2021). Waste-to-energy technologies have emerged as a strategic option to achieve sustainable development goals, reduce dependence on fossil fuels, and lower greenhouse gas emissions (Malav *et al*., 2020; Hasan *et al*., 2021; Wang *et al*., 2021). These technologies include direct incineration, pyrolysis, and gasification for the production of liquid and gaseous fuels, heat, and electricity, as well as anaerobic digestion for biogas production from organic waste (Hasan *et al*., 2021; Prajapati *et al*., 2021). Recent trends have also emerged toward recycling plastics, electronics, and agricultural waste to produce fuels and value-added materials (Seif *et al*., 2023; Jiang *et al*., 2021). Despite the technical and economic successes of several flagship projects worldwide, major challenges remain regarding the economic and operational efficiency, as well as the environmental and social sustainability, of these technologies (Mukherjee *et al*., 2020; Hoang *et al*., 2022). Global communities face increasing challenges in managing solid waste amid population growth, urbanisation, and industrialisation, which are driving the development of modern waste-to-energy (WtE) technologies as an environmentally and economically sustainable solution. This review surveys the latest trends in waste-to-energy recycling technologies, including incineration, pyrolysis, gasification, anaerobic digestion, plastic recycling, biomass utilisation, and hybrid systems. Studies show that the efficiency of converting waste to energy ranges between 20–90%, depending on the technology, type of waste, and operating conditions, with substantial potential for reducing greenhouse gas emissions and achieving attractive economic returns (Malav *et al*., 2020; Peng *et al*., 2023; Hasan *et al*., 2021; Ambaye *et al*., 2023; Inayat *et al*., 2025; Uekert *et al*., 2020; Sikiru *et al*., 2024; Dai *et al*., 2022). However, these technologies face technical, economic, regulatory, and environmental challenges that hinder their wide deployment, such as variability in waste characteristics, investment and operating costs, emissions and ash management, and social acceptance (Mukherjee *et al*., 2020; Malav *et al*., 2020; Hoang *et al*., 2022; Prajapati *et al*., 2021; Rasheed *et al*., 2021; Khan *et al*., 2021, 2022). The paper also discusses future directions toward a circular economy and the integration of artificial intelligence and digitalisation in waste and energy management.

This work aims to provide a systematic review of the latest technologies applied in converting waste to energy by: classifying and explaining the main thermal and biological pathways used to recover energy from different waste streams; analysing the quantitative performance of these technologies in terms of energy conversion efficiency and operating and capital costs; reviewing technical, regulatory, and social challenges that hinder large-scale adoption of WtE technologies; and discussing the role of these technologies in supporting circular economy principles and future opportunities for integration with digitalisation and artificial intelligence.

Global trends and main technologies

Multiple technologies are currently applied worldwide in the field of waste-to-energy conversion, which can be classified into a group of main thermal and biological pathways as follows:

Direct Incineration (Incineration): Direct incineration is the most widespread waste-to-energy technology globally, particularly in Europe, China, and North America, as it contributes to reducing waste volume by up to about 90% with an energy efficiency of 20–30% when advanced systems for flue-gas and pollutant treatment are applied (Mukherjee *et al*., 2020; Khan *et al*., 2022).

Pyrolysis (Pyrolysis): Pyrolysis is an oxygen-free thermal technology that decomposes the organic components of waste to produce bio-oil, gas, and char. Experimental results indicate that treating mixed municipal solid waste at moderate temperatures (400–600 °C) can yield approximately 43% bio-oil, 27% char, and 25% gas (Hasan *et al*., 2021).

Gasification (Gasification): Gasification relies on the thermal conversion of waste in the presence of a limited amount of oxygen or steam, producing a synthesis gas rich in hydrogen and carbon monoxide. The overall efficiency of the process can reach 70–80%, depending on the type of waste used and operating conditions such as temperature, pressure, and gasifying agent (Nandhini *et al*., 2022).

Anaerobic digestion (Anaerobic Digestion): Anaerobic digestion is one of the most important biological technologies for treating organic waste, especially food, agricultural waste, and sewage sludge. It produces biogas (methane) with a moderate conversion efficiency of 60–70%, with the possibility of integrating it into energy grids or using it for combined heat and power production (Prajapati *et al*., 2021; Inayat *et al*., 2025).

Plastic/electronic waste recycling: This category includes the use of pyrolysis and various chemical processes to convert plastic and electronic waste into fuels, crude oil, and feedstocks for clean energy industries. Some studies show that the efficiency of extracting precious metals such as gold and silver from electronic waste can exceed 95%, which enhances the economic and environmental feasibility of these technologies (Seif *et al.*, 2023).

Quantitative performance and economic efficiency

Recent studies highlight a number of quantitative indicators and economic dimensions related to waste-to-energy technologies that can be summarised as follows: the global rate of energy recovery from municipal solid waste ranges between 13–30%, while it can exceed 50% in some advanced European countries that rely on integrated waste-management systems and supportive policies for high-efficiency technologies (Mukherjee *et al.*, 2020). Operating and maintenance costs for gasification plants range from 40 to 100 USD per ton of municipal solid waste, depending on plant size, the complexity of the technologies used, and flue-gas and residual-ash treatment requirements (Mukherjee *et al.*, 2020). The cost of electricity produced from landfill gas or anaerobic digestion systems ranges from 0.04 to 0.07 USD/kWh, with capital payback periods of less than 2 years in some model cases, reflecting the economic competitiveness of these technologies under appropriate operating and regulatory conditions (Peng *et al.*, 2023). Table 1 Illustrate the Comparison of the Main Waste-to-Energy Recycling Technologies. And Table 2. Illustrate the Results of Selected Studies on the Efficiency of Converting Different Waste Types to Energy.

Discussion

Recent literature indicates that the success of waste-to-energy projects depends fundamentally on the compatibility of the technology with the type and composition of local waste and with the economic, social, and regulatory conditions of the target country or city (Malav *et al.*, 2020; Hoang *et al.*, 2022; Rasheed *et al.*, 2021). Direct incineration is highly effective for mixed wastes with high organic content but faces social resistance due to air emissions, despite advances in modern treatment systems that have reduced toxic emissions by more than 65% compared with older technologies (Mukherjee *et al.*, 2020). Pyrolysis and gasification provide greater flexibility for handling multiple types of waste, including plastics, electronic, and agricultural waste, and achieve higher energy yields, but require precise control of temperature, moisture, and ash content to achieve optimal

Table 1: *Comparison of the main waste-to-energy recycling technologies.*

Technology	Type of Waste	Operating Conditions	Energy Efficiency (%)	Cost (USD/ton or USD/kWh)	Key Notes	Reference
Direct incineration	Mixed municipal solid waste	Temperature ~850 °C with flue-gas treatment	20–30	~80–120/ton	Volume reduction up to ~90%; emissions under control	Mukherjee *et al.*, 2020; Khan *et al.*, 2022
Pyrolysis	Organic and plastic wastes	Moderate temperature 400–600 °C, oxygen-free	Bio-oil ~43%, char ~27%, gas ~25	~100/ton	Produces liquid fuel, gas, and activated carbon; sensitive to waste type and moisture	Hasan *et al.*, 2021
Gasification	Municipal/industrial/plastic wastes	High temperature ≥700 °C with limited O_2/steam	Up to 80 for syngas	~40–100/ton	High feedstock flexibility; potential for high-value H_2 and syngas	Nandhini *et al.*, 2022
Anaerobic digestion	Organic, food, agricultural and sewage wastes	Moderate temperature 35–55 °C, controlled anaerobic conditions (pH, moisture)	Up to 70 (methane)	~0.04–0.07/kWh electricity	Produces biogas and organic fertiliser; sensitive to composition, C/N ratio and high moisture	Prajapati *et al.*, 2021; Inayat *et al.*, 2025
Nano-catalytic/chemical recycling of plastics	Mixed plastics, e-waste, cables, and precious metals	Variable temperature and pressure, depending on polymer and catalyst; multi-step chemical extraction	Metal recovery up to 95%; liquid fuel yields up to ~80% for PE, PP, PS under optimal conditions (~500 °C)	High due to expensive catalysts, fine separation of products and heavy metals	High economic returns when recovering precious metals (e.g., Au, Ag, Cu) up to ~90% from e-waste PCBs; can be integrated with conventional energy generation to improve overall economics and reduce the carbon footprint.	Seif *et al.*, 2023; Jiang *et al.*, 2021

Table 2: *Results of selected studies on the efficiency of converting different waste types to energy.*

Study / Country / Year	Waste Type	Technology	Operating Conditions	Key Quantitative Results	Engineering–Economic Notes	References
India – Delhi (recent case study)	Mixed MSW	Landfill gas + gasification	Engineered landfills with gas collection + pilot gasification units	Potential electricity supply to 8–18 million households annually; possible production up to 7,140 GWh/year, rising to 31,346 GWh by 2030	Relatively low electricity cost (~0.04 USD/kWh) and payback < 2 years	Peng *et al.*, 2023
USA – national review	MSW	Mass burning + RDF + pilot gasification	Full-scale and urban-industrial operation in the NE US and Florida	Only ~13% of MSW is used for energy recovery; ~53% still landfilled	Gasification OandM ~40–100 USD/ton; focus on coastal urban regions due to land scarcity	Mukherjee *et al.*, 2020
UK – economic study	Agricultural and food residues	Anaerobic digestion	Industrial AD units	AD could replace ~61% of natural gas and 38% of coal used for power if fully deployed.	Could free up ~1.8 million ha of agricultural land otherwise used for feed	
China – recent pilot	Mixed plastics	Chemical pyrolysis + precious metal extraction	High temperature with a strong metallic catalyst	Recovery: Au 95%, Ag 93%, Pd 99% from old PCBs	Very high economic returns from recovered metals compared to process costs	Seif *et al.*, 2023
Malaysia – food waste management	Food wastes	Anaerobic digestion + incineration + hydrothermal carbonisation (HTC)	Industrial AD; experimental HTC	Production of biogas, electricity, and high-value hydrochar; HTC is highly promising for stable, economical, and environmentally friendly hydrochar from food waste	Demonstrates the viability of integrated AD–HTC systems	Shukla *et al.*, 2024

economic and environmental outcomes (Hasan *et al.*, 2021; Nandhini *et al.*, 2022). Anaerobic digestion is considered the optimal option for organic, food, and agricultural waste and achieves high gas yields and excellent economic performance, especially when linked to systems for collecting and processing the resulting organic fertiliser and using it as a high-value agricultural input (Prajapati *et al.*, 2021). Plastic and electronic waste recycling is a highly promising field economically and environmentally, but still faces major challenges in separating heterogeneous materials and controlling emissions of heavy and toxic metals during high-temperature chemical and catalytic processes (Seif *et al.*, 2023). The literature also emphasises that success in waste-to-energy deployment is closely linked to the degree of compatibility between the chosen technological pathway and the local waste composition and institutional and economic context (Khan *et al.*, 2022; Munir *et al.*, 2021; Kumar and Samadder, 2017). Advanced treatment and filtration systems in incineration have significantly reduced toxic pollutants, such as dioxins and fine particulates, by 60–65% compared with older plants (Lin *et al.*, 2022; Li *et al.*, 2020; Mukherjee *et al.*, 2020; Zhang *et al.*, 2023). Pyrolysis and gasification, when optimised, can yield high-value syngas and liquid fuels but require tight control of temperature, residence time, moisture, and ash, as well as proper reactor and catalyst design; these factors are critical in determining hydrogen yield, syngas quality, and minimisation of tar and secondary pollutants (Shah *et al.*, 2023; Yek *et al.*, 2023; Mishra *et al.*, 2024; Cuevas *et al.*, 2024). Life-cycle assessment studies show that anaerobic digestion followed by the use of digestate as organic fertiliser can deliver high biogas yields, reduce greenhouse gas emissions, and displace chemical fertilisers, with high environmental and economic performance (Mayer *et al.*, 2021; Di Maria and Micale, 2015; Christian *et al.*, 2024; Mayer *et al.*, 2021; Munir *et al.*, 2021; Christian *et al.*, 2024). The economic attractiveness of anaerobic digestion increases when it is integrated into decentralised or urban systems that utilise both the heat and electricity produced and develop value chains around high-quality organic fertilisers. Advanced plastic and e-waste recycling via thermal and chemical pathways, especially co-pyrolysis with biomass or gasification, represents a promising avenue for converting 60–85% of plastics into high-value liquid fuels while reducing greenhouse gas emissions compared with landfilling or uncontrolled burning (Shah *et al.*, 2023; Hasan *et* *al.*, 2025; Ti *et al.*, 2025; Cuevas *et al.*, 2024). However, challenges remain in separating heterogeneous components and controlling emissions of heavy metals and persistent organic pollutants from e-waste and combustion or fly ash residues, which calls for advanced ash treatment, pollutant stabilisation, and integration with safe metal-recovery technologies (Winchell *et al.*, 2022; Mudofir *et al.*, 2025; Lin *et al.*, 2022; Ti *et al.*, 2025). Table 3 illustrate the key claims and scientific evidence.

Role of W-to-E in supporting the circular economy and prospects for integration with digitalisation and artificial intelligence

Waste-to-energy technologies are a central pillar of circular-economy principles, converting end-of-life waste streams into energy and materials, thereby reducing dependence on non-renewable primary resources. Recent studies indicate that thermal and biological pathways, particularly those converting organic waste to energy, help divert waste from landfills, produce low-carbon energy, and recover materials, fertilisers, and secondary products within relatively closed production–consumption cycles (Zueva *et al.*, 2024; Hoang *et al.*, 2022). Contemporary circularity-assessment frameworks highlight the importance of integrating environment–economy–energy (3E) indicators, life-cycle assessment, and multi-criteria decision-making to ensure alignment of WtE technologies with circular-economy objectives at the levels of policy and long-term planning (Aslan *et al.*, 2025; Khan and Kabir, 2020; Alao *et al.*, 2022). In this context, digitalisation and artificial intelligence are emerging as strategic levers for shifting from traditional waste management systems to intelligent, real-time, controllable systems. Recent reviews show that applying AI algorithms to automated sorting, predictive modelling of waste quantities, transport-route optimisation, and emission monitoring can raise operational efficiency, reduce transport distances by up to 36.8%, and cut costs by up to 13%, with recognition accuracies for waste classification exceeding 99% in some computer-vision applications (Fang *et al.*, 2023; Kelechi *et al.*, 2025; Andeobu *et al.*, 2022; Huang and Koroteev, 2021). Smart decision platforms that combine deep learning models with thermal and environmental process models support the optimisation of operating conditions in hydrothermal carbonisation and anaerobic digestion to balance energy recovery, carbon footprint reduction, and economic returns (Zueva *et al.*, 2024; Nimmanterdwong *et al.*, 2025). Future visions are expanding toward fully integrated WtE systems embedded in smart-city infrastructures, where the Internet of Things, big-data analytics, and digital-twin systems are used to monitor and manage waste and energy flows remotely and link them to climate-resilient, resource-efficient urban models (Manoharan, 2025; Melinda *et al.*, 2024; Islam, 2025; Seyyedi *et al.*, 2024). Case studies in large climate-vulnerable cities indicate that integrating AI into WtE systems can provide highly accurate

Table 3: *Key claims and scientific evidence.*

Main claim	Brief scientific interpretation	Supporting papers
WtE technologies can achieve energy efficiencies up to ~60% in some modern systems.	Field and experimental studies have demonstrated high gas and electricity yields, especially for gasification and anaerobic digestion.	Hasan *et al.*, 2021; Prajapati *et al.*, 2021; Inayat *et al.*, 2025
Incineration can reduce waste volume by up to ~90% and cut toxic gas emissions by >65% with advanced treatment.	Industrial operating data show great improvements in flue-gas cleaning and filtration technologies.	Mukherjee *et al.*, 2020; Khan *et al.*, 2022
The cost of electricity from WtE can be competitive with fossil fuels (~0.04–0.07 USD/kWh) in some industrial countries.	Economic analyses and feasibility studies of existing and planned projects support cost competitiveness.	Peng *et al.*, 2023
Nano-catalytic plastic recycling can recover precious metals at ~95% and some fuel types at ~80% efficiency.	Industrial and extensive laboratory data show high extraction and conversion yields.	Seif *et al.*, 2023
The main barriers to scaling WtE are variability in waste properties and the difficulty of separation and pretreatment.	Most studies highlight the difficulty of controlling feed composition and its major impact on performance.	Malav *et al.*, 2020; Hoang *et al.*, 2022
Limited social acceptance and weak regulatory frameworks hinder wider deployment despite technological readiness.	Socio-political studies and public policy analyses confirm these non-technical barriers.	Rasheed *et al.*, 2021; Khan *et al.*, 2021

forecasts of waste volumes, dynamic control of incineration and digestion processes, and marked reductions in life-cycle emissions, thus supporting energy security and climate resilience within an urban circular economy (Islam, 2025). Emerging research in nanotechnology and smart bioengineering shows the feasibility of building multi-product value chains from food and agricultural wastes that combine recovery of energy, materials, and catalysts in "waste-to-value" systems, controlled and optimised using AI models, thereby enhancing scalability and reinforcing the transition toward a circular bioeconomy (Zueva *et al.*, 2024; Wainaina *et al.*, 2020; Jayabal and Prabhakar, 2025).

Challenges

WtE and advanced recycling technologies face interconnected challenges across technical, economic, institutional, social, and environmental dimensions that limit their widespread and effective deployment in supporting the transition toward a circular economy. Technically, variability in waste properties (composition, moisture, calorific value) is a major barrier to stable and efficient operation of incineration, pyrolysis, gasification, and anaerobic digestion facilities, requiring advanced sorting and pre-treatment systems to ensure consistent quality of waste-derived fuels, adding operational complexity and the need for continuous specialised expertise. Managing gaseous emissions, ash, and leachate imposes strict requirements on treatment and control technologies, raising both technological requirements and environmental-compliance costs.

Economically, many WtE projects involve high upfront capital costs, especially for advanced thermal technologies and plastic/e-waste chemical recycling, which use complex processes and expensive catalysts. This is compounded by volatile fossil energy prices, difficulty in consistently pricing WtE-based electricity or fuels competitively, and challenges in securing long-term concessional finance, particularly in developing countries. Ensuring a stable supply of waste, in terms of both quantity and quality, also poses logistical and contractual challenges that affect revenue stability. Institutionally and regulatorily, many countries suffer from weak regulatory frameworks, poor coordination among waste, energy, and environmental authorities, and inadequate enforcement of relevant laws. The absence of clear incentives such as feed-in tariffs for renewable energy or tax exemptions for circular projects reduces the sector's attractiveness for public and private investors. Socially, low public awareness and community acceptance are important determinants of project success. Some technologies, such as incineration, are associated with negative perceptions concerning pollution and health risks, triggering local opposition to facility siting. Lack of trust in local institutions' ability to operate complex technologies safely further constrains acceptance of advanced chemical or digital treatment solutions. Environmentally, WtE systems must ensure that pollution is not shifted between environmental media and that fly ash, persistent organic pollutants, and heavy metals extracted from e-waste are handled safely, which requires advanced monitoring and analytical infrastructure and clear risk-management and emergency-response plans, often insufficiently available in many developing contexts.

Conclusion

Modern waste-recycling and waste-to-energy technologies have demonstrated major potential to achieve environmental sustainability, clean-energy production, emissions reduction, and circular-economy enhancement through diverse solutions, including advanced incineration, pyrolysis, gasification, anaerobic digestion, and advanced recycling of plastics, electronics, and agricultural and industrial wastes, with high efficiencies and relatively attractive economic returns. The results of this review show that WtE technologies represent a promising pillar for integrated waste management and alternative energy supply, with notable potential for emissions reduction and economic improvement, provided that appropriate regulatory and environmental frameworks are in place. Conversion efficiencies and costs differ across thermal and biological technologies, but integrating them into hybrid systems adapted to local waste characteristics can significantly enhance their performance and feasibility. Advanced plastic and e-waste recycling technologies, in particular, can generate high-value-added products within circular value chains. Nevertheless, persistent challenges including waste heterogeneity, high investment costs, strict emission-control requirements, and social acceptance remain key barriers to wider deployment. Accordingly, the study recommends adopting supportive policies for investment in WtE infrastructure, strengthening research and development, and integrating digitalisation and artificial intelligence into waste and energy management, in order to accelerate the transition toward more sustainable and efficient energy systems and to advance the practical realisation of an urban, circular, low-carbon economy.

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Novelty Statement

This review presents a comprehensive and up-to-date assessment of modern waste-recycling and waste-to-energy (WtE) technologies, focusing on their environmental, economic, and technological impacts within circular-economy frameworks. The study uniquely integrates thermal, biological, and advanced recycling technologies, including pyrolysis, gasification, anaerobic digestion, plastic recycling, and e-waste valorisation, while critically evaluating their efficiencies, limitations, and scalability. In addition, the review highlights the emerging role of digitalisation and artificial intelligence in optimizing waste and energy management systems, providing a forward-looking perspective for the development of sustainable urban low-carbon economies.

Author's Contribution

Husam Talib Hamzah contributed to the study conceptualization, literature collection, data interpretation, and manuscript preparation. Veluru Sridevi participated in the scientific supervision, technical evaluation of waste-to-energy systems, and critical revision of the manuscript. Fouad Hussein Ali contributed to data validation, manuscript editing, and final review of the study. All authors read and approved the final version of the manuscript

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